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Nanomaterials and Plant Abiotic Stress in Agroecosystems

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DUE to the human activities, several xenobiotics like nanomaterials have been contaminated the environment. These nanomaterials have been gained much more attention from scientists worldwide. The fate and transformation of nanomaterials in agroecosystems were and still one of the most issues all over the world. Therefore, enormous studies have been published concerning these nanomaterials and their applications in different fields including agricultural, medicinal and industrial sectors. The agricultural applications include soil and water nano-remediation, plant nano-nutrition, plant nano-protection, etc. Moreover, the agri-nanotechnology has many environmental and agricultural challenges including agri-sustainability, management of plant diseases and crop protection, remediating the environmental pollution, water management, minimizing the loss of nutrients and their optimizing as well as ameliorating plant abiotic stresses. On the other hand, nanomaterials under certain concentrations may generate and exhibit many toxic effects on plants due to inducing different reactive species like oxygen and nitrogen. Therefore, further studies are needed at different levels including molecular and subcellular levels in order to determine the behavior of nanomaterials in inhibiting and/or in inducing plant stress. The mode of action of this behavior also is needed more elucidations under different agroecosystem conditions. This review is an attempt to evaluate the behavior of nanomaterials under plant abiotic stress and agroecosystem conditions. The role of nanomaterials in ameliorating plant abiotic stresses mainly will be also highlighted.

Keywords: Nanomaterials, Plants, Agroecosystems, Abiotic stress, Sustainable.

Introduction

Production of high yield from crop plants depends mainly on the availability of high quality soil, water and other environmental conditions including temperature and light (Hakeem 2015; Meena et al. 2017; van der Laan et al. 2017). Any deviation in these conditions will lead to adverse effect on plant productivity at different levels started from mild decline in productivity reaching to classification of affected region as a marginal (Daryanto et al. 2017; Donfouet et al. 2017; He et al. 2017). In addition, climate changes and man-made interventions lead to sharp decline in fertile soil and suitable conditions for food crop production (Khan and Akhtar 2015; Chen et al. 2017). Also traditional methods used for irrigation, fertilization and other agricultural processes may increase this problem due to the accumulation and uncontrolled transformation of added materials (Bellarby et al. 2016; van der Laan et al. 2017). One of the solutions for this problem is the use of new technologies in irrigation and fertilization and search for less toxic forms for plant nutrition. On the other hand, the development of new strains withstands abiotic stresses is required. Natural nanoparticles are a native component of biological systems (nanoclay, many chemicals derived from soil organic matter, lipoproteins, exosomes, magnetosomes, viruses, ferritin) which have diverse structures with wide-spectrum biological roles (Li et al. 2013; Hedayati et al. 2016). Therefore, nanotechnology, a new emerging and fast growing science can help in ameliorating most of these stress factors throw different mechanisms including antioxidant defense system and providing less toxic and more efficient fertilizers (Zuverza-Mena et al. 2016).

Many plant stresses have been reported by

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several researchers including abiotic and biotic stress (e.g., Wani et al. 2016; Abiri et al. 2017; Calanca 2017). Concerning the plant abiotic stresses, they include salinity, drought, flooding, chilling, freezing, ultraviolet radiation, etc, which causes a great loss in crop production worldwide (Wani et al. 2016; Li et al. 2017). Some distinguished books about plant abiotic stress have been published by Springer such as Hirt and Shinozaki (2004), Rai and Takabe (2006), Khan et al. (2008), Pareek et al. (2010), Ahmad and Prasad (2012), Fritsche-Neto and A. Borém (2012), Khan et al. (2012), Khan et al. (2015), Pandey (2015), Al-Khayri et al. (2016) and Srinivasa Rao et al. (2016). Furthermore, recent studies also have been published including different cases of plant abiotic stress (e.g., Rossini et al. 2016; Sah et al. 2016; Asensi-Fabado et al. 2017; Li et al. 2017; Mudalkar et al. 2017; Wang et al. 2017). Due to the multiple abiotic stresses and the increasing chances of global climate change, an urgent need is requested for mitigation and adaptation of these plant abiotic stresses (Grover et al. 2016; Wani et al. 2016). Therefore, the investigation of different effects of abiotic stresses on plant growth and development is crucial issue at different levels including biochemical, physiological and molecular levels (Wani et al. 2016). Different plant mechanisms in counteracting the abiotic stresses and maintaining their growth should be a great significance. The using of nanomaterials is an emerging solution among the accepted solutions of plants towards abiotic stresses (Hatami et al. 2016; Reddy et al. 2016; de la Rosa et al. 2017; Khan et al. 2017).

Due to their unique characteristics, nanomaterials already have been used in several applications including medicinal, industrial and agricultural sectors (Servin and White 2016; Zhang et al. 2016; Khan et al. 2017; Zuverza-Mena et al. 2017). Concerning the agricultural application of nanomaterials, there is an increasing and unlimited uses in agriculture and food systems including nanofertilizers (Tarafdar et al. 2014; Chhipa and Joshi 2016; Dubey and Mailapalli 2016), nanopesticides (Chhipa and Joshi 2016; Dubey and Mailapalli 2016), soil nano-reclaimants (Patra et al. 2016; Floris et al. 2017), nanosensors for nano-farming (Honeychurch 2014; Chhipa and Joshi 2016; Dubey and Mailapalli 2016; Yılmaz et al. 2017), soil and water nanoremediators, etc. (Ingle et al. 2014; Gomes et al. 2016; Gil-Díaz et al. 2016a, b; Gil-Díaz et al. 2017). These nanomaterials may help in reducing the consumption of different agro-chemicals (fertilizers, pesticides, etc.) leading to minimizing the environmental pollution and hence the sustainable agriculture (Dwivedi et al. 2016; Khan et al. 2016; Panpatte et al. 2016; Pulimi and Subramanian 2016).

Regarding the relationship between nanomaterials and plant stress, many studies have been published explaining more details about this relation (e.g., Banerjee and Kole 2016; Kole et al. 2016; Nair 2016; Zaytseva and Neumann 2016; Khan et al. 2017). The main distinguished effect of plant abiotic stress is to cause in general the oxidative stress (Servin and White 2016). Under this oxidative stress, nanomaterials may help stressed-plants in enhancing their defense system including the antioxidative enzymes mainly peroxidase, superoxide dismutase and catalase (Patra et al. 2016). On the other hand, these nanomaterials under higher concerntration may cause also oxidative stress on plants (Li et al. 2015; Zhang et al. 2015; Saharan and Pal 2016; Zaytseva and Neumann 2016) due to the accummulation of reactive species (oxygen and nitrogen) leading to a damage in proteins, nucleic acids and cell membrane (Khan et al. 2017). Therefore, the interaction between nanomaterials and plants under abiotic stress should be investigated under different levels including the physiological, biochemical and cellular levels. Hence, the aim of this work was to focus on the plant abiotic stress and how can nanomaterials be used in enhancing growth of stressed plants and their behavior also under the stress from nanomaterials. The roles of nanomaterials in terrestrial environments will be also highlighted.

Abiotic stresses and plants: problems and challenges

Under normal conditions, all living organisms can ideally grow and develop but under undesirable conditions several problems can happen. These unfavourable conditions include stresses and/ or environmental constraints. The plant stresses could cause losses in crop production. Thus, crop productivity faces a lot of environmental stresses including biotic and abiotic ones (Wani et al. 2016; Abiri et al. 2017). Concerning the abiotic stresses, they include salinity, drought, heavy metals, flooding, chilling, freezing, heat, ozone and ultraviolet radiation. Whereas, the biotic stress includes different pathogens like bacteria, virus, fungi, etc (Abiri et al. 2017; Calanca 2017; Lu et al. 2017; Khan et al. 2017). Therefore, crucial important investigations are needed to know how abiotic stresses affect plant growth and its development at different levels including the physiological, biochemical and molecular studies (Cramer et al. 2011; Hasanuzzaman et al. 2013; Wani et al. 2016). Moreover, in order to produce more food and feed to overcome the ever increasing human populations, it should be prevented any crop losses as possible. So, the study of plant abiotic stress recently has gained unprecedented importance (Sah et al. 2016).

Several investigations have been carried out regarding plant abiotic stresses including drought (Aroca 2012; Hossain et al. 2016a, b; Kaushal and Wani 2016; Xuan et al. 2016; Aslam et al. 2017; Lu et al. 2017; Nxele et al. 2017; Sheikh Mohammadi et al. 2017), salinity (Kaushal and Wani 2016; Xuan et al. 2016; Khan et al. 2017; Jiang et al. 2017; Nxele et al. 2017), heavy metals (Lemtiri et al. 2016; Shahid et al. 2017), flooding (Kamal and Komatsu 2016; Loreti et al. 2016; Azizi et al. 2017), chilling (Xu et al. 2016; Ding et al. 2017), heat (Ohama et al. 2016; Buchner et al. 2017; Prasad et al. 2017), ozone (Alves et al. 2016; Łabanowska et al. 2016; Li et al. 2016) and ultraviolet radiation (Pérez et al. 2016; Ren et al. 2016; Verdaguer et al. 2017).

It is well known that, plants may be exposed to different combinations of abiotic and biotic stresses at the same time under field conditions. Concerning stress combinations, it is reported about common stress combinations including drought and salinity, salinity and heat, drought and pathogen (Suzuki et al. 2014; Rossini et al. 2016; Li et al. 2017; Nxele et al. 2017). This enforced many researchers recently to focus on different interactions among combined abiotic and biotic stress under molecular and other levels (Pandey et al. 2015; Ramegowda and Senthil-Kumar 2015; Nankishore and Farrell 2016; Sinha et al. 2016). Therefore, different tailored molecular and physiological responses by plants have been recorded under these combined stresses. These responses may occur in case of plants exposed to simultaneous stresses but can not deduce in case of different individual stresses (Ramegowda and Senthil-Kumar 2015; Pandey et al. 2015). Thus, the responses of plants to abiotic and biotic stresses are dynamic and complex. Concerning multiple and integrated omics studies, it could be used them in discovering new areas of interactions and regulation as well as response of stress kinetics and identification of multiple response phases (Suzuki et al. 2014; Rossini et al. 2016).

Among abiotic stresses salinity and drought represent a great threat to crop production all over the world. This threat will be accelerated in frame of the global climate change as well as the frequency and severity of different stresses. Furthermore, these abiotic stresses including drought and salinity may cause a loss in crop production about 50 % (Kaushal and Wani 2016; Nahar et al. 2016; Nxele et al. 2017). On the other hand, it is estimated that, the annual losses in agricultural production resulting from the salt-affected lands are approximately US$ 12 billion (Chakrabarty et al. 2016). Several plants can synthetize and then accumulate osmolytes or osmoprotectants (Table 1) including amino acids (proline, glycine, glutamine, etc.), quaternary ammonium compounds (e.g., glycine betaine, β-alanine betaine, proline betaine), tertiary sulphonium compounds (dimethyl sulphoniopropionate or DMSP), sugars (sucrose, trehalose, fructose, maltose, etc.) and sugar alcohols (pinitol, mannitol, myoinositol, ononitol and sorbitol) under stress conditions (Fig. 1; Suprasanna et al. 2016; Vicente et al. 2016).

Therefore, under drought and salinity stresses plants have a hormonal regulation system including abscisic acid (ABA), salicylic acid (SA), melatonin (*N*-acetyl-5-methoxytryptamine) and nitric oxide (NO). These previous molecules are important in regulating plant status during drought, controlling the opening of stomata, photorespiration and antioxidant defenses (Li and Liu 2016). A strong relation among drought, the global climate changes and greenhouse emissions leading to an expansion in the arid land mass as well as great damages to agriculture due to elevated temperatures (Xue et al. 2016). So, the plant abiotic stress is one of the most important challenges facing several countries all over the world. The main effect of drought and salinity stresses can be represented in the plant metabolic functions and maintenance of turgor pressure as well as the disrupt the redox balance by aggravating the production of reactive oxygen or nitrogen species causing oxidative injury (Chakrabarty et al. 2016). Therefore, great problems and challenges concerning plants abiotic stresses face the agricultural production, hence emerging and novel solutions should be addressed. One of the most important solutions is to use the nanomaterials in alleviating the harmful effects of these stresses (Fig. 2).

TABLE 1. List of some protective effects of different exogenously applied osmoprotectants under salt stress (NaCl) to rice crop (*Oryza sativa* L.)

