Chapter

# Role of Nanoparticles in Abiotic Stress

*Mohd. Tariq, Shipra Choudhary, Harjeet Singh, Mohd. Asif Siddiqui, Hirdesh Kumar, Asad Amir and Neelesh Kapoor*

## Abstract

Nanotechnology is currently seeking much attention of researchers because of their wide applications in diverse sectors including agriculture. The influence of nanoparticles on physiological state of plants at the different levels of their organization, beginning from molecular, has been studied at various plants. It is known that nanoparticles in different concentrations can impact both positive and negative biological effects. Nanomaterials confer profound uses for sustainable crop production, reducing loss of nutrients, suppression of diseases and thereby enhancing the yields. Concerning the role of nanomaterials in alleviating the damage of plant abiotic stresses or in inhibiting plant growth and its toxicity, further studies are essential under different levels including plant molecular and cellular levels. A wide variety of research has been conducted to study plant responses to waterlogging stress that include various disciplines like molecular, biochemical, and physiological, anatomical and morphological examinations. Nano technological implications for curbing water-logged conditions recently came into limelight and have drawn much attention in the last few years. Nanotechnology is defined as the systems and processes which operate at a scale of 100 nm or less. Nanotechnology has many applications in the field of agriculture. There are majority of nano-materials which are known for its plant growth promoting effects. Nanoparticles have unique physiochemical properties such as high reactivity, particle morphology, and large surface area. They also boost the plant metabolism.

**Keywords:** abiotic stress, crop plants, heat stress, heavy metals, nanoparticles, salinity

## 1. Introduction

Population explosion during the last few decades has led to increased pressure on the agriculture sector by an upsurge of continuously increasing food demand. Natural resources of the world are continuously diminishing at a much faster pace than their renewal and the agriculture sector is no exception to this presently prevailing scenario. Sustainability issues due to population explosion, climate change, urbanization, habitat loss assisted by environmental issues are some of the global challenges faced by the green plants including the agriculture sector [1]. Plants, the vital component of our planet remain always exposed to different environmental variations and numerous stress factors throughout their life. Unlike animals, plants are deprived of motility to a better place on the arrival of any kind of stress either *biotic* or *abiotic*. To combat such stresses, nature has provided these living entities with certain defensive mechanisms that help these sessile organisms to endure these unpleasant situations. Though plants develop several mechanisms which involve avoidance, escapism, and tolerance, to deal against adverse conditions their responses could vary appreciably even in the same plant species. For this reason, the identification of tolerant plant species is always the major concern towards sustainable agriculture and crop production [2]. Major abiotic stresses which affect plants include *heat, salinity, cold drought, flooding/submergence (anoxia), chemical toxicities*, and *excess light* [3].

Technological advancements in the last few decades have led to profound structural changes in the agriculture sector and improvisation of plant health dealing with different *abiotic* stresses, improvements required to increase the production rate in ways that promote food security and public health improvement remains the matter of concern. So, there is a major concern among scientific communities to raise world food crop production by 70% [4]. In such varying environmental scenarios, it is needful to recognize an area of research to conquer the technical challenges in addressing the yield barrier, resource use efficiency, and development of environmentally accepted technology [5].

Nanotechnology and nano-sciences have come out as powerful and promising tool dealing with nearly all the aspects of the masses and people's life in 21st century that include medicine, agriculture, industrial, environment, electronics with application in numerous preparations [6, 7]. Precise potential to control and fabricate matters at nano-scale remain the beauty of this newly emerging scientific discipline. Nanotechnology has emerged out broadly into the '*agri-food sector*' which include the nanosensors, tracking devices, targeted delivery of required components, food safety, new product developments, precision processing, smart packaging, and others [8–11]. Nanotechnology offers a wide research area and provides possibilities for a large scope of diverse applications and advantages in fields of biotechnology and agriculture-based research such as disease prevention [12], nutrient management by nano-fertilizers [13], nano-pesticides or nano-herbicides [14, 15], mitigating abiotic stress [2]. Also, nanotechnology holds good promises for solving the problem associated with abiotic stresses to obtain sustainability in the field of agriculture [2].

Improving plant traits against different diseases and abiotic and biotic stresses such as drought, salinity, plant diseases, and others is one of the primary objectives of biotechnological research. Nanotechnology-enabled gene sequencing is expected to introduce rapid and cost-effective capability within a decade [16], thereby leading to more effective identification and usage of plant gene trait resources that could help plants in overcoming adversities due to different abiotic stresses. Considering these issues in this article, we are dealing with how nanotechnology can be made useful for mitigating various abiotic stresses of crops and various mechanisms associated with them [1].

## 2. Abiotic stress in crops and current scenario

Plants are constantly exposed to various stress factors throughout their life span. As per the data available, the relative decreases in potential maximum yields associated with abiotic stress factors vary between 54 and 82% [17]. Crops confront various types of abiotic stress and it has been well documented as well that among stresses, extreme temperatures (freezing, cold, heat), water availability (drought, flooding), and ion toxicity (salinity, heavy metals) are the major causes which adversely affect the plant growth and productivity worldwide [18–21]. These abiotic stresses are interconnected to osmotic stress that results in the disruption of ion

*DOI: http://dx.doi.org/10.5772/intechopen.99928*


**Figure 1.**
*Types of abiotic stress with their effects on growth of plants.*

distribution and cell homeostasis. Crop plants are adversely affected by abiotic stress conditions. On account of the current scenario, more than about 50% loss of yield/year is sole because of abiotic stresses such as drought, salinity, heat, and cold. In developing countries, drought and low soil fertility has been proved to be a major cause for affecting crop production [22]. Recently, several transcription factors (TFs) due to their efficacy as a master regulator, have been proving as a potential candidate for genetic engineering to bread stress-tolerant crops and improve stress tolerance [23]. Six Asian region countries namely Bangladesh, China, India, Indonesia, Pakistan, and Thailand are actively involved in the Research and Development related activities for the development of abiotic stress-tolerant crops [24]. Various abiotic factors along with their probable significance are depicted in **Figure 1**.

