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REVIEW

Role of Nanoparticles on the Alleviation of Abiotic Stress Tolerance: A Review

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Nanotechnology has become a dynamically demand driven developing industry with a multiple applications in material manufacturing, computer chips, medical diagnosis, energy and health care, cancer therapy, targeted drug delivery, electronics, cosmetic industry, biosensors and crop improvement. It was estimated that by year 2014, more than 15% of all products in the global market will have some kind of nanotechnology incorporated into their manufacturing process. Nanoparticles penetrate into specific cellular locations because of their extreme small size and acquired some peculiar properties play significant role in the protection of plants against various abiotic stresses. The application of nanoparticles increased germination and seedling growth, physiological activities including photosynthesis and nitrogen metabolism, leaf activities of CAT, POX and APX, chlorophyll contents, protein, carbohydrate contents and yield, and also positive changes in gene expression indicating their potential use in crop improvement. Nanoparticles enhances the water stress tolerance via enhancing root hydraulic conductance and water uptake in plants and showing differential abundance of proteins involved in oxidation-reduction, ROS detoxification, stress signalling, and hormonal pathways. Proteomic techniques have contributed substantially in understanding the molecular mechanisms of plant responses against various stresses by providing a link between gene expression and cell metabolism. As the coding regions of genome are responsible for plant adaptation to adverse conditions, protein signatures provide insights into the nanoparticles at proteome level. The recent contributions of plant proteomic research to elaborate the complex molecular pathways and the mobility of the nanoparticles is very high, which leads to rapid transport of the nutrient to all parts of the cultivated plants with the use of nano preparations in stressful conditions.

Key words: Abiotic stress, Nanoparticles, Oxidative stress, Antioxidant enzymes, Osmolytes

The world population is gradually increased nearly 9.6 billion people by 2050, such that agricultural production must increase by 70−100% to meet its food demand. The current agrochemicals deteriorate the abiotic and biotic stresses on crops and reduce the crop productivity. The new biotechnology tools and technologies or biochemical pathways that protect plants from stress, there is a high level of public concern about the safety of transgenic crops and improve the efficiency to achieve food security safely and sustainably (Mueller *et al.*, 2012; Suzuki *et al.*, 2014). In general, nanoparticles are potential materials for the site-specific delivery of nucleotides, proteins and chemicals under in vitro conditions for achieving vital goals such as improving crop growth and yield as well as resistance against stressful cues (Rastogi *et al.*, 2019). Nanotechnology deals with nanomaterials smaller than 100 nm in at least one dimension that can be manipulated at the atomic or molecular level. In agriculture, the fast developing field provide potential and rapid solutions to promote plant growth and increase crop yield. Moreover, nanoparticles are also used in agriculture for the efficient and controlled delivery of fertilizers, herbicides, pesticides and for improving soil physico-chemical properties such as water holding capacity. A nanoparticle is a very fine matter particle with a diameter between 1 and 100 nm. Nanoparticles possess unique physico-chemical properties quite different from those of the same matter with larger size (Vishwakarma *et al.*, 2018; Cele, 2020). The promising effects of engineered nanoparticles have been shown in seed treatment and germination, plant growth and development, pathogen diagnostics, and toxic agrochemicals detection. In particular, metal oxide nanoparticles are increasingly incorporated into agricultural products, including fertilizers, additives for soil remediation, growth regulators, pesticides, herbicides or disposal of waste and polluted water (Du *et al.*, 2017). The introduction of nanoparticles in terrestrial ecosystems may change the profile of soil-plant systems. Plants are an essential base component of all ecosystems and play a critical role on the fate and transport of nanoparticles in the environment through their assimilation into the plants and subsequent bioaccumulation (Monica and Cremonini, 2009).

The induction of nanoparticles has shown to reduce plant metabolic activity such as photosynthesis and the production of reactive oxygen species (ROS) in plant cells. These reactive oxygen free radicals may oxidize double bonds on fatty acid tails of membrane phospholipids in a process known as lipid peroxidation and damage membranes resulting in a reduction of plant growth and potentially death (Xing *et al.*, 2010; Yuan *et al.*, 2018). To avoid the stressful effects of ROS, a set of antioxidant defence mechanisms in plant cells have evolved by increasing antioxidant enzyme activities, altering lipid peroxidation, and increasing antioxidant defence capacity, such as superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), glutathione reductase (GR) and others. Malondialdehyde (MDA) is an end product of lipid peroxidation and is commonly used as a biomarker to index oxidative injury. Under environmental stress, chlorophyll content may change, influence the functioning of the photosynthetic apparatus, and thus affect whole plant metabolism. Therefore, these enzymatic responses chlorophyll content and MDA concentration have been suggested to be a reliable marker of metal toxicity in macrophytes and to determine long-term plant biochemical responses to different exposure regimes (Thippeswamy *et al.*, 2021).

Nanoparticles released into the environment interact with air, water and soil. This often changes the surface properties of the particles which can result in particle aggregation or changes in particle charge and other surface properties. These effects have been studied in water ecosystems and soil and show the importance of understanding nanoparticles and their environmental setting as a “complex” that needs to be looked at in its entirety in order to understand particle behaviour in the environment A current debate addresses whether nanoparticles can cause toxicity as a contaminant in, for example, soil or water, via a “piggyback” mechanism on natural organic matter. The main plant physiological indices of the toxic effects of nanoparticles are the germination percentage, root elongation; biomass and leaf number (Lee *et al.* 2010).