Rice variety or cultivar	Salinity and protectant doses (duration)	Protective effects	Reference
Rice variety Giza 177 and Giza 178	30 and 60 mM NaCl, 25 mM trehalose (12 h)	High antioxidant enzymes activity in shoots of salinity treated Giza 178 more than Giza 177; trehalose stimulated the activities of CAT, POX, SOD	Abdallah et al. (2016)
Rice cv. BRRI dhan 49 and cv. BRRI dhan 54	150, 300 mM NaCl and 5 mM glycinebetaine (48 h)	Enhanced antioxidant system; reduction of oxidative stress parameters (lipid peroxidation and H_2O_2) and lipoxygenase activity; improved MG detoxification system	Hasanuzzaman et al. (2014)
Rice cv. BRRI dhan 49 and cv. BRRI dhan 54	150, 300 mM NaCl and 5 mM proline (48 h)	Increased contents of AsA and GSH, ratio of GSH/ GSSG and activities of APX, MDHAR, DHAR, GR, GPX, CAT; improved oxidative stress and MG toxicity tolerance	Hasanuzzaman et al. (2014)
Rice cv. KDML105	100 mM NaCl and 10 mM proline (6 days)	Increased FW and DW, reduced Na^+ / K^+ ratio, increased endo-proline; pregulated transcription of genes encoding several antioxidant enzymes	Nounjan et al. (2012)
Rice cv. KDML105	100 mM NaCl and 10 mM trehalose (6 days)	Increased FW and DW, reduced Na^+/K^+ ratio and endo- proline	Nounjan et al. (2012)
Rice cv. KDML105	170 mM NaCl and 5, 10 mM sorbitol 5, 10 mM trehalose (24 h)	Enhanced growth, reduced H_2O_2 and lipid peroxidation (indicated by MDA) contents and electrolyte leakage	Theerakulpisut and Gunnula (2012)

Abbreviations: ascorbic acid (AsA), glutathione (GSH), superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), peroxidase (POD), monodehydroascorbate reductase (MDHAR), dehydroascorbate reductase (DHAR), glutathione reductase (GR), glutathione peroxidase (GPX), glutathione-*S*-transferase (GST), oxidized glutathione (GSSG), malondealdehyde (MDA), methylglyoxal (MG), fresh and dry weight (FW and DW). Osmoprotectants are small, non-toxic molecules at low concentrations, efficiently maintain osmotic balance and stabilize proteins and membranes under salt, drought or other stress conditions (Nahar et al. 2016)

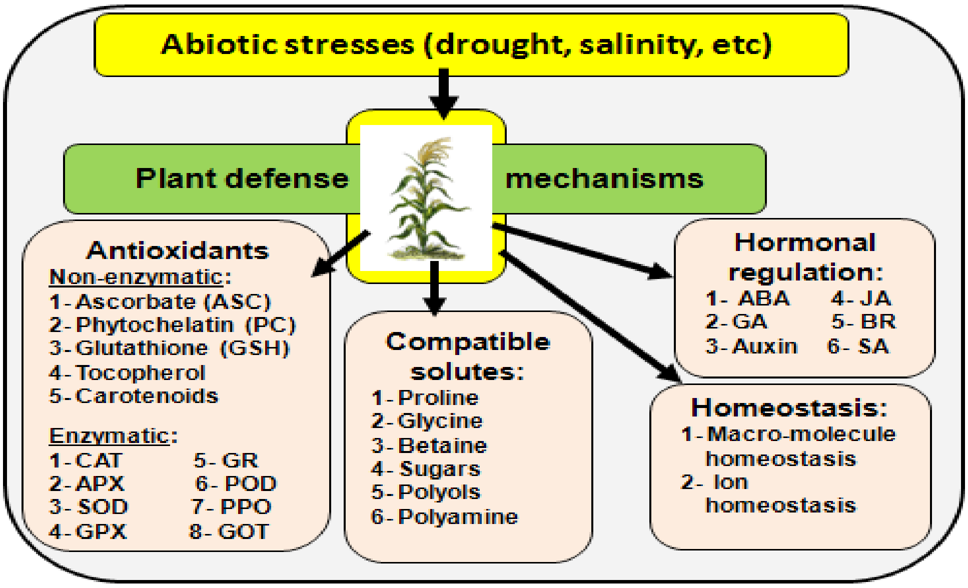

Fig. 1. Different plant defence mechanisms induced in response to abiotic stress, whereas plant enzymatic antioxidants include catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR), glutathione peroxidase (GPX), superoxide dismutase (SOD), polyphenoloxidase (PPO), glutamic oxaloacetic transminase (GOT), peroxidase (POD), and phytohormones include abscisic acid (ABA), gibberellic acid (GA), jasmonic acid (JA), salicylic acid (SA), brassinosteroids (BR) (adapted from Sengupta et al. 2016)

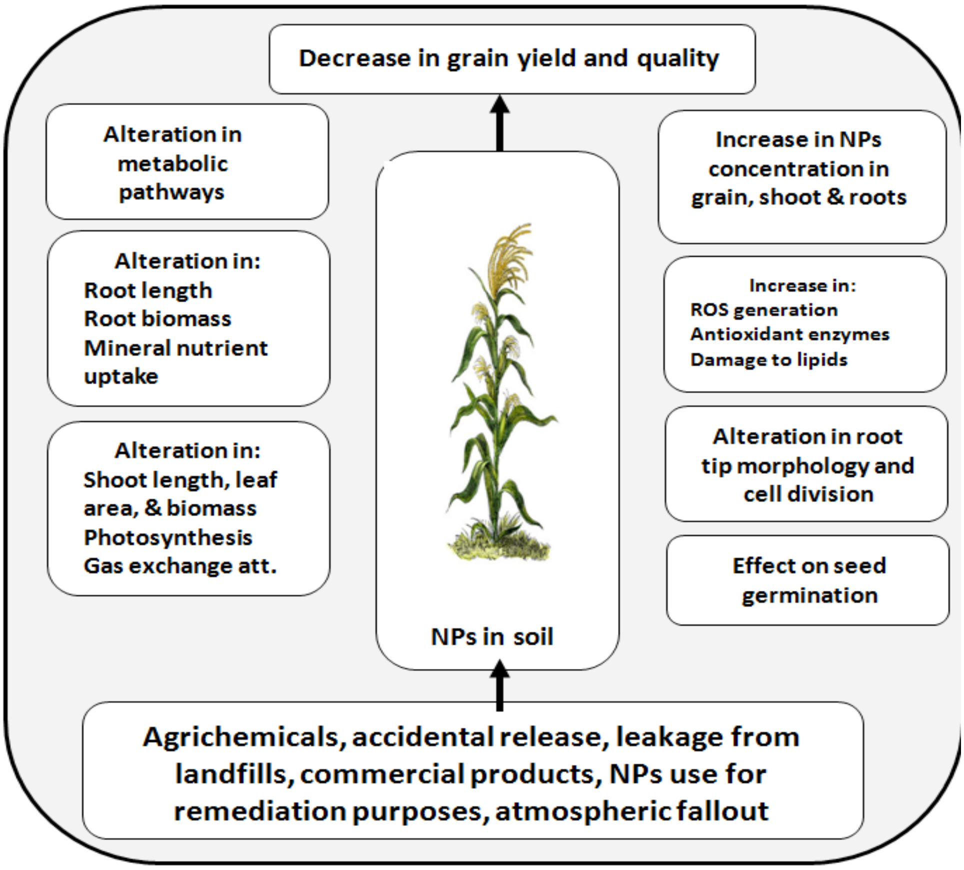

Fig. 2. Possible sources of nanoparticles (NPs) in the soil and their effects on growth and physiology of plants. Under stress from nanparticles, a decrease in grain yield and its quality may be happened due to several actions from plants such as alteration in root, shoot, growth and physiology as well as some metabolic pathways of whole plant (ROS: reactive oxygen species; adapted from Rizwan et al. 2017)

Nanomaterials and agroecosystems

Due to the several unique physicochemical properties of nanoparticles or nanomateriales, nanotechnology has already penetrated many fields for great novel applications in the agriculture sector. These physicochemical properties include a very high reactivity, high surface area, tunable pore size and particle morphology (Belal and El-Ramady 2016; Mani and Mondal 2016; Panpatte et al. 2016; Servin and White 2016; Shalaby et al. 2016). Concerning the agricultural sectors, the applications of nanotechnology have been used in several fields including the fertilization sector (Mastronardi et al.2015; Chhipa 2016; Chhipa and Joshi 2016; Dubey and Mailapalli 2016; Mani et al. 2016; Monreal et al. 2016; Panpatte et al. 2016), plant protection (Bhattacharyya et al. 2016; Nuruzzaman et al. 2016; Saharan and Pal 2016; Li et al. 2017), food sector (Ghanbarzadeh et al. 2016; Eleftheriadou et al. 2017; Grumezescu 2017; Li et al. 2017), precision farming (Gouma et al. 2016; Chhipa and Joshi 2016; Neethirajan 2017), remediation of terrestrial environments (Belal and El-Ramady 2016; Gil-Díaz et al. 2016a, b; Gomes et al. 2016; Patra et al. 2016; Gil-Díaz et al. 2017), etc. These nanoparticles or nanomaterials can enhance the ability of plants to uptake nutrients, therefore increase the fertility of soils as well as crop production. Moreover, salt-affected soils management also can be achieved using these nanomaterials (Patra et al. 2016).

Agroecosystem environments include soils, sediments, plants, water, air etc. These environments may suffer from several stresses even abiotic or biotic. These stresses represent the vital pressure or main problem in deterioration of the agricultural production. There are many case studies regarding these stresses such as salt-affected soils, polluted soils and water, global climate changes, marginal lands, wetlands, bushfires and agroforests, etc (Abhilash et al. 2016; Amini et al. 2016; Bhardwaj et al. 2016).

The previous agro-environments have multiple stresses like salt-affected soils (e.g., salinity and drought stress), polluted lands (e.g., oxidative stress), global climate changes (e.g., drought, flooding and salinity), etc (Khan et al. 2016; Pulimi and Subramanian 2016; Rossi et al. 2016; Singh and Lee 2016; Venkatachalam et al. 2016; Joo and Zhao 2017; Rizwan et al. 2017). Concerning salinity, it is one of the most serious environmental challenges that cause great decline in yield and development of plant species. In fact, salinity is one of the major yield limiting factors for crop plants mainly in arid and semiarid regions of the world (Munns 2005).

It is well known that, a great threat to land productivity can be posed due to the presence of soluble salts in the waters and soils including surface water and groundwater. A decline in agricultural productivity also can be observed because of the toxic effect of high salt content to plants, restricting plant water uptake and preventing uptake of plants essential nutrients. Furthermore, salt affected soils characterized by many problems including the high Na content, poor porosity, waterlogging and loss of nutrients as well as the hydraulic constraints. Several approaches to manage salt-affected marginal lands have been used including the chemical reclamation and the nanomaterials (Patra et al. 2016). Therefore, it could be used nanomaterials or nano-reclaimants in developing and reclamation salt-affected soils. These nano-reclaimants (e.g., nano gypsum, nano calcium and magnesium compounds, etc.) are more efficient and readily manufacturable as well as enhancement hydraulic characteristics and soil stability (Mukhopadhyay and Kaur 2016; Patra et al. 2016).On the other hand, some studies have been focused on the using of nanomaterials in handling with salt-affected soils (Patra et al. 2016). Therefore, it could be reclaimed the salt-affected soils using these previous nano- reclaimants including many advantages as presented in Table 2.

TABLE 2. Different beneficials resulted from nanotechnology intervention in salt-affected soils

Processes	Details
Reducing salt concentration in soil solution	Enhancement Na removal, soil stability and hydraulic characteristics using polymeric carriers in nano-reclaimants *via* clay binding processes
Improving soil drainage	Removing Na^+ from soil solution leads to improve crop growth by improving soil structure in subsurface and sub soils using nano-Ca^{2+}, nanoferrites as well as biofriendly nanopolymers
Replacing Na^+ by Ca^{2+}	Nano-Ca^{2+}, nano-Mg^{2+} and nano-K^+ can be used in removing Na^+ from soil because of the high selectivity and spontaneous reactions (negative ΔG^0) for Ca^{2+} over Na^+ for all clay minerals
Changing carbonate chemistry	Capping/encapsulating Na_2CO_3 with nanopolymers and nano-composites selectively may yield products which are insoluble and may be leached through preferential flows as well as formation of nanoorganic carbonates could be another possibility
Prevention of Na_2CO_3 formation	Nanomaterials including nanocalcium carbonates, nano-Ca^{2+}, nano-Mg^{2+}, nano-K^+ and nano-iron oxides may be used in preventing Na_2CO_3 formation in soils
Addition of K^+	It could be used some nanomaterials like nano-K^+ in clay minerals like illite in accelerating ion exchange reactions (Ca^{2+}, Mg^{2+} and Na^+) to reduce exchangeable sodium saturation
Solubilizing of $CaCO_3$	Calcium carbonate could possibly be solubilized by the application of nano-Ca^{2+}, nano-Mg^{2+} and nano-Fe oxides
Precipitation	Nanopolymers and nano-organic substances may be used in forming complexes or insoluble salts with harmful ions and precipitated
Common ion effect	Nano-iron oxides, nano-Ca^{2+} and nano-Mg^{2+} may be applied to counter adverse effect of Na^+ as a well-known phenomenon

Source: Mukhopadhyay and Kaur (2016); Patra et al. (2016).