## 3. Role of nanotechnology in abiotic stress

Nanotechnology is a platform for developing tools and technology for the improvement of the bio system [25]. Nanoparticles (NPs) are small molecular aggregates with dimensions of 1-100 nm [26]. NPs have been investigated to improve plant growth, development, and productivity and thus, proving their use to overcome various abiotic and biotic stress of crops [27]. In the last decade, the science of nanotechnology has attained, a promising position to mitigate the constraints associated with the aforementioned stresses to achieve a secure future of agriculture worldwide and nano technological findings possess immense potential to open up numerous ways in the field of biotechnology and agriculture [28, 29]. Some of them are discussed here in detail:

### 3.1 Heat stress

The negative impacts of heat stress (also Thermal stress) on plants are substantial, detrimental, and often account for reduced crop yield and productivity as well.

Adverse thermal environments pose a great challenge for crop plants to sustain and survive. In addition to it, another major concern remains the global climatic change i.e., an overall increase in the average global temperature of the earth that had led to increased thermal stress on plants and other organisms along with altered patterns of precipitation. Leaving aside all these problems, defining and quantifying heat stress remains a daunting task. In general, heat stress is categorized relative to some estimate of an optimal thermal range that is characteristic of each species in question.

Heat stress involves elevated temperature at such a harsh level for a long enough time that could result in irreparable loss to the development of plants [30, 31]. Heat stress enhances the Reactive Oxygen Species (ROS) generation and causes oxidative stress, as a result of which membrane lipid degeneration and leakage of membrane ion occur which led to degradation of the protein [32–35], in addition to decreased rate of photosynthesis and chlorophyll content [36]. Several studies have been conducted by many workers from time to time to access the applicability of nanotechnology to minimize heat stress. Selenium nanoparticle application in the low concentration found reducing the effect of heat stress by increasing hydration ability, chlorophyll content, and development of plant [37]. Also, Selenium nanoparticles at low concentrations exhibit antioxidative properties to plants, while oxidative stress had been induced by the high concentration of Se nanoparticles [38, 39]. Plants synthesize several heat shock proteins and molecular chaperones during the period of heat stress [40]. Other proteins are assisted by heat shock proteins in sustaining their fidelity in stress conditions [30] and are involved in heat stress resistance. It was already in reports that multiwall carbon nanotubes could upregulate gene expression of heat shock proteins *viz.* HSP90 [41]. Also, maize plants exposed to CeO2 nanoparticles depicted excessive generation of H2O2 and upregulation of HSP70 [42]. Furthermore, TiO2 nanoparticles treatment reduced the effect of heat stress by stomatal opening regulation [43].

### 3.2 Salinity

Salinity, a major type of abiotic stress factor, limits the production of food and deteriorates the quality of ever-increasing growth in food crops. For scientific communities, increased salinity remains a major constraint to attain sustainable crop production. Worldwide, 20% of cultivated land is facing salinity stress and the amount is increasing day by day. The majority of crop plants species belong to the category of glycophytes, which are highly susceptible to salt stress hence are the most critical environmental abiotic stress that can ruin crop production [44, 45]. Most salinity problems arise due to excess sodium chloride (NaCl) which is widely distributed along with coastal and arid region soils and water supplies. Higher levels of NaCl impose at least three types of problems for higher plants. These include: (i) the osmotic pressure in the external solution can exceed the osmotic pressure in the plant cells and therefore require an osmotic adjustment by the cells to avoid desiccation; (ii) sodium, in excess, can disrupt the uptake and transport of nutritional ions such as K and Ca; and (iii) both Na and Cl can exert direct toxic effects on membranes and enzyme systems [46]. Besides the aforementioned problems, 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 that salinity stress exerts on crop plants. Most vital processes of plants like photosynthesis, protein synthesis, and lipid metabolisms, etc. are badly affected by salinity stress [47]. Salt stress is associated with oxidative stress too. However, to confront salt stress-induced oxidative stress, plants are very well equipped with a defense system of various antioxidant enzymes that include superoxide dismutase (SOD) and peroxidase (POD). The SOD constitutes the first line of defense against ROS [48] and dismutase superoxide radicals to H2O2, whereas POD reorganizes H2O2 into water and oxygen [49]. Besides oxidative stress, salt stress also creates osmotic stress, which reduces the ability of plants to take up water and minerals [50]. Also, plants have been found to abide by osmotic stress by the provision of accumulation of osmolytes, such as proline (Pro) and Glycine Betaine (GB) [51]. Application of nano-fertilizers is a quite hopeful method that can potentially increase plant resource use efficiency and help in reducing environmental toxicity due to the accumulation of unused chemical fertilizers and pesticides in the soil. Therefore, the application of nano-fertilizers could serve as an alternative approach to overcome soil toxicity issues and other associated stresses.

Adverse effects of salinity stress on crop plants have been extensively studied by many workers from time to time. Hussein and Abou-Baker [52] conducted experiments to study the foliar application of nano zinc to mitigate the adverse effect of salinity and confirmed that diluted seawater could be used in the irrigation of the cotton plant. They reported that increasing the application rate of nano-Zn may reduce phosphorous (P) absorption and translocation to leaves and consequently reduce the P/Zn ratio. They suggested that an additional dose of P-fertilizer with nano-Zn could be used to avoid the P/Zn imbalance. Avestan et al., [53] in their investigations proposed that salinity stress treatments were detrimental to morphological and physiological parameters of strawberry plants. They found that nSiO2 treatments suppressed the negative effects of salinity, possibly by improving the Epicuticular Wax Layer (EWL); and nSiO2 treatments enabled salt-stressed plants to better maintain their chlorophyll content and leaf relative water content (RWC) and relative water protection (RWP) relative to controls (no SiO2). They concluded their findings by suggesting three possible directions for future research: (1) Further exploring how variation in the timing of silicon treatments influences EWL deposition by testing EWL at multiple plant developmental stages; (2) investigation of whether there is genetic variation for EWL deposition in strawberry; and (3) testing to distinguish the benefit of greater EWL deposition in saline conditions relative to the benefit of the other signaling and physiological changes that are linked to increased silicon uptake.

