**Review Article**

**Potential of Nano-Particles in Mitigating Abiotic Stress in Crops**

**ABSTRACT**

Global warming, anthropogenic activities, and other inevitable factors have caused climate change, resulting in occurrence of numerous abiotic stresses. These abiotic stresses not only reduce agriculture productivity but also result in degradation of natural resources (Shahzad *et al*., 2018). Different studies documented significant yield reduction in numerous crops under abiotic-stress conditions (Khan *et al*., 2018). Development and progress in plant science have revealed different aspects and mechanisms of abiotic stresses induced detrimental effects on crop plants. Nonetheless, development in plant physiology and genetics and other applied biological studies developed stress tolerant plants and further showed how plants can be made tolerant to different abiotic stress conditions and what aspects should be further investigated. Nanotechnology is a new and emerging technology, which relies on the application of nanoparticles (NPs) with small radius in order to enhance abiotic-stress tolerance in plants (Moisala *et al*., 2003). These include the use of nanoparticles, which have been shown to have a positive effect on plant performance under stress conditions (Yadav *et al*., 2020). The use of nano-scale agrochemicals, including nano-pesticides, nano-herbicides, and nano-fertilizers, has recently acquired increasing interest as potential plant-enhancing technologies (Abdel Latef *et al*., 2017).

*Keywords*: Anthropogenic, Abiotic Stress, Nanotechnology, Nanoparticles, Agro-chemicals

1. **INTRODUCTION**

Nanoparticles are small molecules of 1-100nm dimensions (Roco, 2003) including very small size, nanoparticles may also acquire some other physio-chemical properties, that is, improved reactivity, large surface area, malleable pore size, as well as diverse morphology (Nel *et al*., 2006). The word **“Nano”** is derived from a **Greek** word which means **extremely small or dwarf**. In the present circumstance, nanoparticles have potential to boost plant growth and development, used as herbicides, nano-pesticide, and nano-fertilizers, etc. that can proficiently release their content in required amounts to target cellular organelles in plants. There is an extensive scope of nanotechnology in the agriculture sector and the potential uses of nanoparticles are still unknown, particularly their role and mechanism in plant growth and development (Manzer *et al*., 2015). Therefore, there is a constant need to develop novel approaches with the support of nanotechnology and nanoparticles that not only increase the crop production and yield, but also minimize the nutrient losses of fertilizers and augment their effective availability to plants. Most of the chemical fertilizer applied in the field remains un-utilized by plants and gets accumulated in the soil leading to increased soil toxicity; therefore application of nano-fertilizers could help to reduce such problems (DeRosa *et al*., 2010; Nair *et al*., 2010). Plants cannot move from their growing place so they cannot escape from environmental stress conditions, that is, salinity, drought, chilling, heat, heavy metals, water-logging, UV radiation, etc. These stresses produce reactive oxygen species (ROS) in plants and cause oxidative burst. Extreme generation of ROS degrades macromolecules and membrane lipids (Foyer and Noctor, 2000), prompts toxicity in cells (Shen *et al*., 2010; Yadav *et al*., 2014), as well as conquers growth of plant (Khan *et al*., 2016). On responding to heavy metal stress, plants accumulate polyphosphates, metal-chelates and organic acids that results in limiting as well as requisitioning of toxic metals in the plasma membrane. Furthermore, nano particles play an important role in the growth and development of plants, and are also involved in the protection of plants against different abiotic stress conditions (Khan *et al*., 2017). The nanoparticles imitate the activities of anti-oxidative enzymes and scavenge these ROS (Wei and Wang, 2013). Small size and large surface area of nanoparticles are available to toxic metals for binding, thus condensed the accessibility and toxicity of heavy metals (Worms *et al*., 2012). Photosynthesis is an important process of plants; however, during abiotic stress conditions, nanoparticles improve photosynthesis rate by conquering oxidative and osmotic stress and defending the photosynthetic system (Siddiqui *et al*., 2014). Therefore, the response of plants to nanoparticles varies from plant species and type or concentration of nanoparticles. Apart from their beneficial effects several nanoparticles show toxicity symptoms (Begum and Fugetsu, 2012). Exposure of some nanoparticles prompts oxidative stress and causes decline in germination rate, root and shoot length, loss of photosystem and crop yields (Wang *et al*., 2016), and nutritive value of crop plants (Peralta-Videa *et al*., 2014). The nanoparticles also alter expression of genes involved cell biosynthesis, cell organization, electron transport, and energy pathways in biotic and abiotic stress responses (Aken, 2015). Nanotechnology has a lot of potential for agriculture by reducing the effects of climate change and enhancing abiotic stress-controlling techniques (Mahakham *et al*.,2017). The use of biotechnologies at the nanoscale (i.e., nano particles) to defeat abiotic stress constitutes the emerging field of nanobiotechnology (Banerjee *et al*.,2016; Cheng *et al*., 2016). Nanotechnology is emerging as a promising technique in tackling the harmful effects of abiotic stresses. Different processes are used to create nanoparticles from metal, metal oxides, or plants. Metals can be converted into nanoparticles using physical, biological, or chemical processes. Reports available indicate that researchers developed the concept of green nanoparticles that can be produced economically by plants (Sharma *et* al., 2009; Iravani *et* al., 2011) and the effectiveness and potential of plant-derived NPs are currently being studied to determine whether they can guard crop plants against stresses, and ultimately enhance crop production.

