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REVIEW ARTICLE

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

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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)

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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 TiO_2-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 (CeO_2, Fe and Fe-oxides, K, Ag, TiO_2 and ZnO), metalloids (Si and SiO_2), 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 CO_2 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

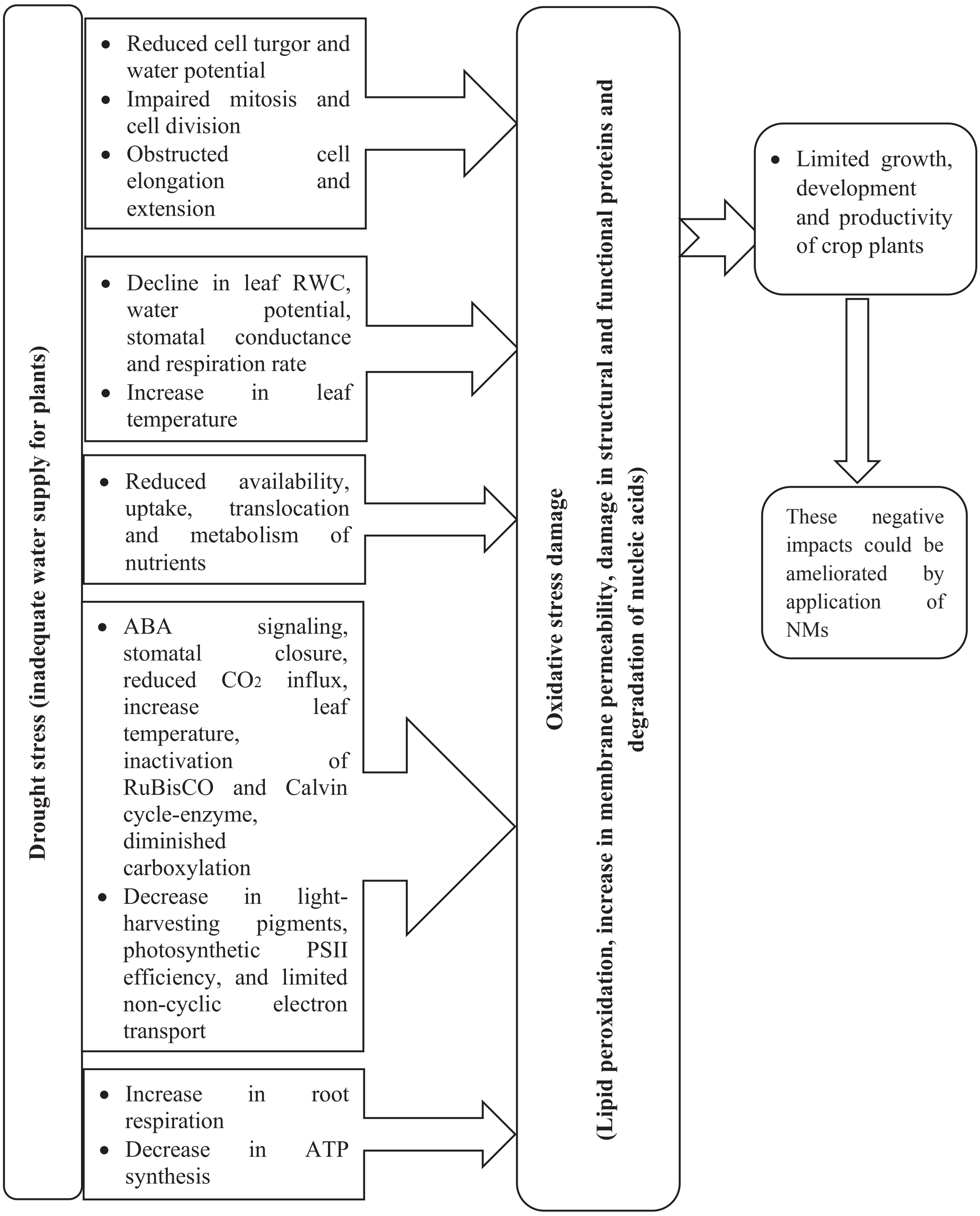


Figure 1. The adverse effects of drought stress on different physio-biochemical processes in plants. RWC: relative water content; ABA: abscisic acid; NMs: nanomaterials.

