25 Nanoweapons to Fight with Salt and Drought Stress

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Abstract

Plants face various abiotic and biotic stresses throughout their life cycle which adversely affect plant growth development and ultimately yield. Drought, salinity, and heat stress are most prevalent abiotic stresses, threatening the global food security. Plants fight with these stresses by altering their physiological, molecular, and biochemical pathways but stress sensitive plants are unable to cope with stresses. In this regard, exploration of some novel strategies and their exploitation are need of the hour to mitigate stress and improve yield. Nanoparticles emerged as magic bullets for agriculturists, farmers, and scientists to improve plant performance under stress conditions. Several studies have depicted the use of nanoparticles in mitigation of abiotic stresses to enhance crop productivity. The size of these particles ranges from 1 to 100 nm, and are available in the form of plant growth promoters, herbicides, pesticides as well as fertilizers. Several reports showed that application of inorganic and/or organic nanoparticles confer tolerance in plants against stresses. These particles enhance plants tolerance by modulating their physiological, biochemical and molecular routes as well as their gene expression. Nanoparticles minimize oxidative stress by enhancing the radical scavenging potential and antioxidant enzymatic and non-enzymatic activities of plants. These particles crosstalk with various plant hormones to make plants thrive under stress. Thus, supplementation of nanoparticles emerged as novel strategy to improve plant tolerance.

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25.1 Introduction

Plants encounter with various abiotic (natural or anthropogenic stress) and biotic stresses throughout their course of life. Among abiotic stresses, temperature stress (heat and cold stress), water stress (drought stress and flooding), and salt stress are major threats for sustainable crop production (Fig. 25.1) (Zhang et al. 2020). These stresses modulate plants at morphological, physiological, anatomical, biochemical, and molecular level temporarily or permanently which hamper plant growth and development and ultimately reduce crop yield. Plants exposed to salt stress experience osmotic stress (water deficit) during initial stage of stress followed by hyperionic stress (high concentration of ions Na^+ and Cl^- in cytosol) as well as oxidative stress (production of reactive oxygen species) at later stage of salt stress. The adverse effect of osmotic stress (physiologically dry soil) due to salinity on plants is similar to drought stress (physical dry soil). Oxidative stress occurs due to production of reactive oxygen species (superoxide radicals ($O_2^{\cdot -}$), singlet oxygen ($^1O_2$), hydrogen peroxide (H_2O_2), hydroxyl radical ($OH^{\cdot -}$), hydroperoxyl radical ($HO_2^{\cdot}$), alkoxy radical ($RO^{\cdot}$), peroxyl radicals ($ROO^{\cdot}$), and excited carbonyl (RO)) which leads to disruption of cell membrane and ultimately cell death (Hasanuzzaman et al. 2013). Ionic stress leads to accumulation of sodium ions (Na^+) in cytosol, which disturbs ion homeostasis by disturbing uptake of potassium (K^+) and calcium ions (Ca^+) which are essential macroelements for plant growth and development. It also leads to premature leaf fall and affects crop yield. Drought stress (low moisture content in soil) causes drastic loss in crop yield in arid regions. It negatively affects plant growth and development, one of them is reduction in leaf expansion (decrease in photosynthetic area) due to decrease in water content of leaf. Other effects include production of reactive oxygen species, decrease in leaf area, and in severe conditions wilting and ultimately plant death. Plants either fight with these stresses or avoid it to nullify the negative effects of stresses on themselves. The plants which fight with stresses are called stress tolerant plants, and the ability of plants to fight with stresses is known as their tolerance. The plants having low tolerance for stresses are known

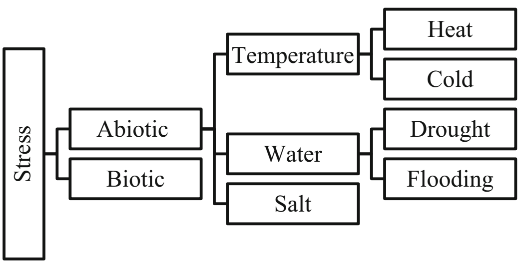

Fig. 25.1 Major stresses faced by plants during its life

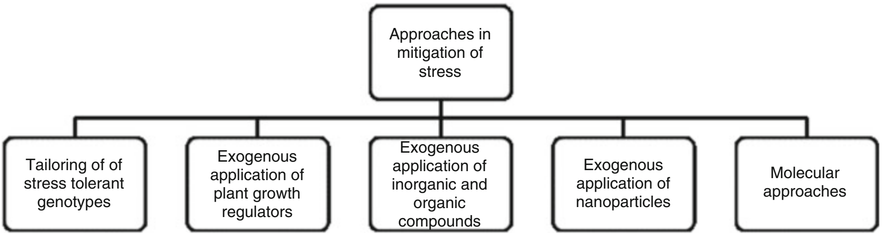

Fig. 25.2 Approaches in mitigation of drought and salt stress

as stress sensitive plants. The plants which avoid stresses are called escapers. Halophytes have in-built mechanisms to fight with salt stress (tolerance mechanism). These are called salt stress tolerant plants. Ephemeral plants complete their life cycle before the onset of dry period (avoidance mechanism). These are known as drought escapers.

