



Potential of Nano-particles in Mitigating Abiotic Stress in Crops

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Climate change, triggered by anthropogenic activities and other inexorable factors, has led to a surge in abiotic stresses, compromising agricultural productivity and exacerbating environmental degradation (Shahzad et al., 2018). Empirical evidence suggests that abiotic stresses significantly impair crop yields, underscoring the need for innovative solutions (Khan et al., 2018). Recent advances in plant sciences have elucidated the complex mechanisms underlying abiotic stress-induced damage to crop plants. Conversely, breakthroughs in plant physiology, genetics, and applied biology have paved the way for the development of stress-tolerant crop varieties. Furthermore, the nascent field of nanotechnology has emerged as a promising tool for enhancing plant resilience to abiotic stresses through the strategic application of nanoparticles (NPs) (Moisala et al., 2003). Studies have demonstrated that NPs can positively impact plant performance under stress conditions (Yadav et al., 2020). Moreover, the use of nano-scale agrochemicals, including nano-formulated pesticides, herbicides, and fertilizers, has garnered significant attention as a potential means of augmenting plant growth and productivity (Abdel Latef et al., 2017).

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1. INTRODUCTION

Nanoparticles, measuring 1-100nm in diameter (Roco, 2003), exhibit distinct physio-chemical properties due to their minuscule size. These properties include enhanced reactivity, expansive surface area, adaptable pore size, and diverse morphology (Nel et al., 2006). The term "nano" originates from the Greek word for "extremely small" or "dwarf." Presently, nanoparticles have the potential to augment plant growth and development, serving as herbicides, nano-pesticides, and nano-fertilizers that can precisely release their content to target cellular organelles in plants. The agricultural sector can greatly benefit from nanotechnology, with nanoparticles' roles and mechanisms in plant growth and development still being explored (Manzer et al., 2015). To boost crop production and yield while minimizing nutrient losses, innovative approaches leveraging nanotechnology and nanoparticles are necessary. Conventional chemical fertilizers often remain unutilized by plants, accumulating in the soil and increasing toxicity; nano-fertilizers can mitigate this issue (DeRosa et al., 2010; Nair et al., 2010). Plants are immobile and cannot escape environmental stressors such as salinity, drought, chilling, heat, heavy metals, waterlogging, and UV radiation. These stresses trigger the production of reactive oxygen species (ROS), causing oxidative burst and damaging macromolecules and membrane lipids (Foyer and Noctor, 2000). ROS toxicity can impede plant growth (Khan et al., 2016). In response to heavy metal stress, plants accumulate polyphosphates, metal-chelates, and organic acids to sequester toxic metals in the plasma membrane. Nanoparticles play a crucial role in plant growth and development, protecting plants against abiotic stress conditions (Khan et al., 2017). Nanoparticles mimic antioxidant enzymes, scavenging ROS (Wei and Wang, 2013). Their small size and large surface area enable binding to toxic metals, reducing their accessibility and toxicity (Worms et al., 2012). During abiotic stress, nanoparticles can enhance photosynthesis by mitigating oxidative and osmotic stress and safeguarding the photosynthetic system (Siddiqui et al., 2014). However, plant responses to nanoparticles vary depending on plant species, nanoparticle type, and concentration. While nanoparticles exhibit beneficial effects, some can induce toxicity symptoms (Begum and Fugetsu, 2012). Exposure to certain nanoparticles can trigger

oxidative stress, reducing germination rates, root and shoot length, and crop yields (Wang et al., 2016), as well as affecting nutritive value (Peralta-Videa et al., 2014). Nanoparticles can also alter gene expression involved in cell biosynthesis, organization, electron transport, and energy pathways during biotic and abiotic stress responses (Aken, 2015). Nanotechnology has immense potential for agriculture, particularly in mitigating climate change and enhancing abiotic stress management (Mahakham et al., 2017). The application of nanobiotechnology, which utilizes nanoparticles to counter abiotic stress, is an emerging field (Banerjee et al., 2016; Cheng et al., 2016). Researchers have developed the concept of green nanoparticles, which can be produced economically using plants (Sharma et al., 2009; Iravani et al., 2011). The effectiveness and potential of plant-derived nanoparticles in protecting crop plants against stresses and enhancing crop production are being explored.