The most promising opportunities for nanomaterials and nanotechnology approaches to fuel the agri-tech revolution, the fundamental challenges currently preventing their broad development and application for sustainable agriculture, and the research needed to address these challenges. The importance of taking a systems perspective on all proposed agri-tech solutions to ensure that they are sustainable, rather than shifting the environmental burden for one environmental cubicle to alternative. Plants are primary producers that play an important role in an ecological system (Patlolla *et al.*, 2012). Presently, various engineered nanoparticles are widely used in the plant sciences to improve crop yield but it brings some defects to the environment (Cañas *et al.*, 2008; Nandini *et al.*, 2020). Releasing a huge amount of engineered nanoparticles into the environment is an inevitable predicament. The nanoparticles alter the mobility of the plants' cells through physical, chemical, and biological transformations that causes threat to the eco-systems (Lee *et al.*, 2013). Nanoparticles may accumulate in plants to a higher-level and also can enter into the food chain and cause adverse effects in several organisms (Patlolla *et al.*, 2012). Moreover, plant cells interact with engineered nanoparticles and induce cell disrupts and leads to cytotoxicity (Wang *et al.*, 2008). Nanoparticles induce phytotoxic, cytotoxic, and genotoxic defects in plants led to decreased plant growth, seedling growth rate, slow germination, and root elongation (Wang *et al.*, 2012). Phytotoxicity alludes to abandons in plant growth, seed germination, and root extension (Brunner *et al.*, 2006). Genotoxicity in plants can initiate harm to the hereditary material and can prompt mutagenicity and cancer-causing nature (Kang *et al.*, 2008). Hence, the researchers have many questions in their minds about the risks and benefits of nanoparticles (Raskar and Lawre, 2013). The various engineered nanoparticles that have been proposed as effective agrochemical delivery systems. Once beneficial nanoparticles reach different parts of plants, they boost photosynthetic rate, biomass measure, chlorophyll content, sugar level, build-up of osmolytes and antioxidants. Nanoparticles also improve nitrogen metabolism, enhance chlorophyll as well as protein content and upregulate the expression of abiotic- and biotic stress-related genes. Herein, we review the state of art of different modes of application, uptake, transport and prospective beneficial role of nanoparticles in stress management and crop improvement (Singh *et al.*, 2021).

Nanoregulators under abiotic stress tolerance

Abiotic stress in the form of drought, heat, excess salinity, cold, nutrient deficits, chemical toxicity or oxidative stress, is the primary cause of crop loss worldwide (Atkinson and Urwin, 2012). The key strategies employed by plants to enhance their stress tolerance include the upregulation of functional and structural protectants, such as compatible solutes and antioxidants (Wang *et al.*, 2003). The targeted, smart delivery of low doses of nanoparticles to improve the plant's response to abiotic stresses such as drought, extreme heat, heavy metals in soils or elevated salinity, making them more resilient against these threats (Lowry *et al.*, 2019). The stress responsive platforms could deliver agrochemicals when needed in response to elevated temperature, to manage heat stress; in response to low pH, to deliver materials into the root zone; in response to high pH (>7), to deliver antimicrobials in phloem; or in response to pathogen presence (Xin *et al.*, 2018). The impact of nanoparticles on plants will depend on various parameters, such as composition, concentration, size, and the physical and chemical properties of the nanoparticles (Shalaby *et al.*, 2016). These strategies, which can increase plant resistance to biotic and abiotic stresses, will make the agriculture system more resilient and less sensitive to climate change. The scientific community has a major concern to overcome loss in crop productivity induced by abiotic stress. Several Nanoparticles are being studied to assess their potential in protecting plants from abiotic stresses, improving plants, and modulating various plant processes. Nanoparticles are ultrafine particles with dimensions in the range between 1 and 100 nm. The distinctive physiochemical attributes and innate surface area to volume ratio of nanoparticles has led to myriad applications in agricultural and biomedical industries (Jalil and Ansari, 2019). Nanoparticles have an impact at very low concentrations and their effects on plants are type and dose dependent; they have been shown to be an attractive alternative for the manufacture of nanofertilizers, which are more efficient and effective than traditional fertilizers. In seeking a sustainable future for agriculture, nanotechnology is gaining attention as a way to overcome problems related to abiotic and biotic stress. The major advantage of nanofertilizer is that these are not only the best micro-nutrients but also aids in reclamation of soil. The presence of a certain amount of various nanoparticles has shown substantial beneficial effects on different plant species. (Zhu *et al.*, 2019). However, the influence of a particular nanoparticle is dependent upon the dose, type, shape, structure, solubility and duration of the treatment (Aslani *et al.* 2014).

The contribution of myriads of nanoparticles in overcoming the challenges by various researchers worldwide (Table 1). Nanoparticles are prepared either with organic polymers and/or inorganic elements. Inorganic nanoparticles includes metals like Aluminium (Al), Cobalt (Co), Bismuth (Bi), Iron (Fe), Copper (Cu), Gold (Au), Molybdenum (Mo), Nickel (Ni), Tin (Sn), Silver (Ag), Titanium (Ti), Tungsten (W), Zinc (Zn), metal oxides (SnO_2, Al_2O_3, In_2O_3, CuO, ZrO_2, Cu_2O, MgO, La_2O_3, NiO, ZnO, TiO_2, CeO_2) and quantum dots, while liposomes, dendrimers, carbon nanomaterials, and polymeric micelles are examples of bio-organic nanoparticles (Rajput *et al.* 2017). Nanoparticles get absorbed 15–20 times more by the plants than the bulk nutrients (Lv *et al.* 2019). Nanoparticles have been deployed in agriculture to escalate the rate of seed germination and plant growth (Vera-Reyes *et al.* 2018) and also to protect plants from various abiotic stresses such as high and/or low temperature, salinity, drought, and flooding (Elhawat *et al.* 2018). The use of nanoparticles in abiotic stress responses in plants, highlighting their advantages and potential uses.