Therefore, it could be concluded that, nanomaterials have a great impact on different agroecosystems including both positive and negative effects. Concerning the negative effects, nanomaterials may cause many toxic effects on plants, soil microbes, or aquatic organisms. Whereas, the positive side for nanomaterials includes using these materials in remediation both polluted soil and water, in delivery nanonutrients or other substances, in alleviation the damage effects of abiotic stresses on plants, etc. So, a wise and sustainable application of nanomaterials in agroecosystems should be used.

Role of nanomaterials in ameliorating plant abiotic stresses

It is reported that, nanomaterials can be used for sustainable crop production, in reducing loss of nutrients, in suppressing of diseases and then enhancing the yields (Nair 2016; Khan et al. 2017). It is also documented that, nanomaterials have several benefits including enhancement of plant growth stages starting from seed germination, seedling vigor, initiation and growth of roots, and photosynthesis reaching to flowering under low concentrations (Banerjee and Kole 2016; Kole et al. 2016). Concerning the protection of plants against the oxidative stress, nanomaterials may behave or mimic the role of antioxidative enzymes like peroxidase, superoxide dismutase and catalase (Zaytseva and Neumann 2016). Phytotoxicity may happen under higher concentration of nanomaterials as a result of the generation of reactive oxygen species and accumulation of these reactive species may damage both of membrane of cells and proteins as well as nucleic acids (Khan et al. 2017). Many effects of nanomaterials on plants under abiotic stress have been reported as presented in Table 3 and Fig. 3, whereas a survey for some beneficial and harmful effects for nanomaterials tabulated in Table 4. It could represent some nanomaterials and their roles in alleviating the abiotic stress such as nano-silica, nano silver, nano zinc, and nano titanium as follows:

Nano- silica (nano- SiO_2)

Naturally, plants contain silicon (Si) in considerable concentrations, ranging from 1 to 10% or higher of the dry matter. This fluctuation in Si levels in different plant species may be attributed to the variations in Si uptake ability of the roots (Parveen and Hussain 2008). Silicon, being a beneficial element provides significant benefits to plants at various ionic compositions. Nano-Si plays an important role in the mitigation of salt stress. Many reports about the ability of nano-Si to counteract the negative effects of salt on plant growth rates were recorded (e.g., Wang et al. 2010; Wang et al. 2011). So, the use of nano-silica can be more efficient than the large particles and facilitate its uptake through plant root system. Also, nano-silica affect xylem humidity, water translocation and enhance turger pressure, thus leaf relative water content and water use efficiency will be increased. It is reported that, nano-SiO_2 particles absorbed better and faster than micro-SiO_2, Na_2SiO_3, and H_4SiO_4 when applied on seeds or roots of maize plants (Suriyaprabha et al. 2012).

On the other hand, silicon deposition in the tissues helps to mitigate water stress by reducing the rate of transpiration, enhancing photosynthesis process by improving light receiving efficiency through keeping the leaf rigid and erect, preventing chlorophyll degradation and increasing tolerance insect attack (Ali et al. 2012; Siddiqui et al. 2014). Silicon also is known to reduce uptake of Na^+ by improving K^+: Na^+ ratio and ameliorate the toxicity of other heavy metals. Almutairi (2016a) studied the effect of nano-silicon application on the expression of salt tolerance genes in germinating tomato seedlings under salt stress. These results suggest that N-Si plays an important role in improving seed germination and growth in saline environments. Siddiqui and Al-Whaibi (2014) revealed that, application of 8 g L^{-1} of nano-SiO_2 significantly enhanced tomato seed germination potential and improved percent seed germination, average germination time, seed germination index, vigor index, seedling fresh weight and dry weight.

Nano-silicon is responsible for a number of improvements which lead finally to enhancement plant growth and productivity under both salinity and drought. This includes nutrient elements homeostasis, modification of gas exchange attributes, osmotic adjustment by regulating the synthesis of compatible solutes, stimulation of antioxidant enzymes and gene expression in plants (Qados 2015). Nano-Si also enhances plant growth under heavy metal stress. The suggested mechanisms include reducing active heavy metal ions in growth media, chelation and stimulation of antioxidant systems in plants, complexation and co-precipitation of toxic metals with Si, compartmentation and structural alterations in plants and regulation of the expression of metal transport genes. However, these mechanisms might be associated with plant species, genotypes, metal elements, growth conditions, duration of the stress imposed and so on. Therefore, the generalization of Si-mediated alleviation of metal toxicity should be therefore made with caution (Adrees et al. 2015). Various studies describe the ameliorative effect of Si application on plants under heavy metals or dangerous toxic elements, like Al, Cd, Pb, Cr or Cu (Shen et al. 2014; Keller et al. 2015). Liu et al. (2015) indicated that nano-Si is more efficient than common Si in terms of alleviation of the toxic effects of lead (Pb) on rice growth, it prevent Pb transfer from rice roots to the shoot system of the plant and reduce Pb accumulation in grains, especially in high-Pb accumulating- cultivars and the soils with high levels of Pb pollution.

Silver nanoparticles (AgNPs)

The possibility of application of silver nanoparticles in improvement of plant productivity was assayed by many authors (e.g., Shelar and Chavan 2015), plant growth (e.g., Kavehet al. 2013; Vannini et al. 2013) and enhancing photosynthetic quantum efficiency and chlorophyll content (Sharma et al. 2012; Hatami and Ghorbanpour 2013). Silver nanoparticles are also used as antimicrobial agents to manage plant diseases (Lamsal et al. 2011). Application of silver nanoparticles has been found quite effective in improving resistance against salinity during germination of fennel (Ekhtiyari et al. 2011) and cumin (Ekhtiyari and Moraghebi 2011). It is reported that exposure to AgNPs alleviated the adverse effects of salt stress and improved the germination, root length and seedling fresh and dry weight of tomato seeds under NaCl stress (Almutairi 2016b).

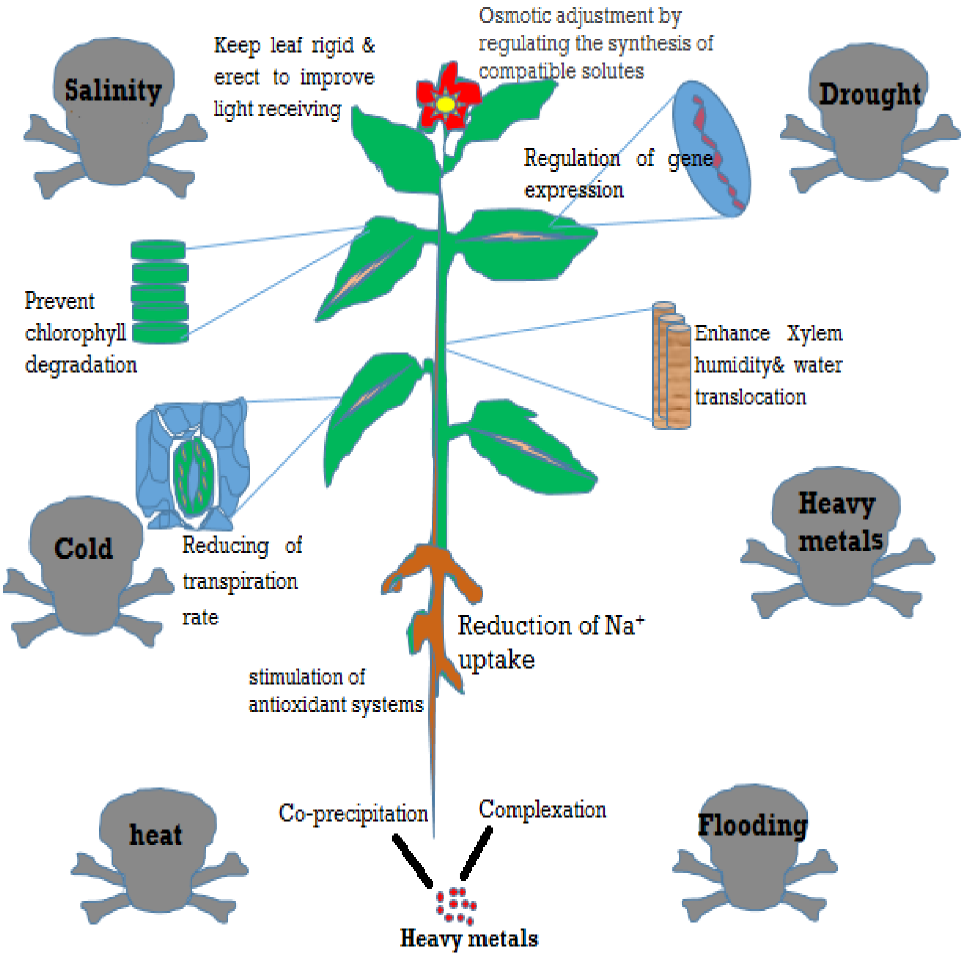

Fig. 3. Different kind of abiotic stresses on plants including drought, salinity, cold, heat, flooding and heavy metals as well as the role of nanomatetials. Different behavior of plants under these stresses can be noticed due to nanomaterials

TABLE 3. Alleviating effects of nanomaterials (NMs) on some abiotic stresses including drought, salinity and flooding stresses in plants

Nanomaterial (diameter)	Plant species	Different effects	Ref.
Drought stress			
Nano TiO_2	Wheat (*Triticum aestivum* L.)	Increasing growth, yield, gluten and starch content of wheat	(1)
Nano TiO_2	Flax (*Linum usitatissimum* L.)	Enhancing chlorophyll and carotenoids content, improving flax growth and yield attributes, decreasing H_2O_2 and malondialdehyde (MDA) content	(4)
Nano TiO_2	Basil (*Ocimum basilicum* L.)	Improving the negative effects of drought stress on basil plants	(5)
Nano Fe	*Carthamus tinctorius*	Reducing impact of drought and improving yield of safflower	(3)
Nano Zero valent Fe	*Arabidopsis thaliana* L.	Activation of plasma membrane H^+-ATPase, stomatal opening, increasing Chl content and plant biomass, maintaining normal drought sensitivity, increasing CO_2 assimilation in thale cress plants	(7)
Nano SiO_2	*Crataegus sp.*	A positive significant effect on photosynthetic rate, stomatal conductance and plant biomass, non-significant effect on chlorophyll and carotenoid content	(6)
Nano ZnO	Soybean (*Glycine max* L.)	Increasing germination percentage and germination rate, decreasing in seed residual fresh and dry weight of soybean	(2)
Salinity stress			
Nano SiO_2	Tomato (*Lycopersicum esculentum* L.)	Lower levels of nano-SiO_2 enhanced seed germination potential, root length and dry weight. Higher levels suppressed seed germination characteristics	(8)
Nano SiO_2	Cherry tomatoes (*Solanum* lycopersicum L.)	Alleviating the effect of salinity on fresh weight, chlorophyll content, photosynthetic rate and the leaf water content	(9)
Nano SiO_2	Basil (*Ocimum basilicum* L.)	Increasing fresh and dry weight, chlorophyll content and proline content	(10)
Nano SiO_2	Lens (*Lens culinaris* Medik.)	Enhancing seed germination and seedling growth	(11)
Nano SiO_2 (10 nm)	Squash (*Cucurbita pepo* L.)	Improving seed germination and growth characteristics, reduced levels of MDA, H_2O_2 and electrolyte leakage, reducing chlorophyll degradation and oxidative damage, enhancing photosynthetic parameters antioxidant enzymes	(12)
Nano SiO_2	Faba bean (*Vicia faba* L.)	Enhancing seed germination, increasing growth, activities of antioxidant enzymes relative water content and total yield	(13)
Nano SiO_2 (20 nm)	Tomato (*Solanum lycopersicum* L.)	Up-regulating the expression profile of four salt stress genes and six genes were down-regulated, suppressing the effect of salinity on seed germination rate, root length and fresh weight	(16)
Nano ZnO and Fe_3O_4	*Moringa peregrina*	Reduction in Na^+ and Cl^- contents, increasing N, P, K^+, Ca^{2+}, Mg^{2+}, Fe, Zn, total chlorophyll, carotenoids, proline, carbohydrates, crude protein and enzymatic and non-enzymatic antioxidants	(14)
Nano ZnO	Sunflower (*Helianthus annuus* L.)	Increasing growth, net CO_2 assimilation rate, sub-stomatal CO_2 content, chlorophyll content, Fv/Fm and Zn content and decreasing Na^+ content in leaves	(15)
Flooding stress			
Nano Ag	*Crocus sativus*	Blocking of ethylene signaling, promotion of root growth	(17)
Nano Al_2O_3	Soybean (*Glycine max* L.)	Regulation of energy metabolism and cell death, improved growth	(18)
Nano Ag	Soybean (*Glycine max* L.)	Reducing generation of cytotoxic byproducts of glycolysis, increasing the abundance of stress-related proteins, enhancing seedling growth	(19)

