Chapter

Nanotechnology a Potential Tool to Mitigate Abiotic Stress in Crop Plants

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Abstract

The response of plants to abiotic stress is complex and involves changes in their morphology, physiology and metabolism. A number of strategies are being followed to enhance the tolerance of abiotic stress conditions, including the development of genetically-engineered varieties containing various gene constructs believed to enhance the performance under stress conditions. Nanotechnology is a versatile field and has found application in almost all the existing fields of science. 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 signaling, and hormonal pathways. The mobility of the nanoparticles is very high, which leads to rapid transport of the nutrient to all parts of the plant. In particular, the most actual is to find ways to increase the adaptation potential of cultivated plants with the use of nanopreparations in stressful conditions.

Keywords: nanoparticles, abiotic stress, drought, salinity, ROS, crop plants

1. Introduction

World population is increasing day by day and by 2050 it is expected to reach 9.1 billion, but agricultural production is not rising at a parallel pace. Raising productivity is a challenge as the area under cultivation is likely to remain constant or even decrease due to increasing pressure on land for nonagricultural uses. While increased investments and technological breakthrough can improve availability, these may not necessarily translate into increased accessibility and absorption of food. With climate change on the trail, abiotic stresses are considered to be a major constraint for sustaining crop productivity. As per one of the estimates approximately 70% of yield reduction of crops is directly or indirectly influenced by abiotic stresses [1]. Abiotic stress leads to a series of morphological, physiological, biochemical and molecular changes that adversely affect plant growth and productivity. Drought, salinity and extreme temperatures are the most prevalent

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abiotic stresses, threatening the global food security. Development of stress tolerant plants can be a worthwhile strategy to win over the problem of decreasing global food production. Conventional breeding methods have met with limited success in improving the stress tolerance of crop plants involving inter-specific or inter-generic hybridization. The conventional breeding approaches are limited by the complexity of stress tolerance traits, as well as the low genetic variability of yield components under stress condition and lack of efficient selection criteria. It is important, therefore, to look for alternative strategies to develop stress tolerant crops. All traditional breeding methods including selection, hybridization, polyploidy and mutation have utilized for genetic improvement of crop plants. Albeit supplementary success in history of crop improvement in agricultural crops, their yield at present reached a plateau and there exists food insecurity and poverty in many developing countries. For this purpose exploration of novel strategies and their exploitation in complement to existing traditional and advanced breeding tools is the need of the hour. Now-a-days the global demand is to increase food production with limited available resources and minimum but efficient use of fertilizer and pesticides that can check pollution in the environment which ushered in new agricultural technologies to reshape modern agriculture. Among the latest technology, nanotechnology is most promising one in the era of agriculture and plant biotechnology [2]. The application of nanoparticles or nanodevices affect various developmental stages both positive and negative impact on plant growth. Nanotechnology comprises novel properties of nanomaterial that make easy for agricultural research in crop improvement program as well as alleviation to stresses [3]. Nanotechnology has been provisionally defined as relating to materials, systems and processes which operate at a scale of 100 nanometers (nm) or less. 'Nano' usually refers to a size scale between 1 and 100 nm. Nano materials are composed of components with very small size, and these components have impacts on the properties of materials at the macro level. Nanomaterials have a relatively larger surface area when compared to the same mass of material produced in a larger form. Nano particles can make materials more chemically reactive and affect their strength or electrical properties. The particles have high surface to volume ratio that increases their reactivity and possible biochemical activity [4].

2. Types of nanomaterials used

Nanomaterials have applications in the field of nanotechnology, and displays different physical chemical characteristics from normal chemicals (i.e. silver nano, carbon nanotube, fullerene, photocatalyst, carbon nano, silica). Common types of nanomaterials include nanotubes (Single walled carbon nanotube, multi walled carbon nanotube), dendrimers, quantum dots, fullerenes, metal (Ag, Si, Au, etc.) and metal oxide (TiO_2, SiO_2, ZnO, CuO, etc.) based. Nano-scale materials can occur in nature; both natural and manmade processes (such as volcanic activity or diesel combustion) can also give rise to nanometer-sized materials unintentionally. There are two processes for nanomaterial creation including "bottom-up" processes (such as self-assembly) that create nanoscale materials from atoms and molecules, and "top-down" processes (such as milling) that create nanoscale materials from their macro-scale counterparts. Nanomaterials can be nanoscale in one dimension (e.g. surface films), two dimensions (e.g. strands or fibers), or three dimensions (e.g. particles). They can exist in single, fused, aggregated or agglomerated forms with spherical, tubular, and irregular shapes.