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 pH buffer (Ali *et al.,* 2017) and reduces photo-damage in thylakoid membranes (Lawlor & Cornic, 2002).

Drought induces oxidative stress via the production of ROS including superoxide radical ($O_2^{-\bullet}$), hydrogen peroxide (H_2O_2), and hydroxyl radical ($OH^\bullet$) that cause oxidative damage to lipids, proteins, and DNA (Schieber & Chandel, 2014). Enzymatic and non-enzymatic antioxidants are involved in cellular defense mechanism responses for ROS detoxification. Superoxide dismutases (SOD) covert $O_2^{-\bullet}$ stress through dismutation reaction of O_2 and H_2O_2 (Schieber & Chandel, 2014). As a result, H_2O_2 can be converted into H_2O 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, *"Nanomaterial means a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1–100 nm"* (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

Table 1. Effects of carbon-based NMs in ameliorating drought stress-induced damage in different plant species.

Nanomaterials			Plant species	Effects	Reference
Type	Conc.	Application method			
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			cell injury	
MWCNTs	30 mg/L	Seed priming	*Alnus subcordata* C.A. Mey.	Increasing seedling growth traits	Rahimi *et al.* (2016)
	50 mg/L	Foliar spray	*Salvia mirzayanii Rech.* f. and Esfand	Improving chlorophyll index, electrolyte leakage, total phenolics, and antioxidant capacity	Chegini *et al.* (2017)
	0.5-1 g/L	Seed socking	*Cucurbita pepo* L.	Enhancement of water uptake, seed germination and seedling growth	Karami & Sepehri (2017)
	125-1000 µg/mL	Seed socking	*Hordeum vulgare* L.	Oxidative injury, negative effects on seed germination and seedling growth	Hatami (2017)
	50-100 mg/L	Seed priming	*Dodonaea viscosa* Jacq.	Improving seed germination and growth traits	Yousefi *et al.* (2017)
Fullerol					
$[(C_{60}(OH)_{24}]$	70-700 µmol/L	Foliar spray	*Beta vulgaris* L.	Able to bind with water in distinct cell compartments and possessed hydroscopic and antioxidant activities	Borišev *et al.* (2016)
$[(C_{60}(OH)_{27}]$	10-100 mg/L	Seed priming	*Brassica napus* L.	Repressing ROS accumulation by enhancing the regulatory mechanisms on enzymatic and non-enzymatic antioxidants and ABA accumulation	Xiong *et al.* (2018)

NMs: 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 stimulation effect of CNTs may be attributed to the up-regulation of genes involved in cell division/cell wall formation and water transport, such as those controlling synthesis of water channel protein "aquaporins" (Khodakovskaya *et al.,* 2012).