Applications of nanoparticles in abiotic stress tolerance

Micronutrients play critical roles in the tolerance of crop plants against abiotic and biotic stresses. The roles of individual nanoparticles in regulating plant growth and metabolism in stressed plants are briefly discussed.

Zinc (Zn) nanoparticles

Zinc modulates the function, structure, and activity of many enzymes. There is also considerable evidence that zinc oxide nanoparticles promote plant growth and enhance biomass accumulation (Brown *et al.*, 1993). Zinc is a vital micronutrient for organisms including plants. It has numerous fundamental roles in the cell. In addition, zinc is also involved in the functioning of intra- and inter-cellular signalling and DNA transcription (Caldelas and Weiss, 2017). Zinc is believed to have various pivotal roles in plants particularly when they are subjected to stress conditions (Sofy *et al.*, 2020). The zinc oxide nanoparticles are being used in numerous commercial applications and are expected to benefit agriculture as well. Zinc nanoparticles are thought to be a sound remedy for ameliorating harsh environmental stresses. Zinc nanoparticles are considered as vital metal oxide, having multiple beneficial impacts on plants (Caldelas and Weiss, 2017). It was demonstrated that treatment with zinc based nanoparticles improved plant morphological and physiological characteristics under stress conditions. The evaluation of pot experiment effects on zinc oxide nanoparticles or zinc salt amendment on the growth of sorghum, an important but less-well-studied cereal. The efficacies of two exposure pathways were compared with respect to yield, macronutrient use efficiency, and grain zinc enrichment (Dimkpa *et al.*, 2017). The application of zinc oxide and zinc oxide nanoparticles application on plants and observed that zinc oxide nanoparticles increased photosynthetic pigments, osmolyte biosynthesis, ionic regulation, and antioxidative enzyme activities, but lowered proline and total soluble sugars (Alabdallah and Alzahrani, 2020). While studying the synergistic effect of zeolite, zinc, silicon and boron nanoparticles on potato under salinity stress. These soil applications improved the growth and yield as well as physiological traits (Mahmoud *et al.*, 2019). These improvements were related to the improvement in the retention of water and nutrients, increased nutrient use efficiency, photosynthesis, and enzymatic antioxidant activities in the plants supplemented with the combined application of zeolite, zinc, silicon and boron nanoparticles under salt stress (Mahmoud *et al.*, 2019). Furthermore, low doses of zinc nanoparticles exert positive, while high doses cause toxicity even under non stress conditions (Molnar *et al.*, 2020). The impact of exogenously applied zinc oxide nanoparticles on rapeseed grown under stress and observed the reduced ion leakage and improved Hill reaction thereby affecting the stress response genes, e.g., the expression of ARP increased while that of SKRD2, MYC and MPK4 dsxecreased (Hezaveh *et al.*, 2019).

These reports evident that the role of Zinc nanoparticles in ameliorating abiotic stress, but future studies should be focused on to understand the molecular effects and mode of actions of these nanoparticles under abiotic stress conditions.

Silver (Ag) Nanoparticles

The growing number of fungi and pests resistant to existing chemical pesticides has highlighted the need for new approaches to crop protection. Silver nanoparticles have received significant attention as a potential nanopesticide in agriculture and the significant applications in multiple industries due to their distinctive physiochemical characteristics (Khan *et al.*, 2020). It is believed that antifungal and antibacterial properties have potentially used for wastewater treatment (Sheng *et al.*, 2018). Silver nanoparticles are known to improve multiple growth characteristics including germination and growth via modulating numerous physio-biochemical traits in plants (Soliman *et al.*, 2020; Mohamed *et al.*, 2017). The seed of *Pennisetum glaucum* with silver nanoparticles and the plants raised from these primed seed showed reduced oxidative damage under stress because of enhanced antioxidant enzyme activities. The leaf Na^+/K^+ ratio was suppressed by silver nanoparticles, whereas flavonoids and phenolic contents increased (Khan *et al.*, 2020). The seed presowing treatment with silver nanoparticles improved the growth, proline, soluble sugars, and POD activity of stressed wheat seedlings (Mohamed *et al.* 2017). In wheat, the silver nanoparticles influence the germination and grain yield under stress by modulating photosynthetic efficiency and plant hormones as the levels of 6-benzylaminopurine, 1-naphthalene acetic acid, and indole-3-butyric acid increased, whereas those of abscisic acid (ABA) decreased (Abou-Zeid and Ismail, 2018). There are few reports on silver nanoparticles as a potential solution for allaying the negative impact of stress on plants. Hence, future studies should focus on deciphering their role in managing abiotic stress tolerance at physio-biochemical and molecular levels. Many researchers suggested the use of silver nanoparticles with considerable caution and care, since they can release silver ion (Ag^+) in the environment, and this ion being highly toxic in nature, can be hazardous for organisms (Tortella *et al.*, 2020). The influence of silver nanoparticles on plant growth and up to what extent they cause any prospective risk to the environment and health of the organisms (Yan and Chen, 2019).