3. Uptake, translocation, and accumulation of nanoparticles (NPs) into the plants

The uptake of CB and MB NMs by plants is a very recent field of study. Among CB NMs, the most studied materials are the fullerene C_{70}, the fullerol ($C_{60}(OH)_{20}$) and CNTs; while the most studied MB NMs are TiO_2, Au, Ag, Cu, CeO_2, FeO, and ZnO NPs. Uptake, translocation, and accumulation of NPs depend on the species of plant and the size, type, chemical composition, functionalization, and stability of the NPs. Usually, NPs enter the plant root system through the lateral root junctions and reach the xylem through the cortex and the pericycle [5]. The mechanism behind interaction of nanoparticles with plant system is primarily based on chemical processes which create reactive oxygen species, ion cell membrane transport activity, oxidative damage and lipid peroxidation. Once enter in the plant cells NPs react with sulfhydryl, carboxyl groups and ultimately alter the protein activity. The NPs may form complexes with membrane transporters or root exudates and subsequently be transported into the plants [6, 7]. Nanomaterials move from leaves to roots, stem, and developing grain, and from one root to another. One of the main passages of uptake and transportations to the shoot and leaves of plant is the Xylem [8, 9]. The nanomaterials are capable of penetrating through the leaf cuticle and into the cell cytoplasm [10]. In the cytoplasm, the NMs may bind with different cytoplasmic organelles and interfere with the metabolic processes at that site [11]. One of the pathways also reported particle size of 20 nm Ag nanoparticles may be transported inside the cells through plasmodesmata [12, 13]. A study on generational transmission of C_{70}-NOM in rice plants and find the presence of black aggregates of C_{70} in the leaves of the second generation of the plants treated with fullerenes only in their first generation [14].

4. Plant response to abiotic stress

Among the abiotic stresses, drought, salinity, alkalinity, submergence and mineral toxicity/deficiencies are considered as major factors that contribute to decrease crop growth and productivity [15]. Plants face various environmental stresses throughout their life cycle, therefore they develop their defense against environmental stresses at various levels by modulating molecular, biochemical and physiological pathways. In order to cope these stresses, plants adopt molecular routes by appropriate alteration of gene expressions. There are several studies which indicated that nanoparticles mediated effect on plants growth and development is concentration dependent. Nanoparticles are involved in upregulating the activities of antioxidant enzymes like, SOD, CAT and POD [16].

4.1 Effect of nanoparticles on drought stresses

Water is a vital component for plant survival and essentially required for transport of nutrients, therefore water deficiency leads to drought stress, which resulted into weakened vitality of plants [17]. Nanotechnology promises the significant effort to mitigate the drought stresses. Several recent studies (**Table 1**) have evaluated nanoparticle-mediated in different stresses [18, 19].

The application of different concentrations of silica nanoparticles improves the plant tolerance toward drought stress in Hawthorns (*Crataegus* sp.), the physiological and biochemical responses varies in hawthorn seedlings to different concentrations of silica nanoparticles at different level of drought stress from