1. **HISTORY OF NANO-TECHNOLOGY:**

The first mention of the term ‘Nanotechnology’, is usually used by Mr. R. Feynman in 1959 at the session of the American Physical Society. The word “nanotechnology” was introduced for the first time into a scientific world by N. Taniguchi at the international conference on industrial production in Tokyo in 1974. (Tolochko, N.K., 2000).

1. **SYNTHESIS OF NANO-PARTICLES:**

Two main approaches are used for the synthesis of nano-materials:

1. Top-down approaches and
2. Bottom-up approaches

**3.1 Top-down approaches:**

In top-down approaches, bulk materials are divided to produce nanostructured materials. Top-down methods include mechanical milling, laser ablation, etching, sputtering, and electro-explosion.

**3.1.1 Mechanical milling:**

Mechanical milling is a cost effective method for producing materials at the nano-scale level from bulk materials. Mechanical milling is an effective method for producing blends of different phases, and it is helpful in the production of nano-composites.

**3.1.2 Electro-spinning:**

Electro-spinning is one of the simplest top-down methods for the development of nano structured materials. It is generally used to produce nano- fibers from a wide variety of materials, typically polymers (Ostermann *et al*., 2011). One of the important breakthroughs in electro-spinning was coaxial electro-spinning. In coaxial electro-spinning, the spinneret comprises two coaxial capillaries. In these capillaries, two viscous liquids, or a viscous liquid as the shell and a non-viscous liquid as the core, can be used to form core shell nano-architectures in an electric field. This method has been used for the development of core-shell and hollow polymer, inorganic, organic, and hybrid materials (Kumar *et al*., 2014).

**3.1.3 Lithography:**

Lithography is a useful tool for developing nano-architectures using a focused beam of light or electrons. Lithography can be divided into two main types: masked lithography and mask less lithography (Pimpin *et al*., 2012). In masked nanolithography, nano patterns are transferred over a large surface area using a specific mask or template. Masked lithography includes photolithography (Szabo *et al*., 2013). Nano imprint lithography (Kuo *et al*., 2003) and soft lithography (Yin *et al*., 2000).

**3.1.4 Sputtering:**

Sputtering is a process used to produce nano materials via bombarding solid surfaces with high-energy particles such as plasma or gas. Sputtering is considered to be an effective method for producing thin films of nano-materials.

**3.1.5 Laser ablation**

Laser ablation synthesis involves nanoparticle generation using a powerful laser beam that hits the target material (Zhang *et al*., 2017). During the laser ablation process, the source material or precursor vaporizes due to the high energy of the laser irradiation, resulting in nano-particle formation. Utilizing laser ablation for the generation of noble metal nano-particles can be considered as a green technique, as there is no need for stabilizing agents or other chemicals (Amendola *et al*., 2009, Su *et al*., 2018).

**3.2 Bottom-up approaches**

**3.2.1. Chemical vapour deposition (CVD):**

Chemical vapour deposition methods have great significance in the generation of carbon-based nano-materials. In CVD, a thin film is formed on the substrate surface via the chemical reaction of vapour-phase precursors.(Jones *et al*., 2008) A precursor is considered suitable for CVD if it has adequate volatility, high chemical purity, good stability during evaporation, low cost, a non-hazardous nature, and a long shelf-life (Machac *et al*., 2020).

**3.2.2 The sol–gel method:**

The sol–gel method is a wet chemical technique that is extensively used for the development of nano-materials. This method is used for the development of various kinds of high-quality metal-oxide-based nano-materials (Danks *et al*., 2016).

**3.2.3 Green/biological synthesis:**

The synthesis of diverse metal nanoparticles utilizing bioactive agents, including plant materials, microbes, and various bio wastes like vegetable waste, fruit peel waste, eggshell, agricultural waste, algae, and so on, is known as “green” or “biological” nanoparticle synthesis (Kumari *et al*., 2022).

**4. CHARACTERIZATION OF NANO-PARTICLES:**

**4.1Transmission Electron Microscopy (TEM):**

Transmission electron microscopy is an important nanoparticle characterization techniques that employs a focused electron beam on a thin (typically less than 200 nm) sample to produce micrographs of nanoscale materials (Williams and Carter, 2009). Current electron microscopes can achieve resolutions down to 0.05–0.1 nm by reducing image distortion by aberration correctors, hence providing high-resolution images with atomic resolution (Keefe and Horn, 2004; Dahmeen *et al*., 2009). TEM also enables studying the crystalline structure of selected microscopic regions of crystalline materials by spatially confining and focusing the impinging beam and detecting the resulting electron diffraction pattern (Zhou and Greer, 2016).

4**.2. Scanning Electron Microscopy (SEM)**

Scanning electron microscope enables imaging the sample surface by detecting secondary electrons emitted from the sample upon interaction with the impinging electron beam (Goldstein *et al*., 2018).

**4.3 Dynamic Light Scattering (DLS)**

Dynamic light scattering estimates the particle size from the Brownian diffusion of the particles in solution. A laser is transmitted through a measurement cell containing the particle suspension, and the random thermal motion of the particles causes time-dependent fluctuations of the intensity of the scattered light. DLS size estimation is based on the determination of the free diffusion coefficient of suspended particles (Pecora *et al*., 2000).

**4.4 Mass Spectrometry:**

Mass spectrometry was used originally for the characterization of nano-particle composition by revealing the stoichiometry of their building blocks after digestion and dissolution. With the introduction of soft ionization techniques, such as electro spray ionization (ESI) and matrix-assisted laser desorption ionization (MALDI) the separation and detection analyze the samples in the Mega Dalton range, such as ion-mobility spectrometry (IMS), time-of-flight (TOF) analysis, and single particle inductively coupled plasma-mass spectrometry (Bishop *et al*., 2018).

