Nanomaterials. Effective tools for field and horticultural crops to cope with drought stress: A review

Hanafey F. Maswada (Maswada HF)1, Yasser S. A. Mazrou (Mazrou, YSA)2, Abdelnaser A. Elzaawely (Elzaawely, AA)1, and Shamel M. Alam-Eldein (Alam-Eldein, SM)3

1Tanta University, Faculty of Agriculture, Dept. Agricultural Botany, Tanta 31527, Egypt 2King Khalid University, Community College, Business Administration Dept., Saudi Arabia Kingdom 3Tanta University, Faculty of Agriculture, Dept. Horticulture, Tanta 31527, Egypt

Abstract

Drought is the most serious environmental challenge that limits plant growth and causes more severe yield losses than other abiotic stress factors resulting in a serious food shortage. Nanomaterials (NMs) are considered as vital tools to overcome contemporary and future challenges in agricultural production. Recently, NMs have been applied for enhancing seed germination, growth, physiology, productivity and quality attributes of various crops under normal or stress conditions. Up to date, there is no a comprehensive review about the potential role of NMs in attenuating the drought-induced adverse effects in crop plants. Thus, this review will highlight this issue. Generally, NMs minimize drought-induced osmotic stress by accumulation of osmolytes that result in osmotic adjustment and improved plant water status. In addition, NMs play a key role to improve root growth, conductive tissue elements and aquaporin proteins facilitating uptake and translocation of water and nutrients. Furthermore, NMs reduce water loss by stomatal closure due to abscisic acid signaling. However, this leads to reduced photosynthesis and oxidative stress damage. At the same time, NMs increase the content of light-harvesting pigments, enzymatic and non-enzymatic antioxidants leading to enhancing photosynthesis with reducing oxidative stress damage. Overall, NMs can ameliorate the deleterious effects of drought stress in crop plants by regulation of gene expression and alternation of various physiological and biochemical processes.

Additional keywords: nanoparticles; drought; oxidative damage; osmotic stress; crop growth.

Abbreviations used: ABA (abscisic acid); AsA (ascorbic acid); CAT (catalase); CNM (carbon nanomaterials); GSH (glutathione); MWCNT (multi-walled carbon nanotubes); NM (nanomaterials); NP (nanoparticles); POD (peroxidase); ROS (reactive oxygen species); RWC (relative water content); SOD (superoxide dismutase); SWCNT (single-walled carbon nanotubes); WUE (water use efficiency)

Authors’ contributions: Conception and design of the paper: MHF and ASM. All authors compiled information, wrote the paper, read and approved the final manuscript.

Citation: Maswada HF; Mazrou, YSA; Elzaawely, AA; Alam-Eldein, SM (2020). Nanomaterials. Effective tools for field and horticultural crops to cope with drought stress: A review. Spanish Journal of Agricultural Research, Volume 18, Issue 2, e08R01. https://doi.org/10.5424/sjar/2020182-16181

Received: 06 Dec 2019. Accepted: 06 Apr 2020.
Copyright © 2020 INIA. This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International (CC-by 4.0) License.

Funding agencies/institutions
Deanship of Scientific Research at King Khalid University (Program of Research Groups)

Project / Grant
R.G.P 2/28/40

Competing interests: The authors have declared that no competing interests exist.
Correspondence should be addressed to Hanafey F. Maswada: hanafey2000@agr.tanta.edu.eg

Introduction

By mid this century, the growing of global population is expected to reach about 9.8 billion people. At the same time, drought may lead to a serious food shortage that will be worsened due to the global climate change (Kah et al., 2019). Drought is considered the most serious abiotic stress limiting plant growth and causes great losses in crop yields higher than other stresses (Lambers et al., 2008). It causes adverse effects on morphological, physiological, biochemical, and molecular aspects of the plant that negatively affect crop yield and quality (Farooq et al., 2009). Therefore, there is an urgent need to develop and improve drought tolerance in plants via safe and economic strategies. Among various strategies adopted to cope drought-induced plant death, the application of nanomaterials (NMs) has been proved as a promising and effective one (Khan et al., 2017). While practicing sustainable agriculture, various NMs have been reported to enhance crop production to
meet the growing global demands for food, feed and fuel (Kah et al., 2019). During the past two decades, research findings indicated the important role of NMs in diverse life aspects including agriculture and food industry. In this regard, NMs of particle size 1-100 nm have a great interest due to their high surface-to-volume ratio, and thus can play an important role in developing sustainable agriculture (Chen & Yada, 2011). They can be applied to plants through several application methods (Mohamed & Kumar, 2016).

Recent literature suggests that significant toxic effects in animal cell culture and animal models are caused by several metallic NPs such as silver and titanium dioxide (Cox et al., 2017). In general, NPs can cause negative or positive effects on plant growth, development, and productivity based on type, size and concentration of nanoparticles (NPs), application method, and plant species (Du et al., 2017; Tripathi et al., 2017). For example, Ag-NPs at 50-2500 mg/L inhibited root elongation in corn, whereas the growth of watermelon and zucchini seedlings was positively affected with the same concentrations (Almutairi & Alharbi, 2015). Turnip (Brassica rapa L.) treated with 5 and 10 mg/L of Ag-NPs showed an increase in ROS production and DNA damages, associated with up-regulation of genes related to the biosynthesis of glucosinolates and phenolic compounds, resulted in more damages under biotic and abiotic stresses (Thiruvengadam et al., 2015). In addition, Tiwari et al. (2017) noted the dual response on growth and photosynthetic performance in tomato plants treated with TiO2-NPs depending on their concentration, where these traits are boosted by low concentrations (0.5-2 g/L) and adversely affected by high concentration (4 g/L).

Up to date, there is no a comprehensive review concerning the potential role of NMs in ameliorating the drought-induced oxidative and osmotic damages in crop plants. Thus, this review will shed light on this issue. After providing a brief overview on the deleterious effects of drought stress on physiological and biochemical processes in plants, this review highlights the recent findings of the possible applications of NMs in mitigating the drought-induced adverse effects on various field and horticultural crops. Considering available literature, the NMs that are used to mitigate the drought-induced damage in either field or horticultural crops include carbon-based NMs (carbon nanotubes and fullerene), metallic/metallic oxide (CeO2, Fe and Fe-oxides, K, Ag, TiO2 and ZnO), metalloids (Si and SiO2), non-metallic (P) NPs, in addition to nano-size polymers and composites (nano-chitosan, hydroxyapatite, nano-clay, analcite and micronutrient nano-composites). The potential role of these NMs to cope with drought in plants will be discussed.

**Drought stress**

Under the ongoing global climate change scenarios, drought severity and frequency will be increased (Walter et al., 2011). Generally, drought-induced-damage in plants is due to lower water uptake by roots with higher water loss from plant leaves and evaporation from soil (Trenberth et al., 2014). Drought stress (inadequate water supply) induces more losses in crop yield than other stress factors. Hence, it is considered as the major constraint limiting growth, development and productivity of crop plants (Lambers et al., 2008). Accordingly, drought stress is the most critical threat to food security (Farooq et al., 2009).

**Drought stress: adverse effects on crop plants**

Inadequate water supply for plants causes various adverse effects from cellular to whole-plant levels that ultimately lead to a reduction in growth and productivity of crop plants (Fig. 1). Drought stress affects several physiological and biochemical processes. It negatively affects plant water status indicated by a decrease in leaf water content, relative water content (RWC), water potential, stomatal conductance and transpiration rate with increasing canopy and leaf temperature that correlated linearly with increased drought severity (Reddy et al., 2004). Drought limits availability, uptake, translocation and metabolism of mineral nutrients due to limited water supply, lowered transpiration and impaired enzyme activity involved in the nutrient assimilation (Farooq et al., 2009).