2. 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).

3. SYNTHESIS OF NANO-PARTICLES:

For the synthesis of nano-materials the approaches are:

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

3.1 Top-Down Approaches

Top-down fabrication techniques involve the reduction of bulk materials into nanostructured entities. This approach encompasses various methods, including mechanical fragmentation, laser-induced breakdown, selective removal of material through etching, and the ejection of particles via sputtering or electro-explosive processes. These techniques enable the precision engineering of materials at the nanoscale, opening up new avenues for the development of nanostructured materials with tailored properties.

3.1.1 Mechanical milling

Mechanical milling offers a economically viable approach for downsizing bulk materials to the nanoscale. This technique is particularly adept at generating multiphase blends, thereby facilitating the production of nanocomposite materials. By leveraging mechanical milling, researchers can effectively synthesize complex materials with tailored properties, making it an attractive method for various industrial and technological applications.

3.1.2 Electro-spinning

Electro-spinning is a straightforward top-down approach for fabricating nanostructured materials. This technique is commonly employed to produce nano-fibers from a diverse range of materials, predominantly polymers (Ostermann et al., 2011). A significant advancement in electro-spinning is the development of coaxial electro-spinning. This method utilizes a spinneret with two concentric capillaries, enabling the simultaneous use of two viscous liquids or a viscous liquid and a non-viscous liquid to create core-shell nanostructures within an electric field. This technique has been successfully applied to fabricate core-shell and hollow nano-architectures comprising polymer, inorganic, organic, and hybrid materials (Kumar et al., 2014).

3.1.3 Lithography

Lithography is a versatile technique for crafting nano-architectures, leveraging a focused beam of light or electrons to achieve high-resolution patterns. This method can be broadly categorized into two distinct types: masked lithography and maskless lithography (Pimpin et al., 2012). Masked nanolithography involves the transfer of nano-patterns onto a large surface area using a specifically designed mask or template. This category encompasses various techniques, including photolithography (Szabo et al., 2013), nanoimprint lithography (Kuo et al., 2003), and soft lithography (Yin et al., 2000). These approaches enable the precise fabrication of nanostructures, paving the way for innovative applications in fields like nanotechnology and materials science.

3.1.4 Sputtering

Sputtering is a fabrication technique that involves bombarding a solid target with high-energy

species, such as ions or atoms, to eject and deposit material onto a substrate. This process enables the creation of nanostructured materials, including thin films, with tailored properties. The sputtering method is particularly advantageous for producing uniform, high-quality thin films, making it a valuable tool in the development of nano-materials for various applications.

3.1.5 Laser ablation

Laser ablation synthesis is a technique that harnesses the energy of a high-powered laser beam to generate nanoparticles from a target material (Zhang et al., 2017). The process involves the vaporization of the source material or precursor due to the intense laser irradiation, leading to the formation of nanoparticles. Notably, laser ablation offers a green approach for producing noble metal nanoparticles, as it eliminates the need for stabilizing agents or other chemicals, thereby reducing the environmental footprint (Amendola et al., 2009, Su et al., 2018). This method provides a clean and efficient route for synthesizing nanoparticles with tailored properties.

3.2 Bottom-Up Approaches

3.2.1 Chemical Vapour Deposition (CVD)

Chemical vapor deposition (CVD) techniques play a pivotal role in the synthesis of carbon-based nano-materials. This process involves the formation of a thin film on a substrate surface through the chemical reaction of vapor-phase precursors (Jones et al., 2008). To be suitable for CVD, a precursor must exhibit a combination of desirable properties, including sufficient volatility, high chemical purity, stability during evaporation, affordability, non-toxicity, and a long shelf-life (Machac et al., 2020). The careful selection of precursors is crucial for achieving high-quality CVD-grown nano-materials with tailored properties.

3.2.2 The sol-gel methods

The sol-gel process is a versatile wet chemical technique that has gained widespread acceptance for the fabrication of nano-materials. This method has proven particularly effective for the synthesis of high-purity metal-oxide-based nano-materials, offering unparalleled control over their composition, structure, and properties (Danks et al., 2016). The sol-gel approach has emerged as a powerful tool for crafting a wide

range of nano-materials with tailored characteristics.