Khan [54] in his studies investigated the effect of nano TiO2 in several plant developmental processes including defense against environmental stresses. They concluded that the cumulative effect of the parameters under consideration contributed to improved growth and yield of tomato plants. Therefore, based on the assessment of results it was propounded that nano-TiO2 at the rate of 20 mg/l proved best in enhancing the growth, yield, and quality of tomatoes. In one more study, conducted by Yassen et al., [55] on the cucumber (*Cucumis sativa*) effect of silicon dioxide nanoparticles was assessed where the results indicated an increase in nitrogen and phosphorus, content and uptake and decrease in Na content and uptake when adding SiO2 nano fertilizer. The findings of the study suggested that silicon dioxide nano fertilizer can exert a positive effect on the growth and yield of cucumber.

### 3.3 Heavy metal stress

Nano biotechnology growing as a technology that could make the environment cleans. Nanoparticles, often regarded as particles having a significant amount of surface area with unique physical and chemical properties and having applications in reducing the negative effects of heavy metals on the natural wealth [56, 57]. Some workers have exploited nanotechnology to explore plant phytotoxicity caused by heavy metals in various environments. Although nanoparticles are cost-effective in reducing heavy metal toxicity in plants [58], mitigation of heavy metal-induced root growth inhibition and oxidative stress in the plant has been barely studied [58, 59].

Heavy metal ions were productively adsorbed by magnetic nanoparticles ($Fe_3O_4$) [57]. In addition, Nanoscale zero-valent iron (nZVI) nanomaterials are core-shell structures that are in use for decreasing metal toxicity. Ronavari et al. [60] reported that nZVI nanoparticles are for immobilizing heavy metal ions due to their distinct structure. Also, Fajardo et al. [61] found that lead and zinc mobility and availability decreased when soils were treated with nZVI. The addition of nZVI and active carbon efficiently immobilized copper, lead, cadmium, and chromium in sediments, thus, decreasing the bioavailability and toxicity of heavy metals [62].

Nano hydroxyapatite (nHAp) particles are also in use to remediate metal toxicity. nHAp have been successfully applied to remediate soils contaminated by metals and to purify wastewater due to their outstanding ability to absorb heavy metals like copper (II), zinc (II), lead (II), and cadmium (II) [63]. Zhang et al. [64] found that nHAp effectively decreased the exchangeable fractions of Pb and Cd in contaminated sediments, especially for Pb, and dramatically decreased the metal(loid) ion concentration in pore water.

Carbon nanotubes (CNTs) were discovered by [65] and can be used as absorbents. They can be (i) single-walled carbon nanotubes (SWCNTs) and (ii) multi-walled carbon nanotubes (MWCNTs) [66, 67] and are promising nanomaterial to remove organic and inorganic toxic compounds [68, 69].

### 3.4 Drought stress

Plants have been always combating water stress for millions of years, ever since they first left the water bodies and conquered and colonized dry land. When drought strikes, higher plants are the first victims that have always been obliged to endure it or to adjust their life cycles to avoid it. Thus, a major means of propulsion behind the evolution and emergence of land plants has been their need to search for water, to absorb it, to transport it, and retain it. Even so, drought is still the major constraint to crop production [46, 70, 71]. The term '*Drought*' does not merely represent lack of rainfall instead for plant physiologists, it is a concurrence of various environmental stresses that includes: (i) low soil moisture availability; (ii) high evaporative load, (iii) high temperature, (iv) high solar irradiance, (v) increased soil hardness, (vi) unavailability of nutrients and (vii) accumulation of salts in the topsoil region.

Taran et al., [72], in their studies have shown that Cu-Zn-nanoparticles reduced the negative effect of drought action upon plants of steppe ecotype Acveduc. In particular, increased activity of antioxidative enzymes reduced the level of accumulation of Thiobarbituric Acid Reactive Substances (TBARS) and stabilized the content of photosynthetic pigments, and increased relative water content in leaves. Colloidal solution of Cu-Zn-nanoparticles had a less significant influence on these indexes in seedlings of the *Stolichna* variety under drought. They studied the use of binary compositions of nanoparticles in agro-technologies to enhance the biological productivity of agriculture systems. Ashkavand et al., [73] studied the effect of $SiO_2$ nanoparticles on drought resistance in hawthorn seedlings and concluded that silicon nanoparticles (SNPs) can increase plant resistance to drought stress. It could be explained by the improvement of photosynthesis rate and stomatal conductance by SNPs pretreatments. Application of silicon on two sorghums (*Sorghum bicolor* (L.) Moench) cultivars possessing different drought susceptibility exhibited improved drought tolerance irrespective of their drought susceptibility by lowering shoot to root (S/R) ratio, which perhaps could be an indicator of improved root growth and the maintenance of the photosynthetic rate. These findings could be attributed to improving the drought tolerance of sorghum via the augmenting water uptake efficiency of plants [2, 74]. Applications of silver nanoparticles

(AgNPs) has also been appreciated in diminishing negative effects of drought stress on lentil (*Lens culinaris* Medic). Significant effects of different concentrations of Polyethylene glycol (PEG) and silver nanoparticles on germination rate and germination percentage, root length, root fresh, and dry weight in lentil seeds were reported [75]. In a study, conducted by Sedghi et.al [76], it was observed that nano zinc oxide has the potential to enhance seed germination percentage thereby, overcoming water stress.

### 3.5 Water logging

Over irrigation, prolonged periods of precipitation coupled with poor soil drainage system gives rise to a condition called *'water logging'*. Both, natural vegetation and agriculture crops are equally affected by this worldwide occurring condition of waterlogging. The waterlogged soils offers/presents an unpleasant and uneasy environment for normal growth and development of plants because: (i) air spaces occupied by water delays the exchange and diffusion of gases between the roots (rhizosphere) and atmosphere [77]; (ii) levels of dissolved oxygen are depleted from soil solution by respiration of soil inhabitants and roots [78] and (iii) flooding of fields is often associated with the release of toxic compounds and obnoxious gases. Depending upon the height of the water column produced, flooding can be classified as (i) *waterlogging*, when it is superficial and encase only the roots, and (ii*) submergence*, when water completely covers the aerial plant tissues [79]. In both types of flooding, the movement of oxygen from the air to plant tissues is highly disrupted [80], producing a natural condition known as hypoxia (<21% O2) [79].