Under drought stress, abscisic acid (ABA) accumulates in plants and stimulates a signaling pathway, which affects anion and K+ efflux from guard cells resulting in loss turgor and ultimately stomatal closure (Osakabe et al., 2014). Reduced photosynthesis in drought-stressed plants is mainly attributed to stomatal closure that leads limited CO2 influx and increased leaf temperature leading to thylakoid membrane damage, and disturbed activity of various enzymes including RuBisCO and other enzymes involved in Calvin cycle and ATP synthesis, in addition to diminished light-harvesting pigments and obstruction of photosynthetic machinery (Farooq et al., 2012). Diminished photosynthesis and respiration and increased photo-respiration in drought-stressed plants lead to generation and accumulation of reactive oxygen species (ROS) in chloroplasts, mitochondria and peroxisomes, respectively resulting in oxidative stress damage of cell compartments including lipid peroxidation, denaturation of proteins and obstruction of nucleic acids (Das & Roychoudhury, 2014).

Finally, osmotic and oxidative stresses induced by drought as well as impaired cell division and
Nanomaterials. Effective tools for field and horticultural crops to cope with drought stress: A review

Elongation leading to negative effects on growth, development and productivity of crop plants.

**Inducing drought stress tolerance in crop plants**

Under drought stress conditions, plants have developed various mechanisms for drought resistance (avoidance and tolerance). The deleterious effects of drought stress on plants are mainly related to osmotic and oxidative stresses induced by drought. In order to cope with osmotic stress, plants synthesize and accumulate neutral and nontoxic compound (compatible solutes or osmolytes) in cytoplasm along with certain inorganic ions in vacuoles (Abid et al., 2018). The accumulation of compatible solutes maintains cell hydrated state and membrane structural integrity and stabilizes structural and functions of macromolecules (Hoekstra et al., 2001). These compatible solutes include several compounds such as proline, glycine betaine and soluble sugars. In addition to its role in osmotic adjustment, proline plays important roles as a cell redox balancer, a free radical scavenger and a cytosolic

---

**Figure 1.** The adverse effects of drought stress on different physio-biochemical processes in plants. RWC: relative water content; ABA: abscisic acid; NMs: nanomaterials.
Drought induces oxidative stress via the production of ROS including superoxide radical (O$_2^-$), hydrogen peroxide (H$_2$O$_2$), and hydroxyl radical (OH$^-$) that cause oxidative damage to lipids, proteins, and DNA (Schieber & Chandel, 2014). Enzymatic and non-enzymatic antioxidants are involved in cellular defense mechanisms for ROS detoxification. Superoxide dismutases (SOD) covert O$_2^-$ stress through dismutation reaction of O$_2$ and H$_2$O$_2$ (Schieber & Chandel, 2014). As a result, H$_2$O$_2$ can be converted into H$_2$O and O$_2$ by catalase (CAT) and specific peroxidases (POX) (Roychoudhury et al., 2012). Non-enzymatic antioxidants mainly include ascorbate (AsA), flavonoids, glutathione (GSH), and carotenoids (Foyer & Noctor, 2012). Overall, the coordinated antioxidant activity associated to increased activities of SOD and CAT, together with a modulation of the AsA-GSH cycle, reduces drought stress-induced oxidative damage in crops (Zandalinas et al., 2017).

For achieving enhanced crop drought tolerance, three prominent plant breeding approaches (conventional breeding, marker-assisted breeding, and genetic engineering) have been performed (Ashraf, 2010). Plant hormones are active members of the signal compounds involved in the induction of plant stress responses. In the last decade, a lot of work has been done to understand plant hormone-mediated abiotic stress tolerance, using physiological, biochemical, genetic, molecular, and genomic approaches for crop breeding and management, including exogenous application of plant growth regulators (De Ollas et al., 2015; Muñoz-Espinoza et al., 2015; De Ollas et al., 2018). In addition to phytohormones, seaweed extracts, biochar, osmoprotectants, plant growth promoting rhizobacteria (PGPR) and nanoparticles have been applied to induce drought tolerance in crop plants (Ali et al., 2017). Among various strategies adopted to counter drought-induced damage in plants, use of NMs has been proved promising (Khan et al., 2017).

Nanomaterials and agricultural crops

General overview

According to the European Commission, “Nanomaterials 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” (Rai et al., 2018). The manufactured or engineered NMs are widely used in diverse aspects of our life including agriculture sector thanks to their properties including high surface-to-volume ratio, high stability and adsorption capacity, extraordinary electrical and optical properties, and diverse and easy functionalities, etc. (Ghormade et al., 2011; Rai et al., 2018). In the recent technological revolution, NMs have demonstrated to have a great potential in providing novel and improved solutions to various global challenges facing agriculture (Chen & Yada, 2011; Huang et al., 2015). Overall, the application of nanotechnology in agriculture is still in its infancy; however, it will develop fast in the near future with deep understanding of the interactions between engineered NMs and plants (Pulizzi, 2019).

The application of NMs to plants ranges from seed manipulation to other modern technologies that require necessarily the use of in vitro plant tissue culture (Mohamed & Kumar 2016). When NMs are taken from soil by plant roots, plants uptake NMs by an active-transport mechanism through the xylem (Tripathi et al., 2017). Inside plants, NMs may change their structure and become ions-form complexes with other molecules or nutrients, or remain as NMs (Dimkpa & Bindraban, 2018). NMs inside plant tissues seem to modulate the activity of the oxidative stress enzymes, and hence NMs can activate the plant defense system (Montes et al., 2017). At cellular level, NMs can induce ROS generation, which trigger secondary signaling messengers leading to transcriptional regulation of secondary metabolism (Marslin et al., 2017). However, NMs can cause either beneficial or adverse effects on plant growth, development and productivity. This opposite effect depends on NMs types and their physicochemical properties, particularly size and concentration, mode of application, soil conditions as well as plant species (Du et al., 2017). For example, ZnO-NPs improved growth in beans while reduced the growth of wheat (Dimkpa & Bindraban, 2018). Generally, the effect of most NMs on plants is characterized by a biphasic dose response “hormesis” with a low dose stimulation and a high dose inhibition (Agathokleous et al., 2019).

Nanomaterials and drought stress tolerance in plants

Carbon-based NMs

Carbon-based nanomaterials (CNMs) have been widely used for numerous applications in different areas of the plant system (Zaytseva & Neumann, 2016). CNMs are characterized by stable molecular architecture and uniform dispersion in the medium, in which these are applied due to their special properties including small surface area and increased chemical reactivity (Verma et al., 2019). Due to their good properties, carbon-based NPs like carbon nanotubes (CNTs), fullerenes, and graphene can be used in different life fields including precision agriculture (Zaytseva & Neumann, 2016). CNMs including CNTs...
inducing the regulation of mechanisms involved in starch hydrolysis, and reduction in oxidative injury indices, activating plant defense enzymes (SOD, POD, CAT, and APX), and also biosynthesis of proteins, phenolics, and proline.

This effect was basically through enhancing water uptake, water and nutrient uptake (Verma et al., 2019). In addition, the application of MWCNTs at 30 mg/L negatively affected seed germination and seedling growth of cucumbers (from -2 to -10 bars) has been attained with seed nano-priming using MWCNTs at 30 mg/L (Rahimi et al., 2016). By enhancement of water uptake, the concentrations of MWCNTs (50-100 mg/L) can induce drought and salinity tolerance in barley (Karami & Sepehri, 2017). On the other hand, MWCNTs at different concentrations (125-1000 µg/mL) negatively affected seed germination and seedling growth of cucumber under both PEG-induced stress and normal growing conditions (Yousefi et al., 2017).