Previous findings proved the potential role of SWCNTs with diameter of 1-3 nm, and MWCNTs with diameter of 5-40 nm (Zaytseva & Neumann, 2016) in ameliorating cell damages caused by drought stress. Hatami *et al.* (2017) reported a positive effect of SWCNTs at low concentration (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. (Hopbush) 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. 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, $C_{60}(OH)n$), 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 [$(C_{60}(OH)_{24}$] 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 (α-FeOOH), nano-hematite (α-Fe_2O_3), nano-maghemite (ɤ-Fe_2O_3), nano-magnetite (Fe_2O_4), and nano-iron pyrite (FeS_2) 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_2O_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; Zareii *et al.,* 2014). Soil application of 1% iron oxide NPs (maghemite, γ-Fe_2O_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 γ-Fe_2O_3 (3.4 mg/L) and Fe_3O_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 copticum* 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			Plant species	Effects	Reference
Type	Conc.	Application method			
Metallic and metallic oxides NPs					
CeO_2	100 mg/kg	Soil	*Glycine max* (L.) Merr.	Improved biomass, photosynthetic performance, RuBisCO activity and WUE	Cao *et al.* (2018)
	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)
	-	Foliar spray	*Carthamus tinctorious* L.	Improving yield, yield components and oil percentage	Zareii *et al.* (2014)
	100 mg/kg	Soil	*Triticum aestivum* L	Increased photosynthesis, Fe concentration, grain yield and decreased the oxidative stress	Adrees *et al.* (2020)
γ-Fe_2O_3 NPs	1%	Soil	*Helianthus annuus* L.	Growth improvement	Martínez-Fernandez *et al.* (2015)
	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)
Fe_3O_4 NPs	0.8 mg/L	*In vitro* culture media	*Fragaria* × *ananassa* Duch.	Adapting strawberry plants to drought before transplanting in the field	Mozafari *et al.* (2018)
TiO_2-NPs	0.02%	Foliar spray	*Triticum aestivum* L.	Increased yield and yield components as well as gluten and starch content	Jaberzadeh *et al.* (2013)
	10 mg/L	Foliar spray	*Linum usitatissimum* L.	Increased photosynthetic pigments, protein and seed oil contents and decreased lipid peroxidation	Aghdam *et al.* (2016)
	0.03%	Foliar spray	*Ocimum basilicum* L.	Improved RWC, anthocyanin concentration, and catalase activity	Kiapour *et al.* (2015)
	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	Shallan *et al.* (2016)
	20 mg/L	Foliar spray	*Eruca sativa* Mill.	Enhanced H2S and cysteine synthesis that led to improving in antioxidant activity, accumulation of osmolytes and RWC with reduction in H2O2, lipid peroxidation and electrolyte leakage	Khan & Alzuaibr (2018)
	10 mg/L	Foliar spray	*Dracocephalum moldavica* L.	Accumulation of proline and reduction in ROS (H_2O_2) and lipid peroxidation	Mohammadi *et al.* (2014)
	30-50 mg/L	Foliar spray		Increased essential oils and phenolic compounds	Kamalizadeh *et al.* (2019)
K-NPs	2.5 g/L	Foliar spray	*Cucurbita pepo* L.	Increasing growth traits and stomatal conductance	Gerdini (2016)
Ag-NPs	40 g/ha	Irrigation water	*Carum copticum* (L.) Link	No positive effect on WUE and yield characteristics	Seghatoleslami *et al.* (2015)
	10 µg/mL	Seed socking	*Lens culinaris* Medikus	Enhanced germination percentage and seedling growth traits	Hojjat (2016)
ZnO-NPs	1000 mg/L	Seed socking	*Glycine max* (L.) Merr.	Increasing germination, and decreasing seed residual fresh and dry weight of seedlings	Sedghi *et al.* (2013)
	1000 mg/L	Foliar spray	*Helianthus annuus* L.	Increasing seed yield and water use efficiency	Seghatoleslami & Forutani (2015)
	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	Rameshraddy *et al.* (2017)
	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)

foliar application of TiO_2-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-TiO_2 (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-TiO_2 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-TiO_2 (50 mg/L) increased yield characteristics under drought conditions

Table 2. Continued.

Nanomaterials			Plant species	Effects	Reference
Type	Conc.	Application method			
Metalloids and non-metallic NPs					
SiO_2-NPs	100 mg/L	Irrigation water	*Crataegus aronia* L.	Increasing RWC, electrolyte leakage, pigments, carbohydrate and proline contents as well as photosynthetic rate, stomatal conductance and plant biomass	Ashkavand *et al.* (2015)
	1 mM	Foliar spray	*Lolium perenne* L.	Improving mineral nutrient values and other quality indices	Mahdavi *et al.* (2016)
Si-NPs	1-2 mM	Seed socking	*Lycopersicum esculentum* Mill.	Enhancing germination rate	Haghighi *et al.* (2013)
	200 mg/kg	Soil	*Cucurbita pepo* L.	High Si and K concentration regulated transpiration and maintained ion homeostasis	Alsaeedi *et al.* (2019)
P-NPs	0.5-1.0 mg/L	Foliar spray	*Gossypium barbadense* L.	Improving macro and micro-nutrients uptake	Hussien *et al.* (2015)