Depending upon certain parameters like temperature, microbial respiration activity, frequency, and duration of soil saturation, the depletion of dissolved oxygen in waterlogged soils leads to conditions called *'hypoxia* 'and *'anoxia'* within few hours to days. In recent years, flooding stress and its subordinates like submergence, waterlogging, hypoxia, and anoxia, were investigated extensively in plants, especially in *Arabidopsis* and rice, to pinpoint molecular elements that may play a vital role in flood tolerance. Roots of the plants remain the first victims that are worst hit by flooding. Plant roots facing waterlogging stress follow glucose metabolism according to the classical scheme of alcoholic fermentation in an oxygen deficit medium *(anaerobiosis)*, where self-poisoning of tissues takes place as a result of the formation of end products of fermentation mainly ethanol. Maintenance of an appropriate oxygen supply and energy balance is paramount for the survival of the root system to waterlogging stress.

Nanotechnology has provided new discernment to the problems arising in plants and food science (post-harvest products) and offers novel approaches to the rational selection of raw materials. Silver Nano Particles (SNPs) are the most commonly used nanomaterials in the field of nanotechnology after carbon nano-tubes that every day is added in its application to the nano-world. In this sense, nanoparticles are useful tools as an excessive water supply induces hypoxia in plants [80], increases the vulnerability to pathogen attack [81], and limits the flow of light to the plant [82].

During recovery after a flooding event, plants experience oxidative stress [83] and must remobilize nutrients to achieve a normal homeostatic state [84]. Concerning the protection of plants against oxidative stress, nanomaterials are found to mimic the role of first-line defense antioxidative enzymes like peroxidase, superoxide dismutase, and catalase, which are supposed to form the antioxidant defense grid [85]. Also, plants respond to flooding and the associated stress by changes in gene expression that are finely regulated at a multilevel scale from epigenetics [86] to transcriptional [80, 87] and translational regulation [88].

Rezvani et al., [89] conducted experiments to study the effect of Nano silver ions (as an ethylene inhibitor on the growth of Saffron (*Crocus sativus*) under flooding conditions. Corms of saffron were soaked with different concentrations of nano-silver ranging from 0 to 120 ppm (0, 40, 80, and 120) and planted under flooding stress or non-flooding stress conditions and the results of the investigations showed that the number of roots, root length, fresh and dry weight of roots and leaves were reduced by 10-day flooding stress. Soaking the saffron corms with 40 or 80 ppm concentration of Nano silver rewarded the effect of flooding stress on the root number by increasing it. Also, it was found that 40 ppm of nano-silver increased the root length in stress. 80 ppm concentration of nano-silver was found to increase leaves dry weight. In another study conducted on the same plant (*C. sativus*) under flooding stress, foliar application of Nano silver was accessed by Sorooshzadeh *et al.,* [90]. Results of the investigations showed that flooding stress led to a significant reduction in weight and height of the plant and the number of corms per plant was increased by increasing the concentration of nano-silver. In all, they concluded that flooding stress and Nano silver had a significant interaction effect on all parameters under consideration of the study.

## 4. Mechanism of abiotic stress control by nanoparticles (NPs)

Developing technology for improving food production, minimizing crop productivity loss is the prerequisite for obtaining sustainability in the field of agriculture. Abiotic stress of plants is considered a major emerging problem in the field of agriculture, its diverse types include salinity drought, waterlogging, submergence, heavy metal stresses, and mineral and metal toxicity/deficiencies that minimize crop growth and productivity [91–93]. A decrease in productivity is mainly attributed to these factors. Plant throughout their lifespan has to face various types of abiotic stress and has to come up with strong defense mechanisms to cope up with them. Investigation on NPs has reported that they help plants to overcome abiotic stress by their concentration-dependent impact on plant growth and development [73, 94–96]. It is also reported that various antioxidant enzymes like catalase (CAT), peroxidase (POD), superoxide dismutase (SOD) were found to enhance their activity using NPs [97]. Depending upon their chemical composition, size,

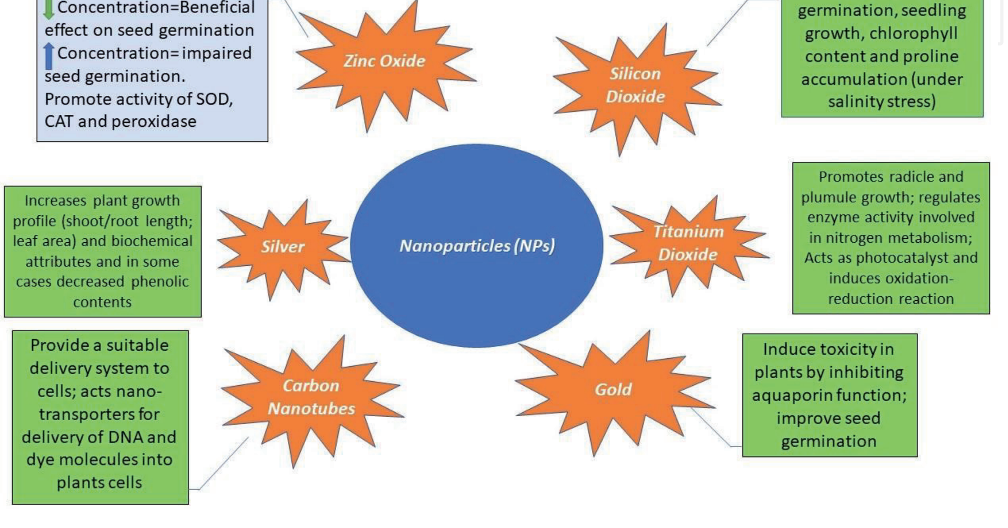


**Figure 2.**
*Various nanoparticles with their effect on plant growth.*

surface covering, reactivity, NPs interact with plants in various ways causing many morphological and physiological changes and play a very vital role in improving crop plants. NPs has both positive and negative effect on plant growth and development [98]. Some NPs along with their possible effect (negative and positive) on a plant are depicted in **Figure 2.**