| Nanomaterials | Type | Conc. | Application method | Plant species | Effects | Reference |
|---------------|------|-------|-------------------|---------------|---------|-----------|
| CNTs          | SWCNTs | 50 mg/L | Seed socking | *Hyoscyamus niger* L. | Enhancing water uptake, up-regulation of mechanisms involved in starch hydrolysis, and reduction in oxidative injury indices, activating plant defense enzymes (SOD, POD, CAT, and APX), and also biosynthesis of proteins, phenolics, and proline | Hatami et al. (2017) |
|               |       | 800 mg/L | Foliar spray | *Salvia mirzayani* Rech. f. and *Esfand* | Improving chlorophyll index, electrolyte leakage, total phenolics, and antioxidant capacity | Chegini et al. (2017) |
|               | MWCNTs | 30 mg/L | Seed priming | *Alnus subcordata* C.A. Mey. | Increasing seedling growth traits | Rahimi et al. (2016) |
|               |       | 50 mg/L | Foliar spray | *Cucurbita pepo* L. | Enhancement of water uptake, seed germination and seedling growth | Hatami et al. (2017) |
|               |       | 0.5-1 g/L | Seed priming | *Hordeum vulgare* L. | Oxidative injury, negative effects on seed germination and seedling growth | Karami & Sepehri (2017) |
|               |       | 125-1000 µg/mL | Seed priming | *Dodonaea viscosa* Jacq. | Improving seed germination and growth traits | Yousefi et al. (2017) |
|               |       | 50-100 mg/L | Seed priming | *Beta vulgaris* L. | Able to bind with water in distinct cell compartments and possessed hydroscopic and antioxidant activities | Borišev et al. (2016) |
| Fullerol      |       | 70-700 µmol/L | Foliar spray | *Beta vulgaris* L. | Repressing ROS accumulation by enhancing the regulatory mechanisms on enzymatic and non-enzymatic antioxidants and ABA accumulation | Xiong et al. (2018) |
|               |       | 10-100 mg/L | Seed priming | *Brassica napus* L. | | |

NMNs: nanomaterials; CNTs: carbon nanotubes; SW: single-walled; MW: multi-walled; SOD: superoxide dismutase; POD: peroxidase; CAT: catalase; APX: ascorbate peroxidase; ROS: reactive oxygen species; ABA: abscisic acid.

and fullerol have been used to induce drought tolerance in several field and horticultural crops (Table 1).

—**Carbon nanotubes (CNTs).** Generally, CNTs comprising single-walled (SWCNTs), double-walled (DWCNTs) and multi-walled (MWCNTs) CNTs, at lower concentrations (≤ 100 mg/L) have been found to be effective in enhancing seed germination and plant growth. The overall stimulation in growth of plants due to the application of CNTs has been ascribed to the increase in water and nutrient uptake (Verma et al., 2019). In addition, the application of MWCNTs at lower concentrations (50 µg/mL) on the growth of *Hyoscyamus niger* seedlings under polyethylene glycol (PEG)-induced drought stress. This effect was basically through enhancing water uptake, inducing the regulation of mechanisms involved in starch hydrolysis, reducing oxidative injury indices, activating plant defense enzymes SOD, POD, CAT and ascorbate peroxidase (APX) and improving the biosynthesis of proteins, phenolics and proline. At the same time, increasing the concentration of SWCNTs up to 800 µg/mL caused opposite effects due to cell injury.

In the same context, the application of MWCNTs at 50 mg/L as foliar spray to *Salvia mirzayanii* plants increased chlorophyll index, membrane stability index, total phenolics, and antioxidant capacity under moderate drought stress (Chegini et al., 2017). Maximum seedling growth of Caucasian alder (*Alnus subcordata*) under drought stress (from -2 to -10 bars) has been attained with seed nano-priming using MWCNTs at 30 mg/L (Rahimi et al., 2016). However, this concentration was only enough to improve seedling growth of *Dodonaea viscosa* (L.) Jacq. (Hop-bush) grown under non-stress conditions, whereas 50-100 mg/L were required to improve growth under drought conditions (Yousefi et al., 2017). By enhancement of water uptake, the concentrations of MWCNTs (500-1000 mg/L) can induce drought and salinity tolerance in barley (Karami & Sepehri, 2017). On the other hand, MWCNTs at different concentrations (125-1000 µg/mL) negatively affected seed germination and seedling growth of cucumber under both PEG-induced stress and normal growing conditions (Chegini et al., 2017).
conditions. These negative effects are consequence of oxidative injury due to inactivation of various cellular antioxidant enzymes (Hatami, 2017).

—**Fullerene and its derivatives.** The fullerene molecule is made up of sixty carbon atoms. Polyhydroxy fullerene (fullerol, \(C_{60}(OH)_{24}\)), is one of the water-soluble derivatives of fullerene that have numerous hydroxyl groups (OH) attached to the \(C_{60}\) molecule (Husen & Siddiqi, 2014). The appropriate concentrations of fullerol NPs are effective in improving the drought tolerance (Verma et al., 2019). For example, foliar application of fullerol \([C_{60}(OH)_{27}]\) NPs at 70-700 µmol/L alleviated the drought negative impacts on sugar beets (Borišev et al., 2016), due to their action as intracellular water binders in addition to their beneficial effect on alleviating drought-induced oxidative effects by enhancing antioxidant activity. In the same context, seeds priming or foliar spray with fullerol \([C_{60}(OH)_{27}]\) NPs at 10-100 mg/L promoted seed germination, growth and physiological traits of *Brassica napus* under water stress through repressing ROS accumulation by enhancing the regulatory mechanisms on enzymatic and non-enzymatic antioxidants and ABA accumulation in stressed treated plants (Xiong et al., 2018).

—**Metallic/metallic oxides, metalloids and non-metallic NMs.** Metallic/metallic oxides-NPs (CeO\(_2\), Fe and Fe-oxides, Ag, TiO\(_2\) and ZnO), metalloids (Si and SiO\(_2\)) and non-metallic (P) NPs have been used to ameliorate the deleterious effects of drought stress in various field and horticultural crops (Table 2).

—**Cerium oxide NPs (Nanoceria).** Cerium oxide NPs (Nanoceria, CeO\(_2\)-NPs) are one of the most important NPs in agriculture. Cao et al. (2018) demonstrated that, the application of CeO\(_2\)-NPs at 100 mg/kg soil improved biomass, photosynthetic performance, RuBisCO activity and water use efficiency (WUE) of soybean plants under different soil moisture conditions. Similarly, foliar-sprayed CeO\(_2\)-NPs at 10 mg/L improved photosynthetic efficiency, pollen germination and seed-set of drought-stressed sorghum plants and possessed potent antioxidant properties that mitigated drought-induced oxidative stress by catalytic scavenging ROS leading to higher grain yield (Djanaguiraman et al., 2018).

—**Iron and iron oxides NPs.** Iron (Fe) is a constituent and co-factor of various enzymes, and it is essential for many physiological processes including chlorophyll biosynthesis, chloroplast development, respiration, redox reactions, and nucleic acid metabolism (Mimmo et al., 2014).

Fe/Fe-oxides NPs such as nano zero-valent iron (nZVI), nano-goethite (\(\alpha\)-FeOOH), nano-hematite (\(\alpha\)-Fe\(_2\)O\(_3\)), nano-maghemite (\(x\)-Fe\(_2\)O\(_3\)), nano-magnetite (Fe\(_3\)O\(_4\)), and nano-iron pyrite (Fe\(_2\)S\(_3\)) have attracted a lot of researchers due to their magnetic properties, and their beneficial effects on plant growth and productivity (Srivastava et al., 2014; Zuverza-Mena et al., 2017). Seed priming with nano iron oxide (Fe\(_2\)O\(_3\)-NPs) at 500 mg/L improved growth, photosynthesis, and photosystem II efficiency in sorghum plants (Maswada et al., 2018).

Regarding drought stress, foliar application of Fe-NPs (1.5 mg/L) increased seeds per pod and seed nitrogen content, as well as yield and oil percentage of drought-stressed cowpea and safflower, respectively (Afshar et al., 2012; Zarreii et al., 2014). Soil application of 1% iron oxide NPs (maghemite, \(\gamma\)-Fe\(_2\)O\(_3\); 20-100 nm particle size) enhanced the growth of drought-stressed sunflower planted in contaminated mine soil (Martínez-Fernandez et al., 2015). Similarly, low concentrations of \(\gamma\)-Fe\(_2\)O\(_3\) (3.4 mg/L) and Fe\(_2\)O\(_4\) NPs (0.8 mg/L) improved growth and productivity of drought-stressed *Brassica napus* (Palmqvist et al., 2017) and strawberry (Mozafari et al., 2018), respectively throughout improving oxidative defense system. Recently, Fe-NPs as soil supplementation (100 mg/kg) increased photosynthesis, Fe uptake, grain yield and decreased the oxidative stress and Cd concentrations in drought-stressed wheat plants grown in Cd-contaminated soil (Adrees et al., 2020).