through increasing plant pigments, accumulation of total soluble sugars, proline, total phenols, total soluble proteins, and antioxidant enzymes activity (Shallan *et al.,* 2016). TiO_2-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 H_2S and cysteine that improved the antioxidant activity, accumulation of osmolytes and RWC with the simultaneous decrease in H_2O_2 content and lipid peroxidation (Khan & Alzuaibr, 2018). Likewise, Moldavian dragonhead plant treated with TiO_2-NPs (10 mg/L) showed accumulation of proline and reduction in ROS (H_2O_2) and lipid peroxidation, and thereby counteracted the negative impacts of drought stress (Mohammadi *et al.,* 2014). Recently, Kamalizadeh *et al.* (2019) found that TiO_2-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 TiO_2-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 $ZnSO_4$-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 (Alsaeedi *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

Table 3. Effects of nano-size polymers and composites in ameliorating drought stress-induced damage in different plant species.

Nanomaterials			Plant species	Effects	Reference
Type	**Conc.**	**Application method**			
Chitosan- NPs					
S-nitrosoglutathione (NO donor) encapsulated into nano-chitosan	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	Silveira *et al.* (2019)
Metallic and metallic oxides NPs					
Hydroxyapatite NPs	20 µg/mL	Seed socking	*Corchorus capsularis* L.	Increasing seedling growth traits	Das *et al.* (2016)
Nano-clay	1 g/L	Nutrient solution	*Solanum tuberosum* L.	Improving yield, yield components and oil percentage	Soltani *et al.* (2018)
Analcite-NPs	500-1500 mg/L	Soil	*Triticum aestivum L.* and *Zea mays* L.	Increased photosynthesis, Fe concentration, grain yield and decreased the oxidative stress	Zaimenko *et al.* (2014)
Nano-$FeSO_4$ and nano-$MnSO_4$	1 and 1.5 g/L	Foliar spray	*Brassica napus* L.	Enhancing growth and agronomic traits by reducing ROS damage and improving oxidative defense system	Pourjafar *et al.* (2016)
ZnO, B_2O_3, and CuO nano-composite	1.77, 0.92 and 0.8 g/L	Foliar spray	*Glycine max* (L.) Merr.	Adapting strawberry plants to drought before transplanting in the field	Dimkpa *et al.* (2017)
Zn/Cu- NPs	1%	Seed priming	*Triticum aestivum* L.	Increased yield and yield components as well as gluten and starch content	Taran *et al.* (2017)

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 agrochemical due to its easly absorption with plant surface (Kananont *et al.,* 2010; Sonia & Sharma, 2011).