**5. CLASSIFICATION OF NANO-PARTICLES:**

**5.1 Carbon-based NPs**

Fullerenes and Carbon Nano Tubes (CNTs) are the two essential sub-categories of carbon-based NPs. They are globular hollow cages, like allotropic forms of carbon, are found in fullerenes. Due to their electrical conductivity, high strength, structure, electron affinity and adaptability, they have sparked significant economic interest. These materials are classified in pentagonal and hexagonal carbon units, each of which is sp2 hybridized (Astefanei *et al*., 2015).

**5.2. Metal NPs**

These NPs have distinctive electrical properties due to well-known localized surface Plasmon resonance (LSPR) features. Cu, Ag, and Au nanoparticles exhibit a broad absorption band in the visible region of the solar electromagnetic spectrum (Khan *et al*., 2019).

**5.3. Ceramics NPs**

Ceramic NPs are tiny particles made up of inorganic, non-metallic materials that are heat-treated and cooled in a specific way to give particular properties. Ceramic NPs are used in various applications, including coating, catalysts, and batteries (Sigmund *et al*., 2006).

**5.4 Lipid-based NPs**

These NPs are helpful in several biological applications because they include lipid moieties (Khan *et al*., 2019).

**5.5 Semiconductor NPs**

Semiconductor NPs have qualities similar to metals and non-metals. They have unique physical and chemical properties that make them useful for various applications. They can make smaller and faster electronic devices, such as transistors and can be used in bio imaging and cancer therapy (Biju *et al*., 2008).

**5.6 Polymeric NPs**

Polymeric NPs with a size between 1 and 1,000 nm can have active substances surface-adsorbed onto the polymeric core or entrapped inside the polymeric body. These NPs are often organic, and the term polymer nanoparticle (PNP) (Khan *et al*., 2019).

1. **MECHANISM OF UPTAKE, TRANSPORT AND TRANSLOCATION OF NANOPARTICLES IN PLANTS:**

The uptake, accumulation and interference of NPs with key metabolic processes in different plant tissues may have positive or negative effects on plants, depending on their dosage, movement, characteristics, and reactivity (Mirzajani *et al*., 2013). NPs can reach plant tissues through the root system or above-ground parts such as root junctions and wounds. As a carrier, NPs must pass through several physiological barriers until they are taken up by the plant and translocated (Dietz and Herth, 2011). Some NPs have been shown to develop larger pores in the cell wall to enter the cell (Kurepa *et al*., 2010). NPs can be transferred to other plant tissues via the apoplastic and symplastic pathways ( Ma *et al*., 2010). Wong *et al*. (2016) suggested a lipid exchange mechanism for NPs transport into plant cells. NPs-Plant Interaction Pathways NPs may affect plant metabolism by delivering micronutrients (Liu and Lal, 2015), gene regulation (Nair and Chung, 2014), and interfering with several oxidative processes in plants (Hossain *et al*., 2015, Foyer and Noctor, 2005), (Van Breusegem and Dat, 2006). Several studies have found an increase in lipid peroxidation and DNA damage in plants while interacting with NPs (Saha and Dutta 2017). The increase in ROS levels can cause apoptosis or necrosis, resulting in plant cell death (Faisal *et al*., 2013). Despite its destructive nature, ROS play a role in biological activities, including stress tolerance (Sharma *et al.*, 2012). The balance between ROS generation and scavenging determines whether ROS has a destructive or signaling function (Sharma *et al.*, 2012). Several studies have demonstrated that plants exposed to NPs produce more antioxidant molecules (Costa and Sharma, 2016). High concentrations of NPs have a negative impact on photosynthesis, resulting in growth retardation or death in plants. (Tripathi *et al.*, 2017).

1. **APPLICATIONS OF NPS IN AGRICULTURE INDUSTRY**

NPs may be used in agriculture for a variety of reasons, including:

**7.1 Pesticides and herbicides**

Nanoparticles (NPs) can be used to deliver pesticides and herbicides in a targeted manner, minimizing the potential for environmental contamination (Khan *et al*., 2019).

**7.2 Fertilizers and plant growth**

Nano fertilizers offer an opportunity for efficiently improving plant mineral nutrition. Some studies have shown that nano-materials can be more effective than conventional fertilizers, with a controlled release of nutrients increasing the efficiency of plant uptake and potentially reducing adverse environmental outcomes (Khan *et al*., 2019) NPs used to deliver fertilizers to plants more efficiently, reducing the amount of fertilizer needed, and reducing the risk of nutrient runoff (Kopittke *et al*., 2019).

1. **ROLE OF NANOPARTICLES IN PLANTS**

**8.1 Improving plant health**: Maintain the health of plants and soil by reducing chemical spread and nutrient loss (Rasheed *et al*., 2022).

**8.2 Increasing crop yield**: Boosts crop yield and productivity (Aqeel *et al*., 2022).

**8.3 Improving nutrient uptake**: Absorb nutrients more efficiently by loading nutrients and delivering them to different parts of the plant (Zhang *et al*., 2024).

**8.4 Improving water uptake**: NPs can help plants improve their water uptake (Thabet *et al*., 2024).

**8.5 Improving grain yield**: Increases grain yield and harvest index (Rasheed *et al*., 2022).

**8.6 Improving disease detection and management**: NPs can help with efficient disease detection and management (Thabet *et al*., 2024).

