

## Exploring The Potential of ZnONPs As An Eco-Friendly Strategy For, Enhancing Plant Growth And Mitigating Environmental Stressors

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**Keywords:** Potential of ZnONPs, Enhancing Plant Growth And Mitigating Environmental Stressors

Received on 01 Mar 2026

Accepted on 21 Mar 2026

Published on 04 Apr 2026

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### Abstract

Zinc nanoparticles (ZnNPs) are developing as a viable tool in sustainable agriculture, providing eco-friendly options for increasing plant development and reducing environmental stress. Because of their distinct physicochemical features, ZnNPs can promote nutrient absorption, seed germination, and plant resistance to abiotic and biotic stressors. This study discusses current advances in ZnNPs production, their effects on plant development, stress-reduction mechanisms, and potential environmental implications. The use of ZnNPs manufactured using green technologies, such as medicinal plant extracts, provides a sustainable solution that reduces environmental risks.

## Introduction

Synthetic fertilizers and pesticides are frequently used in modern farming methods, which can degrade soil, pollute water and leave behind harmful residues. Nanotechnology has become an innovative area with potential uses in agriculture as a result of these difficulties. Because of its function in plant nutrition and stress tolerance, zinc nanoparticles (ZnNPs) stand out among other nanoparticles.

An important micronutrient, zinc (Zn) participates in the metabolism of many plants, including hormone control, protein synthesis, and enzyme activation. But in many agricultural soils, zinc deficiency is common, resulting in stunted development, decreased productivity, and heightened vulnerability to stress. Compared to traditional Zn fertilizers, ZnNPs provide a special answer because of their improved bioavailability and absorption efficiency due to their nanoscale size.

The potential of zinc nanoparticles (ZnNPs) to enhance plant development and alleviate environmental stressors such as salinity, drought and heavy metal toxicity is examined in this study. We also go over the environmental effects of ZnNPs and their environmentally friendly production.

## BIOSYNTHESIS OF ZINC NANOPARTICLES

### Green Synthesis of ZnNPs

Using plant extracts to create ZnNPs is becoming more popular as an eco-friendly alternative to traditional chemical or physical synthesis techniques. ZnNPs biosynthesis has been conducted using a variety of medicinal plants, such as *Ocimum sanctum*, *Azadirachta indica*, *Aloe vera*, and *Moringa oleifera*.

For instance, a research by (Agarwal *et al.*, 2017) showed that *Moringa oleifera* leaf extract could successfully synthesize ZnNPs. Flavonoids and phenolic acids, two phytochemicals included in the extract, functioned as both stabilizing and reducing agents, producing stable zinc nanoparticles with growth-promoting and antibacterial qualities.

Similarly, ZnNPs were synthesized utilizing *Azadirachta indica* (neem) extracted, according to (Buggana *et al.*, 2024). High stability and considerable promise for promoting plant development and inhibiting plant diseases were demonstrated by the resultant nanoparticles.

### Advantages of Green Synthesis

**Eco-friendly:** Less harmful chemicals and dangerous byproducts are needed.

**Economical:** Makes use of easily accessible plant components.

**Biocompatible:** Generates nanoparticles that are less likely to harm soil microorganisms and plants.

## EFFECTS OF ZnNPs ON PLANT GROWTH

### Improved Seed Germination and Seedling Growth

It has been demonstrated that ZnNPs improve early seedling development and seed germination rates. In comparison to bulk ZnSO<sub>4</sub>, (Rai-Kalal and Jajoo, 2021) discovered that adding ZnNPs to wheat (*Triticum aestivum*) seeds greatly enhanced germination rates and root elongation. ZnNPs' increased surface area improved Zn availability and uptake.

### Enhanced Nutrient Uptake

By promoting root growth and raising nutrient transporter function, ZnNPs can enhance nutrient intake. Applying ZnNPs to tomato (*Solanum lycopersicum*) plants enhanced their uptake of Zn as well as other vital nutrients including nitrogen (N) and phosphorus (P), according to (Ahmed *et al.*, 2023). As a result plant growth and yield enhanced.

### Increased Photosynthetic Efficiency

The synthesis of chlorophyll and the activity of photosynthetic enzymes depend on zinc. According to (Rizwan *et al.*, 2019), applying ZnNPs to maize (*Zea mays*) increased its chlorophyll content and photosynthetic efficiency. Higher biomass production was a result of the nanoparticles' increased expression of genes linked to photosynthetic processes.