The various strategies are sought and adopted to cope with stresses or to improve plant tolerance against stresses (Fig. 25.2). One of them is tailoring of stress tolerant genotypes with high grain yield followed by their screening under natural stress conditions in fields. The development of tolerant varieties is time consuming and labour-intensive with limited success. The screening of these genotypes for their tolerance against stress is extra burden for scientists and researchers. The degree of tolerance varies among different genotypes. So alternative approaches are sought, and applied for mitigation of these stresses, and maximize yield potential of crops. The most prevalent approach is upgradation of plant tolerance mechanism against stresses by exogenous application of plant growth regulators, osmoprotectants, biofertilizers, inorganic and organic compounds as well as nanoparticles. The utilization of nanotechnology in agriculture to cope with stress as well as for sustainable crop production drew attention of scientists, researchers, agriculturists, and farmers (Heidarabadi 2022).

25.2 What Are Nanoparticles?

The term nanotechnology was first earned by scientist Norio Taniguichi, a professor at Tokyo University of Science, in 1974, and this technology came into limelight during twentieth century (Khan and Rizvi 2014) and attained prominent position in field of science, engineering, medical, agriculture, and industries in the twenty-first century. The nanomaterials (NMs) are proved as Kohinoor gems in the field of agriculture. These are used in the form of plant growth promoters or stimulants, pesticides, herbicides, fertilizers, pesticides carriers, and plant growth regulators. Plant growth stimulants nanoparticles are employed for alleviation of negative effects of stress by modulation of their tolerance mechanisms at physiological, biochemical as well as at molecular level. The dimensions of NMs range from 1 nm to 100 nm with large surface-to-volume ratio, and these are available in one dimension (surface films), two dimensions (strands and films), and three dimensions (nanoparticles (NPs)). On the basis of mode of synthesis, the NPs are of three types: natural, incidental, and synthetic (engineered). The synthetic NPs are synthesized either from bulk chemicals (top-down approach) or from atoms or ions (bottom-up approach) by physical, chemical, and biological methods (using microorganisms and plants (green factories)). The NPs prepared using plant extracts are called green nanoparticles, and this is cost-effective and eco-friendly approach for synthesis of NPs. The synthesis of nanoparticles using pant extract is called green synthesis or phytosynthesis (not confused with photosynthesis), e.g. synthesis of selenium NPs using stem extract of *Leucas lavandulifolia* (Kirupagaran et al. 2016). On the basis of their nature, NPs are of two types: (a) inorganic NPs and (b) organic NPs. a) Inorganic NPs are further divided into two groups:

1. Metallic and metallic oxides NPs (Au NPs, Ag NPs, CuO, ZnO, Fe_2O_3)
2. Metalloid and metalloid oxides NPs (SiO_2 NPs)

b) Carbon nanoparticles (quantum dots, carbon nanotubes, Fullerenol NPs ($C_6O(OH)_{24}$)) are involved in the category of organic NPs (Taran et al. 2017).

25.3 Inorganic Nanoparticles

25.3.1 Silver NPs (Ag NPs)

Hojjat (2016) observed positive effect of AgNPs in lentils exposed to drought stress. The application of Ag NPs enhanced germination rate, germination percentage, root length, root fresh, and dry biomass of lentils under drought stress.

25.3.2 Gold NPs (Au NPs)

The gold nanoparticles are included in the category of metal nanoparticles. The potential role of Au NPs in inducing tolerance against salinity was observed in wheat by Wahid et al. (2022). These NPs minimized oxidative stress by modulating activities of antioxidant enzymes. The improvement in plant growth attributes under saline conditions with application of Au NPs was also reported (Wahid et al. 2022).

25.3.3 Zinc Oxide NPs (ZnO NPs)

Zinc is included in the category of essential microelement. In tomato, the role of these NPs to cope with salt stress was observed by Faizan et al. (2021). The tomato seedlings were subjected to salt stress (150 mM), and foliar application of ZnO NPs at concentration of 10, 50, and 100 mg/L was given at 25 DAS (days after sowing).