References: **(1)** Jaberzadeh et al. (2013), **(2)** Sedghi et al. (2013), **(3)** Zareii et al. (2014), **(4)** Aghdam et al. (2015), **(5)** Kiapour et al. (2015), **(6)** Ashkavand et al. (2015), **(7)** Kim et al. (2015), **(8)** Haghighi et al. (2012), **(9)** Haghighi and Pessarakli (2013), **(10)** Kalteh et al. (2014), **(11)** Sabaghnia and Janmohammadi (2014), **(12)** Siddiqui et al. (2014), **(13)** Qados and Moftah (2015), **(14)** Soliman et al. (2015), **(15)** Torabian et al. (2016), **(16)** Almutairi (2016), **(17)** Rezvani et al. (2012), **(18)** Mustafa et al. (2015a), **(19)** Mustafa et al. (2015b)

Source: from Khan et al. (2017)

TABLE 4. The beneficial effects of engineered nanomaterials on plants compared with the harmful effects of these nanoparticles

Item in details	Selected References
The beneficial effects nanomaterials (under low concentration)	
(1)- Nanomaterials have an important role in plant development and growth parameters such as:	Ma and Gao (2015); Zhang et al. (2015); Khan et al. (2017); Zuverza-Mena et al. (2017)
- **Seed germination**: nanomaterials (e.g. nano-TiO_2) help plants in water absorption, regulate water permeability, activate of genes responsible for water channel protein and improving germination of seeds	Zheng et al. (2005); Heinen and Chaumont (2009); Khodakovskaya et al. (2011)
- **Germination rate:** due to the nanomaterials penetration into the seed coupled, an increase in seed water uptake	Khodakovskaya et al. (2009); Zaytseva and Neumann (2016)
- **Plant growth:** nanomaterials (e.g. nano-TiO_2) improve through enhancing N metabolism and photosynthesis as well as better cell growth by regulating cell cycle	Yang et al. (2006); Mingyu et al. (2007a, b); Khodakovskaya et al. (2011)
(2)- Nanoparticles also can play a significant role in the protection of plants against various abiotic stresses	Khan et al. (2017); Reedy et al. (2016); Hatami et al. (2016)
(3)- These nanomaterials enhance and mimic the action of antioxidative enzymes as well as scavenging the ROS	Rico et al. (2013a, b); Taran et al. (2016)
(4)- Small size and large surface area of these nanoparticles provide access for toxic metals for binding and thus reduced availability and toxicity of metals	Worms et al. (2012); Pulimi and Subramanian (2016)
(5)- Nanomaterials can protect the photosynthetic system as well as improving the photosynthesis process by suppressing oxidative and osmotic stresses	Miller et al. (2017); Zuverza-Mena et al. (2017)
The harmful of nanomaterials on plants (under high concentration)	
(1)- Nanomaterials show some distinguished toxicity symptoms at high concentration	Slomberg and Schoenfisch, (2012)
(2)- Nanomaterials also alter gene expression involved in biotic and abiotic stress responses including cell biosynthesis, cell organization, electron transport and energy pathways	Aken (2015); Hristozov et al. (2016); Khan et al. (2017)
(3)- Excess of nanomaterials in the growth medium induces oxidative stress and causes reduction in germination rate, root and shoot length and loss of photosynthesis, chlorophyll and then reduce biomass	Barhoumi et al. (2015); Da Costa and Sharma (2016); Wang et al. (2016); Zuverza-Mena et al. (2017)
(4)- Excess of nanomaterials in growth medium may reduce nutritive value of crop plants	Peralta-Videa et al. (2014); Khan et al. (2017)

Source: Khan et al. (2017).

Zinc oxide nanoparticles (nano-ZnO)

Zinc (Zn) is among the important key micronutrient required for the optimum growth and development of plants which carries vital metabolic reactions within the plants to promote growth and development. Despite its role in the growth and development of plants, Zn also plays a vital role in reducing toxic heavy metals uptake by plants, thereby prevents plants from the heavy metal toxicity such as Cd (Baybordi 2005). Zinc also has an important role in plants survival under environmental stress conditions, where it plays a role in enhancing or preparing the plants to tolerate drought stress (Cakmak 2008). It plays a considerable role in stomatal regulation owing to its ability to maintaining membrane integrity and retaining potassium content of the cells as well as a role in plant water relations (Khan et al. 2004). In an experiment on chickpea, it is indicated that Zn deficiency reduced the plant ability to adjust osmotic pressure in under drought conditions (Khan et al. 2004). Zinc influence auxin production (Waraich et al. 2011a), where it represents a co-enzyme for tryptophane synthesis, a precursor to indole acetic acid production which promotes the root development and water deficiency tolerance in plants (Waraich et al. 2011b). As mentioned earlier, the supplementation of micro element in small size (nano size) facilitate its uptake by plant and reduce the used dose. So, the previous functions of zinc can be achieved more efficiently when using nano zinc. It is investigated that, yield and water use efficiency of sunflower plant using nano-ZnO under water stress compared with bulk ZnO (Seghatoleslami and Forutani 2015). The result indicated that, in full irrigation treatment the highest seed and biomass were related to bulk ZnO treatments, but under water stress conditions the highest biomass and water use efficiency was related to nano-ZnO treatment. Totally the result indicated that application of nano-ZnO increased seed yield and water use efficiency**.**

Nano titanium oxide (nano-TiO_2)

Titanium has significant biological effects on plants, being beneficial at low levels but toxic at higher concentrations. Photo-catalytic degradation of pesticides with TiO_2 and other catalyst has shown promise as potential water remediation method (Lee et al. 2003). Nano-TiO_2 can improve photosynthetic apparatus and enhance a plant's ability to capture sunlight, that affects the manufacture of pigments and the transformation of light energy to active electron and chemical activity and thus increase photosynthetic efficiency as in maize, especially under drought stress (Akbari et al. 2014). Nano-TiO_2 also was observed to promote the growth of spinach through an increase in photosynthetic rate and nitrogen metabolism in spinach (Yang et al. 2006). Nano-TiO_2 can enhance plant water and nitrogen use and stimulate some antioxidant enzyme activities, such as SOD, POD and CAT such as in canola (Mahmoodzadeh et al. 2013) and wheat plants (Jaberzadeh et al. 2013). Shallan et al. (2016) investigated the effects of nano-TiO_2 and nano-SiO_2 on chemical constituents and yield characteristics of cotton plant under drought stress. The results showed that pretreatment of cotton plants under drought stress with nano-TiO_2 or nano-SiO_2 caused increasing of pigments 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 enhancement of yield characteristics. The optimum concentration of nano-TiO_2 and nano-SiO_2 to alleviate the drought stress in cotton plants was 50 ppm and 3200 ppm, respectively. Finally, it can be concluded that foliar application of nano-TiO_2 or nano-SiO_2 could improve the drought tolerance of cotton plants. On the other hand, application of nano-TiO_2 can decrease cadmium (Cd) stress and increase Cd uptake in soybean plants. The suggested mechanism is the formation of new bonds in the plant tissue with the Cd/nano-TiO_2 particles (Singh and Lee 2016).

Therefore, it could be concluded the role of low concentrations of nanomaterials in ameliorating of the plant abiotic stress through some mechanisms such as protecting plants against different abiotic stresses by (1) activating the plant cell signals due to over production of reactive oxygen species (ROS) and/or reactive nitrogen species (RNS) and (2) stimulating plant defense system (enzymatic and non-enzymatic antioxidant activities), accumulating of osomolytes and free amino acids as well as nutrients (Khan et al. 2017), whereas these nanomaterials may be caused a toxicological effects on plants under high concentrations (Husen and Siddiqui 2014). It is worth to mention that, the application of nanomaterials to stressed plants (or under adverse environmental conditions) may enhance the generation process of different reactive species (ROS and RNS) leading to damage resulting from the oxidative stress (Chichiriccò and Poma 2015; Khan et al. 2017).

Conclusion

Great challenges face the global agricultural production including the changes in climate, the depletion of water and land resources, energy problems, abiotic stresses, etc. The proper solutions in facing these challenges should be more sustainable and more eco-friendly. The agri-nanotechnology is considered one of the most important and promising issues in this context. It is found that, nanomaterials can alleviate the damage resulting from different abiotic stresses through activating process of plant defense system. It is also well known that, these nanomaterials have the ability to penetrate plant tissues due to their small size. These nanomaterials also can improve the facilities of surface area to be more effective in adsorption process and in delivery targeted substances. Due to the properties of nanomaterials, they can regulate water uptake by plant tissues, hence promote the seed germination and plant growth. Concerning the role of nanomaterials in alleviating the damage of plant abiotic stresses or in inhibiting plant growth and its toxicity, further studies are essential under different levels including plant molecular and cellular levels. Although, a few reports have some interpretations regarding the toxic effects of nanomaterials on plants, there is still an urgent need to elucidate the residual effects of applied nanomaterials on different agroecosystems.

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References

Abdallah M.M.-S., Z.A. Abdelgawad and H.M.S. El-Bassiouny (2016) Alleviation of the adverse effects of salinity stress using trehalose in two rice varieties. *South African Journal of Botany* **103**, 275–282.

Abdel-Haliem M E. F., H. S. Hegazy, N. S. Hassan and D. M. Naguib (2017) Effect of silica ions and nano silica on rice plants under salinity stress. *Ecological Engineering*, **99**, 282-289.

Abhilash P. C., V Tripathi, S. A Edrisi, R K Dubey, M Bakshi, P. K. Dubey, H. B. Singh and S D. Ebbs (2016) Sustainability of crop production from polluted lands. *Energ. Ecol. Environ.* **1**(1), 54–65. DOI: 10.1007/s40974-016-0007-x.

Abiri R, N A Shaharuddin, M Maziah, Z N B Yusof, N Atabaki, M Sahebi, A Valdiani, N Kalhori, P Azizi and M M. Hanafi (2017) Role of ethylene and the APETALA 2/ethylene response factor superfamily in rice under various abiotic and biotic stress conditions. *Environmental and Experimental Botany,* **134**, 33-44.

Adhikari T, Sarkar D, Mashayekhi H, Xing B (2016) Growth and enzymatic activity of maize (*Zea mays* L.) plant: solution culture test for copper dioxide nano particles. *J Plant Nutr* **39** (1), 99–115.

Adrees M., Ali, S., Rizwan, M., Zia-ur-Rehman, M., Ibrahim, M., Abbas, F., Irshad, M. K. (2015) Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: a review. *Ecotoxicology and Environmental Safety*, **119,** 186-197.

Ahmad P. and M.N.V. Prasad (2012) *Abiotic Stress Responses in Plants: Metabolism, Productivity and Sustainability.* DOI: 10.1007/978-1-4614-0634-1, Springer New York

Akbari G. A., Morteza, E., Moaveni, P., Alahdadi, I., Bihamta, M. R., Hasanloo, T. (2014) Pigments apparatus and anthocyanins reactions of borage to irrigation, methylalchol and titanium dioxide. *International Journal of Biosciences* **4** (7), 192-208.

Ali S., Farooq, M. A., Yasmeen, T., Hussain, S., Arif, M. S., Abbas, F., Zhang, G. (2013) The influence of silicon on barley growth, photosynthesis and ultra-structure under chromium stress. *Ecotoxicology and Environmental Safety,* **89,** 66-72..

Al-Khayri J. M., Shri Mohan Jain and Dennis V. Johnson (2016) *Advances in Plant Breeding Strategies: Agronomic, Abiotic and Biotic Stress Traits.* DOI: 10.1007/978-3-319-22518-0, Springer International Publishing Switzerland.

Almutairi Z. M (2016a) Effect of nano-silicon application on the expression of salt tolerance genes in germinating tomato (*Solanum lycopersicum* L.) seedlings under salt stress. *Plant Omics Journal* **9** (1), 106-114.