## 5. Conclusion

Nanotechnology, a multi-disciplinary approach, has emerged out as a powerful discipline in the last few years and is revolutionizing various fields like medicine, agriculture, industrial, environment, electronics, etc. Nanotechnology is emerging as a tool for agriculture by empowering it with tools to conquer nutritional poverty and food scarcity. Nanoparticles are proven beneficial to boost plant growth, development, and increase yield capacity and help to overcome biotic and abiotic stress. The use of nanotechnology will lay a strong platform and will permit a secure future towards sustainability, crop productivity, and overcome abiotic stresses, where loss can be minimized and yield could be enhanced. The most effective way for understanding the action of the mechanisms of NPs applications is to apply the present knowledge by collaborating with various disciplines that may include molecular biology, plant physiology, plant breeding, cytology, soil physics along nanotechnology. Such associations could be helpful for the encouragement of multi-disciplinary projects that may be carried worldwide. Nanotechnology promises new insights into the mechanism of various abiotic stress tolerance in plants to complement physiological studies. Also, there is a need to detangle various factors responsible for abiotic stress. The implementation of action mechanisms of NPs will require information and expertise from the aforementioned disciplines to combat various stress effects. The applicability of nanotechnology needs to be commercialized from laboratory to agricultural fields.

## Author details

Mohd. Tariq[1,2†*], Shipra Choudhary[2†], Harjeet Singh[3†], Mohd. Asif Siddiqui[2], Hirdesh Kumar[2], Asad Amir[2] and Neelesh Kapoor[4]

1 G. B. Pant National Institute of Himalayan Environment, Almora, Uttarakhand, India

2 Department of Biotechnology and Microbiology, Meerut Institute of Engineering and Technology, Meerut, Uttar Pradesh, India

3 Cattle Genetics and Breeding Laboratory, Central Institute for Research on Cattle, Meerut, Uttar Pradesh, India

4 Department of Fingerprinting, College of Biotechnology, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

*Address all correspondence to: tariq.du14@gmail.com

† These authors have contributed equally.

## References

[1] Chen, H. and R. Yada (2011). Nanotechnologies in agriculture: New tools for sustainable development. Tends in Food Science and Technology. **22**: 585-594.

[2] Saxena, R., Tomar, R. S., and Kumar, M. (2016). Exploring nanobiotechnology to mitigate abiotic stress in crop plants. Journal of Pharmaceutical Sciences and Research, *8*(9), 974.

[3] Lavania, D., Singh, A.K., Siddiqui, M.H., Al-Whaibi, M.H. and A. Grover (2015). Abiotic stress tolerant transgenic plants and nanotechnology. In: *Nanotechnology and Plant Sciences* (Eds. M.H. Siddiqui *et al.*) Springer International Publishing Switzerland, pp. 165-181.

[4] FAO (2009). High Level Expert Forum-How to Feed the World in 2050. Economic and Social Development, Food and Agricultural Organization of the United Nations, Rome, Italy.

[5] Jalil, S.U. and M.I. Ansari (2019). Nanoparticles and abiotic stress tolerance in plants: synthesis, action, and signaling mechanisms. In: *Plant Signaling Molecules.* Elsevier Publishing, pp.549-561.

[6] Gruere, G., Narrod, C., and Abbott, L. (2011). Agriculture, food and water nanotechnologies for the poor: Opportunities and constraints. International Food Policy Research Institute (IFPRI). Policy Brief 19 June, 2011.

[7] Scott, N.R., and Chen, H. (2003). Nanoscale science and engineering on agriculture and food systems. In: Roadmap Report of National Planning Workshop. Washington D.C. November 18-19, 2002.

[8] Dasgupta N, Ranjan S, Mundekkad D et al (2015) Nanotechnology in agro-food: from field to plate. Food Res Int 69:381-400

[9] Huang Q, Yu H, Ru Q (2010) Bioavailability and delivery of nutraceuticals using nanotechnology. J Food Sci 75: R50–R57.

[10] McClements DJ, Decker EA, Park Y, Weiss J (2009) Structural design principles for delivery of bioactive components in nutraceuticals and functional foods. Crit Rev Food Sci Nutr 49:577-606. doi:10.1080/10408390 902841529

[11] Ranjan S, Dasgupta N, Chakraborty AR et al (2014) Nanoscience and nanotechnologies in food industries: opportunities and research trends. J Nanoparticle Res 16:2464. doi:10.1007/ s11051-014- 2464-5

[12] Carmen IU, Chithra P, Huang Q et al (2003) Nanotechnology: a new frontier in food science. Food Technol 57:24-29

[13] Priester JH, Ge Y, Mielke RE et al (2012) Soybean susceptibility to manufactured nanomaterials with evidence for food quality and soil fertility interruption. PNAS 109:E2451–E2456

[14] Marchiol L (2012) Synthesis of metal nanoparticles in living plants. Italian J Agro 7: 37.

[15] Prasad R (2014) Synthesis of silver nanoparticles in photosynthetic plants. Journal of Nanoparticles Article ID 963961, pp: 1-8.

[16] Branton, D., Deamer, D.W., Marziali, A., Bayley, H., Benner, S.A., Butler, T., et al. (2008). the potential and challenges of nano pores sequencing. Nature Biotechnology, **26** (10): 1146-1153.

[17] Bray EA, Bailey-Serres J, Weretilnyk E. In: Gruissem W, Buchannan B, Jones R (Eds.)

Biochemistry and Molecular Biology of Plants, Responses to abiotic stresses, American Society of Plant Biologists, Rockville, MD, 2000; pp. 1158-1249.

[18] Gill SS, Khan NA, Anjum NA, Tuteja N. Amelioration of Cadmium Stress in Crop Plants by Nutrient Management: Morphological, Physiological and Biochemical Aspects. Plant Stress (Spl issue) 2010; (In press)

[19] Khan NA, Singh S. (Eds.) Abiotic Stress and Plant Responses. IK International Publishing House Pvt. Ltd., New Delhi, 2008; pp. 1-299.

[20] Mahajan S, Tuteja N. Cold, salinity and drought stress: an overview. Arch Biochem Biophys 2005; 444: 139-158.

[21] Tuteja N. Mechanisms of high salinity tolerance in plants. Meth Enzymol 2007; 428: 419-438.

[22] Clair, S. B. S., and Lynch, J. P. (2010). The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. Plant and Soil, *335*(1-2), 101-115.