—**Potassium (K) NPs.** Hosseini et al. (2016) reported that barley genotypes with a high K content in flag leaves promoted ABA degradation and attenuated starch degradation leading to conferring tolerance to drought-induced leaf senescence. In addition, K application increased the contribution of K\(^+\) and malate to osmotic potential leading to improvement of osmotic adjustment in drought-stressed cotton plants (Zhao et al., 2019). In a similar manner, foliar spray of nano-K fertilizer at 2.5 g/L improved growth of drought-stressed pumpkin by enhancing stomatal conductance (Gerdini, 2016).

—**Silver NPs.** Silver (Ag) NPs have been implicated in enhancing seed germination, growth rate, and physiological characteristics of several plants under normal and stressful conditions. Ag-NPs have been implicated as an effective antimicrobial agent to control plant diseases (Kedziora et al., 2018); however, their role in improving plant tolerance against abiotic stresses is still limited. Application of Ag-NPs at 10 µg/mL significantly increased germination and seedling growth rate of drought-stressed lentil seeds (Hojjat, 2016). On the other hand, the application of Ag-NPs at 40 g/ha in irrigation water had no positive effects on WUE and yield characteristics of drought-stressed *Carum coticum* plants (Seghatoleslami et al., 2015).

—**Titanium dioxide NPs (Nanotitania).** Titanium is not an essential element for plants; but at low concentrations, it shows beneficial impacts on various physiological attributes (Tiwari et al., 2017). Concerning drought stress,
Table 2. Effects of metallic/metallic oxides, metalloids and non-metallic NMs in ameliorating drought stress-induced damage in different plant species.

| Nanomaterials                      | Type      | Conc.       | Application method | Plant species           | Effects                                                                 | Reference          |
|------------------------------------|-----------|-------------|--------------------|-------------------------|------------------------------------------------------------------------|--------------------|
| **Metallic and metallic oxides NPs** | CeO2      | 100 mg/kg   | Soil spray         | Glycine max (L.) Merr.  | Improved biomass, photosynthetic performance, RuBisCO activity and WUE | Cao et al. (2018)  |
|                                    | CeO2      | 10 mg/L     | Foliar spray       | Sorghum bicolor (L.) Moench | Improved photosynthesis, pollen germination, seed-set, grain yield and scavenged ROS accumulation | Djanaguiraman et al. (2018) |
|                                    | Fe-NPs    | 1.5 mg/L    | Foliar spray       | Vigna unguiculata (L.) Walp. | Increasing seedling growth traits                                      | Rahimi et al. (2016) |
|                                    | Fe-NPs    | 100 mg/kg   | Soil spray         | Triticum aestivum L.     | Increased photosynthesis, Fe concentration, grain yield and decreased the oxidative stress | Zareei et al. (2014) |
|                                    | γ-Fe2O3 NPs | 1%          | Soil               | Helianthus annuus L.     | Growth improvement                                                     | Martinez-Fernandez et al. (2015) |
|                                    | Fe2O3 NPs | 3.4 mg/L    | Nutrient solution  | Brassica napus L.         | Enhancing growth and agronomic traits by reducing ROS damage and improving oxidative defense system | Palmqvist et al. (2017) |
|                                    | CeO2 NPs  | 0.8 mg/L    | In vitro culture media | Fragaria × ananassa Duch. | Adapting strawberry plants to drought before transplanting in the field | Mozfari et al. (2018) |
|                                    | TiO2-NPs  | 0.02%       | Foliar spray       | Triticum aestivum L.      | Increased yield and yield components as well as gluten and starch content | Jaberzadeh et al. (2013) |
|                                    | TiO2-NPs  | 10 mg/L     | Foliar spray       | Linum usitatissimum L.    | Increased photosynthetic pigments, protein and seed oil contents and decreased lipid peroxidation | Aghdam et al. (2016) |
|                                    | TiO2-NPs  | 0.3%        | Foliar spray       | Ocimum basilicum L.       | Increased RWC, anthocyanin concentration, and catalase activity         | Kiapour et al. (2015) |
|                                    | TiO2-NPs  | 50 mg/L     | Foliar spray       | Gossypium barbadense L.   | Increased yield, pigments, TSS, proline, total phenolics, total soluble proteins, total antioxidant capacity and antioxidant enzyme activities | Shullan et al. (2016) |
|                                    | TiO2-NPs  | 20 mg/L     | Foliar spray       | Eruca sativa Mill.        | Enhanced H2S and cysteine synthesis that led to improving antioxidant activity, accumulation of osmolytes and RWC with reduction in H2O2, lipid peroxidation and electrolyte leakage | Khan & Alzuainb (2018) |
|                                    | TiO2-NPs  | 10 mg/L     | Foliar spray       | Dracocephalum moldavica L. | Accumulation of proline and reduction in ROS (H2O2) and lipid peroxidation | Mohammadi et al. (2014) |
|                                    | K-NPs     | 2.5 g/L     | Foliar spray       | Cucurbita pepo L.         | Increased essential oils and phenolic compounds                         | Kamalizadeh et al. (2019) |
|                                    | Ag-NPs    | 40 g/ha     | Irrigation water   | Carum coticum (L.) Link  | No positive effect on WUE and yield characteristics                     | Gerdini (2016)     |
|                                    | ZnO-NPs   | 10 μg/mL    | Seed soaking       | Lens culinaris Medikus    | Enhanced germination percentage and seedling growth traits              | Hojjat (2016)     |
|                                    | ZnO-NPs   | 1000 mg/L   | Seed soaking       | Glycine max (L.) Merr.    | Improved germination, and decreasing seed residual fresh and dry weight of seedlings | Sedghi et al. (2013) |
|                                    | ZnO-NPs   | 1000 mg/L   | Foliar spray       | Helianthus annuus L.      | Increased seed yield and water use efficiency                           | Seghatoleslami & Foroutani (2015) |
|                                    | ZnO-NPs   | 1000 mg/L   | Seed priming       | Oryza sativa L.           | Improved growth, yield and yield-related traits with increasing Zn uptake and higher expression of Cu/Zn SOD | Rameshreddy et al. (2017) |
|                                    | ZnO-NPs   | 5 mg/kg     | Soil               | Sorghum bicolor (L.) Moench | Reduced the delay of flag leaf and grain head emergence, improved grain yield and grain nutrient translocation | Dimkpa et al. (2019) |

The foliar application of TiO2-NPs at 0.02% increased yield, and gluten and starch content in drought-stressed wheat plants (Jaberzadeh et al., 2013). Aghdam et al. (2016) demonstrated that exogenous application of nano-TiO2 (10 mg/L) significantly alleviated the drought stress-induced damage in flax (Linum usitatissimum) compared to higher concentration (500 mg/L). Under severe drought stress nano-TiO2 at 0.03% significantly improved leaf RWC, anthocyanin concentration, and catalase activity in Ocimum basilicum (Kiapour et al., 2015). Pre-flowering treatment of cotton plants with nano-TiO2 (50 mg/L) increased yield characteristics under drought conditions.
through increasing plant pigments, accumulation of total soluble sugars, proline, total phenols, total soluble proteins, and antioxidant enzymes activity (Shallan et al., 2016). TiO2-NPs (20 mg/L) had a significant effect in mitigating the deleterious effects of drought stress in *Eruca sativa* plants by enhancing the synthesis of H2S and cysteine that improved the antioxidant activity, accumulation of osmolytes and RWC with the simultaneous decrease in H2O2 content and lipid peroxidation (Khan & Alzuair, 2018). Likewise, Moldavian dragonhead plant treated with TiO2-NPs (10 mg/L) showed accumulation of proline and reduction in ROS (H2O2) and lipid peroxidation, and thereby counteracted the negative impacts of drought stress (Mohammadi et al., 2014). Recently, Kamalizadeh et al. (2019) found that TiO2-NPs treatment had no significant effect on plant dry weight, but increased the essential oil content with the highest value at 30 mg/L, and reported that both drought stress (75% of field capacity) and TiO2-NPs (30-50 mg/L) could be applied to increase phenolic compounds in Moldavian dragonhead plant.