Silicon dioxide (SiO_2) Nanoparticles

Silicon is not an integral plant nutrient and it is reported to contribute in various essential metabolic pathways in plants under abiotic stress conditions such as salt, low temperature and metals stress (Javaid *et al.*, 2019). Silicon supplementation to salt stressed plants is thought to improve plant water status via resisting water loss (Abdelaal *et al.*, 2020). Silicon storage in epidermal cell walls limiting the water loss from the leaf cuticle and enhanced the transpiration rate in stress plants (Thorne *et al.*, 2020). Various reports have depicted that silicon application to stressed plants resulted in improved photosynthesis, vegetative growth, and dry matter production, as well as decreased shoot Na^+ and Cl^- deposition and improved K^+ accumulation (Hurtado *et al.*, 2020). Nano forms of silicon are believed to impose a positive influence on plants, especially under abiotic stresses. For instance, the nano-SiO_2 on stressed wheat cultivars is reported enhanced seed germination and growth (Mushtaq *et al.*, 2019). Nano SiO_2 enhanced soybean seedling growth under abiotic stress through improving leaf K^+ concentration, and levels/activities of biological antioxidants. Furthermore, nano-SiO_2 decreased leaf Na^+, lipid peroxidation and generation of toxic ROS in soybean plants under abiotic stress (Farhangi-Abriz and Torabian, 2018). Treatment with SiO_2 nanoparticles is believed to limit the salt-induced adverse functionalities of anatomical and biochemical attributes in plants. The silicon dioxide nanoparticles application to strawberry plants maintained epicuticular wax structure and improved photosynthetic pigments, but resulted in lower accumulation of osmolytes than that of salt treated plants (Avestan *et al.*, 2019). In tomato, supplementation of silicon nanoparticles under abiotic stress maintained the concentrations of chlorophylls and glutathione reductase (GSH), and enhanced phenylalanine ammonia lyase (PAL) activity, and the levels of fruit vitamin C compared with those in the non-treated plants grown under salt stress (Pinedo-Guerrero *et al.*, 2020). Lack of studies related to the use of silicon nanoparticles for ameliorating salt stress demands further research in this domain.

Hence, future studies should focus on the molecular and biochemical mechanisms associated with enhanced salt stress tolerance achieved through the supplementation of silicon nanoparticles.

Copper (Cu) Nanoparticles

Copper is a crucial metal-based micronutrient that influences various vital metabolic reactions in plants. The most excessively occurring and important copper based protein is plastocyanin in the chloroplast, which aids electron transfer in the lumen of thylakoid that is vital for mediating photosynthesis in plants (Yamasaki *et al.*, 2008). Copper is known to perform a vital role in photosynthesis, ethylene perception, respiration, and metabolisms of C and N (Iqbal *et al.*, 2018). Additionally, copper influences plant metabolism as several redox reactions enzymes comprised copper as an essential component of their structures (Lwalaba *et al.*, 2020). The copper application to plants reduces harmful impacts of salinity on water relations, photosynthesis, and nutrition through upregulation of the antioxidant defense and increased levels of osmoprotectants and amino acids in maize plants (Iqbal *et al.*, 2018). Copper nanoparticles supplementation to plants is therefore considered as a beneficial strategy under normal and stress conditions. For instance, in tomato plants, foliar applied copper nanoparticles mitigated salt stress via improving the growth performance and Na^+/K^+ ratio (Arif *et al.*, 2018). In the same study copper nanoparticles improved glutathione (GSH) by 81%, phenols by 16%, vitamin C by 80%, and phenols by 7.8% in the fruit compared with controls. In addition, copper nanoparticles also enhanced the activity of leaf ascorbate peroxidase (APX) by 140%, SOD by 8%, glutathione peroxidase (GPX) by 26%, and CAT by 93% (Pérez-Labrada *et al.*, 2019). The copper nanoparticles on tomato under salt stress and reported enhanced growth by promoting the expression level of SOD and jasmonic acid (JA) genes, which resulted in mitigation of ionic and oxidative stresses. The application of copper nanoparticles could effectively enhance salt tolerance through activating the antioxidant defense mechanism and by the octadecanoid pathway of jasmonates (Hernández-Hernández *et al.*, 2018). Therefore, the research at physio-biochemical and molecular levels is required to find the mode of actions of copper nanoparticles to achieve abiotic stress tolerance.

Iron oxide (Fe_2O_3) Nanoparticles

Iron is a vital inorganic element for living organisms including plants. It functions in numerous vital cellular processes, including chlorophyll biosynthesis, respiration, and photosynthesis (Kim and Guerinot, 2007). Iron plays a vital role in the biosynthesis of a number of key proteins associated with plant metabolism, cell respiration, repair of DNA, transport and balance of oxygen, and photosynthesis process, thereby influencing overall crop productivity (Chan-Rodriguez and Walker 2018). In addition, iron assists plants in acquiring stress tolerance (Tripathi *et al.*, 2018). More specifically, iron has been observed to mediate salt tolerance via upregulating key antioxidative enzymes (Singh and Bhatla, 2016). Different studies have exhibited a significant mediating effect of iron nanoparticles in acquiring plant stress tolerance. For instance, the effect of Fe_2O_3 in nano-forms enhanced growth, and enzymatic activities under abiotic stress conditions on plants (Moradbeygi *et al.*, 2020). It is examined that the combined treatment of Fe_2O_3 nanoparticles and salicylic acid alleviated salt stress via improving K^+/Na^+ ratio, Iron content, the activities of antioxidant machinery (SOD, CAT, POD, and polyphenol oxidase), endogenous salicylic acid, and some key osmolytes. These alterations improved root and shoot growth, leaf pigments, membrane stability index, and seed yield of plants. The foliar supplementation of Iron nanoparticles on *Helianthus annuus* grown under saline regime improved the activities of polyphenol oxidase, CAT and POD (Torabian *et al.*, 2018). Hence, it can be inferred that iron nanoparticles have great potential to ameliorate stress, but the information on the specific metabolic pathways to be elucidated.