**8.7 Improving food quality and safety**: Improves food quality and safety through innovative packaging materials (Thabet *et al*., 2024).

**9. INVOLVEMENT OF NANOPARTICLES IN MITIGATION OF DIFFERENT ABIOTIC STRESS**

**9.1. Drought Stress**

* Drought is considered a major abiotic stress that can drastically limit crop production (Al-Ashkar *et al*., 2021). ZnO NPs in soybean seeds under arid conditions increases the germination percentage of the seeds (Sedghi *et al.*, 2013).Cu and Zn NPs in wheat increases their antioxidant enzyme activity and relative moisture content, decreases thio barbituric acid levels, affects reagent precipitation, stabilizes photosynthetic pigment levels in leaves, and reduces the effects of stress (Taran *et al*., 2017). Foliar usage of TiO2 NPs in wheat is effective to overcome the yield reduction caused by drought stress (Jaberzadeh *et al*., 2013). SiO2 NPs applied to hawthorn grown under drought stress reduced photosynthesis and stomatal conductivity (Ashkavand *et al*., 2015). Silicon (Si) NPs have been reported to ameliorate the effects of drought stress in bananas (Khan *et al*., 2016).

In chickpea plants, the application of Si NPs to the soil reduces the negative effects of drought by increasing the relative moisture content in the plants (Rasheed *et al*., 2020).

**9.2 Salinity Stress:**

The use of Ag NPs in salt-stressed cumin plants substantially improves plant salt resistance (Ekhtiyari and Moraghebi, 2012). SiO2 NPs has also been shown to enhance the developmental parameters, chlorophyll content, Pro accumulation, and up-regulation of antioxidant enzyme activities in tomato and squash plants under salinity stress (Siddiqui *et al*., 2014). Pre-application of Ag NPs to wheat seeds alters antioxidant enzyme activities, reduces oxidative damage, and elevates salt-stress tolerance in such plants (Kashyap *et al*., 2015).

The use of NPs in wheat not only enhances plant development but also improves germination under salt-stress conditions (Shi *et al*., 2016). Furthermore, Fe3O4 NPs protects mint plants from oxidative stress caused by increased NaCl content. Use of Ag NPs in *Lathyrus sativus* under salt stress improves germination percentage, shoot and root length, and enhanced osmotic regulation leads to reduced the negative effects of salinity (Khan *et al*., 2019). Application of Cu NPs to the soil reduced oxidative stress in wheat and significantly increased plant development and yield (Noman *et al*., 2020).

**9.3 Heavy metal stress**

The application of Si NPs on maize plants under arsenic (As) stress reduced the total chlorophyll, carotenoid content, and total protein content; as well as mitigates the adverse effects of As stress on maximum quantum efficiency, photochemical and non-photochemical quenching of FS II (Tripathi *et al*., 2017). Soil application of TiO2 NPs can effectively limit Cd toxicity by enhancing the physiological parameters and photosynthetic rate in soybean plants (Singh and Lee, 2016). Si NPs can reduce Al toxicity by activating the antioxidant defense mechanism in maize plants (de Sousa *et al*., 2019). The combined use of foliar ZnO NPs and soil bio-char in plants was found to be more effective against Cd stress (Rizwan *et al*., 2019). 20 mgL-1 of Fe3O4 NPs reduced Cd accumulation and improved Cd toxicity by increasing nutrient uptake in tomato plants (Rahmati zadeh *et al*., 2019). Under HMs stress conditions, the application of NPs in the soil, regulates the expression of HMs transfer genes in plants, increases the activity of plant antioxidant systems, improves physiological functions, and stimulates the production of protective substances such as root secretions, phytochelatin, and organic acids (Zhou *et al*., 2021).

**10. CONCLUSION:**

` Nanoparticles lessen abiotic stress-induced damage by stimulating the defense mechanism of plants. The very small size of nano-particles enable them to easily penetrate as well as control ion channels, which supports germination of seed and plant growth; further more, their large surface area assists high absorption as well as targeted delivery of molecules (Khan *et al*., 2019). In addition, some reported data illuminated that nanoparticles initiates signaling substance in cytosol as recognized by nanoparticle-specific proteins. Hence, initiates signaling by promoting gene expression and results in improvement of resistance to stress.

1. **FUTURE ASPECTS AND CHALLENGES**

Nano-biotechnology has the potential to improve stress tolerance, stress sensing/ detection, targeted delivery and controlled release of agrochemicals, transgenic events, and seed nano-priming in plants (Wu and Li, 2022). Future research on evaluating the biological effects of nano enzymes i.e., Mn3O4 NPs in plants under stress conditions should be on top of our priorities. Understanding how NPs improve plant stress tolerance will enable researchers to design tailor-made nano materials targeting agricultural challenges.