3.2.3 Green/biological synthesis

The fabrication of metal nanoparticles using eco-friendly biological agents, such as plant extracts, microbial cultures, and various organic waste materials, including fruit and vegetable residues, eggshells, agricultural byproducts, and algal biomass, is collectively referred to as "green" or "biogenic" nanoparticle synthesis (Kumari et al., 2022). This sustainable approach leverages nature's resources to produce nanoparticles with unique properties, offering a promising alternative to traditional chemical synthesis methods.

4. CHARACTERIZATION OF NANO-PARTICLES

4.1 Transmission Electron Microscopy (TEM)

Transmission electron microscopy (TEM) is a powerful characterization technique that utilizes a focused electron beam to produce high-resolution images of nanoscale materials. By examining thin samples (typically <200 nm) with a TEM, researchers can obtain detailed micrographs that reveal the intricate structures of nanoparticles (Williams and Carter, 2009). Modern electron microscopes have achieved remarkable resolutions, ranging from 0.05 to 0.1 nm, thanks to advanced aberration correctors that minimize image distortion (Keefe and Horn, 2004; Dahmeen et al., 2009). Furthermore, TEM enables the examination of crystalline structures at the microscopic level by confining and focusing the electron beam, allowing researchers to detect electron diffraction patterns and gain insights into the atomic arrangements of crystalline materials (Zhou and Greer, 2016).

4.2 Scanning Electron Microscopy (SEM)

The scanning electron microscope (SEM) facilitates the visualization of sample surfaces by capturing secondary electrons that are emitted as a result of interactions between the sample and the incident electron beam (Goldstein et al., 2018). This technique provides high-resolution images of surface topography, allowing researchers to examine the morphology and microstructure of various materials.

4.3 Dynamic Light Scattering (DLS)

Dynamic light scattering (DLS) is a technique that assesses particle size by analyzing the Brownian motion-induced fluctuations in scattered light intensity. When a laser beam passes through a suspension of particles in a measurement cell, the thermal motion of the particles creates random variations in the scattered light intensity over time. The DLS method estimates particle size by determining the translational diffusion coefficient of the suspended particles, which is a measure of their rate of diffusion (Pecora et al., 2000). This approach provides valuable insights into the size distribution and dynamics of particles in solution.

4.4 Mass Spectrometry

Initially, mass spectrometry was employed to characterize the composition of nanoparticles by determining the stoichiometry of their constituent building blocks following digestion and dissolution. However, the advent of soft ionization techniques, such as electrospray ionization (ESI) and matrix-assisted laser desorption/ionization (MALDI), has enabled the analysis of intact nanoparticles and large biomolecules. Advanced mass spectrometry techniques, including ion mobility spectrometry (IMS), time-of-flight (TOF) analysis, and single-particle inductively coupled plasma mass spectrometry (ICP-MS), have further expanded the capabilities of this analytical tool, allowing for the separation and detection of mega-Dalton-range species (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 sp^2 hybridized (Astefanei et al., 2015).

5.2 Metal NPs

Nanoparticles exhibit unique electrical properties, largely attributed to their localized surface

plasmon resonance (LSPR) characteristics. Specifically, nanoparticles composed of copper, silver, and gold display a pronounced absorption band within the visible spectrum of the solar electromagnetic radiation, a phenomenon that has been extensively documented (Khan et al., 2019). This distinctive optical property renders these nanoparticles highly sensitive to their surrounding environment, making them attractive candidates for various applications.

5.3 Ceramics NPs

Ceramic nanoparticles are ultrafine particles composed of inorganic, non-metallic materials that undergo a controlled thermal treatment and cooling process to impart specific properties. These nanoparticles have found widespread applications in various fields, including coatings, catalysis, and energy storage devices such as batteries, where they exhibit enhanced performance and functionality (Sigmund et al., 2006).

5.4 Lipid-Based NPs

The incorporation of lipid components into these nanoparticles renders them particularly useful in various biological applications, where their unique properties can be leveraged to achieve specific outcomes (Khan et al., 2019).