[23] Wang H, Wang H, Shao H, Tang X (2016) Recent Advances in Utilizing Transcription Factors to Improve Plant Abiotic Stress Tolerance by Transgenic Technology. Front Plant Sci 7: 67.

[24] Verma, A. K., and Deepti, S. (2016). Abiotic stress and crop improvement: current scenario. Adv Plants Agric Res, *4*(4), 00149.

[25] Fortina, P., Kricka, L.J., Surrey, S., Grodzinski, P., 2005. Nanobiotechnology: the promise and reality of new approaches to molecular recognition. Trends Biotechnol. 23, 168.

[26] Roco, M.C., 2003. Broader societal issue of nanotechnology. J. Nanopart. Res. 5, 181-189.

[27] Giraldo, J. P., Landry, M. P., Faltermeier, S. M., McNicholas, T. P., Iverson, N. M., Boghossian, A. A., ... and Strano, M. S. (2014). Plant nanobionics approach to augment photosynthesis and biochemical sensing. Nature materials, *13*(4), 400-408

[28] Perez-de-Luque, A. and R. Diego (2009). Nanotechnology for parasitic plant control. Pest Manag. Sci. **65**: 540-545.

[29] Torney, F., Trewyn, B.G., Lin, V.S.Y. and K. Wang (2007). Mesoporous silica nanoparticles deliver DNA and chemicals into plants. Nat. Nanotechnol. **2**: 295-300.

[30] Wahid, A. (2007). Physiological implications of metabolites biosynthesis in net assimilation and heat stress tolerance of sugarcane (*Saccharum officinarum*) sprouts. J. Plant Res. **120**: 219-228.

[31] Zandalinas, S. I., Mittler, R., Balfagón, D., Arbona, V., and Gómez-Cadenas, A. (2018). Plant adaptations to the combination of drought and high temperatures. Physiologia plantarum, *162*(1), 2-12.

[32] Banerjee, A., and Roychoudhury, A. (2018). Abiotic stress, generation of reactive oxygen species, and their consequences: An overview. *Revisiting the role of reactive oxygen species (ROS) in plants: ROS Boon or bane for plants*, 23-50.

[33] Karuppanapandian, T., Wang, H.W., Prabakaran, N., Jeyalakshmi, K., Kwon, M. and K. Manoharan (2011). 2,4-dichlorophenoxyacetic acid-induced leaf senescence in mung bean (*Vigna radiate* L. Wilczek) and senescence inhibition by co-treatment with silver nanoparticles. *Plant Physiol.* Biochem. **49**: 168-217.

[34] Moller, I.M., Jensen, P.E. and A. Hansson (2007). Oxidative modifications to cellular components in plants. Ann. Rev. Plant Biol. **58**: 459-481.

[35] Savicka, M. and N. Skute (2010). Effects of high temperature on

malondialdehyde content, superoxide production and growth changes in wheat seedlings (*Triticum aestivum* L.). Ekologija **56**: 26-33.

[36] Prasad, P.V.V., Pisipati, S.R., Momcilovic, I. and Z. Ristic (2011). Independent and combined effects of high temperature and drought stress during grain filling on plant yield and chloroplast EF-Tu Expression in spring wheat. J. Agron. Crop Sci. **197**: 430-441.

[37] Haghighi, M., Abolghasemi, R. J.A. Teixeira da Silva (2014). Low and high temperature stress affect the growth characteristics of tomato in hydroponic culture with Se and nano-Se amendment. Sci. Hortic. **178**: 231-240.

[38] Hartikainen, H., Xue, T. and V. Piironen (2000). Selenium as an antioxidant and prooxidant in ryegrass. Plant Soil **225**: 193-200.

[39] Hasanuzzaman, M., Nahar, K. and M. Fujita (2014). Silicon and selenium: two vital trace elements that confer abiotic stress tolerance to plants. Emerging Technologies and Management of Crop Stress Tolerance. Elsevier, The Netherlands, pp. 377-422

[40] Schulze, E.-D., Beck, E. and K. Muller-Hohenstein (2005). Plant Ecology. Springer, Berlin.

[41] Khodakovskaya, M.V., de Silva, K., Nedosekin, D.A., Dervishi, E., Biris, A.S. E.V. Shashkov (2011). Complex genetic, photothermal, and photoacoustic analysis of nanoparticle-plant interactions. Proc. Natl. Acad. Sci. U. S. A. **108**: 1028-1033.

[42] Zhao, L., Peng, B., Hernandez-Viezcas, J.A., Rico, C., Sun, Y. and J.R. Peralta- Videa (2012). Stress response and tolerance of Zea mays to $CeO_2$ nanoparticles: cross talk among H2O2, heat shock protein and lipid peroxidation. ACS Nano **6**: 9615-9622.

[43] Qi, M., Liu, Y. and T. Li (2013). Nano-TiO2 improves the photosynthesis of tomato leaves under mild heat stress. Biol. Trace Elem. Res. **156**: 323-328.

[44] Flowers, T. J. (2004). Improving crop salt tolerance. Journal of Experimental botany, *55*(396), 307-319.

[45] Munns, R., and Tester, M. (2008). Mechanisms of salinity tolerance. Annu. Rev. Plant Biol., *59*, 651-681.

[46] Basra, A.S. and R. K Basra. (1997). In: "Mechanisms of environmental stress resistance in plants". *Drought resistance in plants* (eds). Basra, A.S. and R.K Basra, Harwood Academic Publishers, Netherlands, pp 1-42

[47] Parida, A. K., and Das, A. B. (2005). Salt tolerance and salinity effects on plants: a review. Ecotoxicology and environmental safety, *60*(3), 324-349.

[48] Alscher, R. G., Erturk, N., and Heath, L. S. (2002). Role of superoxide dismutases (SODs) in controlling oxidative stress in plants. Journal of experimental botany, 53(372), 1331-1341.

[49] Weydert, C. J., and Cullen, J. J. (2010). Measurement of superoxide dismutase, catalase and glutathione peroxidase in cultured cells and tissue. Nature protocols, *5*(1), 51.

[50] Munns, R., James, R. A., and Läuchli, A. (2006). Approaches to increasing the salt tolerance of wheat and other cereals. Journal of experimental botany, *57*(5), 1025-1043.