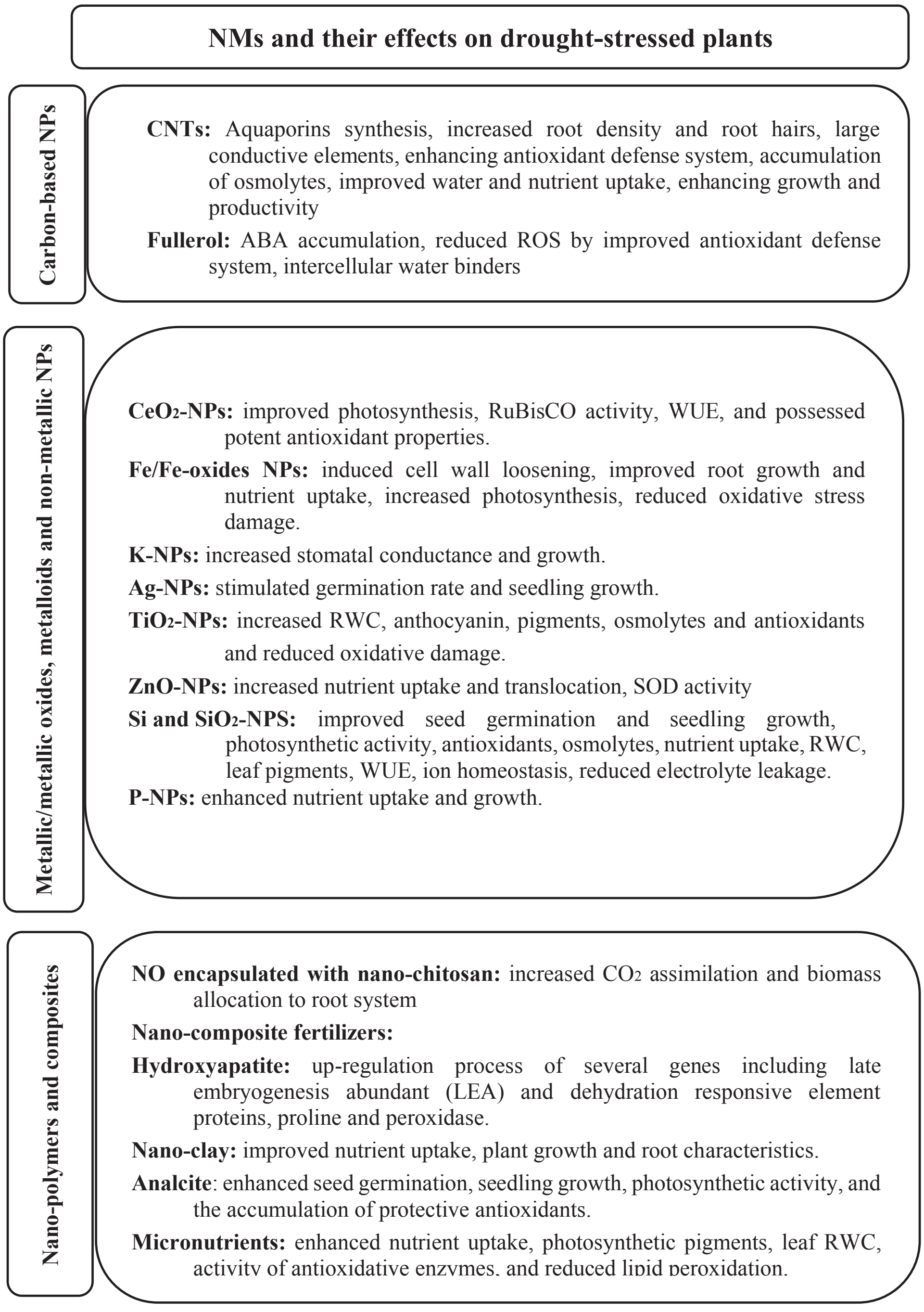
Chitosan NPs are usually used with different bulk or other nanoparticles (nano-composites). For example, nano chitosan-NPK fertilizer application promotes the growth and productivity of wheat plants grown in sandy soil (Abdel-Aziz *et al.,* 2016). Recently, seed treatment and foliar application of Zn-chitosan 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-nitrosoglutathione) into chitosan NPs, as foliar spray at 100 µM, increased leaf CO_2 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 ($Ca_5(OH)(PO_4)_3$) 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 ($H_2Al_2O_6Si$) and analcite ($AlSi_2O_6$-H_2O) have been used to improve 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-$FeSO_4$ (1 g/L) and nano-$MnSO_4$ (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, B_2O_3, and CuO NPs minimized the adverse effects of drought stress



NMs and their effects on drought-stressed plants

Carbon-based NPs

CNTs: Aquaporins synthesis, increased root density and root hairs, large conductive elements, enhancing antioxidant defense system, accumulation of osmolytes, improved water and nutrient uptake, enhancing growth and productivity

Fullerol: ABA accumulation, reduced ROS by improved antioxidant defense system, intercellular water binders

Metallic/metallic oxides, metalloids and non-metallic NPs

CeO_2-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.

TiO_2-NPs: increased RWC, anthocyanin, pigments, osmolytes and antioxidants and reduced oxidative damage.

ZnO-NPs: increased nutrient uptake and translocation, SOD activity

Si and SiO_2-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-polymers and composites

NO encapsulated with nano-chitosan: increased CO_2 assimilation and biomass allocation to root system

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.

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