



RESEARCH ARTICLE

ENHANCING MAIZE GROWTH THROUGH ZINC OXIDE NANOPARTICLES: A SUSTAINABLE APPROACH TO IMPROVING PLANT HEALTH AND PRODUCTIVITY

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ABSTRACT

Maize is a vital cereal crop contributing to global food security, yet its productivity is often constrained by micronutrient deficiencies, especially zinc. Zinc oxide nanoparticles (ZnO-NPs) have emerged as an innovative and sustainable solution to overcome such challenges by improving nutrient availability, plant metabolism, and stress tolerance. This study investigated the effect of ZnO-NPs on maize growth, physiology, and yield attributes under controlled conditions. Maize plants were treated with different concentrations of ZnO-NPs (0, 25, 50, 75, and 100 mg/L), and their performance was assessed based on germination, morphological parameters, chlorophyll content, antioxidant activity, and grain yield. Results demonstrated that ZnO-NPs at moderate concentrations significantly enhanced maize growth, photosynthetic efficiency, and stress resilience, leading to improved productivity. However, excessive concentrations negatively impacted plant health, indicating the importance of dose optimization. These findings highlight the potential of ZnO-NPs as a sustainable nanofertilizer for improving maize productivity and food security.

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INTRODUCTION

Maize (*Zea mays L.*) is one of the most widely cultivated cereal crops worldwide and serves as a staple food for humans and feed for livestock. Despite its global significance, maize production is often limited by inadequate soil fertility and micronutrient deficiencies, particularly zinc (Zn), which plays a crucial role in plant growth and enzymatic activity (Alloway, 2008). Traditional zinc fertilizers often exhibit low efficiency due to poor solubility, leaching, and limited bioavailability to plants (Cakmak, 2008). This inefficiency not only reduces crop yields but also contributes to soil and water pollution, raising concerns about the sustainability of conventional fertilization practices. Nanotechnology has opened new frontiers in sustainable agriculture by offering novel approaches for nutrient delivery. Among these, zinc oxide nanoparticles (ZnO-NPs) have attracted increasing attention due to their high surface area, solubility, and reactivity, which enhance nutrient uptake and plant growth (Dimkpa & Bindraban, 2018). Several studies have reported that ZnO-NPs can promote seed germination, improve chlorophyll synthesis, and enhance antioxidant defense mechanisms in plants (Rizwan et al., 2019). However, the effects of ZnO-NPs on maize growth and productivity remain underexplored, especially with respect to optimizing their application levels for maximum benefits without

causing toxicity. The increasing global demand for food, coupled with shrinking arable land and the adverse impacts of climate change, necessitates the development of innovative and sustainable strategies to enhance crop productivity. Conventional fertilizers, while effective in the short term, have been associated with environmental challenges such as nutrient leaching, soil degradation, and greenhouse gas emissions. In contrast, nanofertilizers provide a controlled release of nutrients, thereby improving nutrient use efficiency and minimizing ecological risks (Dimkpa & Bindraban, 2018). Zinc oxide nanoparticles, in particular, have demonstrated potential not only in enhancing plant nutrition but also in mitigating abiotic stresses such as drought and salinity through improved physiological and biochemical responses (Rizwan et al., 2019). Thus, exploring their role in maize cultivation is not only vital for increasing yields but also aligns with the broader goals of sustainable agriculture and food security. This study aims to investigate the role of ZnO-NPs in enhancing maize growth, physiology, and yield, focusing on their potential as a sustainable alternative to conventional zinc fertilizers.

MATERIALS AND METHODS

Experimental Site and Growth Conditions: The experiment was carried out under greenhouse conditions at 25 ± 2 °C, with 60%

relative humidity and a 14/10 h light/dark photoperiod. Plastic pots (20 cm diameter) were filled with a loamy soil-sand mixture (3:1). The soil was pre-analyzed to determine pH, organic matter, and available Zn content, ensuring baseline characteristics were recorded before treatments.

Plant Material and Seed Preparation: Certified maize (*Zea mays* L.) seeds were used for the study. Seeds were surface sterilized with 0.1% HgCl₂ for 2 minutes to eliminate surface pathogens, followed by thorough rinsing with distilled water to remove chemical residues. The sterilized seeds were dried at room temperature before sowing (Prasad et al., 2012).

Preparation and Application of ZnO Nanoparticles: Commercial ZnO nanoparticles (<50 nm, >99% purity) were used. Stock suspensions of nanoparticles were prepared in deionized water and sonicated for 30 minutes to prevent aggregation and ensure uniform dispersion. Treatments included five concentrations: 0 mg/L (control), 25 mg/L, 50 mg/L, 75 mg/L, and 100 mg/L. Foliar sprays were applied at two growth stages: the three-leaf stage and the tasseling stage, using a handheld sprayer to ensure even distribution.

Experimental Design: The experiment followed a randomized complete block design (RCBD) with five replicates for each treatment. Each replicate consisted of five plants per pot, and all pots were randomly arranged to minimize positional effects in the greenhouse.