Manganese (Mn) Nanoparticles

Manganese is a crucial micronutrient for optimum plant growth of plant. It is also an integral for the biosynthesis of gibberellic acid, carotenoids, and sterols (Eaton, 2015). The putative role of manganese is the reinforcement of the plant's defense system against multiple abiotic stresses (Ye *et al.*, 2019). Manganese is reported to enhance photosynthetic and respiratory enzymes and inhibit nitrate accumulation in plant tissues under abiotic stress conditions (Zarabimafi and Pour, 2014). The manganese supplementation to plants is improve the membrane stability index, chlorophyll content, and nitrate reductase activity (Shahi and Srivastava, 2018). In another report, the application of manganese caused recovery from chlorosis and restricted growth due to saline stress (Rahman *et al.*, 2016). The use of manganese nanoparticles for mitigating abiotic stresses is getting considerable attention these days due to their ameliorating ability through influencing various physio-biochemical traits. The influence of manganese nanoparticles promoted root growth, reduced lignin and proteins, and also decreased the redistribution of Ca, Mn, Na, and K contents between the root and aerial portions (Ye *et al.*, 2020). To understand the role of manganese nanoparicles more attention is required on this domain to decipher the potential and novel roles of manganese nanoparticles in mediating abiotic stress tolerance.

Titanium dioxide (TiO_2) Nanoparticles

Titanium is a transition metal and the ninth abundant element having 0.33% share in the earth's outer layer composition (Buettner and Valentine, 2012). It is reported to have a beneficial effect on plant performance via altering enzyme activities, and improving chlorophyll pigments and photosynthesis (Carbajal-Vazquez ´ *et al.*, 2020). Titanium is considered to play an integral role in maximizing plants' ability against unfavorable stresses (Lyu *et al.*, 2017). During the last few years, the use of titanium oxide nanoparticles has been demonstrated to improve crop production under favorable and unfavorable environments (Abdel Latef *et al.*, 2018). The evaluated effect of titanium oxide on plants under stress depicted that 100 mg L^{-1} titanium oxide promoted plant growth under stress which was ascribed to improvement in the activities of some key enzymes (Gohari *et al.*, 2020). In another study, the differential concentrations of titanium oxide nanoparticles observed that the three concentrations (0·01%, 0·02% and 0·03%) applied to salt stressed broad bean plants, the lowest concentration (0.01%) reinforced salt tolerance via enhancing enzymatic activities, amino acids, soluble sugars, and proline (Abdel Latef *et al.*, 2018). Although titanium nanoparticles are being effectively used for many purposes, studies depicting their possible role under salt stress are rare. Thus, there is a need to elucidate how metabolic pathways are triggering upon titanium nanoparticles application in abiotic stress tolerance.

Cerium (Ce) Nanoparticles

Cerium nanoparticles are widely used in semiconductor, cosmetics, optical, medical, drug delivery, and fuel cells industries (Barrios *et al.*, 2016; Hussain *et al.*, 2019). Low doses of cerium nanoparticles influence physio-biochemical characteristics in plants under normal growth conditions (Salehi *et al.*, 2018). In wheat plants, low levels of cerium nanoparticles are reported to enhance growth and photosynthesis, while high concentration negatively affected these processes (Abbas *et al.*, 2020). The accumulation of cerium nanoparticles in different plant organs was observed to be a dose dependent phenomenon (Singh *et al.*, 2019). Cerium nanoparticles are also known for their abiotic stress relieving ability in plants (Rossi *et al.*, 2019; Hussain *et al.*, 2019). The findings of cerium nanoparticles induced higher photosynthetic efficiency and biomass in treated plants than those observed in untreated plants. The application of cerium nanoparticles under saline regimes in plants induced a variety of anatomical changes resulting into high Na^+ flow towards shoot, and low Na^+ accumulation in roots, leading to better physiological status and salinity tolerance of the plants (Rossi *et al.*, 2017). In a recent study, the morpho-physiological, biochemical and molecular mechanisms involved in cerium nanoparticles induced seed priming in cotton (*Gossypium hirsutum*) under salinity stress (An *et al.*, 2020). The increased biomass and growth, while a differential expression of root transcripts in response to seed priming with cerium nanoparticles. The cerium nanoparticles seed priming induced salinity tolerance was related to ROS pathways, ion homeostasis, and Ca^{2+} signaling pathways. Besides the afore-mentioned reports, research on cerium nanoparticles in inducing salinity tolerance in plants is rare. The future research should be conducted with the major aim to evaluate mode of actions of cerium nanoparticles on molecular mechanisms in plants encountering the threat of climate change associated abiotic stresses.