### Enhanced Antioxidant Enzyme Activity

According to (Li *et al.*, 2023) the golden turnip genotype showed varying levels of antioxidant enzyme activity in the roots and turnips during drought stress. Under drought stress, we found that the turnips' levels of H<sub>2</sub>O<sub>2</sub> and MDA somewhat increased while their levels of ascorbic acid slightly decreased. When applied topically, 0.1% ZnNPs and ZnSO<sub>4</sub> dramatically increased the amount of ascorbic acid in drought-stressed turnip roots.

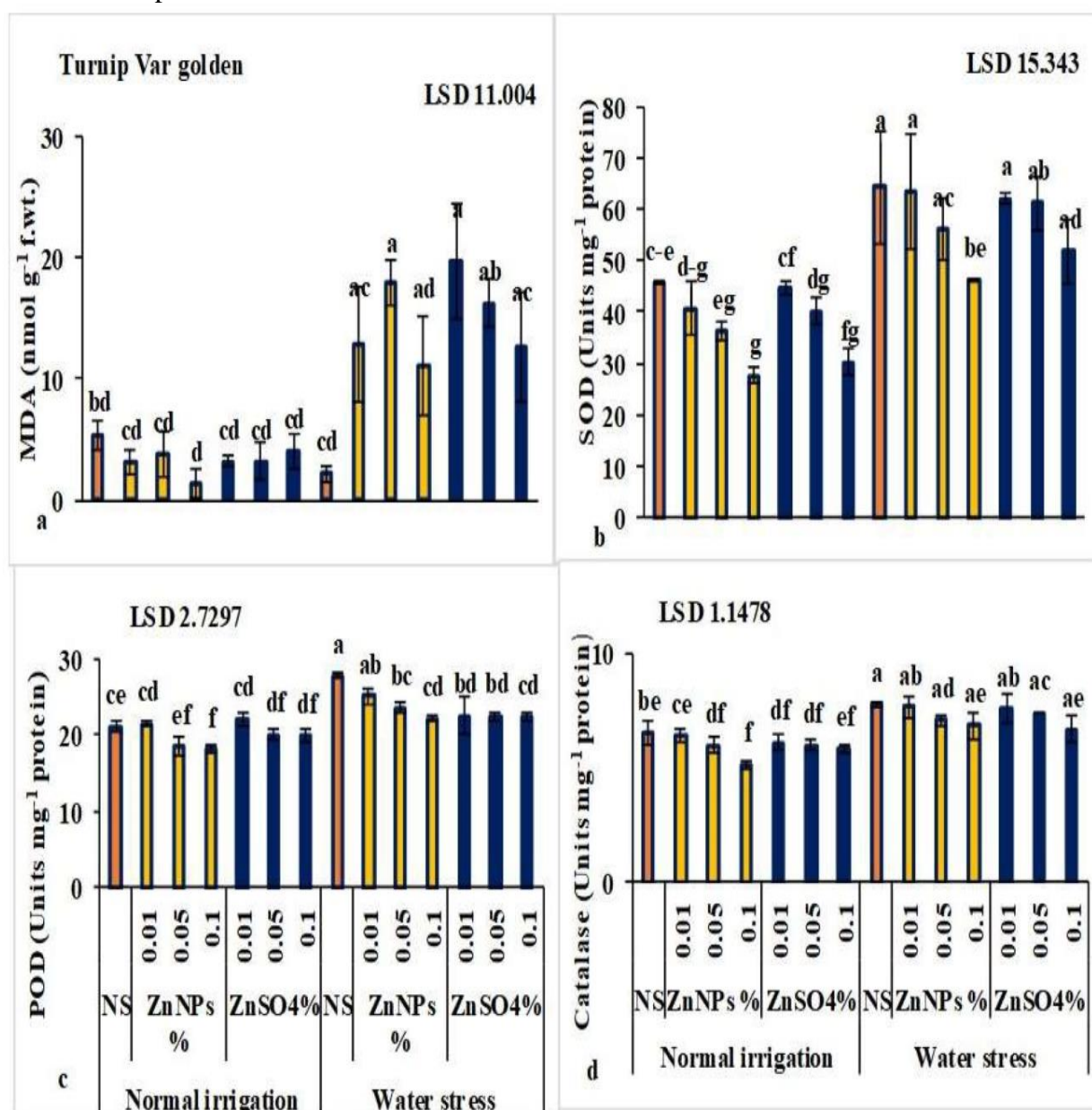


Figure 1: ZnNPs in stress mitigation (Li *et al.*, 2023)

### Drought Stress

One significant abiotic stressor influencing agricultural output is drought. ZnNPs can decrease oxidative damage brought on by drought stress and improve the efficiency of plant water usage. According to (Sedghi *et al.*, 2021), foliar ZnNPs spray increased leaf water content and decreased lipid peroxidation in drought-stricken soybean (*Glycine max*) plants, improving growth and production.