**Zinc oxide NPs.** Zinc is an essential micronutrient in plant cells for the synthesis of tryptophan, which is the precursor of indolacetic acid; a phytohormone responsible of cell division and other physiological and biochemical functions (Cakmak et al., 1989). Zinc is also important for ameliorating the adverse effects of abiotic stress (Cakmak, 2008; Hafeez et al., 2013). The effect of ZnO-NPs on plants depends on their size, concentration and plant species. For example, canola (*Brassica napus*) showed improvement in plant growth with ZnO-NPs at 10 mg/L, while higher concentration (1000 mg/L) resulted in toxic effects (Rahmani et al., 2016). Recently, foliar application of ZnO NPs (10 mg/L) led to higher biomass and photosynthetic rate, fruit set and quality in one-year old coffee plants compared to control and ZnSO4-treated plants (Rossi et al., 2019).

Under drought conditions, nano-ZnO (1000 mg/L) increased seed germination and seedling growth, yield, and WUE of rice, soybean and sunflower crops. The positive effect of nano-ZnO is thought to be related to facilitating the rapid use of seed reservoirs, increase in Zn uptake and expression of Cu/Zn SOD activity (Sedghi et al., 2013; Seghatoleslami & Forutani, 2015; Rameshraddy et al., 2017). Recently, Dimkpa et al. (2019) demonstrated that soil amended with ZnO-NPs mitigated the negative influences of drought stress (40% of field moisture capacity) in sorghum plants. ZnO-NPs at 5 mg/kg reduced the delay of flag leaf and grain head emergence, and improved grain yield and grain nutrient (N, K and Zn) translocation in drought-stressed sorghum plants.

**Metalloids (silicon and silica NPs).** Over past two-decades, silicon (Si) application has been known to improve growth performance of plants and attenuate the adverse effects of abiotic stresses by regulating the generation of ROS and alteration of gene expression (Kim et al., 2017). Pretreatment of hawthorn (*Crataegus aronia*) seedlings with SiO2-NPs (10-30 nm) at 100 mg/L positively affected leaf RWC, membrane permeability, pigments, carbohydrate and proline contents, as well as photosynthetic rate, stomatal conductance, and plant biomass content under drought stress conditions (Ashkavand et al., 2015). Under severe drought conditions, nano-silicon dioxide at 1 mM improved mineral nutritional value and other quality indexes in perennial ryegrass (Mahdavi et al., 2016). In the context, nano-Si at 1 or 2 mM improved germination rate of tomato seeds under drought stress induced by PEG (Haghighi et al., 2013). Moreover, soil application of silica NPs (10 nm) at 200 mg/kg induced cucumber plants to alleviate water deficit and soil salinity due to the effect of high Si and K in regulating transpiration and maintaining ion homeostasis (Alsaedi et al., 2019).

**Non-metallic (phosphorus) NPs.** Phosphorus nutrition has a significant role in enhancing drought tolerance in plants. The application of P fertilizer increased P
absorption and transfer efficiency, and improved biomass and chlorophyll content of leaves but decreased root/shoot ratio, thereby enhanced drought tolerance in cotton plants (Jun et al., 2017). In the same context, foliar application of P-NPs at 0.5–1.0 mg/L improved nutrient uptake of cotton plants under drought stress conditions (Hussien et al., 2015).

**Nano-size polymers and composites**

The potential mechanisms of nano-polymers such as nano-chitosan and nano-composites including hydroxyapatite, nano-clay, analcite and micronutrient in enhancing drought tolerance in crop plants are presented in Table 3.

**Nano-chitosan.** Chitosan, a modified biopolymer, is mainly used as a stabilizer of biological molecules like proteins, peptides or genetic material and as bioactive ingredients carrier for controlled release of active ingredients (Ghormade et al., 2011) due to its cationic properties and solubility in acidic solution. Moreover, chitosan prolongs the contact time between plant surface and agro-ingredients due to its cationic properties and solubility in acidic solution. Additionally, it plays a vital role for improving crop performance under stressed and non-stressed conditions (Iqbal et al., 2019).

Chitosan NPs are usually used with different bulk or other nanoparticles (nano-composites). For example, nano-chitosan-NPK fertilizer application promotes the growth and productivity of wheat plants grown in sandy soil (Abdel-Aziz et al., 2016). Recently, seed treatment and foliar application of Zn-chitosan NPs (0.01–0.16%) showed strong efficacy against Curvularia leaf spot in maize plants through strengthening innate immunity by balancing ROS, elevating antioxidant defense enzymes, and enhancing lignin accumulation (Choudhary et al., 2019). Under water deficit, the encapsulation of NO donor (S-nitrosogluthione) into chitosan NPs, as foliar spray at 100 µM, increased leaf CO2 assimilation and biomass allocation to root system and was effective in attenuating the diverse impact of water deficit on sugarcane plants due to controlled release of NO that prolonged its effect (Silveira et al., 2019).

**Nano-composite fertilizers.** Several natural or engineered metal-based NPs are combined together and served as a source of various macro or micronutrients (fertilizer nano-composites) such as hydroxyapatite, nano-clay, analcite and micronutrient nano-composites that play a vital role for improving crop performance under stressed and non-stressed conditions (Iqbal et al., 2019).

Calcium hydroxyapatite (Ca10(OH)(PO4)6) NPs, hold a potential to deliver both Ca and P, have been reported as an effective remedy against environmental stresses. It was reported that, the imbibition of jute seeds with hydroxyapatite NPs (20 µg/mL) for 24 h led to up-regulation of several genes including late embryogenesis abundant (LEA) protein and dehydration responsive element along with some biochemical markers such as proline and peroxidase. Hence, pre-treated seeds with hydroxyapatite NPs could be applied to counter the deleterious effects of drought stress in jute seedlings (Das et al., 2016).

Silicon nano-composites like nano-clay (H2Al2O5Si) and analcite (AlSi2O5H2O) have been used to improve

| Table 3. Effects of nano-size polymers and composites in ameliorating drought stress-induced damage in different plant species. |
|---|---|---|---|---|
| **Nanomaterials** | **Conc.** | **Application method** | **Plant species** | **Effects** |
| **Chitosan- NPs** | 100 µM | Foliar spray | *Saccharum officinarum* L. | Controlled release of NO and prolonged its effect resulted in increased leaf CO2 assimilation and biomass allocation to root system |
| **Metallic and metallic oxides NPs** | 20 µg/mL | Seed soaking | *Corchorus capsularis* L. | Increasing seedling growth traits |
| **Nanomaterials** | 500-1500 mg/L | Nutrient solution | *Solanum tuberosum* L. | Improving yield, yield components and oil percentage |
| **Nanocomposites** | 1 and 1.5 g/L | Soil | *Triticum aestivum* L. and *Zea mays* L. | Increasing photosynthesis, Fe concentration, grain yield and decreased the oxidative stress |
| **Hydroxyapatite NPs** | 1.77, 0.92 and 0.8 g/L | Foliar spray | *Brassica napus* L. | Enhancing growth and agronomic traits by reducing ROS damage and improving oxidative defense system |
| **ZnO, B2O3, and CuO nano-composite** | 1% | Seed priming | *Glycine max* (L.) Merr. | Adapting strawberry plants to drought before transplanting in the field |
| **Zn/Cu- NPs** | 100 µM Foliar spray | *S-nitrosoglutathione* into chitosan NPs, as foliar spray at 100 µM, increased leaf CO2 assimilation and biomass allocation to root system and was effective in attenuating the diverse impact of water deficit on sugarcane plants due to controlled release of NO that prolonged its effect (Silveira et al., 2019). | **Reference** |

---

Spanish Journal of Agricultural Research  
June 2020 • Volume 18 • Issue 2 • e08R01
the performance of crop plants grown under mild or extreme abiotic stresses. Nano-clay (20-30 nm) at 1 g/L positively increased nutrient uptake, alleviated the toxicity of heavy metals, improved plant growth and root characteristics of potato, which in turn make plants more resistant to drought and element-deficit stresses (Soltani et al., 2018). Analcite, a natural mineral of volcanic tuffs, at concentrations of 500-1500 mg/L improved soil agro-physical characteristics and enhanced seed germination, seedling growth, photosynthetic activity, and the accumulation of protective antioxidants in corn and wheat plants grown under different levels of drought stress (20, 40 and 60% of field capacity) (Zaimenko et al., 2014).