Potassium (K) Nanoparticles

Potassium is one the promising essential element that plays a vital role in crucial processes related to growth, metabolism, and unfavorable stress alleviation in plants (Jan *et al.*, 2017). The application of potassium is widely reported to benefit crop plants under stress conditions (Hatam *et al.*, 2020). The foliar supplementation of potassium was reported to remediate salt stress in wheat plants via decreasing salt-induced oxidative stress, and increasing morphological traits, photosynthetic pigments, and osmolytes such as total carbohydrates, total phenolics and proline as well as antioxidative enzyme activities (Jan *et al.*, 2017). Although the researchers are accomplishment great efforts in searching to bind the benefits of nanotechnology towards managing crop issues, there is still a considerable need to fully focus on this approach. While evaluating the role of K_2SO_4 nanoparticles on *Medicago sativa* L., the treatment with potassium nanoparticles under salt stress altered the physiological characteristics via lowering the electrolyte leakage resulting in improved activities of important antioxidant enzymes and osmoprotectants (El-Sharkawy *et al.*, 2017). There are no much reports on the use of potassium nanoparticles for remediating abiotic stress in plants, and so, demands attention of future research for evaluation of different concentrations of potassium nanoparticles on various test plants to decipher the specific physiological and molecular traits.

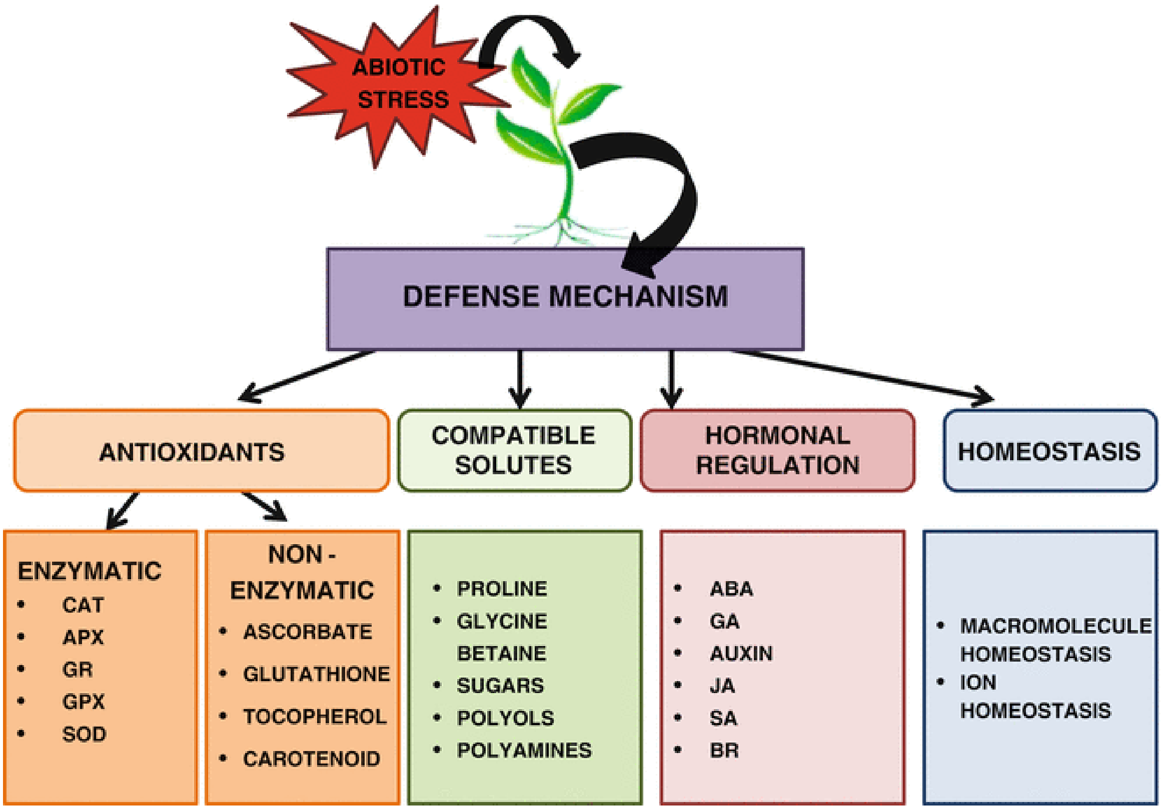

Figure. 1. Different plant defence mechanisms induced in response to abiotic stress, whereas plant enzymatic antioxidants include catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR), glutathione peroxidase (GPX), superoxide dismutase (SOD), polyphenoloxidase (PPO), glutamic oxaloacetic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