[51] Wutipraditkul, N., Wongwean, P., and Buaboocha, T. (2015). Alleviation of salt-induced oxidative stress in rice seedlings by proline and/or glycinebetaine. Biologia Plantarum, *59*(3), 547-553.

[52] Hussein, M. M., and Abou-Baker, N. H. (2018). The contribution of nano-zinc to alleviate salinity stress on cotton

plants. Royal Society open science, *5*(8), 171809.

[53] Avestan, S., Ghasemnezhad, M., Esfahani, M., and Byrt, C. S. (2019). Application of Nano-Silicon Dioxide Improves Salt Stress Tolerance in Strawberry Plants. Agronomy, 9(5), 246.

[54] Khan, M. N. (2016). Nano-titanium Dioxide (Nano-TiO2) mitigates NaCl stress by enhancing antioxidative enzymes and accumulation of compatible solutes in tomato (*Lycopersicon esculentum* Mill.). J. Plant Sci, *11*, 1-11.

[55] Yassen, A., Abdallah, E., Gaballah, M., and Zaghloul, S. (2017). Role of Silicon dioxide nano fertilizer in mitigating salt stress on growth, yield and chemical composition of Cucumber (*Cucumis sativus* L.). *Int.* J. Agric. Res, *22*, 130-135.

[56] Dickinson, M. and T.B. Scott (2010). The application of zero-valent iron nanoparticles for the remediation of a uranium-contaminated waste effluent. J. Hazard. Mater. **178**: 171-179.

[57] Shen, Y., Tang, J., Nie, Z., Wang, Y., Ren, Y. and L. Zuo (2009). Preparation and application of magnetic $Fe_3O_4$ nanoparticles for wastewater purification. Sep. Purif. Technol. **68**: 312-319.

[58] Wang, M., Chen, L., Chen, S. and Y. Ma (2012). Alleviation of cadmium-induced root growth inhibition in crop seedlings by nanoparticles. Ecotoxicol. Environ. Saf. **79**: 48-54.

[59] Lin, L., Zhou, W., Dai, H., Cao, F., Zhang, G. and F. Wu (2012). Selenium reduces cadmium uptake and mitigates cadmium toxicity in rice. J. Hazard. Mater. **235**: 343-351.

[60] Ronavari, A., Balazs, M., Tolmacsov, P.,Molnar, C., Kiss, I., Kukovecz, A. and Z. Konya (2016). Impact of the morphology and reactivity of nanoscale zero-valent iron (NZVI) on dechlorinating bacteria. Water Res. **95**: 165-173.

[61] Fajardo, C., Ortiz, L.T., Rodriguez-Membibre, M.L., Nande, M., Lobo, M.C. and M. Martin (2012). Assessing the impact of zero-valent iron (ZVI) nanotechnology on soil microbial structure and functionality: a molecular approach. Chemosphere **86**: 802-808.

[62] Chen, W.F., Zhang, J., Zhang, X., Wang, W. and Y. Li (2016). Investigation of heavy metal (Cu, Pb, Cd, and Cr) stabilization in river sediment by nano-zero-valent iron/activated carbon composite. Environ. Sci. Pollut. Res. Int. **23**: 1460-1470.

[63] Silva, M.M., Pérez, D.V., Wasserman, J.C., Santos-Oliveira, R. and M.A.V. Wasserman (2017). The effect of nanohydroxyapatite on the behavior of metals in a microcosm simulating a lentic environment. Environ. Nanotechnol. Monit. Manage. **8**: 219-227.

[64] Zhang, Z., Li, M., Chen, W., Zhu, S., Liu, N. and L. Zhu (2010). Immobilization of lead and cadmium from aqueous solution and contaminated sediment using nanohydroxyapatite. Environ. Pollut. **158**: 514-519.

[65] Iijima, S. (1991). Helical microtubules of graphitic carbon. Nature **354**: 56-58.

[66] Ihsanullah, A.A., Al-Amer, A.M., Laoui, T., Al-Marri, M.J., Nasser, M.S., Khraisheh, M. and M.A. Atieh (2016). Heavy metal removal from aqueous solution by advanced carbon nanotubes: critical review of adsorption applications. Sep. Purif. Technol. **157**:141-161.

[67] Trojanowicz, M. (2006). Analytical applications of carbon nanotubes: a review. Trac-Trends in Analytical Chemistry **25**: 480-489.

[68] Gong, J.L., Wang, B., Zeng, G.M., Yang, C.P., Niu, C.G., Niu, Q.Y., Zhou,

W.J. and Y. Liang (2009). Removal of cationic dyes from aqueous solution using magnetic multi-wall carbon nanotube nanocomposite as adsorbent. J. Hazard. Mater. **164**: 1517-1522.

[69] Tang, W.W., Zeng, G.M., Gong, J.L., Liang, J., Xu, P., Zhang, C. and B.B. Huang (2014). Impact of humic/fulvic acid on the removal of heavy metals from aqueous solutions using nanomaterials: a review. Sci. Total Environ. **468-469**: 1014-1027.

[70] Boyer, J.S. (1982). Plant productivity and environment. Science **218:** 443-448.

[71] McWilliam, J.R. (1986). The national and international importance of drought and salinity effects on agricultural production. Australian Journal of Plant Physiology **13:** 1-14.

[72] Taran, N., Storozhenko, V., Svietlova, N., Batsmanova, L., Shvartau, V., and Kovalenko, M. (2017). Effect of zinc and copper nanoparticles on drought resistance of wheat seedlings. Nanoscale research letters, *12*(1), 60.

[73] Ashkavand, P., Tabari, M., Zarafshar, M., Tomášková, I., and Struve, D. (2015). Effect of $SiO_2$ nanoparticles on drought resistance in hawthorn seedlings. Forest Research Papers, 76(4), 350-359.

[74] Hattori T, Inanaga S, Araki H, An P., Morita S, Luxová M, Lux A., "Application of silicon enhanced drought tolerance in Sorghum bicolour,". Physiologia Plantarum, 2005,123, 459-466.

[75] Hojjat, S. S., and Ganjali, A. (2016). The effect of silver nanoparticle on lentil seed germination under drought stress. Int J Farm Allied Sci, *5*(3), 208-212.