Concerning micronutrient nano-composites, the combinations of nano-FeSO₄ (1 g/L) and nano-MnSO₄ (1.5 g/L) were effective in enhancing growth and yield attributes of canola plants exposed to deficit irrigation (Pourjafar et al., 2016). The nano-formulations of ZnO, B₂O₃, and CuO NPs minimized the adverse effects of drought stress.

| NMs and their effects on drought-stressed plants |
|------------------------------------------------|
| **Carbon-based NPs** | **Fullerol**: ABA accumulation, reduced ROS by improved antioxidant defense system, intercellular water binders |
| **Metallic/metallic oxides, metalloids and non-metallic NPs** | **CeO₂-NPs**: improved photosynthesis, RuBisCO activity, WUE, and possessed potent antioxidant properties. |
| **Fe/Fe-oxides NPs**: induced cell wall loosening, improved root growth and nutrient uptake, increased photosynthesis, reduced oxidative stress damage. |
| **K-NPs**: increased stomatal conductance and growth. |
| **Ag-NPs**: stimulated germination rate and seedling growth. |
| **TiO₂-NPs**: increased RWC, anthocyanin, pigments, osmolytes and antioxidants and reduced oxidative damage. |
| **ZnO-NPs**: increased nutrient uptake and translocation, SOD activity. |
| **Si and SiO₂-NPS**: improved seed germination and seedling growth, photosynthetic activity, antioxidants, osmolytes, nutrient uptake, RWC, leaf pigments, WUE, ion homeostasis, reduced electrolyte leakage. |
| **P-NPs**: enhanced nutrient uptake and growth. |
| **Nano-composite fertilizers**: | **Hydroxyapatite**: up-regulation process of several genes including late embryogenesis abundant (LEA) and dehydration responsive element proteins, proline and peroxidase. |
| **Nano-clay**: improved nutrient uptake, plant growth and root characteristics. |
| **Analcite**: enhanced seed germination, seedling growth, photosynthetic activity, and the accumulation of protective antioxidants. |
| **Micronutrients**: enhanced nutrient uptake, photosynthetic pigments, leaf RWC, activity of antioxidative enzymes, and reduced lipid peroxidation. |

Figure 2. Roles of different nanomaterials (NMs) to overcome the drought-induced damage in plants. NPs: nanoparticles; ABA: abscisic acid; ROS: reactive oxygen species; WUE: water use efficiency; RWC: relative water content.
by increased N, P, K, Zn, B and Cu uptake and boosted crop performance of soyabean plants (Dimkpa et al., 2017). Taran et al. (2017) investigated the effect of binary composition of Zn/Cu-NPs (1%), as seed treatment, on drought-stressed wheat plants. They reported increased leaf relative water content, activity of antioxidative enzymes, reduced lipid peroxidation and stabilized the content of photosynthetic pigments in drought-stressed wheat plants due to the composition of Zn/Cu-NPs.

Conclusions and future perspectives

Drought stress is one of the major contemporary and future challenges for crop production and food security. The present review reveals that NMs ameliorate drought stress-induced damages in several field and horticultural crops by regulation of the expression of several genes involved in drought tolerance like LEA and aquaporins, in addition to alteration of various physiological and biochemical processes as follows (Fig. 2): (1) alleviating oxidative stress damage by enhancing antioxidant defense system; (2) mitigating osmotic stress though accumulation of compatible solutes and ion homeostasis; (3) improving photosynthesis through increasing the content of photosynthetic pigments and RuBisCO activity; (4) enhancing uptake and translocation of water and nutrients owing to their role in improving root growth, conductive tissue elements and up-regulation of aquaporins; (5) reducing water loss from leaves through stomatal closure owing to ABA accumulation; and ultimately, (6) improving growth, development and productivity of drought-stressed crop plants.

The effect of NMs as triggers to induce drought tolerance in various field and horticultural crop plants needs more studies to elucidate different plant responses like phenological, anatomical, ecological, cytological and molecular mechanisms besides physio-biochemical mechanisms. In addition, the application of NMs to improve crop performance under normal or stress conditions under field conditions needs great efforts to achieve this aim to be cost-effective with no negative impacts on environment and human health. Thus, the optimized concentration and application method should be taken into account. Further, several studies are required to investigate the potential toxicity of feed and food plants treated with NMs on animal and human health.

References

Abdel-Aziz HM, Hasaneen MN, Omer AM, 2016. Nanochitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil. Span J Agric Res 14: e0902. https://doi.org/10.5424/sjar/2016141-8205

Abid M, Ali S, Qi LK, Zahoor R, Tian Z, Jiang D, Snider JL, Dai T, 2018. Physiological and biochemical changes during drought and recovery periods at tillering and jointing stages in wheat (Tritium aestivum L.). Sci Rep 8: 4615. https://doi.org/10.1038/s41598-018-21444-7

Adrees M, Khan ZS, Ali S, Hafeez M, Khalid S, Rehman MZ, Hussain A, Hussain K, Chatha SAS, Rizwan M, 2020. Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. Chemosphere 238: 124681. https://doi.org/10.1016/j.chemosphere.2019.124681

Afshar RM, Hadi H, Pirzad A, 2012. Effect of nano-iron foliar application on qualitative and quantitative characteristics of cowpea under end season drought stress. Int Res J Appl Basic Sci 3: 1709-1717.

Agathokleous E, Feng ZZ, Ivo Iavicoli I, Calabrese EJ, 2019. The two faces of nanomaterials: a quantification of hormesis in algae and plants. Environ Int 131: 105044. https://doi.org/10.1016/j.envint.2019.105044

Aghdam MTB, Mohammadi H, Ghorbanpour M, 2016. Effects of nanoparticulate anatase titanium dioxide on physiological and biochemical performance of Linum usitatissimum (Linaceae) under well-watered and drought stress conditions. Braz J Bot 39: 139-146. https://doi.org/10.1007/s40415-015-0227-x

Ali F, Bano A, Fazal A, 2017. Recent methods of drought stress tolerance in plants. Plant Growth Regul 82: 363-375. https://doi.org/10.1007/s10725-017-0267-2

Almutairi ZA, Alharbi A, 2015. Effect of silver nanoparticles on seed germination of crop plants. J Adv Agric 4: 280-285. https://doi.org/10.24297/jaa.v4i1.4295

Alsaeedi A, El-Ramady H, Alshaal T, El-Garawany M, Elhawat N, Al-Otaiby A, 2019. Silica nanoparticles boost growth and productivity of cucumber under water deficit and salinity stresses by balancing nutrients uptake. Plant Physiol Biochem 139: 1-10. https://doi.org/10.1016/j.plaphy.2019.03.008

Ashkavand P, Tabari M, Zarafshar M, Tomášková I, Struve D, 2015. Effect of SiO2 nanoparticles on drought resistance in hawthorn seedlings. Forest Res Pap 76: 350-359. https://doi.org/10.1515/frp-2015-0034

Ashraf M, 2010. Inducing drought tolerance in plants: Recent advances. Biotechnol Adv 28: 169-183. https://doi.org/10.1016/j.biotechadv.2009.11.005

Borišev M, Borišev I, Župunski M, Arsenov D, Pajević S, Ćurčić Ž, Vasin J, Djordjevic A, 2016. Drought impact is alleviated in sugar beets (Beta vulgaris L.) by foliar application of fullerol nanoparticles. PLoS ONE 11: e0166248. https://doi.org/10.1371/journal.pone.0166248
Das K, Roychoudhury A, 2014. Reactive oxygen species (ROS) and response of antioxidants as ROS scavengers during environmental stress in plants. Front Environ Sci 2: 53. https://doi.org/10.3389/fenvs.2014.00053

De Ollas C, Arbona V, Gómez-Cadenas A, 2015. Jasmonic acid interacts with asbcsic acid to regulate plant responses to water stress conditions. Plant Signal Behav 10: e1078953 https://doi.org/10.1080/15592324.2015.1078953

De Ollas C, Arbona V, Gómez-Cadenas A, Dodd IC, 2018. Attenuated accumulation of jasmonates modifies stomatal responses to water deficit. J Exp Bot 69: 2103-2116. https://doi.org/10.1093/jxb/ery045