5.5 Semiconductor NPs

Semiconductor nanoparticles exhibit a unique combination of properties, bridging the gap between metals and non-metals. Their distinctive physical and chemical characteristics make them highly versatile, enabling applications in the development of compact and high-speed electronic devices, such as transistors. Furthermore, these nanoparticles have shown promise in biomedical applications, including bioimaging and cancer therapy, where their unique properties can be harnessed to achieve targeted and efficient treatment outcomes (Biju et al., 2008).

5.6 Polymeric NPs

Polymeric nanoparticles, ranging in size from 1 to 1,000 nanometers, can be engineered to incorporate active substances through surface adsorption onto the polymeric core or entrapment within the polymeric matrix. These nanoparticles are typically organic in nature and are commonly referred to as polymer nanoparticles (PNPs),

offering a versatile platform for various applications (Khan et al., 2019).

6. MECHANISM OF UPTAKE, TRANSPORT AND TRANSLOCATION OF NANOPARTICLES IN PLANTS

The interaction between nanoparticles (NPs) and plants is a complex phenomenon that can have both beneficial and detrimental effects, depending on factors such as dosage, movement, characteristics, and reactivity (Mirzajani et al., 2013). NPs can enter plant tissues through various routes, including the root system, above-ground parts, and wounds. To be taken up by plants, NPs must overcome multiple physiological barriers (Dietz and Herth, 2011). Some NPs have been shown to create larger pores in the cell wall, facilitating their entry into cells (Kurepa et al., 2010). Once inside, NPs can be transported to other plant tissues via the apoplastic and symplastic pathways (Ma et al., 2010). A lipid exchange mechanism has also been proposed for NP transport into plant cells (Wong et al., 2016).

The interaction between NPs and plants can influence plant metabolism in various ways, including the delivery of micronutrients (Liu and Lal, 2015), gene regulation (Nair and Chung, 2014), and interference with oxidative processes (Hossain et al., 2015; Foyer and Noctor, 2005; Van Breusegem and Dat, 2006). However, several studies have reported adverse effects of NP-plant interactions, including increased lipid peroxidation and DNA damage (Saha and Dutta, 2017). Elevated levels of reactive oxygen species (ROS) can lead to apoptosis or necrosis, resulting in plant cell death (Faisal et al., 2013). Nevertheless, ROS also play a role in stress tolerance and biological activities (Sharma et al., 2012). The balance between ROS generation and scavenging determines whether ROS have a destructive or signaling function (Sharma et al., 2012). In response to NP exposure, plants have been shown to produce more antioxidant molecules (Costa and Sharma, 2016). However, high concentrations of NPs can negatively impact photosynthesis, leading to growth retardation or death in plants (Tripathi et al., 2017).

7. APPLICATIONS OF NPS IN AGRICULTURE INDUSTRY

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

7.1 Pesticides and Herbicides

The strategic application of nanoparticles (NPs) offers a promising solution for the controlled delivery of pesticides and herbicides, thereby reducing the risk of environmental pollution and promoting more sustainable agricultural practices (Khan et al., 2019).

7.2 Fertilizers and Plant Growth

Nano-fertilizers present a promising approach to enhancing plant mineral nutrition, with research indicating that nano-materials can outperform traditional fertilizers by providing a controlled release of nutrients. This targeted delivery mechanism can optimize plant uptake efficiency while minimizing the potential for environmental degradation (Khan et al., 2019). Furthermore, the use of nanoparticles as fertilizer carriers has been shown to promote more efficient nutrient delivery, reducing the required amount of fertilizer and the associated risk of nutrient runoff into the environment (Kopittke et al., 2019).

8. 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 a significant abiotic stress that can severely impact crop yields (Al-Ashkar et al., 2021). However, research has shown that certain nanoparticles can mitigate the effects of drought stress on plants. For instance, zinc oxide nanoparticles (ZnO NPs) have been found to enhance the germination percentage of soybean seeds under arid conditions (Sedghi et al., 2013). Similarly, copper and zinc nanoparticles (Cu and Zn NPs) have been shown to increase antioxidant enzyme activity and relative moisture content in wheat, while reducing the negative effects of drought stress (Taran et al., 2017). Additionally, titanium dioxide nanoparticles (TiO₂ NPs) have been found to be effective in overcoming yield reduction caused by drought stress in wheat when applied as a foliar spray (Jaberzadeh et al., 2013). Silicon dioxide nanoparticles (SiO₂ NPs) have also been reported to reduce the negative impacts of drought stress on hawthorn plants (Ashkavand et al., 2015). Furthermore, silicon nanoparticles (Si NPs) have been shown to ameliorate the effects of drought stress in bananas (Khan et al., 2016) and chickpea plants, by increasing the relative moisture content and reducing the negative effects of drought (Rasheed et al., 2020).