Almutairi Z. M. (2016b) Influence of silver nano-particles on the salt resistance of tomato (*Solanum lycopersicum* L.) during germination. *Int. J. Agric. Biol.,* **18** (2), DOI: 10.17957/IJAB/15.0114.

Alves E S, B B Moura, A N V Pedroso, F Tresmondi, S R Machado (2016) Cellular markers indicative of ozone stress on bioindicator plants growing in a tropical environment. *Ecological Indicators,* **67**, 417-424.

Amini S., H Ghadiri, C Chen and P Marschner (2016) Salt-affected soils, reclamation, carbon dynamics, and biochar: a review. *J Soils Sediments* **16**, 939–953. DOI: 10.1007/s11368-015-1293-1.

Aroca R (2012) *Plant Responses to Drought Stress from Morphological to Molecular Features.* Springer-Verlag Berlin Heidelberg, DOI: 10.1007/978-3-642-32653-0

Asensi-Fabado M-A, A Amtmann and G Perrella (2017) Plant responses to abiotic stress: The chromatin context of transcriptional regulation. Biochimica et Biophysica Acta (BBA) - Gene Regulatory *Mechanisms,* **1860** (1), 106-122.

Aslam Z., J Z K Khattak and M Ahmed (2017)Drought Tolerance in Cereal Grain Crops Under Changing Climate. In: M. Ahmed, C.O. Stockle (eds.), *Quantification of Climate Variability, Adaptation and Mitigation for Agricultural Sustainability,* pp: 181 – 209. DOI: 10.1007/978-3-319-32059-5_9 Springer International Publishing Switzerland

Azizi S., M. Tabari and G. G. Strike (2017) Growth, physiology, and leaf ion concentration responses to long-term flooding with fresh or saline water of *Populus euphratica*. *South African Journal of Botany,* **108,** 229-236.

Banerjee J and C Kole (2016) Plant Nanotechnology: An Overview on Concepts, Strategies, and Tools. In: C. Kole et al. (eds.), *Plant Nanotechnology,* pp: 1 -14. DOI: 10.1007/978-3-319-42154-4_1, Springer International Publishing Switzerland

Barhoumi L., Oukarroum, A., Taher, L.B., Smiri, L.S., Abdelmelek, H., Dewez, D. (2015) Effects of superparamagnetic iron oxide nanoparticles on photosynthesis and growth of the aquatic plant *Lemna gibba. Arch. Environ. Contam.Toxicol.* **68,** 510–520

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

Bellarby J., G. Siciliano, L.E.D. Smith, L. Xin, J. Zhou, K. Liu, L. Jie, F. Meng, A. Inman, C. Rahn, B. Surridge, P.M. Haygarth (2016) Strategies for sustainable nutrient management: insights from a mixed natural and social science analysis of Chinese cropproduction systems. *Environmental Development* (In Press)

Bhardwaj A.K., S. Srivastava, J.C. Dagar, R.K. Yadav and D.K. Sharma (2016) Removing Bottlenecks in Fertilizing Salt-Affected Soils for Agricultural Production. In: J.C. Dagar et al. (eds.), *Innovative Saline Agriculture*, DOI: 10.1007/978-81-322-2770-0_7, Springer India

Bhattacharyya A, P Duraisamy, M Govindarajan, A A. Buhroo and R Prasad (2016) Nano-Biofungicides: Emerging Trend in Insect Pest Control. In: R. Prasad (ed.), Advances and Applications through Fungal Nanobiotechnology, *Fungal Biology,* pp: 307 – 319. DOI: 10.1007/978-3-319-42990-8_15, Springer International Publishing Switzerland

Buchner O., T Roach, J Gertzen, S Schenk, M Karadar, W Stöggl, R Miller, C Bertel, G Neuner and I Kranner (2017) Drought affects the heat-hardening capacity of alpine plants as indicated by changes in xanthophyll cycle pigments, singlet oxygen scavenging, α-tocopherol and planthormones**.** *Environmental and Experimental Botany*, **133**, 159-175

Cakmak I. (2008) Enrichment of cereal grains with zinc: agronomic or genetic biofortification? *Plant and Soil,* **302** (1-2), 1-17.

Calanca P. P. (2017) Effects of Abiotic Stress in Crop Production. In: M. Ahmed, C.O. Stockle (eds.), *Quantification of Climate Variability, Adaptation and Mitigation for Agricultural Sustainability,* pp: 165 – 180. DOI: 10.1007/978-3-319-32059-5_8 Springer International Publishing Switzerland

Chakrabarty A., M. Aditya, N. Dey, N. Banik and S. Bhattacharjee (2016) Antioxidant Signaling and Redox Regulation in Drought- and Salinity-Stressed Plants. In: M.A. Hossain et al. (eds.), *Drought Stress Tolerance in Plants,* **1**, pp: 465 – 498. DOI: 10.1007/978-3-319-28899-4_20, Springer International Publishing Switzerland 2016

Chen W-Y, T Suzuki and M Lackner (2017) *Handbook of Climate Change Mitigation and Adaptation.* DOI: 10.1007/978-3-319-14409-2, Springer International Publishing Switzerland

Chhipa H, Joshi P (2016) Nanofertilisers, nanopesticides and nanosensors in agriculture. In: Ranjan S, Dasgupta N, Lichtfouse E (eds.) *Nanoscience In Food and Agriculture 1, Sustainable Agriculture Reviews,* **20**. Springer, pp 247–282. doi:10.1007/978-3-319-39303-2

Chhipa H. (2016) Nanofertilizers and nanopesticides for agriculture. *Environ Chem Lett,* DOI: 10.1007/s10311-016-0600-4

Chichiriccò, G., Poma, A. (2015) Penetration and toxicity of nanomaterials in higher plants. *Nanomater.* **5,** 851-873

Cramer G R, K Urano, S Delrot, M Pezzotti and K Shinozaki (2011) Effects of abiotic stress on plants: a systems biology perspective. *Plant Biology,* **11,** 163.

Da Costa M.V.J., Sharma, P.K. (2016) Effect of copper oxide nanoparticles on growth, morphology, photosynthesis, and antioxidant response in *Oryza sativa*. *Photosynthetica* **54**, 110–119.

Daryanto S., L Wang, P-A Jacinthe (2017) Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review. *Agricultural Water Management,* **179**, 18-33.

Davarpanah S., A Tehranifar, G Davarynejad, J Abadía, R Khorasani (2016) Effects of foliar applications of zinc and boron nano-fertilizers on pomegranate (*Punica granatum* cv. Ardestani) fruit yield and quality**.** *Scientia Horticulturae,* **210**, 57-64

de la Rosa G, C García-Castañeda, E Vázquez-Núñez, Á J Alonso-Castro, G Basurto-Islas, Á Mendoza, G Cruz-Jiménez, C Molina (2017) Physiological and biochemical response of plants to engineered NMs: Implications on future design**.** *Plant Physiology and Biochemistry,* **110**, 226-235

Ding F., M Wang and S Zhang (2017) Overexpression of a Calvin cycle enzyme SBPase improves tolerance to chilling-induced oxidative stress in tomato plants. *Scientia Horticulturae,* **214**, 27-33.

Donfouet H P P, A Barczak, C Détang-Dessendre, E Maigné (2017) Crop Production and Crop Diversity in France: A Spatial Analysis. *Ecological Economics*, **134**, 29-39.

Dubey A. and D. R. Mailapalli (2016) Nanofertilisers, Nanopesticides, Nanosensors of Pest and Nanotoxicity in Agriculture. In: E. Lichtfouse (ed.), *Sustainable Agriculture Reviews,* **19**, pp: 307 – 330. DOI: 10.1007/978-3-319-26777-7_7, Springer International Publishing Switzerland

Dwivedi S, Q Saquib, A A. Al-Khedhairy and J Musarrat (2016) Understanding the Role of Nanomaterials in Agriculture. In: D.P. Singh et al. (eds.), *Microbial Inoculants in Sustainable Agricultural Productivity,* pp: 271 – 288. DOI: 10.1007/978-81-322-2644-4_17, Springer India

Ekhtiyari R. and F. Moraghebi (2011) The study of the effects of nano silver technology on salinity tolerance of cumin seed (*Cuminum cyminum* L.). *Plant and Ecosystem* **7** (25), 99-107.

Ekhtiyari R., MOHEBBI, H., Mansouri, M. (2011) The study of the effects of nano silver technology on salinity tolerance of (*Foeniculum vulgare* Mill.). *Plant and Ecosystem* **7** (27), 55-62.

Eleftheriadou M., G Pyrgiotakis and P Demokritou (2017) Nanotechnology to the rescue: using nano-enabled approaches in microbiological food safety and quality. *Current Opinion in Biotechnology*, **44,** 87-93.

Floris B, P Galloni, F Sabuzi and V Conte (2017) Metal systems as tools for soil remediation. *Inorganica Chimica Acta,* **455** (Part 2), 429-445

Forest V, L Leclerc, J-F Hochepied, A Trouvé, G Sarry, J Pourchez (2017) Impact of cerium oxide nanoparticles shape on their *in vitro* cellular toxicity**.** *Toxicology in Vitro,* **38**, 136-141. doi:10.1016/j.tiv.2016.09.022

Fritsche-Neto R. and A. Borém (2012) *Plant Breeding for Abiotic Stress Tolerance.* DOI: 10.1007/978-3-642-30553-5, Springer-Verlag Berlin Heidelberg

Gerdini F. S. (2016) Effect of nano potassium fertilizer on some parchment pumpkin (*Cucurebita pepo*) morphological and physiological characteristics under drought conditions. *Intl J Farm & Alli Sci.* **5** (5), 367-371

Ghanbarzadeh B., A Babazadeh and H Hamishehkar (2016) Nano-phytosome as a potential food-grade delivery system. *Food Bioscience*, **15**, 126-135

Gil-Díaz M., A. González, J. Alonso and M.C. Lobo (2016a) Evaluation of the stability of a nanoremediation strategy using barley plants. *Journal of Environmental Management,* **165**, 150-158.

Gil-Díaz M., P. Pinilla, J. Alonso and M. C. Lobo (2017) Viability of a nanoremediation process in single or multi-metal(loid) contaminated soils. *Journal of Hazardous Materials*, **321**, 812-819

Gil-Díaz M., S. Diez-Pascual, A. González, J. Alonso, E. Rodríguez-Valdés, J.R. Gallego, M.C. Lobo (2016b) A nanoremediation strategy for the recovery of an As-polluted soil. *Chemosphere*, **149,** 137-145

Gomes H. I., G. Fan, L. M. Ottosen, C. Dias-Ferreira and A. B. Ribeiro (2016) Nanoremediation Coupled to Electrokinetics for PCB Removal from Soil. In: A.B. Ribeiro et al. (eds.), *Electrokinetics Across Disciplines and Continents,* pp: 331 – 350. DOI: 10.1007/978-3-319-20179-5_17, Springer International Publishing Switzerland

Gouma P I., S R. Simon, M Stanacevic (2016) Nano-sensing and catalysis technologies for managing food-water-energy (FEW) resources in farming. *Materials Today Chemistry,* **1–2,** 40-45.

Grover M, S Bodhankar, M. Maheswari and C. Srinivasarao (2016) Actinomycetes as Mitigators of Climate Change and Abiotic Stress. In: G. Subramaniam et al. (eds.), *Plant Growth Promoting Actinobacteria,* pp: 203 – 212. DOI: 10.1007/978-981-10-0707-1_13, Springer Science + Business Media Singapore

Grumezescu A. (2017) *Food Preservation.* 1st Edition. Academic Press

Gupta A, Sarkar AK and M Senthil-Kumar (2016)

Global Transcriptional Analysis Reveals Unique and Shared Responses in *Arabidopsis thaliana* Exposed to Combined Drought and Pathogen Stress. *Front Plant Sci.* **7**, 686. DOI: 10.3389/fpls.2016.00686. eCollection 2016.

Hakeem K R (2015) *Crop Production and Global Environmental Issues.* DOI: 10.1007/978-3-319-23162-4, Springer International Publishing Switzerland

Hasanuzzaman M, Alam MM, Rahman A, Hasanuzzaman M, Nahar K, Fujita M (2014) Exogenous proline and glycine betaine mediated upregulation of antioxidant defense and glyoxalase systems provides better protection against salt-induced oxidative stress in two rice (*Oryza sativa* L.) varieties. *Biomed Res Int* **2014**,757219

Hasanuzzaman M, K Nahar, Md. M Alam, R Roychowdhury and M Fujita (2013) Physiological, Biochemical, and Molecular Mechanisms of Heat Stress *Tolerance in Plants. Int. J. Mol. Sci.* **14,** 9643-9684. doi:10.3390/ijms14059643

Hatami M, K Kariman and M Ghorbanpour (2016) Engineered nanomaterial-mediated changes in the metabolism of terrestrial plants. *Science of The Total Environment,* **571**, 275-291

Hatami M., Ghorbanpour, M. (2013) Effect of nano-silver on physiological performance of pelargonium plants exposed to dark storage. *Journal of Horticultural Research,* **21** (1), 15-20.

