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# Harnessing nanotechnology to mitigate abiotic stress and enhance sustainable crop production

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Plants face various abiotic stresses, such as heat, cold, drought, salinity, flooding, and heavy metals. These stresses negatively impact plant growth and development, which affects agricultural productivity and can lead to food security issues, ultimately causing economic losses. Incorporating nanotechnology into modern agriculture can help improve water use efficiency, prevent plant diseases, ensure food security, reduce environmental pollution, and promote sustainability. Nanoparticles can enhance stress tolerance and boost crop yield and quality by stimulating enzyme activity, increasing photosynthetic efficiency, and controlling plant pathogens. The use of nano-agrochemicals, such as nano-pesticides, nano-herbicides, and nano-fertilizers, has grown recently as a promising technology for supporting plant growth. Nanomaterials offer many benefits for sustainable crop production, including reducing nutrient loss, suppressing diseases, and increasing yields.

***Keywords:*** *abiotic stress, nanoparticles, nano fertilizers, crop improvement*

## Introduction

Abiotic stresses such as heavy metals, drought, salinity, and waterlogging are major factors that negatively impact plant growth and crop yields. Climate change, caused by global warming, human activities, and other unavoidable factors, leads to increased abiotic stresses, which reduce agricultural productivity and harm natural resources (Ashok et al., 2018). When plants encounter such stresses, they activate mechanisms that often change their morphological, physiological, and biochemical processes (Senthil et al., 2018). Nanotechnology has become a promising tool in agriculture, helping to reduce the effects of climate change, improve nutrient use efficiency, and manage abiotic stress. The increasing demand for agriculture to accelerate production with maximum output while minimizing inputs. Modern agricultural techniques need to be adopted as conventional methods fail to meet the food demands of the growing global population, which faces challenges like climate change, resource depletion, and shrinking landscapes. It has enough potential to transform the agricultural system and boost food production efficiently and cost-effectively. Nanotechnology offers great potential to increase crop production and productivity on limited land by managing input application through smart delivery systems, nan sensors, nanoscale coatings, and other nanomaterials. This technology is progressing rapidly, and its applications will profoundly energize the agricultural sector in the coming years, leading to a second green revolution. Nanoparticles (NPs), used as nano-fertilizers, have attracted attention because of their large surface area, eco-friendly nature, low cost, unique physicochemical traits, and ability to boost plant productivity (Fatima et al., 2021). Numerous studies have shown that using nanoparticles as nano-fertilizers for targeted micronutrient delivery is efficient, affordable, environmentally friendly, and a practical alternative to chemical fertilizers (Irshad et al., 2021; Shah et al., 2021).

## Nanoparticle-Mediated Crop Enhancement: Uptake, Transport, and Role in Stress Alleviation

Nanoparticles (NPs) have specific physical and chemical properties that allow them to cross cell membranes and interact with living organisms. Their ability to overcome these barriers has led to applications not only in medicine, electronics, and chemical and physical sciences but also in agriculture. In agriculture, nanotechnology can enhance growth and crop yield through various nanoscale products, including nano-fertilizers, nano-herbicides, nano-fungicides, and nano-pesticides (Sharma et al., 2022). An optimal concentration of NPs can be applied using methods like seed, root, pollen, or cell incubation; foliar spraying; irrigation with NPs; direct injection; hydroponic treatment; or delivery via biolistics. Once NPs contact plant cells, they are absorbed through plasmodesmata or endocytosis and transported via apoplastic or symplastic pathways (Azim et al., 2023). When beneficial NPs reach different parts of the plant, they can improve photosynthesis, biomass, chlorophyll content, sugar levels, osmolyte buildup, and antioxidant production. NPs also enhance nitrogen metabolism, increase chlorophyll and protein levels, and upregulate genes related to abiotic and biotic stress (Tripathi et al., 2022).

## Role of Silicon Nanoparticles in Improving Plant Stress Tolerance

A nanoparticle of silicon (Si) is considered essential for plant growth and development, and it helps reduce the toxic effects caused by various environmental stresses in plants. Biogenic silica also acts as a deterrent to multiple plant pathogens, insects, and herbivores (Murali-Baskaran et al., 2021). The beneficial role of Si-nanoparticles (Si-NPs) is relatively underexplored and less characterized in plants. The green synthesis of Si-NPs can be achieved from plant sources and agricultural wastes, which can be applied through hydroponic solutions, soil supplementation, or foliar spraying. Subsequently, they are transported via symplastic or apoplastic pathways from one cell to another through plasmodesmata (Goswami et al., 2022). The mesoporous structure of Si-NPs, with its large surface area, makes them ideal carriers for pesticides and fertilizers, leading to the concepts of nano pesticides or nano fertilizers, their advantages over conventional options, and their potential to reduce damage caused by biotic and abiotic stresses in plants.