9.2 Salinity Stress

Research has demonstrated that nanoparticles (NPs) can play a crucial role in enhancing plant tolerance to salt stress. For instance, silver nanoparticles (Ag NPs) have been shown to significantly improve salt resistance in cumin plants (Ekhtiyari and Moraghebi, 2012). Similarly, silicon dioxide nanoparticles (SiO₂ NPs) have been found to enhance developmental

parameters, chlorophyll content, and antioxidant enzyme activities in tomato and squash plants under salinity stress (Siddiqui et al., 2014). Pre-treatment of wheat seeds with Ag NPs has also been shown to alter antioxidant enzyme activities, reduce oxidative damage, and elevate salt-stress tolerance (Kashyap et al., 2015). Furthermore, the use of NPs in wheat has been found to enhance plant development and improve germination under salt-stress conditions (Shi et al., 2016). Iron oxide nanoparticles (Fe₃O₄ NPs) have also been shown to protect mint plants from oxidative stress caused by increased NaCl content. Additionally, Ag NPs have been found to improve germination percentage, shoot and root length, and enhance osmotic regulation in *Lathyrus sativus* under salt stress (Khan et al., 2019). Copper nanoparticles (Cu NPs) applied to the soil have also been shown to reduce oxidative stress in wheat and significantly increase plant development and yield (Noman et al., 2020).

9.3 Heavy Metal Stress

The application of silicon nanoparticles (Si NPs) to maize plants under arsenic stress has been shown to mitigate the adverse effects of arsenic on photosynthetic parameters, including maximum quantum efficiency and photochemical quenching (Tripathi et al., 2017). Additionally, Si NPs reduced the negative impact of arsenic on chlorophyll, carotenoid, and protein content. Titanium dioxide nanoparticles (TiO₂ NPs) have also been found to limit cadmium toxicity in soybean plants by enhancing physiological parameters and photosynthetic rate (Singh and Lee, 2016). Furthermore, Si NPs have been shown to reduce aluminum toxicity in maize plants by activating the antioxidant defense mechanism (de Sousa et al., 2019). The combined application of zinc oxide nanoparticles (ZnO NPs) and biochar has been found to be more effective in mitigating cadmium stress in plants (Rizwan et al., 2019). Iron oxide nanoparticles (Fe₃O₄ NPs) have also been shown to reduce cadmium accumulation and toxicity in tomato plants by increasing nutrient uptake (Rahmati zadeh et al., 2019). The application of nanoparticles in soil has been found to regulate the expression of heavy metal transfer genes, increase antioxidant activity, improve physiological functions, and stimulate the production of protective substances in plants under heavy metal stress conditions (Zhou et al., 2021).

10. CONCLUSION

Nanoparticles mitigate abiotic stress-induced damage by activating plant defense mechanisms. Their diminutive size enables effortless penetration and regulation of ion channels, facilitating seed germination and plant growth. The large surface area of nanoparticles further enhances molecular absorption and targeted delivery (Khan et al., 2019). Moreover, nanoparticles can initiate signaling cascades by triggering the release of signaling substances in the cytosol, which are recognized by nanoparticle-specific proteins. This, in turn, promotes gene expression, culminating in enhanced stress resistance.

11. FUTURE ASPECTS AND CHALLENGES

Nano-biotechnology holds promise for enhancing plant stress tolerance, detection, and targeted delivery of agrochemicals (Wu and Li, 2022). Future research should prioritize investigating the biological effects of nano-enzymes, such as Mn₃O₄ NPs, on plant stress responses. Elucidating the mechanisms by which nanoparticles improve plant stress tolerance will enable the design of bespoke nano-materials to address pressing agricultural challenges.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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