He C, Z Liu, M Xu, Q Ma, Y Dou (2017) Urban expansion brought stress to food security in China: Evidence from decreased cropland net primary productivity. *Science of The Total Environment,* **576,** 660-670

Hedayati M, P Sharma, D Katyal, F Fagerlund (2016) Transport and retention of carbon-based engineered and natural nanoparticles through saturated porous media. *J Nanopart Res* **18**, 57. DOI: 10.1007/s11051-016-3365-6.

Heinen R.B., Ye, Q., Chaumont, F. (2009) Role of aquaporins in leaf physiology. *J. Exp. Bot.* **11,** 2971–2985.

Hirt H. and K. Shinozaki (2004) Plant Responses to Abiotic Stress**.** *Topics in Current Genetics* **4,** DOI: 10.1007/b84369, Springer-Verlag Berlin Heidelberg

Honeychurch K. C. (2014) *Nanosensors for Chemical and Biological Applications: Sensing with Nanotubes, Nanowires and Nanoparticles*. Elsevier B.V.**,** http://dx.doi.org/10.1016/B978-0-85709-660-9.50014-X

Hossain M A, S H Wani, S Bhattacharjee, D. J. Burritt and L-S P Tran (2016a) *Drought Stress Tolerance in Plants: Physiology and Biochemistry* (Vol. 1). Springer International Publishing Switzerland, DOI: 10.1007/978-3-319-28899-4

Hossain M A, S H Wani, S Bhattacharjee, D. J. Burritt and L-S P Tran (2016b) *Drought Stress Tolerance in Plants: Molecular and Genetic Perspectives* (Vol. 2). Springer International Publishing Switzerland, DOI: 10.1007/978-3-319-32423-4

Hristozov D., S Gottardo, E Semenzin, A Oomen, P Bos, W Peijnenburg, M van Tongeren, B Nowack, N Hunt, A Brunelli, J J. Scott-Fordsmand, L. Tran, A Marcomini (2016) Frameworks and tools for risk assessment of manufactured nanomaterials. *Environment International,* **95**, 36-53

Husen, A., Siddiqi, K.S. (2014) Phytosynthesis of nanoparticles: Concept, controversy and application. *Nanoscale Res. Lett.* **9,** 229–252.

Ingle A. P., A B. Seabra, N Duran, M Rai (2014) Nanoremediation: A New and Emerging Technology for the Removal of Toxic Contaminant from Environment. In: S. Das (Ed.) *Microbial Biodegradation and Bioremediation,* pp: 233-250. Elsevier B. V., http://dx.doi.org/10.1016/B978-0-12-800021-2.00027-3

Jaberzadeh A, Moaveni P, Moghadam HRT, Zahedi H (2013) Influence of bulk and nanoparticles titanium foliar application on some agronomic traits, seed gluten and starch contents of wheat subjected to water deficit stress. *Not Bot Horti Agrobo* **41,** 201–207

Jiang Y., X Ding, D Zhang, Q Deng, C-L Yu, S Zhou and D Hui (2017) Soil salinity increases the tolerance of excessive sulfur fumigation stress in tomato plants**.** *Environmental and Experimental Botany,* **133**, 70-77

Joo S H and D Zhao (2017) Environmental dynamics of metal oxide nanoparticles in heterogeneous systems: A review. *Journal of Hazardous Materials,* **322** (Part A): 29-47. http://dx.doi.org/10.1016/j.jhazmat.2016.02.068

Kamal A. H M and S Komatsu (2016) Jasmonic acid induced protein response to biophoton emissions and flooding stress in soybean. *Journal of Proteomics,* **133**, 33-47.

Kanayama Y. and A. Kochetov (2015) *Abiotic Stress*

Biology in Horticultural Plants. DOI: 10.1007/978-4-431-55251-2, Springer Japan

Kaushal M. and S. P. Wani (2016) Rhizobacterial-plant interactions: Strategies ensuring plant growth promotion under drought and salinity stress. *Agriculture, Ecosystems & Environment,* **231**, 68-78

Keller C., Rizwan, M., Davidian, J. C., Pokrovsky, O. S., Bovet, N., Chaurand, P., Meunier, J. D. (2015) Effect of silicon on wheat seedlings (*Triticum turgidum* L.) grown in hydroponics and exposed to 0 to 30 µM Cu. *Planta*, **241** (4), 847-860.

Khan A L, M Waqas, S Asaf, M Kamran, R Shahzad, S Bilal, M A Khan, S-M Kang, Y-H Kim, B-W Yun, A Al-Rawahi, A Al-Harrasi and I-J Lee (2017) Plant growth-promoting endophyte *Sphingomonas* sp. LK11 alleviates salinity stress in *Solanum pimpinellifolium*. *Environmental and Experimental Botany,* **133,** 58-69

Khan H. R., McDonald, G. K., Rengel, Z. (2004) Zinc fertilization and water stress affects plant water relations, stomatal conductance and osmotic adjustment in chickpea (*Cicer arientinum* L.). *Plant and Soil,* **267**(1-2), 271-284.

Khan M. N, M Mobin, F Mohammad and F J. Corpas (2015) *Nitric Oxide Action in Abiotic Stress Responses in Plants*. DOI: 10.1007/978-3-319-17804-2, Springer International Publishing

Khan M A and M S Akhtar (2015) Agricultural Adaptation and Climate Change Policy for Crop Production in Africa. In: K.R. Hakeem (ed.), *Crop Production and Global Environmental Issues,* DOI: 10.1007/978-3-319-23162-4_18, Springer International Publishing Switzerland

Khan M. N., M. Mobin, Z. K. Abbas, K.A. AlMutairi, Z. H. Siddiqui (2017) Role of nanomaterials in plants under challenging environments. *Plant Physiology et Biochemistry,* **110**, 194-209. DOI: 10.1016/j.plaphy.2016.05.038.

Khan N A., S Singh and S Umar (2008) *Sulfur Assimilation and Abiotic Stress in Plants*. DOI: 10.1007/978-3-540-76326-0, Springer Berlin Heidelberg

Khan N. A., R. Nazar, N. Iqbal and N. A. Anjum (2012) *Phytohormones and Abiotic Stress Tolerance in Plants*. DOI: 10.1007/978-3-642-25829-9, Springer Berlin Heidelberg

Khan N. S., A. K. Dixit and R. Mehta (2016)Nanoparticle Toxicity in Water, Soil, Microbes, Plant and Animals. In: S. Ranjan et al. (eds.), Nanoscience *in Food and Agriculture 2, Sustainable Agriculture Reviews* **21**, pp: 277 – 309. DOI: 10.1007/978-3-319-39306-3_9, Springer International Publishing Switzerland

Khodakovskaya, M., Dervishi, E., Mahmood, M., Xu, Y., Li, Z., Watanabe, F. (2009) Carbon nanotubes are able to penetrate plant seed coat and dramatically affect seed germination and plant growth. *ACS Nano* **3**, 3221–3227.

Khodakovskaya, M.V., de Silva, K., Biris, A.S., Dervishi, E., Villagarcia, H. (2012) Carbon nanotubes induce growth enhancement of tobacco cells. *ACS Nano* **6**, 2128–2135.

Khodakovskaya, M.V., de Silva, K., Nedosekin, D.A., Dervishi, E., Biris, A.S., Shashkov, E.V., Galanzha, E.I., Zharov, V.P. (2011) Complex genetic, photothermal, and photoacoustic analysis of nanoparticle-plant interactions. *Proc. Natl. Acad. Sci.* U.S.A. 108: 1028–1033.

Kole C., D. S Kumar and M V. Khodakovskaya (2016) *Plant Nanotechnology: Principles and Practices*. DOI: 10.1007/978-3-319-42154-4, Springer International Publishing Switzerland

Kuppusamy S., T Palanisami, M Megharaj, K Venkateswarlu and R. Naidu (2016) *In-Situ* Remediation Approaches for the Management of Contaminated Sites: A Comprehensive Overview. In: P. de Voogt (ed.), *Reviews of Environmental Contamination and Toxicology* **236**, pp: 1 - . DOI: 10.1007/978-3-319-20013-2_1, Springer International Publishing Switzerland

Łabanowska M., M Kurdziel, M Filek (2016) Changes of paramagnetic species in cereal grains upon short-term ozone action as a marker of oxidative stress tolerance. *Journal of Plant Physiology,* **190,** 54-66

Lamsal K., Kim, S. W., Jung, J. H., Kim, Y. S., Kim, K. S., Lee, Y. S. (2011) Application of silver nanoparticles for the control of Colletotrichum species *in vitro* and pepper anthracnose disease in field. *Mycobiology,* **39** (3), 194-199.

Lee D. J., Senseman, S. A., Sciumbato, A. S., Jung, S. C., Krutz, L. J. (2003) The effect of titanium dioxide alumina beads on the photocatalytic degradation of picloram in water. *Journal Of Agricultural and Food Chemistry,* **51** (9), 2659-2664.

Lemtiri A., A. Liénard, T. Alabi, Y. Brostaux, D. Cluzeau, F. Francis, G. Colinet (2016)Earthworms *Eisenia fetida* affect the uptake of heavy metals by plants *Vicia faba* and *Zea mays* inmetalcontaminated soils. *Applied Soil Ecology*, **104**, 67-78

Li K-E, Z-Y Chang, C-X Shen and N Yao (2015) Toxicity of Nanomaterials to Plants. In: M.H. Siddiqui et al. (eds.), *Nanotechnology and Plant Sciences,* pp: 101 – 123. DOI: 10.1007/978-3-319-14502-0_6, Springer International Publishing Switzerland

Li L., C Zhao, Y Zhang, J Yao, W Yang, Q Hu, C Wang, C Cao (2017) Effect of stable antimicrobial nano-silver packaging on inhibiting mildew and in storage of rice. *Food Chemistry,* **215**, 477-482

Li N, W-j Qian, L Wang, H Cao, X Hao, Y Yang and X Wang (2017) Isolation and expression features of hexose kinase genes under various abiotic stresses in the tea plant (*Camellia sinensis*). *Journal of Plant Physiology,* **209**, 95-104.

Li Q, Y Yang, X Bao, J Zhu, W Liang, T. M Bezemer (2016) Cultivar specific plant-soil feedback overrules soil legacy effects of elevated ozone in a rice-wheat rotation system. *Agriculture, Ecosystems & Environment*, **232**, 85-92

Li X. and F Liu (2016) Drought Stress Memory and Drought Stress Tolerance in Plants: Biochemical and Molecular Basis. In: M.A. Hossain et al. (eds.), *Drought Stress Tolerance in Plants,* **1**, pp: 17 – 44. DOI: 10.1007/978-3-319-28899-4_2, Springer International Publishing Switzerland

Li W., X Zhu, H Chen, Y He and J Xu (2013) Enhancement of Extraction Amount and Dispersibility of Soil Nanoparticles by Natural Organic Matter in Soils. In: J. Xu et al. (eds.), *Functions of Natural Organic Matter in Changing Environment,* DOI 10.1007/978-94-007-5634-2_139, Zhejiang University Press and Springer Science+Business Media Dordrecht

Liu R., H Zhang and R Lal (2016) Effects of Stabilized Nanoparticles of Copper, Zinc, Manganese, and Iron Oxides in Low Concentrations on Lettuce (*Lactuca sativa*) Seed Germination: Nanotoxicants or Nanonutrients? *Water Air Soil Pollut* **227**, 42. DOI: 10.1007/s11270-015-2738-2

Liu, J., Cai, H., Mei, C., Wang, M. (2015) Effects of nano-silicon and common silicon on lead uptake and translocation in two rice cultivars. *Frontiers of Environmental Science and Engineering,* **9**(5), 905-911.