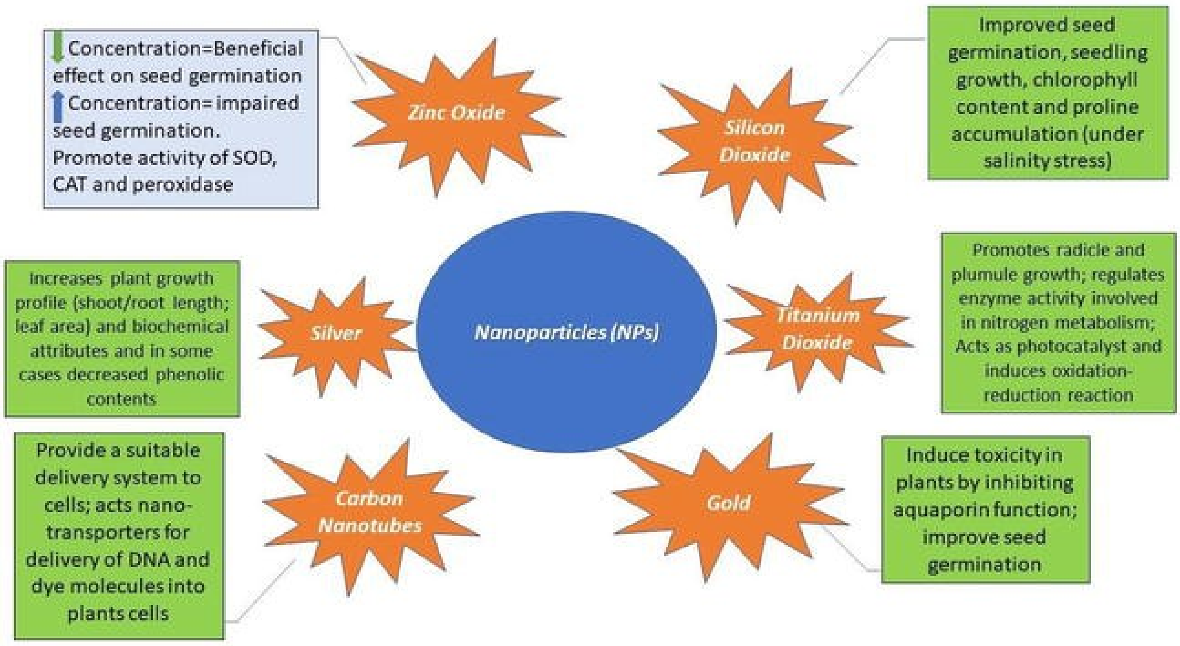

Figure 2. Various nanoparticles with their effect on plant growth. (adapted from Mohd. Tariq *et al.*, 2021).

Table 1. Applications of NPs in the mitigation of stress by altering the morphophysiological responses of plants.

Nanoparticles	**Plants**	**Germination and Morphological Responses**	**Physiological Responses**	**References**
Si (10 µM)	*Pisum sativum* L.	Presence of Si NPs improved the growth in presence of Cr	Si NPs minimized the Cr storage, enhanced the synthesis of defense enzymes and augmented nutrient uptake	Tripathi *et al.*, 2018
ZnO (25 mg/L)	*Leucaena leucocephala*	Application of NPs induced seedling growth	ZnO NPs amendment improved pigments and soluble proteins, reduced peroxidation; there was rise in the antioxidant defense enzymes	Venkatachalam *et al.*, 2017
Fe_3O_4	*Triticum aestivum* L.	Fe_3O_4 NP treatment minimized the inhibitory action of HMs	Fe_3O_4 NPs supplementation improved the level of superoxide dismutase and peroxidase	Konate *et al.*, 2018
Si (19, 48, and 202 nm)	*Oryza sativa* L.	Si NPs enhanced the number of cultured cells and decreased proportionally with the rise in NP size; the treatment maintained the cellular integrity in the presence of metals	Si NPs amendment caused altered expression of genes responsible for reduced metal uptake	Cui *et al.*, 2017
ZnO (0, 50, 75, and 100 mg/L)	*Zea mays* L.	Treatment caused rise in plant length, leaf number, and biomass	ZnO NPs application enhanced chlorophyll content, gas exchange characteristics, and antioxidant enzymes; addition led to reduced content of Cd in root and	Rizwan *et al.*, 2019

			shoot	
ZnO (0, 25, 50, 75, and 100 mg/L) and Fe NPs (0, 5, 10, 15, and 20 mg/L)	*T. aestivum* L.	Treatment induced plant growth, dry weight, and grains under Cd stress	Addition of NPs decreased the loss of electrolyte and activity of superoxide dismutase and peroxidase along with diminished Cd accumulation	Rizwan *et al.*, 2019
Si	*Glycine max* L.	Si NPs minimized the growth inhibitory action of Hg	Incorporation of Si NPs improved the chlorophyll content and reduced the Hg content in root and shoot	Li *et al.*, 2020
Mel-Au (200 μM)	*O. sativa* L.	—	Application of Mel-Au NPs caused reduction of Cd level in root and shoot, improved chlorophyll content and raised the activity of antioxidant enzymes	Jiang *et al.*, 2021
Fe (25 and 50 mg/L)	*O. sativa* L.	Treatment of Fe NPs improved plant length and dry weight	Fe NPs application caused rise in the level of proline, glutathione and phyto-chelatins; Fe NPs addition led to improved defense enzymes and glyoxalase machinery	Bidi *et al.*, 2021
ZnO (10–100 mg/L)	*O. sativa* L.	Amendment of ZnO increased the growth of seedlings	Treatment facilitated reduced accumulation of arsenic in root and shoot together with rise in phytochelatin level	Yan *et al.*, 2021
Cu (25, 50, and 100 mg kg^{-1} of soil)	*T. aestivum* L.	Rise in plant height and shoot dry weight	Increase in N and P content; reduced Cd transport, rise in the level of vital ions and antioxidant pool	Noman *et al.*, 2020
Cu (0, 25, 50, and 100 mg kg^{-1} of soil)	*T. aestivum* L.	Improved biomass and growth	Reduced Cr availability; increase in nutrient uptake; rise in antioxidant content	Noman *et al.*, 2020
Fe_2O_3 (0, 25, 50, and 100 mg kg^{-1} soil)	*O. sativa* L.	Improved fresh and dry biomass; increased height	Augmented detoxifying enzymes, photosynthetic potential, and nutrient uptake attributes; reduced formation of ROS, lowered expression of genes supporting the transport of Cd; restricted Cd mobilization in upper plant parts	Ahmed *et al.*, 2021
Fe_2O_3 (25, 50, and 100 mg kg^{-1} soil)	*T. aestivum* L.	Rise in plant fresh and dry biomass; increase in plant length	Reduced Cd transport; enhanced N, P, and K content; increased antioxidants and pigment content	Manzoor *et al.*, 2021
TiO_2 (0, 100, and 250 mg/L soil)	*Z. mays*	Foliar application improved shoot and root dry weight	Reduced accumulation of Cd; increased activities of antioxidant enzymes	Zhou *et al.*, 2020
SiO_2 (30 and 50 nm)	*G. max*	Improved seedling fresh weight	Improved chlorophyll content; lowered accumulation of Hg in root	Li *et al.*, 2020