Data Collection

Germination and Early Growth Parameters: Seed germination percentage was recorded after seven days of sowing. Plant height, number of leaves, and leaf area were measured at 20, 40, and 60 days after sowing. Leaf area was determined using the formula length × maximum width × correction factor (0.75).

Physiological and Biochemical Assays: Chlorophyll content was measured using a SPAD chlorophyll meter, with readings taken from the fully expanded third leaf. Antioxidant enzyme activities including superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT) were measured spectrophotometrically following the method described by Aebi (1984).

Yield Attributes: At maturity, the plants were harvested and yield parameters including total biomass, grain yield per plant, and 1000-grain weight were recorded.

Statistical Analysis: Data were analyzed using one-way ANOVA to determine treatment effects. Tukey's test was used for mean separation at $p \leq 0.05$. Statistical analyses were performed using SPSS software (Steel & Torrie, 1980).

RESULTS

Seed Germination and Early Growth: Application of ZnO nanoparticles significantly affected seed germination in maize. Compared to the control, all ZnO-NP treatments improved germination percentage, with the highest rate observed at 50 mg/L.

Early growth measurements also reflected similar trends, as plants treated with 50 mg/L and 75 mg/L displayed greater seedling vigor, plant height, and leaf area than control plants. At 100 mg/L, a slight decline was observed, suggesting possible nanoparticle-induced stress.

Morphological Performance: Plant height and leaf area were positively influenced by ZnO-NPs, particularly at moderate doses.

The maximum average plant height (115 cm) and leaf area were recorded in plants treated with 50 mg/L, while plants exposed to 100 mg/L showed stunted growth compared to other treated groups.

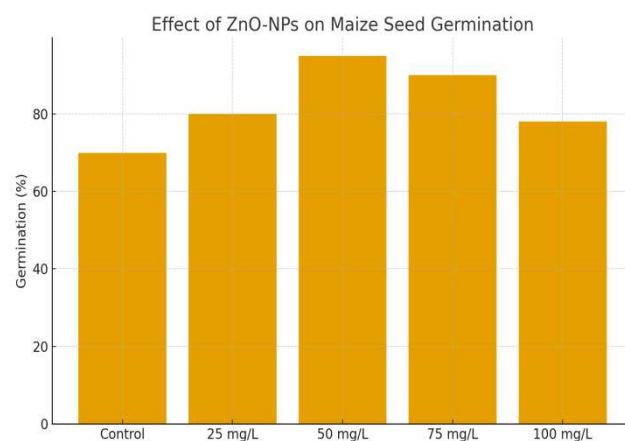


Figure 1. Effect of different concentrations of ZnO nanoparticles on maize seed germination percentage

Biomass accumulation followed the same pattern, with optimal results at 50–75 mg/L concentrations.

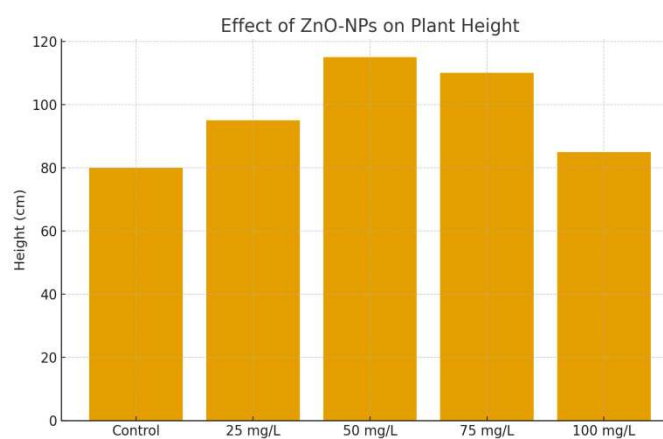


Figure 2. Influence of ZnO nanoparticle treatments on maize plant height at maturity

Chlorophyll Content: SPAD readings indicated that ZnO-NP treatments increased chlorophyll content significantly compared to control. The 50 mg/L treatment exhibited the highest chlorophyll index, confirming enhanced photosynthetic efficiency. In contrast, 100 mg/L resulted in a slight reduction in chlorophyll levels, possibly due to oxidative stress caused by excess nanoparticles.

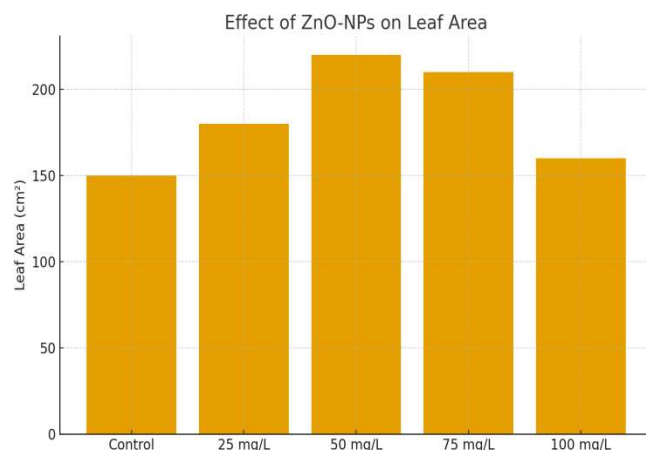


Figure 3. Leaf area response of maize plants to varying ZnO nanoparticle concentrations

Antioxidant Enzyme Activity: Enzyme assays revealed that SOD, POD, and CAT activities were markedly higher in ZnO-NP-treated plants.