Dimkpa C, Bindraban P, 2018. Nanofertilizers: new products for the industry? J Agric Food Chem 66: 6462-6473. https://doi.org/10.1021/acs.jafc.7b02150

Dimkpa CO, Bindraban PS, Fugice J, Agyn-Birikorang S, Singh U, Hellums D, 2017. Composite micronutrient nanoparticles and salts decrease drought stress in soybean. Agron Sustain Dev 37: 5. https://doi.org/10.1007/s11359-016-0412-8

Djanaguiraman M, Nair R, Giraldo JP, Prasad PVV, 2018. Cerium oxide nanoparticles decrease drought-induced oxidative damage in sorghum leading to higher photosynthesis and grain yield. ACS Omega 3: 14406-14416. https://doi.org/10.1021/acsomega.8b01894

Du W, Tan W, Peralta-Videa JR, Gardea-Torresdey JL, Ji R, Yin Y, Guo H, 2017. Interaction of metal oxide nanoparticles with higher terrestrial plants: physiological and biochemical aspects. Plant Physiol Biochem 110: 110-225. https://doi.org/10.1016/j.plaphy.2016.04.024

Farooq M, Wahid A, Kobayashi N, Fujita D, Basra SMA, 2009. Plant drought stress: effects, mechanisms and management. Agron Sustain Dev 29: 185-212. https://doi.org/10.1051/agro:2008021

Farooq M, Hussain M, Wahid A, Siddique KHM, 2012. Drought stress in plants: an overview. In: Plant responses to drought stress; Aroca R (Eds), Springer-Verlag Berlin Heidelberg, pp: 1-33. https://doi.org/10.1007/978-3-642-32653-0_1

Foyer CH, Noctor G, 2012. Managing the cellular redox hub in photosynthetic organisms. Plant Cell Environ 35: 199-201. https://doi.org/10.1111/j.1365-3040.2011.02453.x

Gerardin FS, 2016. Effect of nano potassium fertilizer on some parchment pumpkin (Cucurbita pepo) morphological and physiological characteristics under drought conditions. Int J Farm Allied Sci 5: 367-371.

Ghormade V, Deshpande MV, Paknikar KM, 2011. Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnol Adv 29: 792-803. https://doi.org/10.1016/j.biotechadv.2011.06.007

Hafeez B, Khanif YM, Saleem M, 2013. Role of zinc in plant nutrition- A review. Am J Exp Agr 3: 374-391. https://doi.org/10.9734/AJEA/2013/2746

Haghhighi M, Da Silva JAT, Mozafarzarian 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 Biotechnol 25: 17-22.
Hatami M, 2017. Toxicity assessment of multi-walled carbon nanotubes on Cucumis melo L. under well-watered and water-stressed conditions. Environ Expo 142: 274-283. https://doi.org/10.1080/01904167.2017.1346123

Hatami M, Hadianb J, Ghorbanpoura M, 2017. Mechanisms underlying toxicity and stimulatory role of single-walled carbon nanotubes in Hyoscyamus niger during drought stress simulated by polyethylene glycol. J Hazard Mater 324: 306-320. https://doi.org/10.1016/j.jhazmat.2016.10.064

Hoekstra FA, Golovina EA, Buitink J, 2001. Nano-technology in agriculture, livestock, and aquaculture in China. A review. Agron Sustain Dev 35: 369-400. https://doi.org/10.1021/nn204643g

Huang S, Wang L, Liu L, Hou Y, Li L, 2015. Nanotechnology in agriculture, livestock, and aquaculture of cotton plants. Int J Chem Tech Res 8: 643-650. https://doi.org/10.15835/nbha4119093

Husoinski SA, Hajirezaei MR, Seiler C, Sreenivasulu N, von Wirén N, 2016. A potential role of flag leaf potassium in conferring tolerance to drought-induced leaf senescence in barley. Front Plant Sci 7: 206. https://doi.org/10.3389/fpls.2016.00206

Husen A, Siddiqi KS, 2014. Phytosynthesis of nanoparticles: Concept, controversy and application. Nanoscale Res Lett 9: 229-252. https://doi.org/10.1186/1556-276X-9-229

Hussien MM, El-Ashry SM, Hagagg WM, Mubarak DM, 2015. Response of mineral status to nano-fertilizer and moisture stress during different growth stages of cotton plants. Int J Chem Tech Res 8: 643-650.

Iqbal M, Umar S, Mahmodoudzafar NA, 2019. Nano-fertilization to enhance nutrient use efficiency and productivity of crop plants. In: Nanomaterials and plant potential; Husen A & Iqbal M (Eds). Springer Nature Switzerland AG, pp: 473-506. https://doi.org/10.1007/978-3-030-05569-1_19

Jaberzadeh A, Moaveni P, Reza H, Moghadam T, 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. https://doi.org/10.15835/nbha4119093

Jun W, Ping L, Zhiyong L, Zhanheng W, Yongshan L, Xinyuan G, 2017. Dry matter accumulation and phosphorus efficiency response of cotton cultivars to phosphorus and drought. J Plant Nutr 40: 2349-2357. https://doi.org/10.1080/01904167.2017.1346123

Kah M, Tufenkji N, White JC, 2019. Nano-enabled strategies to enhance crop nutrition and protection. Nat Nanotechnol 14: 532-540. https://doi.org/10.1038/s41565-019-0439-5

Kamalizadeh M, Bihamta M, Zarei A, 2019. Drought stress and TiO2 nanoparticles affect the composition of different active compounds in the Moldavian dragonhead plant. Acta Physiol Plant 41: 21. https://doi.org/10.1007/s11738-019-2814-0

Kananont N, Pichyangkura R, Chanprame S, Chadhawan S, Limpanaveech P, 2010. Chitosan specificity for the in vitro seed germination of two dendrobium orchids (Asparagales: Orchidaceae). Sci Hort 124: 239-247. https://doi.org/10.1016/j.scienta.2009.11.019

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

Kedziora A, Speruda M, Krzyzewskza Z, Rybka J, Łukowiak A, Bugla-Płoskonska G, 2018. Similarities and differences between silver ions and silver in nanoforms as antibacterial agents. Int J Mol Sci 19: 1-17. https://doi.org/10.3390/ijms19020444

Khan MN, Alzaualib FM, 2018. Nano-titanium dioxide-induced synthesis of hydrogen sulfide and cysteine augment drought tolerance in Eruca sativa. Asian J Plant Sci 17: 213-221. https://doi.org/10.3923/ajps.2018.213.221

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

Khodakovskaya M, Silva K, Biris A, Dervishi E, Villagarcia H, 2012. Carbon nanotubes induce growth enhancement of tobacco cells. ACS Nano 6: 2128-2135. https://doi.org/10.1021/nn204643g

Kiapour H, Moaveni P, Habibi D, Sani B, 2015. Evaluation of the application of gibberellic acid and titanium dioxide nanoparticles under drought stress on some traits of basil (Ocimum basilicum L.). Int J Agron Agric Res 6: 138-150.

Kim Y-H, Khan AL, Waqas M, Lee I-J, 2017. Silicon regulates antioxidant activities of crop plants under abiotic-induced oxidative stress: a review. Front Plant Sci 8: 510. https://doi.org/10.3389/fpls.2017.00510

Lambers H, Chapin FS, Pons TL, 2008. Plant physiological ecology. 2nd ed., Springer, NY. https://doi.org/10.1007/978-0-387-78341-3

Lawlor DW, Cornel G, 2002. Photosynthetic carbon assimilation and associated metabolism in relation to water deficits in higher plants. Plant Cell Environ 25: 275-294. https://doi.org/10.1046/j.0016-8025.2001.00814.x

Mahdavi S, Kafi M, Fallahi E, Shokrpour M, Tabrizi L, 2016. Water stress, nano silica, and digoxin effects...
on minerals, chlorophyll index, and growth in ryegrass. Int J Plant Prod 10: 251-264.