**REFERENCES:**

1. Abdel Latef, A. A. H.,; Alhmad, M.F.A. and Abdelfattah, K. E. (2017). The possible roles of priming with ZnO nanoparticles in mitigation of salinity stress in lupine (*Lupinus termis*) plants. *J. Plant Growth Regul*. **36:** 60–70. doi: 10.1007/s00344 016-9618-x.
2. Aken, B.V. (2015). Gene expression changes in plants and micro organ isms exposed to nano materials. *Curr. Opin. Biotechnol*. **33**: 206-219.
3. Al-Ashkar, I.; Alderfasi, A.; Ben Romdhane, W.; Seleiman, M.F.; El-Said, R.A. and Al-Doss, A. (2021). Morphological and genetic diversity within salt tolerance detection in eighteen wheat genotypes. *Pl.* **9:** 287.
4. Amendola, V. and [Meneghetti](https://pubs.rsc.org/en/results?searchtext=Author%3AMoreno%20Meneghetti), M. (2009). Laser ablation synthesis in solution and size manipulation of noble metal nanoparticles. ***Phys. Chem. Chem. Phys.*** **11**: 3805-3821.
5. Ashkavand, P.; Tabari, M.; Zarafshar, M. and Struve, D. (2015). Effect of SiO2 nanoparticles on drought resistance in hawthorn seedlings. **76**: 350-359.
6. Astefanei, A., Nunez, O. and Galceran, M. T. (2015). Characterization and determination of fullerenes: a critical review. *Anal. Chim. Acta* **882:** 1–21.
7. Aqeel, U.; Aftab, T. and Khan, M.M. (2022). A comprehensive review of impacts of diverse nanoparticles on growth, development and physiological adjustments in plants under changing environment. *Chemo.*
8. Banerjee, J. and Kole, C. (2016). Plant nanotechnology: an overview on concepts, strategies and tools, in: C. Kole, *et al*. (Eds.), *Pl. Nanotech. Springer. Cham.* 1–14, <https://doi.org/10.1007/978-3-319-42154-4_1>.
9. Begum, P. and Fugetsu, B. (2012). Phytotoxicity of multi-walled carbon nano-tubes on red spinach (*Amaranthus tricolor* L) and the role of ascorbic acid as an antioxidant. *J. Hazard. Mater*. **243**: 212-222.
10. Biju, V.; Itoh, T.; Anas, A.; Sujith, A. and Ishikawa, M. (2008). Semiconductor quantum dots and metal nanoparticles: syntheses, optical properties, and biological applications. *Anal. Bioanal. Chem.* **391:** 2469–2495.

## Bishop, D.P.M; Grossgarten, D.; Dietrich, A. and Vennemann, N. (2018). Quantitative imaging of translocated silver following nanoparticle exposure by laser ablation-inductively coupled plasma-mass spectrometry. *Anal. Met.* 10: 836.

1. Cheng, H.N., Klasson, K.T.; Asakura, T. and Wu, Q. (2016). Nanotechnology in agriculture, Nanotechnology: Delivering on the Promise, 2, ACS, Washington, DC, 233–242.
2. Costa, M. V. J. D. and Sharma, P. K. (2016). Effect of copper oxide nanoparticles on growth, morphology, photosynthesis, and antioxidant response in *Oryza sativa*. *Photosyn.* **54**: 110–119. doi: 10.1007/s11099-015-0167-5

# Dahmen, U., Erni, R., Radmilovic, V., Ksielowski, C., Rossell, M.D. and Denes, P. (2009). Formaldehyde sensing characteristics of calcium-doped zinc oxide nanoparticles-based gas sensor. *Philos. Trans. R. Soc., A.* 367: 37-95.

# Danks, A. E.; Hall, S. R. and Schnepp, Z. (2016). The evolution of ‘sol–gel’ chemistry as a technique for materials synthesis. *Mater. Horiz.* 3: 91–112.