The application improved tomato plant growth in terms of shoot length, root length as well as fresh and dry biomass and leaf area under salt stress. The physiological attributes (photosynthesis rate, chlorophyll content, and carotenoid content) as well as biochemical parameters (antioxidant enzymes and protein content) also improved with foliar spray of them. Semida et al. (2021) also studied the role of ZnO NPs in stress (water deficit) tolerance in eggplant. The foliar application of NPs alleviated the negative effects of drought stress by improving plant growth, membrane stability, photosynthetic rate, water productivity as well as yield. Application of 50 and 100 ppm ZnO NPs improved fruit yield by 12.2% and 22.6%, respectively of plants exposed to water stress, in comparison with plants grown in fully irrigated soil.

25.3.4 Copper Oxide NPs (CuO NPs)

Copper is one of the microelements in plants. CuO NPs are included in the category of inorganic metal oxide nanoparticles. These NPs amplified drought tolerance in maize when 12-day old seedlings were treated with it. The grain yield reduced significantly under water deficit conditions but application of CuO NPs increased grain yield as well as seed number. It ameliorated the negative effects of water deficient stress on maize yield by enhancing chlorophyll and carotenoid content, which directly increased the photosynthesis rate and grain yield. Significant increase in level of antioxidant enzymes under drought stress with application of CuONPs was also reported. These enzymes fight with reactive oxygen species and minimize the effects of drought stress on plants (Van Nguyen et al. 2022).

25.3.5 Titanium Oxide NPs (TiO_2 NPs)

Titanium oxide is one of the inorganic nanoparticles. Various studies reported the application of TiO_2 NPs in mitigation of salt and drought stress by improving their growth, and enhanced yield. Dawood et al. (2019) fertigated the water deficit soil with these NPs and assessed the performance of four wheat cultivars (Sohag 3, Benisuif 5, Sakha 93, and Sed 12). Under control conditions (water deficit soil), wheat growth in terms of leaf traits is negatively affected. TiO_2 NPs promoted photosynthetic rate, improved leaf health, increased leaf chlorophyll content, LAI (leaf area index) as well as leaf growth (thicker and heavier leaves) and decreased leaf aging.

In other study, the positive effect of foliar application of these NPs under water deficit condition was reported in Dragon head (*Dracocephalum moldavica* L.) (Mohammadi et al. 2016). Water deficit conditions damage cell membrane and lead to oxidative stress. TiO_2 NPs application at different concentrations (10 and 40 ppm) ameliorated effect of water stress by increasing proline content and reducing hydrogen peroxide and MDA content (MDA content is indicator of degree of membrane damage). The stabilization of membrane was also reported by Sompornpailin and Chayaprasert (2020) in *Nicotiana tabacum*. The increase in level of enzymatic and nonenzymatic antioxidants in *Vicia faba* was reported (Khan et al. 2020). Shariatzadeh Bami et al. (2021) reported that application of these NPs at different concentration 10, 20, and 30 ppm modulated molecular pathway in *Artemisia absinthium* L. (a herb), grown under salt stress conditions. The degree of expression of two genes ADS and DBR2 (key gene in biosynthesis pathway of artemisinin) was noted under salt stress with application of NPs. The expression of ADS gene recorded maximum in plants, sprayed with 30 ppm NPs followed by 20 and 10 ppm with salinity stress 50 ppm. While expression of DBR gene showed reverse trend. The maximum expression was observed in plants grown under control conditions (no application of NPs) followed by plants with NPs application. The alternation in biochemical pathways for salt stress tolerance with NPs was reported in *Artemisia absinthium* L. With application of TiO_2 NPs, a significant increase in antioxidant enzymes catalase, peroxidase, superoxide dismutase, polyphenol oxidase, and guaiacol as well as protein concentration was reported as compared to control. These enzymes engulf reactive oxygen species synthesized during later phase of salt stress (Shariatzadeh Bami et al. 2021).

25.3.6 Iron Oxide NPs (Fe_2O_3 NPs)

Iron is one of the micronutrients in plants. It acts as cofactors for various enzymes. It exists in two forms: Fe^{2+} and Fe^{3+} form. The maghemite (yttrium doping-stabilized γ-Fe_2O_3NPs) are used as fertilizers and improve plant growth and development, but their role in drought stress tolerance using maghemite as nanozyme was studied by Palmqvist et al. (2017) in rapeseed. The increase in catalase activity (decrease in H_2O_2 content) as well as membrane stability (decrease in lipid peroxidation) with application of NPs contributed for stress tolerance in these plants. The role of Fe_2O_3 NPs as nanozyme against salt stress tolerance by improving their growth parameters as well as modulating their gene activity in *Eucalyptus tereticornis* was studied by Singh et al. (2022).