Abiotic stresses	Nanomaterial	Concentration	Plant species	Stress responses	Refs.
Drought stress	Nano TiO_2	0.01, 0.02, and 0.03%	Wheat (*Triticum aestivum* L.)	Increasing growth, yield, gluten and starch content of wheat	[20]
	Nano TiO_2	0, 10, 100, and 500 mg L^{-1}	Flax (*Linum usitatissimum* L.)	Enhancing chlorophyll and carotenoids content, improving flax growth and yield attributes, decreasing H_2O_2 and malondialdehyde (MDA) content	[21]
	Nano TiO_2	0%, 0.01% and 0.03%.	Basil (*Ocimum basilicum* L.)	Improving the negative effects of drought stress on basil plants	[22]
	Nano Zero valent Fe		*Arabidopsis thaliana* L.	Activation of plasma membrane H^+-ATPase, stomatal opening, increasing Chl content and plant biomass, maintaining normal drought sensitivity, increasing CO_2 assimilation in thale cress plants	[23]
	Nano SiO_2	0, 10, 50 and 100 mg L^{-1}	*Crataegus* sp.	A positive significant effect on photosynthetic rate, stomatal conductance and plant biomass, non-significant effect on chlorophyll and carotenoid content	[24]
	Nano ZnO	0.5, 1 g L^{-1}	Soybean (*Glycine max* L.)	Increasing germination percentage and germination rate, decreasing in seed residual fresh and dry 8 weight of soybean	[25]
	SiO_2	0, 10, 50 and 100 mg L^{-1}	Hawthorns (*Crataegus* sp.)	SNPs increased plant biomass, xylem water potential and MDA content, especially under drought conditions, RWC and ELI were not affected by the SNP pre-treatments.	[24]
	Silicon		Sorghum (*S. bicolar*)	Increase in leaf area index (LAI), specific leaf weight (SLW), chlorophyll content (SPAD), leaf dry weight (LDW), shoot dry weight (SDW), root dry weight (RDW), total dry weight (TDW)	[26]
	TiO_2 and SiO_2	25, 50, 100 and 200 ppm) or nano-SiO_2 (400, 800, 1600 and 3200 ppm)	Cotton	Increased total phenolics, total soluble proteins, total free amino acids, proline content, total reducing power, total antioxidant capacity, catalase activity peroxidase activity and superoxide dismutase activity in comparison with control	[27]
Salinity stress	Nano SiO_2	25 mM	Tomato (*Lycopersicum esculentum* L.)	Lower levels of nano-SiO_2 enhanced seed germination potential, root length and dry weight. Higher levels suppressed seed germination characteristics	[28]
	Nano SiO_2		Basil (*Ocimum basilicum* L.)	Increasing fresh and dry weight, chlorophyll content and proline content	[29]
	Nano SiO_2		Squash (*Cucurbita pepo* L.)	Improving seed germination and growth characteristics, reduced levels of MDA, H_2O_2 and electrolyte leakage, reducing chlorophyll degradation and oxidative damage, enhancing photosynthetic parameters antioxidant enzymes	[30]

Abiotic stresses	Nanomaterial	Concentration	Plant species	Stress responses	Refs.
	Nano SiO_2		Tomato (*Solanum lycopersicum* L.)	Up-regulating the expression profile of four salt stress genes and six genes were down-regulated, suppressing the effect of salinity on seed germination rate, root length and fresh weight	[31]
	Nano ZnO and Fe_3O_4	30,60,90 mg L^{-1}	Moringa peregrina	Reduction in Na^+ and Cl^- contents, increasing N, P, K^+, Ca^{2+}, Mg^{2+}, Fe, Zn, total chlorophyll, carotenoids, proline, carbohydrates, crude protein and enzymatic and non-enzymatic antioxidants	[32]
	Nano ZnO	2 g L^{-1}.	Sunflower (*Helianthus annuus* L.)	Increasing growth, net CO_2 assimilation rate, sub-stomatal CO_2 content, chlorophyll content, Fv/Fm and Zn content and decreasing Na^+ content in leaves	[33]
	ZnO	2 g L^{-1}.	Sunflower (*Helianthus annuus* L.)	Increase growth, proline content, and some antioxidant enzyme activities	[33]
Flooding stress	Nano Ag	40, 80 or 120 ppm	*Crocus sativus*	Blocking of ethylene signaling, promotion of root growth	[34]
	Nano Al_2O_3		Soybean (*Glycine max* L.)	Regulation of energy metabolism and cell death, improved growth	[35]
	Nano Ag		Soybean (*Glycine max* L.)	Reducing generation of cytotoxic byproducts of glycolysis, increasing the abundance of stress-related proteins, enhancing seedling growth	[35]

Table 1.
Effects of nanomaterials on abiotic stresses.

moderate to severe stress [24]. It was confirmed to positive effect on photosynthesis parameters, malondialdehyde (MDA), relative water content (RWC), membrane electrolyte leakage (ELI) as well as chlorophyll, carotenoid, carbohydrate and proline contents by pre-treatment of SNPs. Perhaps involvement of silicon nano particles in maintaining critical physiological and biochemical attributes in order to induce drought tolerance in hawthorn seedlings under drought stress, but exact mechanism is yet to be understood [24]. Application of silicon on two sorghum cultivars having different drought susceptibility showed improved drought tolerance irrespective of their drought susceptibility by lowering shoot to root (S/R) ratio, which perhaps suggested the improved root growth and the maintenance of the photosynthetic rate [36]. The addition of SiO_2 to plant medium reduces the penetrability of the plasma wall of the leaf cells resulting in the loss of lipid peroxidation and also, SiO_2 protects cellular wall against heat and drought stress [37]. Proline content significantly increased when silica nanoparticles were applied under stress, in comparison with common silica fertilizer [29]. Application of nano-Si caused a significantly increase in the activities of catalase (CAT) and peroxidase (POD) in plant leaves as compared to unstressed plants of faba bean [29], tomato [30] and alfalfa [38]. Furthermore, silica nanoparticles also exhibit its effect on xylem humidity, water translocation and enhance turgor pressure, thus leaf relative water content and water use efficiency will be increased in pants.