1. DeRosa, M.C., Monreal, C., Schnitzer, M., Walsh, R. and Sultan, Y. (2010). Nanotechnology in fertilizers. *Nat. Nanotechnol*. **5**: 91.
2. Dietz, K. J. and Herth, S. (2011). Plant nanotoxicology. *Trends Plant Sci.* **16:** 582–589.
3. Ekhtiyari, R., Mohebbi, H. and Mansouri, M. (2012). The study of the effects of nano silver technology on salinity tolerance of (*Foeniculum vulgare mill*.). *Pl. Ecosyst*. **7**: 55-62
4. Faisal, M., Saquib, Q., Alatar, A. A., Al-Khedhairy, A. A., Hegazy, A. K. and Musarrat, J. (2013). Phytotoxic hazards of NiO-nanoparticles in tomato: a study on mechanism of cell death. *J. Hazard. Mater.* 250–251, 318–332. doi: 10.1016/j.jhazmat.2013.01.063
5. Foyer, C.H. and Noctor, G., (2000). Oxygen processing in photosynthesis: regulation and signalling. *New Phytol*. **146**: 359 -388.
6. Goldstein, J., Newbury, D. E.; Michael, J. R.; Ritchie, N. W. M.; Scott, J. H. J. and Joy, D. C. (2018). Scanning Electron Microscopy and X-Ray Microanalysis, Springer-Verlag, New York.
7. Hossain, Z., Mustafa, G., and Komatsu, S. (2015). Plant responses to nanoparticle stress. *Int. J. Mol. Sci*. **16**: 26644–26653. doi: 10.3390/ijms161125980
8. Iravani, S. (2011). Green synthesis of metal nanoparticles using plants, *Green Chem.* **13**: 2638–2650.
9. Jaberzadeh, A.; Moaveni, P. and Zahedi , H. (2013). Influence of Bulk and Nanoparticles Titanium Foliar Application on some Agronomic Traits, Seed Gluten and Starch Contents of Wheat Subjected to Water Deficit Stress. *Not Bot Horti Agrobo*. **41**: 201-207.
10. Jones, A.M.; Garg, S.; Pham, A.S. and Waite, T.D. (2008). Superoxide-Mediated Formation and Charging of Silver Nanoparticles. [*Environ. Sci. Tech.*](Environ.%20%20Sci.%20Tech.). **45**: 1428–1434 <https://doi.org/10.1021/es103757c>
11. Kashyap, P.L., Xiang, X. and Heiden, P. (2015). Chitosan nanoparticle based delivery systems for sustainable agriculture. *Int. J. Biol. Macromol.* **77**:36–51
12. Keefe, M. A. O. and Shao-Horn, Y. (2004). Imaging Lithium Atoms at Sub-Angstrom Resolution. *Microsc. Microanal*. . **10**: 86.
13. Khan, A., Rashid, R., Murtaza, G., and Zahra, A. (2014). Gold nanoparticles: synthesis and applications in drug delivery. *Trop. J. Pharm. Res*. **13:** 1169–1177.
14. Khan, M.I.R., Khan, N.A., Masood, A., Per, T.S. and Asgher, M. (2016). Hydrogen peroxide alleviates nickel-inhibited photosynthetic responses through increase in use-efficiency of nitrogen and sul fur, and glutathione production in mustard. *Front. Plant Sci*. **7**: 44.
15. Khan, M.N., Mobin, M., Abbas, Z.K., AlMutairi, K.A. and Siddiqui, Z.H., (2017). Role of nanomaterials in plants under challenging environ ments. *Pl. Physiol. Biochem*. **110**: 194- 209.
16. Khan, F., Hussain, S., Tanveer, M., Khan, S., Hussain, H.A. and Iqbal, B. (2018). Coordinated effects of lead toxicity and nutrient deprivation on growth, oxidative status, and elemental composition of primed and non-primed rice seedlings. *Environ. Sci. Pollut. Res.* <https://doi.org/10.1007/s11356-018-2262-1>.
17. Kopittke, P. M., Lombi, E., Wang, P., Schjoerring, J. K., and Husted, S. (2019). Nanomaterials as fertilizers for improving plant mineral nutrition and environmental outcomes. *Environ. Sci.* **6:** 3513–3524. doi: 10.3390/biology10111123
18. Kumar, B., Smita, K., Cumbal, L. and Debut, A. (2014). Biogenic synthesis of iron oxide nanoparticles for 2-arylbenzimidazoles fabrication. *J. Saudi Chem. Soc., in press*. http://dx.doi.org/ 10.1016/j.jscs.2014.01.003.
19. [Kuo](https://pubs.acs.org/action/doSearch?field1=Contrib&text1=Ping-Lin++Kuo), P.L. and Chen, W.N. (2003). Formation of Silver Nanoparticles under Structured Amino Groups in Pseudo-dendritic Poly(allylamine) Derivatives. *J. Phys. Chem. B* . **41**: 11267–11272
20. Kurepa, J., Paunesku, T., Vogt, S., Arora, H., Rabatic, B. M. and Lu, J. (2010). Uptake and distribution of ultrasmall anatase TiO2 Alizarin red S nano conjugates in *Arabidopsis thaliana*. *NanoLett*. **10:** 2296–2302.doi:10.1021/ nl903518f
21. Liu, R. and Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Sci. Total Environ*. **514:** 131–139. doi: 10.1016/j.scitotenv.2015.01.104
22. Ma, X., Geisler-Lee, J., Deng, Y. and Kolmakov, A. (2010). Interactions between engineered nanoparticles (ENPs) and plants: phytotoxicity, uptake and accumulation. *Sci. Total Environ*. **408**: 3053–3061. doi: 10.1016/j.scitotenv.2010. 03.031
23. Machac, P.; Cichon, S.; Lapcak, L. and Fekete, L. (2020). Graphene prepared by chemical vapour deposition process. *Grap. Tech.* **5:** 9-17.
24. Mahakham, W., Sarmah, A.K. and Maensiri, S. (2017). Nanopriming technology for enhancing germination and starch metabolism of aged rice seeds using phytosynthesized silver nanoparticles, *Sci. Rep*. **7**: 8263. https://doi.org/ 10.1038/s41598-017-08669-5
25. Manzer, H., Siddiqui, Mohamed, H., Al-Whaibi, Firoz, M. and Al Khaishany, M.Y.(2015). Role of nanoparticles in plants. *Nanotechnol. Plant Sci*. **19**: 35.
26. Mirzajani, F.; Askari, H.; Hamzelou, S.; Farzaneh, M. and Ghassempur, A. (2013). Effect of silver nanoparticles on Oryza sativa L. and its rhizosphere bacteria. *Ecotoxico. Environ. Safety.* **88**: 48-54. <https://doi.org/10.1016/j.ecoenv.2012.10.018>
27. Moisala, A., Nasibulin, A.G., Kauppinen, E.I., (2003). The role of metal nanoparticles in the catalytic production of single-walled carbon nanotubes—a review. J. *Phys.: Condens. Matter* **15**: 03-11.
28. Nair, P. M. G. and Chung, I. M. (2017). Regulation of morphological, molecular and nutrient status in *Arabidopsis thaliana* seedlings in response to ZnO nanoparticles and Zn ion exposure. *Sci. Total Environ*. **575:** 187–198. doi: 10. 1016/j.scitotenv.2016.10.017
29. Nair, R., Varghese, S.H., Nair, B.G., Maekawa, T., Yoshida, Y. and Kumar, D.S. (2010). Nanoparticulate material delivery to plants. *Plant Sci*. **179:** 154-163.
30. Nel, A., Xia, T., Madler, L. and Li, N., (2006). Toxic potential of materials at the nano level. *Sci*. **311**: 622-627.