Loreti E., H van Veen and P Perata (2016) Plant responses to flooding stress. *Current Opinion in Plant Biology,* **33,** 64-71

Lu H.-D., J-Q. Xue and D-W. Guo (2017) Efficacy of planting date adjustment as a cultivation strategy to cope with drought stress and increase rainfed maize yield and water-use efficiency**.** *Agricultural Water Management*, **179**, 227-235**.**

Ma X and C Gao (2015) Uptake and Accumulation of Engineered Nanomaterials and Their Phytotoxicity to Agricultural Crops. In: M. Rai et al. (eds.), *Nanotechnologies in Food and Agriculture,* pp: 321 – 342. DOI: 10.1007/978-3-319-14024-7_14, Springer International Publishing Switzerland

Mahdavi S., M. Kafi, E. Fallahi, M. Shokrpour and L. Tabrizi (2016) Water stress, nano silica, and digoxin effects on minerals, chlorophyll index and growth in ryegrass. *International Journal of Plant Production,* **10**(2),

Mahmoodzadeh H, Nabavi M, Kashefi H (2013) Effect of nanoscale titanium dioxide particles on the germination and growth of canola (*Brassica napus*). *J Ornamental Hortic Plants* **3**, 25–32

Mani P K and S Mondal (2016) Agri-nanotechniques for Plant Availability of Nutrients. In: C. Kole et al. (eds.), *Plant Nanotechnology,* pp: 263 – 303. DOI: 10.1007/978-3-319-42154-4_11, Springer International Publishing Switzerland

Martínez-Fernández D., Barroso, D., Komárek, M. (2016) Root water transport of *Helianthus annuus* L. under iron oxide nanoparticle exposure. *Environ. Sci. Pollut. Res.* **23**, 1732–1741.

Martínez-Fernández, D., Vítková, M., Bernal, M.P., Komárek, M. (2015) Effects of nanomaghemite on trace element accumulation and drought response of *Helianthus annuus* L. in a contaminated mine soil. *Water Air Soil Pollut.* **226**, 101. doi: 10.1007/s11270-015-2365-y.

Mastronardi E, P Tsae, X Zhang, C Monreal and M C. De Rosa (2015) Strategic Role of Nanotechnology in Fertilizers: Potential and Limitations. In: M. Rai et al. (eds.), *Nanotechnologies in Food and Agriculture,* DOI: 10.1007/978-3-319-14024-7_2, Springer International Publishing Switzerland

Meena R. S., N Gogoi, S Kumar (2017) Alarming issues on agricultural crop production and environmental stresses. *Journal of Cleaner Production,* **142** (Part 4), 3357-3359.

Miller R J., E B. Muller, B Cole, T Martin, R Nisbet, G K. Bielmyer-Fraser, T A. Jarvis, A A. Keller, G. Cherr, H S. Lenihan (2017). Photosynthetic efficiency predicts toxic effects of metal nanomaterials in phytoplankton. *Aquatic Toxicology,* **183**, 85-93

Mingyu S., Fashui, H., Chao, L., Xiao, W., Xiaoqing, L., Liang, C., Fengqing, G., Fan, Y., Zhongrui, L. (2007a). Effects of nano-anatase TiO_2 on absorption, dstribution of light, and photoreduction activities of chloroplast membrane of spinach. *Biol. Trace Elem. Res.* **118**, 120–130.

Mingyu S., Xiao, W., Chao, L., Chunxiang, Q., Xiaoqing, L., Liang, C., Hao, H., Fashui, H. (2007b). Promotion of energy transfer and oxygen evolution in spinach photosystem II by nano anatase TiO_2. *Biol. Trace Elem. Res.* **119**, 183–192.

Mudalkar S, R V Sreeharsha, A R Reddy (2017). Involvement of glyoxalases and glutathione reductase in conferring abiotic stress tolerance to Jatropha curcas L. *Environmental and Experimental Botany,* **134**, 141-150

Mukhopadhyay S S and N Kaur (2016). Nanotechnology in Soil-Plant System. In: C. Kole et al. (eds.), *Plant Nanotechnology,* pp: 329 – 348. DOI: 10.1007/978-3-319-42154-4_13, Springer International Publishing Switzerland

Nahar K., M Hasanuzzaman and M Fujita (2016). Roles of Osmolytes in Plant Adaptation to Drought and Salinity. In: N. Iqbal et al. (eds.), *Osmolytes and Plants Acclimation to Changing Environment: Emerging Omics Technologies*, pp: 37 – 68. DOI: 10.1007/978-81-322-2616-1_4, Springer India

Najafi Disfani M, Mikhak A, Kassaee MZ, Maghari A (2016). Effects of nano Fe/SiO_2 fertilizers on germination and growth of barley and maize. *Arch Agrono Soil Sci.* doi:10.1080/03650340.2016. 1239016

Nankishore A and A. D. Farrell (2016). The response of contrasting tomato genotypes to combined heat and drought stress. *Journal of Plant Physiology,* **202**, 75-82

Neethirajan S. (2017). Recent advances in wearable sensors for animal health management. *Sensing and Bio-Sensing Research,* **12**, 15-29

Nounjan N, Nghia PT, Theerakulpisut P (2012). Exogenous proline and trehalose promote recovery of rice seedlings from salt-stress and differentially modulate antioxidant enzymes and expression of related genes. *J Plant Physiol* **169**. 596–604

Nuruzzaman M, Rahman MM, Liu Y, Naidu R (2016). Nanoencapsulation, nano-guard for pesticides: a new window for safe application. *J Agric Food Chem* **64**,1447–1483

Nxele X., A. Klein and B.K. Ndimba (2017). Drought and salinity stress alters ROS accumulation, water retention, and osmolyte content in sorghum plants. *South African Journal of Botany,* **108**, 261-266.

Ohama N, H Sato, K Shinozaki, K Yamaguchi-Shinozaki (2016). Transcriptional Regulatory Network of Plant Heat Stress Response. *Trends in Plant Science, y* http://dx.doi.org/10.1016/j.tplants.2016.08.015

Pandey G. K. (2015a). *Elucidation of Abiotic Stress Signaling in Plants: Functional Genomics Perspectives,* Vol. 1. DOI: 10.1007/978-1-4939-2211-6, Springer New York

Pandey G. K. (2015b). *Elucidation of Abiotic Stress Signaling in Plants: Functional Genomics Perspectives,* Vol. 2, DOI: 10.1007/978-1-4939-2540-7, Springer New York

Pandey P, Ramegowda V and M Senthil-Kumar (2015). Shared and unique responses of plants to multiple individual stresses and stress combinations: physiological and molecular mechanisms. *Front Plant Sci.* **6**, 723. DOI: 10.3389/fpls.2015.00723. eCollection 2015.

Panpatte D G., Y K. Jhala, H N. Shelat and R V. Vyas (2016). Nanoparticles: The Next Generation Technology for Sustainable Agriculture. In: D. P. Singh et al. (eds.), *Microbial Inoculants in Sustainable Agricultural Productivity,* pp: 289 – 300. DOI: 10.1007/978-81-322-2644-4_18, Springer India

Pareek A, S. K. Sopory, H J. Bohnert and Govindjee (2010). *Abiotic Stress Adaptation in Plants: Physiological, Molecular and Genomic Foundation.* DOI: 10.1007/978-90-481-3112-9, Springer Netherlands

Parveen A, Hussain F. (2008). Salinity tolerance of three range grasses at germination and early growth stages. *Pak. J. Bot.* **40**, 2437-2441.

Patra A. K., T Adhikari and A. K. Bhardwaj (2016). Enhancing Crop Productivity in Salt-Affected Environments by Stimulating

Soil Biological Processes and Remediation Using Nanotechnology. In: J.C. Dagar et al. (eds.), *Innovative Saline Agriculture,* pp: 83 – 103. DOI: 10.1007/978-81-322-2770-0_4, Springer India

Patra P., S R Choudhury, S Mandal, A Basu, A Goswami, R Gogoi, C Srivastava, R Kumar and M Gopal (2013). Effect Sulfur and ZnO Nanoparticles on Stress Physiology and Plant (Vigna radiata) Nutrition. In: P. K. Giri et al. (eds.), *Advanced Nanomaterials and Nanotechnology,* Springer Proceedings in Physics 143, pp: 301 – 309. DOI: 10.1007/978-3-642-34216-5_31, Springer-Verlag Berlin Heidelberg

Peralta-Videa J.R., Hernandez-Viezcas, J.A., Zhao, L., Diaz, B.C., Ge, Y., Priester, J.H., Holden, P.A., Gardea-Torresdey, J.L. (2014). Cerium dioxide and zinc oxide nanoparticles alter the nutritional value of soil cultivated soybean plants. *Plant Physiol. Biochem*. **80**, 128–135.

Pérez G, S Doldán, P Scavone, O Borsani, P Irisarri (2016). Osmotic stress alters UV-based oxidative damage tolerance in a heterocyst forming cyanobacterium. *Plant Physiology and Biochemistry,* **108**, 231-240

Pourjafar L., H. Zahedi and Y. Sharghi (2016). Effect of foliar application of nano iron and manganese chelated on yield and yield component of canola (Brassica napus L.) under water deficit stress at different plant growth stages. *Agricultural Science Digest,* **36**(3).

Prasad P.V., R. Bheemanahalli, S.V. K. Jagadish (2017). Field crops and the fear of heat stress—Opportunities, challenges and future directions. *Field Crops Research,* **200**, 114-121

Pulimi M and S Subramanian (2016). Nanomaterials for Soil Fertilisation and Contaminant Removal. In: S. Ranjan et al. (eds.), *Nanoscience in Food and Agriculture 1, Sustainable Agriculture Reviews* 20, pp: 229 – 246. DOI: 10.1007/978-3-319-39303-2_8, Springer International Publishing Switzerland

Pulimi M. and S. Subramanian (2016). Nanomaterials for Soil Fertilisation and Contaminant Removal. In: S. Ranjan et al. (eds.), *Nanoscience in Food and Agriculture 1, Sustainable Agriculture Reviews* 20, pp: 229 – 246. DOI: 10.1007/978-3-319-39303-2_8, Springer International Publishing Switzerland

Qados A. M. A. (2015). Mechanism of nano silicon-mediated alleviation of salinity stress in faba bean (Vicia faba L.) Plants. *American Journal of Experimental Agriculture* **7**(2), 78.

Rai A. K. and T. Takabe (2006). *Abiotic Stress Tolerance in Plants toward the Improvement of Global Environment and Food.* DOI: 10.1007/1-4020-4389-9, Springer Netherlands

Ramegowda V and M Senthil-Kumar (2015). The interactive effects of simultaneous biotic and abiotic stresses on plants: mechanistic understanding from drought and pathogen combination. *J Plant Physiol.* **15** (176), 47-54. DOI: 10.1016/j.jplph.2014.11.008.

Reddy P. V L, J. A. Hernandez-Viezcas, J. R. Peralta-Videa, J. L. Gardea-Torresdey (2016). Lessons learned: Are engineered nanomaterials toxic to terrestrial plants? *Science of The Total Environment,* **568**, 470-479

Ren Y, J Geng, F Li, H Ren, L Ding, K Xu (2016). The oxidative stress in the liver of Carassius auratus exposed to acesulfame and its UV irradiance products. *Science of The Total Environment,* **571**, 755-762

Rico C.M., Hong, J., Morales, M.I., Zhao, L., Barrios, A.C., Zhang, J.Y., Peralta-Videa, J.R., Gardea-Torresdey, J.L. (2013a). Effect of cerium oxide nanoparticles on rice: a study involving the antioxidant defense system and in vivo fluorescence imaging. *Environ. Sci. Technol.* **47**, 5635–5642.

Rico C.M., Morales, M.I., McCreary, R., Castillo-Michel, H., Barrios, A.C., Hong, J., Tafoya, A., Lee, W.Y., Varela-Ramirez, A., Peralta-Videa, J.R., Gardea-Torresdey, J.L. (2013b). Cerium oxide nanoparticles modify the antioxidative stress enzyme activities and macromolecule composition in rice seedlings. *Environ. Sci. Technol.* **47**, 14110–14118.

Rizwan M, S Ali, M F Qayyum, Y S Ok, M Adrees, M Ibrahim, M Zia-ur-Rehman, M Farid and F Abbas (2017). Effect of metal and metal oxide nanoparticles on growth and physiology of globally important food crops: A critical review. *Journal of Hazardous Materials,* **322** (Part A), 2-16

Rossi L., W Zhang, L Lombardini and X Ma (2016). The impact of cerium oxide nanoparticles on the salt stress responses of Brassica napus L. *Environmental Pollution,* **219**, 28-36

Rossini M. A., G. A. Maddonni and M. E. Otegui (2016). Multiple abiotic stresses on maize grain yield determination: Additive vs. multiplicative effects. *Field Crops Research,* **198**, 280-289

Sah S K., K R. Reddy and J Li (2016). Abscisic Acid and Abiotic Stress Tolerance in Crop Plants. *Front Plant Sci.* **7**, 571. Doi:10.3389/fpls.2016.00571

Saharan V and A Pal (2016). *Chitosan Based Nanomaterials in Plant Growth and Protection.* Springer Briefs in Plant Science, Springer India, DOI: 10.1007/978-81-322-3601-6

Seghatoleslami M. and R. Forutani (2015). Yield and Water Use Efficiency of Sunflower as Affected by nanoZnO and Water Stress. *Journal of Advanced Agricultural Technologies* **2**(1), 34 – 37.