In turnip leaves under drought stress, the amounts of total phenolics, flavonoids, and ascorbic acid (AA) dramatically dropped, whereas the amounts of total soluble sugar (TSS), total soluble protein (TSP), and total free amino acid (TAA) stayed constant. When 0.1% ZnNPs were applied to drought-stressed turnip leaves, the levels of TSS, TSP, TAA and total phenolics increased (Li *et al.*, 2023).

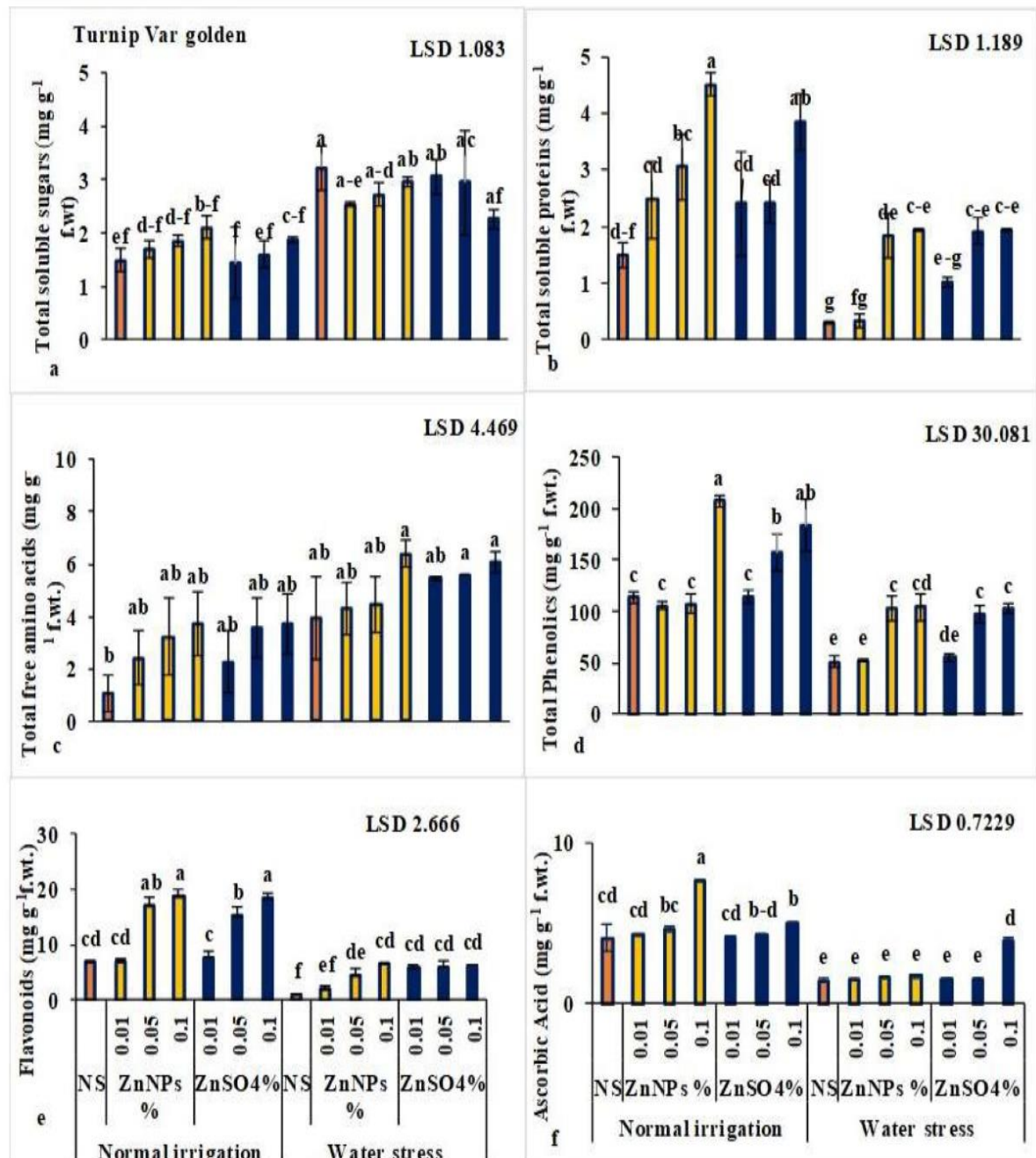


Figure 2: (Li *et al.*, 2023)