Treatment with Rutile (TiO_2) has led to increase germination, germination indices, vigor indices, plant dry weight, chlorophyll formation, activities of ribulose bisphosphonates carboxylase and oxygenase, rate of evaluation of oxygen in the chloroplast leading to promoted photosynthesis [39, 40]. TiO_2 NPs augmented wheat plant growth and yield with its components under water deficit stress condition [20] and also regulates enzymes activity involved in nitrogen metabolism such as nitrate reductase, glutamate dehydrogenase, glutamine synthase, and glutamic-pyruvic transaminase that helps the plants to absorb nitrate. The effects of nano-TiO_2 improved germination, light absorbance, photosynthetic activity and activate Rubisco [41] also promoted antioxidant stress by decreasing the accumulation of superoxide radicals, hydrogen peroxide, malonyldialdehyde content and enhance the activities of superoxide dismutase, catalase, ascorbate peroxidase, guaiacol peroxidase in spinach [42]. Nano- TiO_2 also was observed to promote the growth of spinach through an increase in photosynthetic rate and nitrogen metabolism in spinach [43]. Nano-TiO_2 can enhance plant water and nitrogen use and stimulate some antioxidant enzyme activities, such as SOD, POD and CAT such as in canola [25]. The application of nano zinc oxide has potential to increase seed germination percentage and germination rate in soybean as compared to those were subjected to water stress. It was further suggested that nano zinc oxide application under drought stress decrease seed residual fresh and dry weight, which shows that zinc nanoparticles were effective for using of seed reservoirs to seedling growth and enhance drought tolerance [44]. A study revealed the significant effect of iron nanoparticles under drought stress in plants on traits like number of boll per branch, number of seeds per boll, the 1000 seed weight and yield at probability level of 1%. Foliar application of iron nanoparticles exhibited drought stress mitigating effects on yield components and oil percentage of Goldasht spring safflower cultivars. Application of Fe nanoparticles also enhance yield and yield components at two stages of flowering and granulation, although it was better at flowering stage than seed formation in contrast to drought stress conditions without Fe nanoparticles application [45]. Advances of silver nanoparticles (AgNPs) application of silver nanoparticles (AgNPs) could be attributed toward mitigating water stress mediating loss of plant growth and yield [46].

4.2 Effect of nanoparticles in salinity stress

Salinity is the major concern of scientific community to attain sustainable crop production, it is estimated that more than 20% of cultivated land worldwide is experiencing salinity stress and the amount is increasing day by day. Salinity stress causes the negative impact on various biochemical and physiological processes which are associated with plant growth and yield. Lowering of soil osmotic potential, creation of nutritional imbalance, enhancing specific ionic toxicity (salt stress) or one or more combination of these factors, are some of the common implications of salinity stress experienced by plants [47]. The Application of nanofertilizers could be a potential approach to address such issues of soil toxicity and other associated stress problems. It is reported that silicon nanoparticles and silicon fertilizer exhibited promising effects on physiological and morphological traits on vegetative features of basil under salinity stress. It was evident from results which indicated significant increase in growth and development indices, chlorophyll content and proline level in basil (*Ocimum basilicum*) under salinity stress, when treated with silicon nanoparticles and silicon fertilizer [29]. Application of Nano-SiO_2 particles have shown potential increase in chlorophyll content, leaf fresh weight, leaf dry weight, proline accumulation and upregulated antioxidant enzymes activity under salinity stress [28]. Application of silicon nano-particles on lentil (*Lens culinaris*

Medik.) genotypes under salinity stress revealed significant increase in seed germination and seedling growth, whereas significant reduction in germination percent and seedling growth due to the salinity stress under without treatment of nanoparticles. Adding SiO_2 nanoparticles not only enhance seed germination and early seedling growth but also increase other related traits in lentil genotypes under salinity stress. Therefore, SiO_2 nano-particles ameliorate different defense mechanisms of plants against salt toxicity [48]. Other studies in maize suggested that increase in fresh soot fresh and weight under salinity stress when applied by nano SiO2 [41]. One strategy which silica nanoparticles adopts to mitigate salinity stress in plants is to reduce Na^+ ion concentration, perhaps by reducing Na^+ ion absorption by plant tissues [49]. Since primary impact of salinity stress on plant growth is due to reduction of osmotic potential and toxicity of Na^+ ion. Pure alumina nanoparticles (13 nm) without any modifications reduced root elongation in studied plants cucumber (*Cucumis sativus*), soybean (*Glycine max*), carrot (*Daucus carota*) and cabbage (*Brassica oleracea*), thus potentially retarding the growth of plants [50].