Au (200 μM)	*O. sativa L.*	—	Reduced level of Cd in root and leaves by 33 and 46.2%, respectively; improvement in antioxidant defense enzyme; restricted expression of genes associated with metal transport	Jiang *et al.*, 2021
Si (0, 25, 50, and 100 mg/kg soil)	*T. aestivum L*.	Improved plant height	Improved chlorophyll; photosynthesis; diminished Cd content in tissues;	Jiang *et al.*, 2021
ZnO (0, 50, and 100 mg L^{-1})	*G. max*	Improved root and shoot growth	Reduced arsenic concentration in root and shoot; improved photosynthesis, water loss, photochemical yield; raised antioxidative defense enzymes	Ahmed *et al.*, 2021
Ti (0.1 to 0.25%)	*Vigna radiata L*.	Augmented radicle length and biomass	Decline in the level of ROS and lipid peroxidation; upregulation of genes related with antioxidative enzymes	Katiyar *et al.*, 2020
Se and Si (5, 10, and 20 mg L^{-1})	*O. sativa L.*	—	Lowered accrual of Cd and Pb; improved yield	Hussain *et al.*, 2020

Sulfur Nanoparticles

Sulfur has been demonstrated as a necessary element for the growth and development processes of crop plants. Sulfur is known for its vital roles in the regular functioning of plant chlorophyll and synthesis of crucial proteins (Duncan *et al.*, 2018). It is reported to assuage unfavorable environmental stresses in crop plants, however, the efficiency of S Nanoparticles vary (Liu *et al.*, 2020). The supplementation of sulfur improved photosynthesis and ultimately vegetative characteristics of mustard grown under stress environment through increasing the biosynthesis of GSH (Fatma *et al.*, 2014). In another report, the effect of green synthesized sulfur nanoparticles on lettuce and reported enhanced growth in sulfur treated plants compared to that of untreated lettuce plants. Furthermore, sulphur nanoparticles application to lettuce enhanced osmoprotectants, total phenols, soluble sugars, flavonoids, anthocyanins, and tannin (Najafi *et al.*, 2020). The research on sulfur nanoparticles based supplementation under salt stress is rare and hence, future studies should focus on such applications to advance the knowledge regarding their mode of actions and optimum concentrations effective to mitigate stress induced harmful effects on plant productivity.

Conclusion and future prospects

Nanoparticles present a great opportunity in agriculture, but it is necessary to work on strategies that cope with their accumulation and potential risks for human health and the environment, while adopting the advantages of using nanoparticles in crops. This young field of research is achieving important goals and present an opportunity in the future. Thus far, in vitro analyses have been developed to help in the standardization of the correct dose and type of nanoparticles recommended for each application and crop species, so that any potential toxicity to the environment, crops and food is minimized. Another important issue to take in account, but still little explored to date, is not only the specific accumulation of nanoparticles in edible parts of crops but the bioavailability of the accumulated nanoparticles to the next trophic level. In modern era, nanoparticles use is continuously becoming intensive and integral in different sectors including agriculture. Modern genetic methods possess the potential to improve salinity tolerance in crop plants. However, this involves a huge investment in training, research infrastructure, time and costs. Moreover, genetically modified crops for human consumption, are not so far socially accepted in many regions globally. On the other hand, classical genetic approaches to discover salt resistant plants is considered laborious and time-consuming processes. In view of these serious issues, the use of nanoparticles could be a potential alternative strategy to adopt directly at the farmer field level. In fact, nanotechnology is considered as an excellent tool for bringing improvement in the agriculture sector. But one cannot ignore environmental safety while fulfilling the needs of modern era. It is evident from the summarized studies that nanoparticles impart many advantageous impacts on crop plants under salt stress, however, the higher concentrations applied have quite often shown phytotoxic effects. However, such responses vary with the plant species and salt levels tested. The information from available recent literature to demonstrate the influence of nanoparticles on plants under salt stress, but most of the studies are at infancy stage and have uncovered only targeted physio biochemical processes. Thus, a complete understanding of underlying molecular processes under the interaction of salt stress and nanoparticles is necessary. Moreover, the available reports are mainly controlled condition based, and hence, for commercialization of these nanoparticles, conduction of field experiments is necessary to get a complete understanding into the roles of nanoparticles towards managing salt stress in plants. Moreover, the environmental impact of the widespread use of these nanomaterials needs to be comprehensively studied. This would enable plant scientists to better suggest a particular type of nanoparticle for a particular crop, and to develop environment-friendly and cost-effective nanoparticles for future agriculture use. In view of the multiple natural stresses prevalent under field conditions, future studies should evaluate the role of nanoparticles under multiple stresses. This would facilitate an effective implementation of nanotechnology to mitigate the negative impacts of abiotic stresses. Hence, extensive research is still needed before the actual implementation of nanoparticles to address the salt stress problem at field level. In particular, the negative impacts of nanoparticles on living organisms including humans and livestock should not be overlooked, so a well-focused research in this regard is essentially desired. Accumulation of nanoparticles in edible plant parts can affect the humans and feeding livestock. In this regard, the effect of nanoparticles on the rhizosphere life should also be brought under consideration for future research.

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CONFLICT OF INTERESTS

The authors declare that they have no potential conflicts of interest.

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