25.3.7 Cerium Oxide NPs (Ce_2O_3 NPs)

Cerium oxide NPs act as weapon to fight with stress. The application of these NPs in soil at 500 mg/kg soil, equipped the roots of *Brassica napus* with large apoplastic barriers which led to reduction in transport of Na^+ ions in shoot as well as their accumulation. This provided physiological tolerance to plants against salt stress (Rossi et al. 2017).

25.4 Organic Nanoparticles

25.4.1 Chitosan Nanoparticles (CSNPs)

Chitosan polysaccharide is deacetylated form of chitin, hydrophilic in nature. The use of chitosan NPs in soil, in hydroponics and through foliar spray equipped the plants with protective mechanisms against stress. In periwinkle (*Catharanthus roseus*), 1 g/L chitosan NPs improvised plant tolerance against drought stress (50% FC) (Ali et al. 2021). The drought mediated oxidative stress was also minimized by increasing the activities of enzymes catalase and ascorbate peroxidase. Membrane disruption during salt stress and drought stress leads to leakage of ion. This leakage is indication of membrane stability. The malondialdehyde (MDA) content also indicates membrane stability. In chitosan NPs treated plants, MDA content decreased which is indication of membrane integrity under stress.

Hassan et al. (2021) exposed the same plant to salt stress (NaCl 150 mM), and applied 1% CSNPs as foliar spray. The application of NPs helped the plants to cope with salt stress by modulating their antioxidant enzyme activities (catalase, glutathione reductase, and ascorbate peroxidase) as well as gene expression of MAPK3 (mitogen-activated protein kinases), GS (geissoschizine synthase), and ORCA3 (octadecanoid-derivative responsive AP2-domain). These genes are related to biosynthesis of alkaloids which improve plant tolerance against stress.

25.4.2 Nanoparticles in Alleviation of Salt and Drought Stress

NPs are used as weapons to fight with stress, and these nullify or minimize the deteriorative effects of stresses on plants. These are employed either in soil or through foliar spray. From soil, these particles enter inside the plants through root and from leaves these enter through stomata.

In the plants, NPs alter their morphological, physiological, and biochemical as well as molecular states positively and negatively. Most of the studies reported positive modulation in their tolerance mechanisms against drought and salt stress and improved plant growth and development and ultimately production (Ali et al. 2021; Zulfiqar and Ashraf 2021).

25.4.3 Nanoparticles in Alleviation of Salt Stress

The protective role of ZnO NPs in tomato against salt stress was reported by Hosseinpour et al. (2020). In other study, salt stress negatively affected growth parameters (plant height, number of leaves, fresh and dry biomass of root and shoot) of *Moringa peregrina* but application of Hoagland solution containing ZnO and Fe_3O_4 NPs improved growth attributes as well as biochemical parameters of plants under normal and saline conditions (Soliman et al. 2015). Various reports on the exogenous application of NPs to mitigate salt stress are depicted in Table 25.1.

Table 25.1 List of nanoparticles used in amelioration of salt stress in plants

Sr. No.	Type of nanoparticles used	Plant/crop	Dose of nanoparticles used and mode of application	Level of salinity	References
1	Ag NPs	Wheat	300 ppm, foliar application	100 mM NaCl	Wahid et al. (2022)
2	ZnO NPs	Rice	50 mg/L with hydroponic technique	60, 80, and 100 mM NaCl	Singh et al. (2022)
3	Si NPs	Tomato	0.5, 1, 2, and 3 mM, seed treatment	150 and 200 mM NaCl	Almutairi (2016)
4	Fe_2O_3 and ZnO NPs (alone and in combination)	Wheat	2 g/L, foliar spray	0, 75, and 150 mM NaCl	Fathi et al. (2017)
5	Cu NPs absorbed on 1 g of Cs-PVA hydrogel	Tomato	10 mg application of hydrogel (having Cu NPs) in soil	100 mM NaCl	Hernández-Hernández et al. (2018)
6	Chitosan NPs	Bean	0.1%, 0.2%, and 0.3% dissolved in 0.1% HCl, seed treatment	0, 50, 100, and 150 mM NaCl	Zayed et al. (2017)
7	Poly(acrylic acid) coated cerium oxide nanoparticles (PNC) and DiI-PNC	Cotton	0.9 mM, foliar delivery	200 mM NaCl	Liu et al. (2021)
8	TiO_2 NPs	Moldavian balm	0, 50, 100, and 200 mg/L with hydroponic technique	0, 50, and 100 mM NaCl	Gohari et al. (2020)
9	K_2SO_4 NPs	Alfa alfa	1/10, 1/8, and 1/4 of the full K rate in Hoagland solution with hydroponic technique	0 and 6 dS m^{-1} using $CaCl_2$ $2H_2O$: NaCl (2:1)	El-Sharkawy et al. (2017)
10	Se-NPs	Wheat	50, 75, and 100 mg/L, seed treatment	50, 100, and 150 mM NaCl	Ghazi et al. (2022)
11	TiO_2 NPs	Maize	40,60, and 80 ppm, seed treatment	200 mM NaCl	Shah et al. (2021)
12	TiO_2 NPs	*Artemisia absinthium* L.	0, 10, 20, 30 mg/L, foliar spray	0, 50, 100, and 150 mM NaCl	Bami et al. (2022)