## Noman, M.; Shahid, M.; Ahmed, T. and Hussain, S. (2020). Use of biogenic copper nanoparticles synthesized from a native Escherichia sp. as photocatalysts for azo dye degradation and treatment of textile effluents. [*Environ. Pol.*](https://www.sciencedirect.com/journal/environmental-pollution)257:113-514

1. Ostermann, R., Cravillon, J., Weidmann, C., Wiebcke, M., and Smarsly, B. M. (2011). Metal–organic framework nanofibers via electrospinning. *Chem. Commun.* **47**: 442–444.
2. Peralta-Videa, J.R., Hernandez-Viezcas, J.A., Zhao, L., Diaz, B.C. and Ge, Y.(2014). Cerium dioxide and zinc oxide nano particles alter the nutritional value of soil cultivated soybean plants. *Plant Physiol. Biochem.* **80**: 128-135.
3. Pimpin, A. Suzuki, Y. and Kasagi, N. (2012). “Microelectrostrictive actuator with large out-of-plane deformation for flow-control application,” *J. Microelectromech. Syst.* **16**: 753–764,
4. Rahmatizadeh, R.; Arvin, S.M.J.; Jamei, R. and Mozaffari, H. (2019). Response of tomato plants to interaction effects of magnetic (Fe3O4) nanoparticles and cadmium stress. *J. Pl. Inter.* **14***:* 474-481
5. Rasheed, A.; Li, H.; Tahir, M.M.; [Mahmood](https://loop.frontiersin.org/people/369951), A.; Aslam, M.T.; Shah, A.N. and Hassam, M.U. (2022). The role of nanoparticles in plant biochemical, physiological, and molecular responses under drought stress: A review. *Front. Plant Sci.* DOI 0.3389/fpls.2022.976179

# Rizwan, M.; Ali, S.; Rehman, M.Z.; Arshad, M.; Ali, L. and Imran, M. (2019). Alleviation of cadmium accumulation in maize (Zea maysL.) by foliar spray of zinc oxide nanoparticles and biochar to contaminated soil. *Environ. Pol.* 248: 358-367.

1. Roco, M.C. (2003). Nanotechnology: convergence with modern biology and medicine. *Curr*. *Opin*. *Biotechnol*. **14**(3):337-346 doi: 10.1016/s0958-1669(03)00068-5
2. Saha, N. and Dutta Gupta, S. (2017). Low-dose toxicity of biogenic silver nanoparticles fabricated by *Swertia chirata* on root tips and flower buds of *Allium cepa*. *J. Hazard. Mater*. **330**: 18–28. doi: 10.1016/j.jhazmat.2017.01.021
3. Sedghi, M.; Hadi, M. and Toluie, S.G (2013) Effect of nano zinc oxide on the germination parameters of soybean seeds under drought stress. *Ann. West Uni. Timisoara Ser. Biol.* **16**:73
4. Sharma, V.K., R.A. Yngard, Lin, Y. (2009). Silver nanoparticles: green synthesis and their antimicrobial activities, *Adv. Colloid Interface Sci.* **145:** 83–96, <https://doi.org/10.1016/j.cis.2008.09.002>.

## Shahzad, B., Tanveer, M., Che, Z., Rehman, A., Cheema, S.A., Sharma, A. (2018). Role of 24-epibrassinolide (EBL) in mediating heavy metal and pesticide induced oxidative stress in plants: *a review. Ecotoxicol. Environ. Saf.* 147: 935-944.

## Shi, X.; Li, Z.; Chen, W.; Qiang, L.; Xia, J. and Chen, M. (2016). Fate of TiO2 nanoparticles entering sewage treatment plants and bioaccumulation in fish in the receiving streams. [*Nano. Imp.*](https://www.sciencedirect.com/journal/nanoimpact)3:  96-103

1. Sigmund, W., Yuh, J., Park, H., Maneeratana, V., Pyrgiotakis, G. and Daga, A. (2006). Processing and structure relationships in electrospinning of ceramic fiber systems. *J. Am. Ceramic Soc.* **89:** 395–407.
2. Siddiqui, M.H., Al-Whaibi, Faisal, M. and Alsahli, A.A., (2014). Nano silicon dioxide mitigates the adverse effects of salt stress on *Cucurbita pepo* L. *Environ. Toxicol. Chem*. **33**: 2429 -2437.

# Singh, J. and Lee, B.K. (2016). Influence of nano-TiO2 particles on the bio-accumulation of Cd in soybean plants (Glycine max): A possible mechanism for the removal of Cd from the contaminated soil. *J. Environ. Manage.* 170: 88-96 <https://doi.org/10.1016/j.jenvman.2016.01.015>

# Sousa, A.D.; Saleh, A.M.; Habeeb, T.H.; Hassan, Y.M.; Zrieq, R. and Wadaan, A.M.A. (2019). Silicon dioxide nanoparticles ameliorate the phytotoxic hazards of aluminum in maize grown on acidic soil. *Sci. Total. Environ*. 693: 133-636