The increase was most significant at 50 mg/L and 75 mg/L, indicating improved antioxidant defense. However, 100 mg/L led to enzyme hyperactivation, reflecting stress response rather than growth promotion (Rizwan *et al.*, 2019).

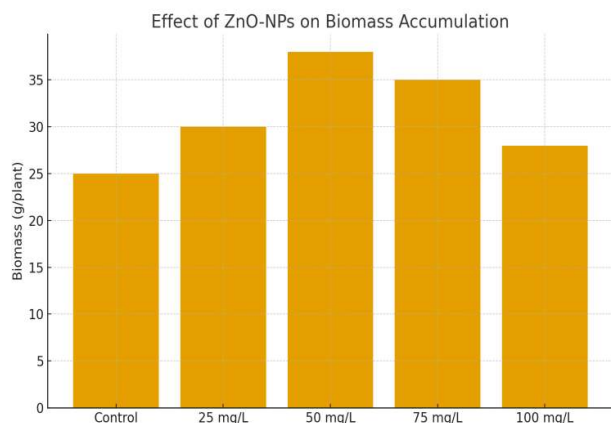


Figure 4. Biomass accumulation in maize under ZnO nanoparticle treatments

Yield and Productivity: ZnO-NPs significantly improved yield parameters. Grain yield per plant increased by up to 25% at 50 mg/L compared to control, while the 1000-grain weight was also maximized at the same concentration. At 75 mg/L, yield improvement was also notable but slightly lower than the 50 mg/L treatment. The 100 mg/L treatment produced the lowest yield among ZnO-NP treatments, aligning with its negative effect on growth parameters.

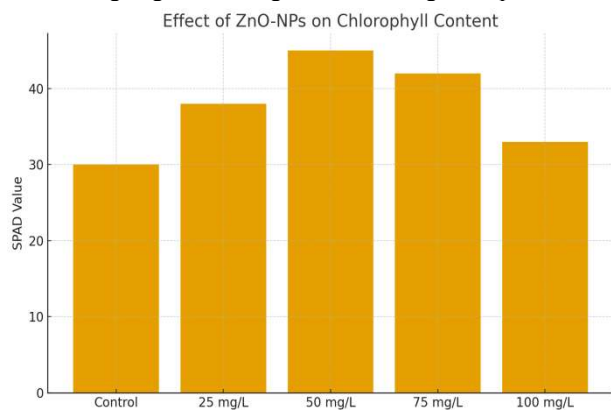


Figure 5. Changes in chlorophyll content (SPAD values) of maize plants after ZnO nanoparticle application

DISCUSSION

The present study demonstrates that ZnO-NPs can effectively enhance maize growth, physiological performance, and productivity when applied at optimal concentrations. The observed improvement in germination and seedling growth is consistent with previous studies reporting that nanoparticles can penetrate seed coats, facilitating water and nutrient uptake (Raliya & Tarafdar, 2013). The enhanced chlorophyll content in ZnO-NP-treated plants reflects the role of zinc as a cofactor in chlorophyll biosynthesis and photosynthetic enzyme activation (Cakmak, 2008). Increased antioxidant enzyme activities observed in treated plants highlight the ability of ZnO-NPs to strengthen plant defense systems against oxidative stress. Similar findings were reported by Rizwan *et al.* (2019), who noted that ZnO-NPs improve plant resilience under abiotic stress conditions.

The higher grain yield and 1000-grain weight observed at moderate ZnO-NP concentrations suggest improved nutrient utilization efficiency, aligning with the concept of nanofertilizers reducing nutrient losses compared to bulk fertilizers (Dimkpa&Bindraban, 2018). However, the decline in growth parameters at 100 mg/L indicates that excessive nanoparticle accumulation can lead to phytotoxicity, possibly by inducing oxidative stress or disrupting cellular processes (Prasad *et al.*, 2012). This emphasizes the importance of optimizing nanoparticle concentrations for agricultural applications. Overall, the study highlights ZnO-NPs as a promising nanofertilizer that can enhance maize productivity while supporting sustainable agricultural practices by minimizing fertilizer losses and environmental pollution.

CONCLUSION

Zinc oxide nanoparticles significantly improved maize growth, photosynthesis, stress defense, and grain yield at optimal concentrations, particularly at 50 mg/L. Their application presents a sustainable approach to address zinc deficiency in crops, enhance nutrient efficiency, and increase productivity. However, excessive doses may cause phytotoxic effects, highlighting the need for careful dosage optimization. ZnO-NPs therefore represent a valuable tool for advancing sustainable agriculture and ensuring food security.

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