(continued)

Table 25.1 (continued)

Sr. No.	Type of nanoparticles used	Plant/crop	Dose of nanoparticles used and mode of application	Level of salinity	References
13	ZnO NPs	Okra	10 mg/L, foliar application	0, 10, 25, 50, 75, and 100% sea water	Alabdallah and Hasan (2021)
14	Se-NPs and ZnO NPs	Rapeseed	150 µmol/L and 100 mg/L seed priming	150 mM NaCl	El-Badri et al. (2021)
15	Ag NPs	Wheat	1 mg/L, seed priming	25 and 100 mM NaCl	Abou-Zeid and Ismail (2018)

25.4.4 Nanoparticles in Alleviation of Drought Stress

Yang et al. (2017), Borišev et al. (2016), and Mohammadi et al. (2016) also reported the protective role of CuO and ZnO NPs in *Triticum aestivum*, Fullerenol nanoparticles in *Beta vulgaris* L., and TiO_2 NPs in *Dracocephalum moldavica* L. against drought stress. In wheat, ZnO and CuO NPs interacted with microorganisms in rhizosphere and improved plant growth and development under drought stress. Various reports on the exogenous application of NPs to mitigate drought stress are depicted in Table 25.2.

Table 25.2 List of nanoparticles used in amelioration of drought stress in plants

Sr. No.	Type of nanoparticles used	Plant/crop	Dose of nanoparticles used and mode of application	Level of stress	References
1	Fe NPs	Wheat	25, 50, and 100 mg/kg, soil application	Drought stress (DC, 35% of soil water holding capacity)	Adrees et al. (2020)
2	Ag NPs and Cu NPs	Wheat	10, 20, and 30 mg/L of Ag NPs and 3, 5, and 7 mg/L of Cu NPs, hydroponic	Osmotic stress of -6, -8, and -10 bars using PEG-6000 (polyethylene glycol)	Ahmed et al. (2021)
3	Ag NPs	Eggplant	0.1, 0.2, 0.5 μmol, foliar application	80% Field Capacity (FC) as control, 50% FC, 35% FC, and 20% FC after the plant establishment	Alabdallah and Hasan (2021)
4	Chitosan NPs	Barley	30, 60, and 90 ppm, soil and foliar application	Withholding of irrigation for 15 days after pollination to maturity (late season stress)	Behboudi et al. (2018)
5	CeO_2 NPs (nanoceria)	Sorghum	10 mg/L, foliar spray	Control: Plants maintained at 100% pot capacity moisture and drought stress: withholding water for 21 days	Djanaguiraman et al. (2018)
6	Chitosan nanoparticles	Salvia abrotanoides	30, 60, and 90 ppm, foliar application	30% FC (severe DS), 50% FC (medium DS), and 100% FC (well-watered, No DS)	Dawood et al. (2019)
7	Se NPs	Wheat	10, 20, 30, and 40 mg/L, foliar application	35% FC (DS) and 100% FC (control)	Ikram et al. (2020)

(continued)

Table 25.2 (continued)