## Silver to Zinc: Investigating the Function of Metal Nanoparticles

Metal nanoparticles present promising opportunities in agriculture by boosting plant growth and supporting food security. Silver, gold, copper, and zinc nanoparticles have unique properties that make them suitable for plant-related applications. Understanding the molecular interactions between these nanoparticles and plants is crucial for harnessing their potential to enhance crop productivity and sustainability. Their potential to increase crop yields, improve stress tolerance, and enhance nutrient-use efficiency, all of which contribute to sustainable farming and food security. Quantifying the benefits and risks shows notable advantages: metal nanoparticles can increase crop productivity by about 20% on average and reduce disease incidence by up to 50% when used as antimicrobial agents (Cruz-Luna et al., 2021). They also decrease nutrient leaching by 30% and promote soil carbon storage by 15%. However, concerns about toxicity, negative effects on non-target organisms, and nanoparticle buildup in the food chain need to be addressed. Additionally, metal nanoparticles affect cellular processes such as sensing, signaling, transcription, translation, and post-translational modifications (Cameron et al., 2022).

## Nanoparticles in Salt-Stress Tolerance

Global-warming-driven water scarcity also forces irrigation with saline water on agricultural lands worldwide, which increases the salt content in the soil. Salinity defined as the buildup of excessive salt in the soil is one of the main challenges facing modern agriculture. It eventually stunts and impairs plant growth and development, leading to plant mortality. Most plants die when NaCl levels exceed 200 mM (Sezhiyan et al., 2023). Salinity significantly affects every stage of a plant's life cycle, including seed germination, seedling growth, vegetative development, and flowering. Many horticultural crops, such as fruits, vegetables, and spices, are affected by salinity. In addition to causing osmotic stress, water stress, oxidative stress, nutritional stress, and reducing cell division, salt stress disrupts ionic balance, impacting numerous biochemical, physiological, and metabolic processes. Biosynthesized Gold Nanoparticles Enhance Salt Stress Tolerance in Wheat by Modulating Nitrogen Metabolism and Defense Mechanisms (Wahid et al., 2022).

## Nanoparticles in Drought-Stress Tolerance

Drought is considered the most harmful environmental stress, reducing crop yield more than any other factor (Subiramaniyam et al., 2022; Sathyabharathi et al., 2022; Packirisamy et al., 2023). According to the Intergovernmental Panel on Climate Change (IPCC), the global temperature is expected to rise by 1.8 to 4.0 °C by 2100, and drought will impact large regions of the world. Drought affects agriculture when plants lack enough moisture to grow properly and complete their life cycles. The severity of drought worsens with ongoing declines in rainfall and increases in evapotranspiration demand. For example, drought stress hampers plant development because water is necessary for cell turgor, which is the pressure exerted by the contained liquid on the cell walls, causing cells to expand. The main effects of drought on crop plants include slower cell division and growth rates, smaller leaves, longer stems and roots, disrupted stomatal oscillations, and altered water and nutrient relationships, leading to lower crop yields and inefficient water use. Zinc Oxide Nanoparticle Foliar Treatment Mitigates Drought Effects in *Solanum melongena* L. (Semida et al., 2021).

### Nanoparticles in Heavy-Metal-Stress Tolerance

Heavy-metal (HM) stress is one of the harmful factors that reduce crop productivity today. Human activities, such as industrialization and urbanization, have caused HM pollution worldwide. The increased use of modern agricultural tools, like chemical pesticides and fertilizers, has also contributed to HM stress in crop plants. Heavy metals such as Hg, Pb, Cd, Ni, Co, Cr, and Ag have harmful effects on plants. Since plants form the base of trophic systems, the likelihood of bioaccumulation of these HMs through the food chain is high, which can lead to chronic health problems such as kidney and liver damage in humans and other animals. These issues negatively affect the quality and quantity of plant-based products, especially in agricultural crops and medicinal plants. Zinc Oxide Nanoparticles Enhance the Tolerance and Remediation Potential of Bacillus spp. against Heavy Metal Stress (Akhtar et al., 2021).

## Conclusion

Nanobiotechnology has the potential to enhance stress tolerance, stress sensing/detection, targeted delivery, and controlled release of agrochemicals, transgenic events, and seed nano priming in plants. Such nanomaterials, free of heavy metals and with high dispersibility, can be developed for agricultural applications. It is also important to investigate the mechanisms behind nano-priming-induced seed germination, breaking seed dormancy, and their interactions with seeds. Understanding how NPs improve plant stress tolerance will help researchers design custom nanomaterials to address agricultural challenges. Additionally, nanomaterials undoubtedly have a promising future, especially regarding their functions in plants. NPs application in the agricultural sector is increasing in popularity due to its regulation, spatial and temporal delivery of nutrients to plants, and its use as nano fertilizers and nano sensors. The application of various NPs, mainly silica, cerium oxide, zinc oxide, and iron oxide, has been widely reported for providing beneficial effects on plant growth and improving abiotic stress tolerance.

## Author contributions

Conceptualization – Ashok Subiramaniyan, Chandrasekaran Perumal, Ashokkumar Natarajan, Selvakumar Gurunathan. Writing (original draft) - Sangeetha Selvam, Shruthika Mohan. Writing (review & editing) - Sangeetha Selvam, Shruthika Mohan, Ashok Subiramaniyan, Chandrasekaran Perumal, Ashokkumar Natarajan, Selvakumar Gurunathan.

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