5. Effect of nanoparticles on antioxidant and molecular aspect of plants

Nanoparticles can interact with biological systems such as plants chemically or mechanically; and these specific interactions originate mainly from their small size, large surface area, and intrinsic catalytic reactivity. There are only few studies describing nanoparticles impact on antioxidant and molecular level. The treatment of silver nanoparticles in *Brassica juncea* [51] augmented the activities of antioxidant enzymes (ascorbate peroxidase, guaiacol peroxidase and catalase) which resulted in decreased level of reactive oxygen species (ROS). When, Ag NPs of 6 nm sizes were applied at the concentration of 5 mg/l, it caused activation of antioxidant system of *Spirodela polyrhiza,* evident by induced activity of superoxide dismutase, catalase and peroxidase [52]. In addition, concentration of reactive oxygen species, glutathione and malondialdehyde was also increased significantly. Application of gold nanoparticles (GNPs) in *Brassica juncea* seedlings a considerable enhancement appears in the activities of antioxidant enzymes such as, ascorbate peroxidase, guaiacol peroxidase, catalase and glutathione reductase along with higher accumulation of H_2O_2 and proline in the GNPs treated plants [53]. H_2O_2 and proline contents are found to be increased with increasing concentration of GNPs. In particular, actions of ascorbate peroxidase (APX), guaiacol peroxidase (GPX) and glutathione reductase (GR) are increased up to 400 ppm concentration of GNPs while GR activity is maximum at 200 ppm GNPs. The exposure of CeO_2 nanoparticles in kidney bean were significance responses of antioxidant enzyme (ascorbate peroxidase, catalase and guaiacol peroxidase) activities in leaf, root and stem [54]. They observed that upon prolonged exposure to 500 mg nano CeO_2/l, the root antioxidant enzyme activities were significantly reduced; simultaneously root soluble protein was increased. Moreover, guaiacol peroxidase enzyme (GPX) activity in leaf was enhanced with nano CeO_2 exposure in order to maintain cellular homeostasis. Gene expression analyses of the model plant Arabidopsis by RT-PCR have provided new insights into the molecular mechanisms of plant responses to Ag NPs. The transcriptional response of Arabidopsis plants exposed to Ag NPs was analyzed using whole-genome cDNA expression microarrays [55] which result in upregulation of 286 genes, including the genes primarily associated with metal and oxidative stress (e.g., vacuolar cation/proton exchanger, superoxide dismutase, cytochrome P450-dependent oxidase, and peroxidase), and down regulation of 81 genes, including the genes involved in plant defense system and hormonal stimuli (e.g., auxin-regulated gene involved in organ size-ARGOS, ethylene signaling pathway, and SAR against pathogens). On the other hand, the effects of silver nanoparticles on proteomic study of rice that reveals silver nanoparticles responsive proteins were primarily associated with oxidative stress response pathway, Ca^{2+} regulation and signaling, transcription, protein degradation, cell wall synthesis, cell division, and apoptosis [56]. The effect of zinc oxide (nZnO) in *Arabidopsis thaliana* [57], fullerene soot (FS) or titanium dioxide ($nTiO_2$) nanoparticles on gene expression in roots and resulted in 660 up- and 826 down-regulated genes, 232 up- and 189 downregulated genes, and 80 up- and 74 down-regulated genes, respectively (expression difference > 2-fold). The genes induced by nZnO and FS included mainly ontology groups annotated as stress responsive, including both abiotic (oxidative, salt, water deprivation) and biotic (wounding and defense to pathogens) stimuli. Application of multi-walled carbon nanotubes markedly influenced tomato seed germination and seedling growth by up-regulating stress-related gene expression [58].

6. Conclusion and perspectives

Application of nanotechnology in agriculture, even at its global level, is at its nascent stage. Nanoscience is leading to the development of a range of inexpensive nanotech applications for enhanced plant growth, biotic and abiotic stress responses. Nanoparticles enhances the 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 signaling and hormonal pathways. Nanoparticles interaction with plant cell results in modification of plant gene expression and biological pathways which ultimately affect plant growth and development. Research on nanotechnology in agriculture a vast study on fabrication, characterization, standardization, biodegradability, ecofriendly nature and also possible uptake and translocation of nanoparticles by plants is needed.

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Conflicts of interest

The authors declare no conflict of interest.

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