Sr. No.	Type of nanoparticles used	Plant/crop	Dose of nanoparticles used and mode of application	Level of stress	References
8	Fe, ZnO, Cu and Co NPs	Soyabean	50 mg/L of Fe, ZnO and Cu NPs, 0.05 mg/L of Co NPs, seed treatment	65–70% soil moisture content (SMC, control) and 30–40% SMC (DS)	Linh et al. (2020)
9	ZnO NPs	Rice	5, 10, 15, 25, and 50 ppm, seed priming	Water holding capacity (WHC, control) at 70% and WHC at 35%	Waqas Mazhar et al. (2022)
10	Yttrium doping-stabilized γ-Fe_2O_3 NPs	Rapeseed	0.5, 0.8, 1, or 2 mg/ml, soil application	–	Palmqvist et al. (2017)
11	ZnO NPs	Sunflower	100 ppm, foliar spray (three times during life cycle)	Irrigation at 3, 6, and 9 days of intervals	Al-Dhalimi and Al-Ajeel (2020)
12	ZnO NPs	Wheat	0.5 and 1.0 mg/L, foliar spray	35%, 60%, and 85% FC	Sadati et al. (2022)
13	Fe_3O_4 NPs (magnetite)	*Setaria italica*	5, 10, 15, 20, 50, 90, and 120 mg/L, seed treatment	Using 10% PEG	Sreelakshmi et al. (2021)
14	Zn and Cu NPs	Wheat	Seed treatment	70% total moisture capacity (TMC, control), 30% TMC	Taran et al. (2017)
15	SiO_2-NPs and Se-NPs alone and in combinations	Strawberry	Se-NPs (25 mg/L), SiO_2-NPs (125 mg/L), and Se/SiO_2-NPs (50 and 100 mg/L) foliar spray (three times during life cycle)	100% FC (control), 60% FC (moderate stress) and 25% FC (severe stress)	Zahedi et al. (2020)

References

Abou-Zeid H, Ismail G (2018) The role of priming with biosynthesized silver nanoparticles in the response of Triticum aestivum L. to salt stress. Egypt J Bot 58:73–85

Adrees M, Khan ZS, Ali S, Hafeez M, Khalid S, Ur Rehman MZ, Hussain A, Hussain K, Chatha SA, Rizwan M (2020) Simultaneous mitigation of cadmium and drought stress in wheat by soil application of iron nanoparticles. Chemosphere 238:124681

Ahmed F, Javed B, Razzaq A, Mashwani ZR (2021) Applications of copper and silver nanoparticles on wheat plants to induce drought tolerance and increase yield. IET Nanobiotechnol 15(1): 68–78

Alabdallah NM, Hasan MM (2021) Plant-based green synthesis of silver nanoparticles and its effective role in abiotic stress tolerance in crop plants. Saudi J Biol Sci 28(10):5631–5639

Al-Dhalimi AM, Al-Ajeel SAH (2020) Effect of plant regulators, zinc nanoparticles and irrigation intervals on leaf content of endogenous hormones and nutrients in sunflower (Helianthus annuus l.). Plant Arch 20(1):2720–2725

Ali EF, El-Shehawi AM, Ibrahim OHM, Abdul-Hafeez EY, Moussa MM, Hassan FAS (2021) A vital role of chitosan nanoparticles in improvisation the drought stress tolerance in Catharanthus roseus (L.) through biochemical and gene expression modulation. Plant Physiol Biochem 161: 166–175

Almutairi ZM (2016) Effect of nano-silicon application on the expression of salt tolerance genes in germinating tomato (Solanum lycopersicum L.) seedlings under salt stress. Plant Omics 9(1): 106–114

Bami SS, Khavari-Nejada RA, Ahadib AM, Rezayatmand Z (2022) TiO2 nanoparticles and salinity stress in relation to artemisinin production and ADS and DBR2 expression in Artemisia absinthium L. Brazilian J of Biol 82:e237214. https://doi.org/10.1590/1519-6984.237214

Behboudi F, Tahmasebi Sarvestani Z, Kassaee MZ, ModaresSanavi SAM, Sorooshzadeh A, Ahmadi SB (2018) Evaluation of chitosan nanoparticles effects on yield and yield components of barley (Hordeum vulgare L.) under late season drought stress. J Water Environ Nanotechnol 3(1):22–39

Borišev M, Borišev I, Župunski M, Arsenov D, Pajević S, Ćurčić Ž, Djordjevic A (2016) Drought impact is alleviated in sugar beets (Beta vulgaris L.) by foliar application of fullerenol nanoparticles. PLoS One 11(11):e0166248

Dawood MF, Abeed AH, Aldaby EE (2019) Titanium dioxide nanoparticles model growth kinetic traits of some wheat cultivars under different water regimes. Plant Physiol Rep 24(1):129–140

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(10):14406–14416

El-Badri AM, Batool M, Wang C, Hashem AM, Tabl KM, Nishawy E, Wang B (2021) Selenium and zinc oxide nanoparticles modulate the molecular and morpho-physiological processes during seed germination of Brassica napus under salt stress. Ecotoxicol Environ Saf 225:112695

El-Sharkawy MS, El-Beshsbeshy TR, Mahmoud EK, Abdelkader NI, Al-Shal RM, MissaouiA M (2017) Response of alfalfa under salt stress to the application of potassium sulfate nanoparticles. Am J Plant Sci 8(8):1751–1773