### Salinity Stress

Because of osmotic stress and ion toxicity, salinity inhibits plant growth. By decreasing Na absorption and increasing antioxidant enzyme activity, ZnNPs aid in the mitigation of salt stress. Applying ZnNPs to rice (*Oryza sativa*) plants in saline environments

enhanced root and shoot growth and reduced Na buildup, according to (Singh *et al.*, 2023).

### **Heavy Metal Toxicity**

The health of plants is seriously threatened by heavy metals like lead and cadmium. By chelating harmful ions and promoting the synthesis of stress-related proteins, zinc nanoparticles (ZnNPs) can reduce heavy metal stress. In mustard plants treated with ZnNPs, (Pishkar *et al.*, 2022) showed decreased cadmium absorption and enhanced growth.

## **MECHANISMS OF ZnNPs ACTION**

### **Enhanced Antioxidant Defense System**

ZnNPs increase plant stress tolerance by triggering antioxidant enzymes like peroxidase (POD), catalase (CAT) and superoxide dismutase (SOD). By neutralizing reactive oxygen species (ROS), these enzymes shield cells from harm (Fariha *et al.*, 2025).

### **Hormonal Regulation**

ZnNPs have an impact on the production and control of plant hormones, including abscisic acid (ABA), cytokinins, and auxins. ZnNPs promoted root and shoot growth by raising indole-3-acetic acid (IAA) levels in tomato plants, as shown by (Zaghdoud *et al.*, 2024).

### **Nutrient Content**

**In Leaves:** The nitrogen (N), phosphorus (P), potassium (K), sulfur (S), magnesium (Mg), boron (B), iron (Fe), and zinc (Zn) content of tomato leaves were all impacted by the foliar application of zinc nanoparticles and zinc oxide nanoparticles. Zinc nanoparticles are a crucial component of multiple enzymes that control different plant metabolic processes. It is also necessary for the production of auxin and proteins and for assisting plants in absorbing more N and P (Hazarat Bilal *et al.*, 2025)

**In Fruits:** The foliar application of zinc oxide nanoparticles had a substantial impact on the levels of nitrogen, phosphorus, potassium, sulfur, and magnesium in the fruits of two tomato cultivars (Abbas *et al.*, 2025). Although a proper zinc dosage improved the amount of boron that plants accumulated, a sufficient zinc treatment might lessen the negative effects of a boron deficit. The foliar application of zinc fertilizers and zinc oxide nanoparticles had a significant impact on the uptake of nutrients like N, P, K, S and Mg by the fruits of two tomato varieties (Aqsa Naseem *et al.*, 2025). The tomato's ability to absorb nutrients may be dependent on the use of biological levels and the different recovery of the applied nutrients. (Ahmed *et al.*, 2023)

## **HEALTH AND FUTURE ASPECTS**

The extensive usage of ZnNPs raises questions about human health and environmental safety notwithstanding their promise. ZnNPs can disturb microbial ecosystems and endanger non-target creatures when they build up excessively in soil and water. Thorough research on ZnNPs' long-term ecological effects is essential (Muhammad Nabeel Sharif *et al.*, 2025).

ZnNPs use in agriculture has enormous potential for managing stress and producing crops in a sustainable manner (Nargis Shaheen *et al.*, 2026). Optimizing ZnNPs formulations, comprehending their interactions with plant-microbe systems, and evaluating their long-term environmental effects should be the main goals of future study. ZnNPs' effectiveness may be further increased by combining them with other nanomaterials and biostimulants. To guarantee the safe application of ZnNPs in agriculture, policymakers must create regulations (Rabiya Javaid *et al.*, 2025).

## **CONCLUSION**

An environmentally responsible and sustainable method of improving plant development and reducing environmental stressors is to use zinc nanoparticles. An economical and environmentally friendly way to produce nanoparticles is by the green synthesis of zinc nanoparticles using plant extracts. In a variety of crops, ZnNPs enhance photosynthetic efficiency, nitrogen uptake, stress tolerance, and seed germination. However, for ZnNPs to be successfully used in agriculture, strict dosage monitoring and environmental effect evaluations are necessary.

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