[76] Sedghi, M., Hadi, M., and Toluie, S. G. (2013). Effect of nano zinc oxide on the germination parameters of soybean seeds under drought stress. *Annales of West University of Timisoara. Series of Biology*, *16*(2), 73.

[77] Jackson, M. B., Fenning, T. M., and Jenkins, W. (1985). Aerenchyma (gas-space) formation in adventitious roots of rice (Oryza sativa L.) is not controlled by ethylene or small partial pressures of oxygen. Journal of Experimental Botany, *36*(10), 1566-1572.

[78] Drew, M. C., and Lynch, J. (1980). Soil anaerobiosis, microorganisms, and root function. Annual Review of Phytopathology, *18*(1), 37-66.

[79] Sasidharan, R., Bailey-Serres, J., Ashikari, M., Atwell, B. J., Colmer, T. D., Fagerstedt, K., ... and Holdsworth, M. J. (2017). Community recommendations on terminology and procedures used in flooding and low oxygen stress research. New Phytologist, *214*(4), 1403-1407.

[80] Lee, S. C., Mustroph, A., Sasidharan, R., Vashisht, D., Pedersen, O., Oosumi, T., ... and Bailey-Serres, J. (2011). Molecular characterization of the submergence response of the Arabidopsis thaliana ecotype Columbia. New Phytologist, *190*(2), 457-471.

[81] Hsu, F. C., Chou, M. Y., Chou, S. J., Li, Y. R., Peng, H. P., and Shih, M. C. (2013). Submergence confers immunity mediated by the WRKY22 transcription factor in Arabidopsis. The Plant Cell, *25*(7), 2699-2713.

[82] Jackson, M. B., and Ram, P. C. (2003). Physiological and molecular basis of susceptibility and tolerance of rice plants to complete submergence. Annals of botany, *91*(2), 227-241.

[83] Yeung, E., van Veen, H., Vashisht, D., Paiva, A. L. S., Hummel, M., Rankenberg, T., ... and Schuurink, R. C. (2018). A stress recovery signaling network for enhanced flooding tolerance in Arabidopsis thaliana. Proceedings of the National Academy of Sciences, *115*(26), E6085-E6094.

[84] Tsai, K. J., Lin, C. Y., Ting, C. Y., and Shih, M. C. (2016). Ethylene-regulated

glutamate dehydrogenase fine-tunes metabolism during anoxia-reoxygenation. Plant physiology, *172*(3), 1548-1562.

[85] Zaytseva, O., and Neumann, G. (2016). Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications. Chemical and Biological Technologies in Agriculture, *3*(1), 17.

[86] Tsuji, H., Saika, H., Tsutsumi, N., Hirai, A., and Nakazono, M. (2006). Dynamic and reversible changes in histone H3-Lys4 methylation and H3 acetylation occurring at submergence-inducible genes in rice. Plant and cell physiology, *47*(7), 995-1003.

[87] Mustroph, A., Lee, S. C., Oosumi, T., Zanetti, M. E., Yang, H., Ma, K., ... and Bailey-Serres, J. (2010). Cross-kingdom comparison of transcriptomic adjustments to low-oxygen stress highlights conserved and plant-specific responses. Plant Physiology, *152*(3), 1484-1500.

[88] Juntawong, P., Girke, T., Bazin, J., and Bailey-Serres, J. (2014). Translational dynamics revealed by genome-wide profiling of ribosome footprints in Arabidopsis. Proceedings of the National Academy of Sciences, *111*(1), E203-E212.

[89] Rezvani, N., Sorooshzadeh, A., and Farhadi, N. (2012). Effect of nano-silver on growth of saffron in flooding stress. World Acad. Sci. Eng. Technol, *6*(1), 517-522.

[90] Sorooshzadeh, A., Hazrati, S., Oraki, H., Govahi, M., and Ramazani, A. (2012). Foliar application of nano-silver influence growth of saffron under flooding stress. In *Proceeding of the 4th international conference "Nanocon-2012* (pp. 510-512).

[91] Tripathi, D.K., Singh, S., Singh, S., Mishra, S., Chauhan, D.K., Dubey, N.K., 2015. Micronutrients and their diverse role in agricultural crops: advances and future prospective. Acta Physiol. Plant. 37 (7), 1-14.

[92] Tripathi, D.K., Singh, V.P., Kumar, D., Chauhan, D.K., 2012. Impact of exogenous silicon addition on chromium uptake, growth, mineral elements, oxidative stress, antioxidant capacity, and leaf and root structures in rice seedlings exposed to hexavalent chromium. Acta Physiol. Plant 34, 279-289. https://doi.org/10.1007/s11738- 011-0826-5.

[93] Upadhyaya, H., Panda, S.K., Dutta, B.K., 2008. Variation of physiological and antioxidative responses in tea cultivars subjected to elevated water stress followed by rehydration recovery. Acta Physiol. Plant. 30 (4), 457-468.

[94] Dimkpa, C.O., Bindraban, P.S., Fugice, J., et al., 2017. Composite micronutrient nanoparticles and salts decrease drought stress in soybean. Agron. Sustain. Dev. 37, 5. https://doi.org/10.1007/s13593-016-0412-8. doi:10.1111/j.1750-3841.2009.01457.x

[95] Mishra, S., Keswani, C., Abhilash, P.C., Fraceto, L.F., Singh, H.B., 2017. Integrated Approach of Agrinanotechnology: Challenges and Future Trends. Front. Plant Sci.8 471. https://doi.org/10.3389/fpls.2017.00471.

[96] Mishra, S., Singh, H.B., 2016. Preparation of biomediated metal nanoparticles. Indian Patent Filed, 201611003248

[97] Laware, S.L., Raskar, S., 2014. Effect of titanium dioxide nanoparticles on hydrolytic and antioxidant enzymes during seed germination in onion. Int. J. Curr. Microbiol. Appl. Sci. 3 (7), 749-760.

[98] Ma X, Geiser-Lee J, Deng Y, Kolmakov A (2010) Interactions between engineered nanoparticles (ENPs) and plants: phytotoxicity, uptake and accumulation. Sci Total Environ 408(16):3053-3061