Faizan M, Bhat JA, Chen C, Alyemeni MN, Wijaya L, Ahmad P, Fangyuan Y (2021) Zinc oxide nanoparticles (ZnO-NPs) induce salt tolerance by improving the antioxidant system and photosynthetic machinery in tomato. Plant Physiol Biochem 161:122–130

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

Ghazi AA, El-Nahrawy S, El-Ramady H, Ling W (2022) Biosynthesis of nano-selenium and its impact on germination of wheat under salt stress for sustainable production. Sustainability 14(3):1784

Gohari G, Mohammadi A, Akbari A, Panahirad S, Dadpour MR, Fotopoulos V, Kimura S (2020) Titanium dioxide nanoparticles (TiO_2 NPs) promote growth and ameliorate salinity stress

effects on essential oil profile and biochemical attributes of Dracocephalum moldavica. Sci Rep 10(1):1–14
Hasanuzzaman M, Nahar K, Alam MM, Roychowdhury R, Fujita M (2013) Physiological, biochemical and molecular mechanisms of heat stress tolerance in plants. Int J Mol Sci 14:9643–9684
Hassan FAS, Ali E, Gaber A, Fetouh MI, Mazrou R (2021) Chitosan nanoparticles effectively combat salinity stress by enhancing antioxidant activity and alkaloid biosynthesis in Catharanthus roseus (L.) G. Don. Plant Physiol Biochem 162:291–300
Heidarabadi MD (2022) Metal nanoparticles and abiotic stress tolerance. In: Advances in plant defense mechanisms. IntechOpen, London
Hernández-Hernández H, González-Morales S, Benavides-Mendoza A, Ortega-Ortiz H, Cadenas-Pliego G, Juárez-Maldonado A (2018) Effects of chitosan–PVA and Cu nanoparticles on the growth and antioxidant capacity of tomato under saline stress. Molecules 23(1):178
Hojjat SS (2016) The effect of silver nanoparticle on lentil seed germination under drought stress. Int J Farming Allied Sci 5:208–212
Hosseinpour A, Haliloglu K, TolgaCinisli K, Ozkan G, Ozturk HI, Pour-Aboughadareh A, Poczai P (2020) Application of zinc oxide nanoparticles and plant growth promoting bacteria reduces genetic impairment under salt stress in tomato (Solanum lycopersicum L. 'Linda'). Agriculture 10(11):521
Ikram M, Raja NI, Javed B, Hussain M, Hussain M, Ehsan M, Rafique N, Malik K, Sultana T, Akram A (2020) Foliar applications of bio-fabricated selenium nanoparticles to improve the growth of wheat plants under drought stress. Green Process Synth 9(1):706–714
Khan MR, Rizvi TF (2014) Nanotechnology: scope and application in plant disease management. Plant Pathol J 13:214–231
Khan MN, AlSolami MA, Basahi RA, Siddiqui MH, Al-Huqail AA, Abbas ZK, Siddiqui ZH, Ali HM, Khan F (2020) Nitric oxide is involved in nano-titanium dioxide-induced activation of antioxidant defense system and accumulation of osmolytes under water-deficit stress in Viciafaba L. Ecotoxicol Environ Saf 190:110152. https://doi.org/10.1016/j.ecoenv.2019.110152
Kirupagaran R, Saritha A, Bhuvaneswari S (2016) Green synthesis of selenium nanoparticles from leaf and stem extract of Leucas lavandulifolia Sm. and their application. J Nanosci Technol 2:224–226
Linh TM, Mai NC, Hoe PT, Lien LQ, Ban NK, Hien LTT, Chau NH, Van NT (2020) Metal-based nanoparticles enhance drought tolerance in soybean. J Nanomater 2020:4056563
Liu J, Li G, Chen L, Gu J, Wu H, Li Z (2021) Cerium oxide nanoparticles improve cotton salt tolerance by enabling better ability to maintain cytosolic K^+/Na^+ ratio. J Nanobiotechnol 19(1):1–16
Mohammadi H, Esmailpour M, Gheranpaye A (2016) Effects of TiO2 nanoparticles and waterdeficit stress on morpho-physiological characteristics of dragonhead (Dracocephalum moldavica L.) plants. Acta Agric Slovenica 107(2):385–396
Palmqvist NG, Seisenbaeva GA, Svedlindh P, Kessler VG (2017) Maghemite nanoparticles acts as nanozymes, improving growth and abiotic stress tolerance in Brassica napus. Nanoscale Res Lett 12(1):1–9
Rossi L, Zhang W, Ma X (2017) Cerium oxide nanoparticles alter the salt stress tolerance of Brassica napus L. by modifying the formation of root apoplastic barriers. Environ Pollut 229:132–138
Sadati SYR, Godehkahriz SJ, Ebadi A, Sedghi M (2022) Zinc oxide nanoparticles enhance drought tolerance in wheat via Physio-Biochemical changes and stress genes Expression. Iran J Biotech 20(1):e3027
Semida WM, Abdelkhalik A, Mohamed GF, Abd El-Mageed TA, Abd El-Mageed SA, Rady MA, Ali EF (2021) Foliar application of zinc oxide nanoparticles promotes drought stress tolerance in eggplant (Solanum melongena L.). Plan Theory 10:421. https://doi.org/10.3390/plants10020421