Sengupta A, M Chakraborty, J Saha, B Gupta and K Gupta (2016). Polyamines: Osmoprotectants in Plant Abiotic Stress Adaptation. In: N. Iqbal et al. (eds.)*, Osmolytes and Plants Acclimation to Changing Environment: Emerging Omics Technologies,* pp: 97 – 127. DOI: 10.1007/978-81-322-2616-1_7, Springer India

Servin A D. and J. C. White (2016). Nanotechnology in agriculture: Next steps for understanding engineered nanoparticle exposure and risk. *NanoImpact* **1**, 9–12. http://dx.doi.org/10.1016/j.impact.2015.12.002

Servin A. D. and J. C. White (2016). Nanotechnology in agriculture: Next steps for understanding engineered nanoparticle exposure and risk. *NanoImpact*, **1**, 9-12.

Shahid M., C Dumat, S Khalid, E Schreck, T Xiong, N K Niazi (2017). Foliar heavy metal uptake, toxicity and detoxification in plants: A comparison of foliar and root metal uptake. *Journal of Hazardous Materials*, **325**, 36-58

Shallan M. A., Hassan H. M., A. A. Namich M. and A. A. Ibrahim (2016). Biochemical and Physiological Effects of TiO_2 and SiO_2 Nanoparticles on Cotton Plant under Drought Stress. *RJPBCS* **7**(4), 1541.

Sharma, P., Bhatt, D., Zaidi, M. G. H., Saradhi, P. P., Khanna, P. K., Arora, S. (2012). Silver nanoparticle-mediated enhancement in growth and antioxidant status of Brassica juncea. *Applied Biochemistry and Biotechnology,* **167**(8), 2225-2233.

Sheikh Mohammadi M H, N Etemadi, M Mehdi Arab, M Aalifar, M Arab and M Pessarakli (2017). Molecular and physiological responses of Iranian Perennial ryegrass as affected by Trinexapac ethyl, Paclobutrazol and Abscisic acid under drought stress. *Plant Physiology and Biochemistry,* **111**, 129-143

Shelar, G. B., Chavan, A. M. (2015). Myco-synthesis of silver nanoparticles from Trichoderma harzianum and its impact on germination status of oil seed. *Biolife,* **3**(1), 109-113.

Shen X., Xiao, X., Dong, Z., Chen, Y. (2014). Silicon effects on antioxidative enzymes and lipid peroxidation in leaves and roots of peanut under aluminum stress. *Acta Physiologiae Plantarum,* **36**(11), 3063-3069.

Siddiqi K S and A Husen (2017). Recent advances in plant-mediated engineered gold nanoparticles and their application in biological system. *Journal of Trace Elements in Medicine and Biology,* **40**, 10-23

Siddiqi K S, Azamal Husen (2017). Recent advances in plant-mediated engineered gold nanoparticles and their application in biological system. *Journal of Trace Elements in Medicine and Biology,* **40**, 10-23

Siddiqui, M. H., Al-Whaibi, M. H. (2014). Role of nano-SiO_2 in germination of tomato (Lycopersicum esculentum Mill.). *Saudi Journal of Biological Sciences, 21*(1), 13-17.

Siddiqui, M. H., Al-Whaibi, M. H., Faisal, M., Al Sahli, A. A. (2014). Nano-silicon dioxide mitigates the adverse effects of salt stress on Cucurbita pepo L. *Environmental Toxicology and Chemistry* **33**(11), 2429-2437.

Singh J. and B. K. Lee (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. *Journal Of Environmental Management,* **170**, 88-96.

Sinha R., Gupta A and M Senthil-Kumar (2016).

Understanding the Impact of Drought on Foliar and Xylem Invading Bacterial Pathogen Stress in Chickpea. *Front Plant Sci.* **7**, 902. DOI: 10.3389/fpls.2016.00902. eCollection 2016.

Slomberg, D.L., Schoenfisch, M.H. (2012). Silica nanoparticle phytotoxicity to Arabidopsis thaliana. *Environ. Sci. Technol.* **46**, 10247–10254.

Srinivasa Rao N. K., K. S. Shivashankara and R. H. Laxman (2016). *Abiotic Stress Physiology of Horticultural Crops.* DOI: 10.1007/978-81-322-2725-0, Springer India

Suprasanna P., G. C. Nikalje and A. N. Rai (2016). Osmolyte Accumulation and Implications in Plant Abiotic Stress Tolerance. In: N. Iqbal et al. (eds.), *Osmolytes and Plants Acclimation to Changing Environment: Emerging Omics Technologies,* pp: 1 – 12. DOI: 10.1007/978-81-322-2616-1_1, Springer India

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*ournal of Nanoparticle Research,* **14**(12), 1-14.

Suzuki N, R M. Rivero, V Shulaev, E Blumwald and R Mittler (2014). Abiotic and biotic stress combinations. *New Phytologist* **203**, 32–43. DOI: 10.1111/nph.12797

Tarafdar J. C., R Raliya, H Mahawar, I Rathore (2014). Development of Zinc Nanofertilizer to Enhance Crop Production in Pearl Millet (Pennisetum americanum). *Agric Res* **3**(3), 257–262. DOI: 10.1007/s40003-014-0113-y

Taran N., L Batsmanova, O Kosyk, O Smirnov, M Kovalenko, L Honchar and A Okanenko (2016). Colloidal Nanomolybdenum Influence upon the Antioxidative Reaction of Chickpea Plants (Cicer arietinum L.). *Nanoscale Research Letters* **11**, 476. DOI: 10.1186/s11671-016-1690-4

Theerakulpisut P, Gunnula W (2012). Exogenous sorbitol and trehalose mitigated salt stress damage in saltsensitive but not salt-tolerant rice seedlings. *Asian J Crop Sci* **4**, 165–170

Van Aken B. (2015). Gene expression changes in plants and microorganisms exposed to nanomaterials. *Current Opinion in Biotechnology,* **33**, 206-219.

van der Laan M., K.L. Bristow, R.J. Stirzaker, J.G. Annandale (2017).Towards ecologically sustainable crop production: A South African perspective. *Agriculture, Ecosystems & Environment,* **236**, 108-119.

Vannini C., Domingo, G., Onelli, E., Prinsi, B., Marsoni, M., Espen, L., Bracale, M. (2013). Morphological and proteomic responses of Eruca sativa exposed to silver nanoparticles or silver nitrate. *PLoS One,* **8**(7), e68752.

Venkatachalam P., M. Jayaraj, R. Manikandan, N. Geetha, Eldon R. Rene, N.C. Sharma, S.V. Sahi (2016). Zinc oxide nanoparticles (ZnONPs) alleviate heavy metal-induced toxicity in Leucaena leucocephalaseedlings: A physiochemical analysis. *Plant Physiology and Biochemistry,* http://dx.doi.org/10.1016/j.plaphy.2016.08.022

Verdaguer D., M A.K. Jansen, L Llorens, L O. Morales, S Neugart (2017). UV-A radiation effects on higher plants: Exploring the known unknown. *Plant Science,* **255**, 72-81.

Vicente O., M Al Hassan and M Boscaiu (2016). Contribution of Osmolyte Accumulation to Abiotic Stress Tolerance in Wild Plants Adapted to Different Stressful Environments. In: N. Iqbal et al. (eds.)*, Osmolytes and Plants Acclimation to Changing Environment: Emerging Omics Technologies,* pp: 13 – 25. DOI: 10.1007/978-81-322-2616-1_2, Springer India

Wang P, X. Sun, X. Jia and F. Ma (2017). Apple autophagy-related protein MdATG3s afford tolerance to multiple abiotic stresses. *Plant Science*, **256**, 53-64

Wang X. D., Ou-yang, C., Fan, Z. R., Gao, S., Chen, F., Tang, L. (2010). Effects of exogenous silicon on seed germination and antioxidant enzyme activities of Momordica charantia under salt stress. *J. Anim. Plant Sci* **6**, 700-708.

Wang X., Wei, Z., Liu, D., Zhao, G. (2011). Effects of NaCl and silicon on activities of antioxidative enzymes in roots, shoots and leaves of alfalfa. *African Journal of Biotechnology* **10**(4), 545.

Wang X., Yang, X., Chen, S., Li, Q., Wang, Hou, C., Gao, X., Wang, L., Wang, S.

(2016). Zinc oxide nanoparticles affect biomass accumulation and photosynthesis in Arabidopsis. *Front. Plant Sci.* **6**, 1243. DOI: 10.3389/fpls.2015.01243.

Wani S. H., V Kumar, V Shriram and S K Sah (2016). Phytohormones and their metabolic engineering for abiotic stress tolerance in crop plants. *The Crop Journal,* **4** (3), 162-176.

Waraich E. A., Ahmad, R., Ashraf, M. Y. (2011b). Role of mineral nutrition in alleviation of drought stress in plants. *Australian Journal of Crop Science,* **5**(6), 764.

Waraich E. A., Ahmad, R., Ashraf, M. Y., Saifullah, Ahmad, M. (2011a). Improving agricultural water use efficiency by nutrient management in crop plants. *Acta Agriculturae Scandinavica, Section B-Soil & Plant Science,* **61**(4), 291-304.

Worms I.A.M., Boltzman, J., Garcia, M., Slaveykova, V.I. (2012). Cell-wall-dependent effect of carboxyl-CdSe/ZnS quantum dots on lead and copper availability to green microalgae. *Environ. Pollut.* **167**, 27–33

Xu J., M Zhang, G Liu, X Yang, X Hou (2016). Comparative transcriptome profiling of chilling stress responsiveness in grafted watermelon seedlings. *Plant Physiology and Biochemistry,* **109**, 561-570.

Xuan Y., Z S Zhou, H B Li and Z M Yang (2016). Identification of a group of XTHs genes responding to heavy metal mercury, salinity and drought stresses in Medicago truncatula. *Ecotoxicology and Environmental Safety,* **132**, 153-163

Xue Y., S-C Lung and M-L Chye (2016). Present Status and Future Prospects of Transgenic Approaches for Drought Tolerance. In: M.A. Hossain et al. (eds.), *Drought Stress Tolerance in Plants,* Vol. 2, DOI: 10.1007/978-3-319-32423-4_20, pp: 549 – 569. Springer International Publishing Switzerland

Yang F., Hong, F., You, W., Liu, C., Gao, F., Wu, C., Yang, P. (2006). Influence of nano-anatase TiO_2 on the nitrogen metabolism of growing spinach. *Biological Trace Element Research,* **110**(2), 179-190.

Yılmaz E., E Özgür, N Bereli, D Türkmen and A Denizli (2017). Plastic antibody based surface plasmon resonance nanosensors for selective atrazine detection. *Materials Science and Engineering: C,* **73**, 603-610

Zaytseva O. and G Neumann (2016). Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications. *Chem. Biol. Technol. Agric.* **3**, 17, DOI: 10.1186/s40538-016-0070-8

Zaytseva O. and G. Neumann (2016). Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications. *Chem. Biol. Technol. Agric.* **3**, 17. DOI: 10.1186/s40538-016-0070-8

Zhang M, R R. Naik and L Dai (2016). *Carbon Nanomaterials for Biomedical Applications.* Springer Series in Biomaterials Science and Engineering Vol. 5, DOI: 10.1007/978-3-319-22861-7, Springer International Publishing

Zhang P, Y Ma and Z Zhang (2015). Interactions between Engineered Nanomaterials and Plants: Phytotoxicity, Uptake, Translocation, and Biotransformation. In: M.H. Siddiqui et al. (eds.), *Nanotechnology and Plant Sciences,* pp: 77 – 99. DOI: 10.1007/978-3-319-14502-0_5, Springer International Publishing Switzerland

Zheng L., Hong, F., Lu, S., Liu, C. (2005). Effect of nano-TiO_2 on strength of naturally aged seeds and growth of spinach. *Biol. Trace Elem. Res.* **105**, 83–91.

Zuverza-Mena N., D. Martínez-Fernández, W. Du, J.A. Hernandez-Viezcas, N. Bonilla-Bird, M.L. López-Moreno, M. Komárek, J.R. Peralta-Videa, J.L. Gardea-Torresdey (2017). Exposure of engineered nanomaterials to plants: Insights into the physiological and biochemical responses-A review. *Plant Physiology et Biochemistry,* **110**, 236-264. DOI: 10.1016/j.plaphy.2016.05.037.

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