1. Su, H.; Jing, K.; Shi, C. and Yao, H. (2018). Synthesis of large surface area FeO3 nanoparticles by SBA-16 template method as high active visible photocatalysts, *J. Nanoparticle Res*. **12**: 967–974, https://doi.org/10.1007/s11051-009- 9647-5.
2. Szabo, I.; Soptei, B.; Naszalyi, L.; Baranyai, P.; Mezo , G.; Hudecz, F. and Bota, A. (2013). On the Selection and Design of Proteins and Peptide Derivatives for the Production of Photo-luminescent, Red-Emitting Gold Quantum Clusters. *Gold Bull.* **46**: 195−203.
3. Taran, N.; Storozhenko, V.; Batsmanova, L. and Kovalenko, M. (2017). Effect of Zinc and Copper Nanoparticles on Drought Resistance of Wheat Seedlings. *Nano. Res. Let.* **12**:60. DOI 10.1186/s11671-017-1839-9

# Thabet, M.; Mohamoud, M,; Ibrahim, I.; Lateef, M.A. and Wang, R. (2024). Adsorption and photo-catalytic degradation activities of a hybrid magnetic mesoporous composite of α-Fe2O3 nanoparticles embedded with sheets-like MgO. J. Wat. Pro. Eng. 60: 105-192 <https://doi.org/10.1016/j.jwpe.2024.105192>

1. Tolochko, N.K., (2000). Nanoscience and Nanotechnologies . History Of Nanotechnology. *Encyclo. Life Sup. Sys.* **6**: 141-152.
2. Tripathi, D. K., Singh, S., Singh, S., Srivastava, P. K., Singh, V. P. and Singh, S., (2017). Nitric oxide alleviates silver nanoparticles (AgNps)-induced phytotoxicity in *Pisum sativum* seedlings. *Pl. Physiol. Biochem.* **110**: 167–177. doi: 10.1016/j.plaphy.2016.06.015
3. Van Breusegem, F. and Dat, J. F. (2006). Reactive oxygen species in plant cell death. *Pl. Physiol*. **141**: 384–390. doi: 10.1104/pp.106.078295
4. Xu, L., Dan, M., Shao, A., Cheng, X., Zhang, C. and Yokel, R.A.(2020). Silver nanoparticles induce tight junction disruption and astrocyte neurotoxicity in a rat blood brain barrier primary triple co-culture model. *Int J Nanomed.* **10**: 6105–6119.
5. Wang, X., Yang, X., Chen, S., Li, Q., Wang and Hou, C. (2016). Zinc oxide nanoparticles affect biomass accumulation and photosynthesis in Arabidopsis. *Front. Pl. Sci*. **6**: 1243.
6. Wei, H. and Wang, E., (2013). Nanomaterials with enzyme-like characteristics (nanozymes): next-generation artificial enzymes. *Chem. Soc. Rev*. **42**: 6060-6093.
7. Wender, H.; Migowski, P.; Feil, A.F.; Teixeira, S.R.; and Dupont, J. (2013). Sputtering deposition of nanoparticles onto liquid substrates: Recent advances and future trends. [*Cord. Chem. Review*](https://www.sciencedirect.com/journal/coordination-chemistry-reviews)*.* **257**:  2468-2483. <https://doi.org/10.1016/j.ccr.2013.01.013>
8. Williams, D.B. and C. B. Carter., (2009). Transmission Electron Microscopy, Springer US, Boston, MA
9. Wong, M. H., Misra, R. P., Giraldo, J. P., Kwak, S. Y., Son, Y. and Landry, M. P.(2016). Lipid exchange envelope penetration (LEEP) of nanoparticles for plant engineering: a universal localization mechanism. *Nano Lett.* **16:** 1161–1172. doi: 10.1021/acs.nanolett.5b04467
10. Worms, I.A.M., Boltzman, J., Garcia, M., Slaveykova, V.I., (2012). Cell wall-dependent effect of carboxyl-CdSe/ZnS quantum dots on lead and copper availability to green microalgae. *Environ. Pollut*. **167**: 27-33

# Wu, H. and Li, Z. (2022). Nano-enabled agriculture: How do nanoparticles cross barriers in plants?. *Pl. Com.* 3: 100-116.

1. Yadav, S.; Modi, P.; Dave, A.; Vijapura, A.; Patel, D. and Patel, M. (2020). Effect of Abiotic Stress on Crops. In Sustainable Crop Production; *Hasanuzzaman,* *M*., *Fujita*, *M*., *Teixeira Filho*, *M.C.M., Nogueira*, *T.A.R., Galindo, F.S*., *Eds.; Intech Open*: London, UK.
2. Yin, B.; Gates, and Xia, Y. Adv. Mater. (2000). **12**: 1426–1430.
3. Zhang, J.Z. (2009). Optical Properties of Metal Oxide Nanomaterials, Opt. Prop. *Spectrosc. Nanomater*. *World Sci.* 181–203, , https://doi.org/10.1142/ 9789812836663\_0006.
4. Zhang, Y., Liu, N., Wang, W., Sun, J., and Zhu, L. (2024). Photosynthesis and related metabolic mechanism of promoted rice (Oryza sativa l.) growth by TiO2 nanoparticles*. Front. Environ. Sci. Engin.* **14**: 1–12. doi: 10.1007/s11783-020-1282-5
5. Zhou, W. and H. F. Greer, (2016). Electron diffraction and HRTEM imaging of beam-sensitive materials. *Eur. J.* *Inorg. Chem*. 941.

# Zhou, P.; Adeel, M.; Shakoor, M.; Guo, M. and Hao, Y. (2021). Application of Nanoparticles Alleviates Heavy Metals Stress and Promotes Plant Growth: An Overview. *Nanomater.* 11:26.