Shah T, Latif S, Saeed F, Ali I, Ullah S, Alsahli AA, Ahmad P (2021) Seed priming with titanium dioxide nanoparticles enhances seed vigor, leaf water status, and antioxidant enzyme activities in maize (Zea mays L.) under salinity stress. J King Saud Univ Sci 33(1):101207
Shariatzadeh Bami S, Khavari-Nejad RA, Ahadi AM et al (2021) TiO2 nanoparticles effects on morphology and physiology of Artemisia absinthium L. under salinity stress. Iran J Sci Technol Trans Sci 45:27–40. https://doi.org/10.1007/s40995-020-00999-w
Singh A, Sengar RS, Rajput VD, Minkina T, Singh RK (2022) Zinc oxide nanoparticles improve salt tolerance in rice seedlings by improving physiological and biochemical indices. Agriculture 12(7):1014
Soliman AS, El-feky SA, Darwish E (2015) Alleviation of salt stress on Moringa peregrine using foliar application of nanofertilizers. J Hortic For 7:36–47
Sompornpailin K, Chayaprasert W (2020) Plant physiological impacts and flavonoid metabolic responses to uptake TiO_2 nanoparticles. Austr J Crop Sci 14:1995. https://doi.org/10.21475/ajcs.20.14.04
Sreelakshmi B, Induja S, Adarsh PP, Rahul HL, Arya SM, Aswana S, Haripriya R, Aswathy BR, Manoj PK, Vishnudasan D (2021) Drought stress amelioration in plants using green synthesised iron oxide nanoparticles. Mater Today Proc 41:723–727
Taran N, Storozhenko V, Svietlova N, Batsmanova L, Shvartau V, Kovalenko M (2017) Effect of zinc and copper nanoparticles on drought resistance of wheat seedlings. Nanoscale Res Lett 12(1):1–6
Van Nguyen D, Nguyen HM, Le NT et al (2022) Copper nanoparticle application enhances plant growth and grain yield in maize under drought stress conditions. J Plant Growth Regul 41:364–375. https://doi.org/10.1007/s00344-021-10301-w
Wahid I, Rani P, Kumari S, Ahmad R, Hussain SJ, Alamri S, Nirmalya Tripathy M, Khan IR (2022) Biosynthesized gold nanoparticles maintained nitrogen metabolism, nitric oxide synthesis, ions balance, and stabilizes the defense systems to improve salt stress tolerance in wheat. Chemosphere 287(2):132–142
Waqas Mazhar M, Ishtiaq M, Hussain I, Parveen A, Hayat Bhatti K, Azeem M, Thind S, Ajaib M, Maqbool M, Sardar T, Muzammil K (2022) Seed nano-priming with zinc oxide nanoparticles in rice mitigates drought and enhances agronomic profile. PLoS One 17(3):e0264967
Yang KY, Doxey S, McLean JE, Britt D, Watson A, Al Qassy D, Anderson AJ (2017) Remodeling of root morphology by CuO and ZnO nanoparticles: effects on drought tolerance for plants colonized by a beneficial pseudomonad. Botany 96(3):175–186
Zahedi SM, Moharrami F, Sarikhani S, Padervand M (2020) Selenium and silica nanostructure-based recovery of strawberry plants subjected to drought stress. Sci Rep 10(1):1–18
Zayed MM, Elkafafi SH, Zedan AM, Dawoud SF (2017) Effect of nano chitosan on growth, physiological and biochemical parameters of Phaseolus vulgaris under salt stress. J Plant Prod 8(5):577–585
Zhang H, Zhao Y, Zhu JK (2020) Thriving under stress: how plants balance growth and the stress response. Dev Cell 55(5):529–543
Zulfiqar F, Ashraf M (2021) Nanoparticles potentially mediate salt stress tolerance in plants. Plant Physiol Biochem 160:257–268