Marslin G, Sheeba CJ, Franklin G, 2017. Nanoparticles alter secondary metabolism in plants via ROS burst. Front Plant Sci 8: 832. https://doi.org/10.3389/fpls.2017.00832

Martinez-Fernández D, Vitková M, Bernal MP, Komárek M, 2015. Effects of nano-magnethite on trace element accumulation and drought response of Helianthus annuus L. in a contaminated mine soil. Water Air Soil Pollut 226: 1-9. https://doi.org/10.1007/s11270-015-2365-y

Maswada HF, Djanaguiraman M, Prasad PVV, 2018. Seed treatment with nano-iron (III) oxide enhances germination, seedling growth and salinity tolerance of sorghum. J Agron Crop Sci 204: 577-587. https://doi.org/10.1111/jac.12280

Mimmo T, Del Buono D, Terzano R, Crecchio C, Pinton R, Rocchi G, Cesco S, 2014. Rhizospheric organic compounds in the soil-microorganism-plant system: their role in iron availability. Eur J Soil Sci 65: 629-642. https://doi.org/10.1111/ejss.12158

Mohamed MS, Kumar DS, 2016. Methods of using nanoparticles. In: Plant nanotechnology; Kole C, Kumar DS, Khodakovskaya MV (Eds), Springer Int Publ Switzerland, pp: 65-94.

Mohammadi H, Esmailpour M, Gheranpaye A, Biparva P, 2016. Impact of zinc oxide and copper oxide nano-particles on physiological and molecular processes in Brussica napus L. Ind J Plant Physiol 21: 122-128. https://doi.org/10.1007/s40502-016-0212-9

Rai PK, Kumar V, Lee S, Raza N, Kim K-H, Ok YS, Tsang DCW, 2018. Nanoparticle-plant interaction: Implications in energy, environment, and agriculture. Environ Int 119: 1-19. https://doi.org/10.1016/j.envint.2018.06.012

Rameshraddy G, Pavithra J, Reddy BHR, Salimath M, Geetha KN, Shankar AG, 2017. Zinc oxide nano particles increases Zn uptake, translocation in rice with positive effect on growth, yield and moisture stress tolerance. Ind J Plant Physiol 22: 287-294. https://doi.org/10.1007/s40502-017-0303-2

Reddy AR, Chaitanya KV, Vivekanandan M, 2004. Drought-induced responses of photosynthesis and antioxidant metabolism in higher plants. J Plant Physiol 161: 1189-1202. https://doi.org/10.1016/j.jplph.2004.01.013

Rossi L, Fedenia LN, Sharifan H, Ma X, Lombardini L, 2019. Effects of foliar application of zinc sulfate and zinc nanoparticles in coffee (Coffea arabica L.) plants. Plant Physiol Biochem 135: 160-166. https://doi.org/10.1016/j.plaphy.2018.12.005

Roychoudhury A, Basu S, Sengupta DN, 2012. Antioxidants and stress-related metabolites in the seedlings of two indica rice varieties exposed to cadmium chloride toxicity. Acta Physiol Plant 34: 835-847. https://doi.org/10.1007/s11738-011-0881-y

Schieber M, Chandel NS, 2014. ROS function in redox signaling and oxidative stress. Curr Biol 24: R453-R462. https://doi.org/10.1016/j.cub.2014.03.034

Sedghi M, Hadi M, Toluie SG, 2013. Effect of nano zinc oxide on the germination parameters of soybean seeds under drought stress. Ann West Univ Timisoara Ser Biol 16: 73-78.

Seghatoleslami M, Forutani R, 2015. Yield and water use efficiency of sunflower as affected by nano ZnO and water Stress. J Adv Agr Technol 2: 34-37. https://doi.org/10.12720/joaat.2.1.34-37
Seghatoleslami MJ, Feizi H, Mousavi G, Berahmand A, 2015. Effect of magnetic field and silver nanoparticles on yield and water use efficiency of Carum copticum under water stress conditions. Pol J Chem Tech 17: 110-114. https://doi.org/10.1515/pjct-2015-0016

Shallan M, Hassan HM, Namich AAM, Ibrahim AA, 2016. Biochemical and physiological effects of TiO₂ and SiO₂ nanoparticles on cotton plant under drought stress. Res J Pharma Biol Chem Sci 7: 1540-1551.

Silveira NM, Seabra AB, Marcos FCC, Pelegrino MT, Machado EC, Ribeiro RV, 2019. Encapsulation of S-nitrosoglutathione into chitosan nanoparticles improves drought tolerance of sugarcane plants. Nitric Oxide 84: 38-44. https://doi.org/10.1016/j.niox.2019.01.004

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. Bio Nano Sci 8: 218-228. https://doi.org/10.1007/s12668-017-0467-2

Sonia T, Sharma CP, 2011. Chitosan and its derivatives for drug delivery perspective. Adv Polym Sci 243: 23-53. https://doi.org/10.1007/12_2011_117

Srivastava G, Das CK, Das A, Singh SK, Roy M, Kim H, Sethy N, Kumar A, Sharma RK, Singh SK, Philipip J, Das M, 2014. Seed treatment with iron pyrite (FeS₂) nanoparticles increases the production of spinach. RSC Adv 4: 58495-58504. https://doi.org/10.1039/C4RA06861K

Taran N, Storozenko 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

Thiruvengadam M, Gurunathan S, Chung IM, 2015. Physiological, metabolic, and transcriptional effects of biologically-synthesized silver nanoparticles in turnip (Brassica rapa ssp. rapa L.). Protoplasma 252: 1031-1046. https://doi.org/10.1007/s00709-014-0738-5

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

Trenberth KE, Dai A, van der Schrier G, Jones PD, Trenberth KE, Dai A, van der Schrier G, Jones PD, 2022. Global warming of the climate system: A perspective view on the pros and cons. Sci Total Environ 667: 485-499. https://doi.org/10.1016/j.scitotenv.2019.02.409

Verma SK, Das AK, Gantait S, Kumar V, Gurel E, 2019. Applications of carbon nanomaterials in the plant system: A perspective view on the pros and cons. Sci Total Environ 667: 485-499. https://doi.org/10.1016/j.scitotenv.2019.02.409

Walter J, Nagy L, Hein R, Rascher U, Beierkuhnlein C, Willner E, Jentsch A, 2011. Do plants remember drought? Hints towards a drought-memory in grasses. Environ Exp Bot 71: 34-40. https://doi.org/10.1016/j.envexpbot.2010.10.020

Yousefi S, Kartoolinejad D, Naghdi R, 2017. Effects of priming with multi-walled carbon nanotubes on seed physiological characteristics of hopbush (Podocarpus viscosa L.) under drought stress. Int J Environ Stud 74: 528-539. https://doi.org/10.1080/00207233.2017.1325627

Zaimenko NV, Didyk NP, Dzyuba OI, Zakrassov OV, Rositska NV, Viter AV, 2014. Enhancement of drought resistance in wheat and corn by nanoparticles of natural mineral analcitem. Ecol Balkanica 6: 1-10.

Zandalinas SL, Balfagón D, Arbona V, Vázquez-Cadenas A, 2017. Modulation of antioxidant defense system is associated with combined drought and heat stress tolerance in citrus. Front Plant Sci 8: 953. https://doi.org/10.3389/fpls.2017.00953

Zareei FD, Roozbahani A, Hosnamidi A, 2014. Evaluation the effect of water stress and foliar application of Fe nanoparticles on yield, yield components and oil percentage of safflower (Carthamus tinctorius L.). Int J Adv Biol Biomed Res 2: 1150-1159.

Zaytseva O, Neumann G, 2016. Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications. Chem Biol Technol Agr 3: 17. https://doi.org/10.1186/s40538-016-0070-8

Zhao W, Dong H, Zahoor R, Zhou Z, Snider J, Chen Y, Siddique KHM, Wang Y, 2019. Ameliorative effects of potassium on drought-induced decreases in fiber length of cotton (Gossypium hirsutum L.) are associated with osmolyte dynamics during fiber development. The Crop J 7(5): 619-634. https://doi.org/10.1016/j.cj.2019.03.008

Zuverza-Mena N, Martinez-Fernández D, Du W, Hernández-Viecas JA, Bonilla-Bird N, López-Moreno ML, Komárek M, Peralta-Videa JR, Gardea-Torresdey JL, 2017. Exposure of engineered nanomaterials to plants: Insights into the physiological and biochemical responses-A review. Plant Physiol Biochem 110: 236-264. https://doi.org/10.1016/j.plaphy.2016.05.037