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RESEARCH ARTICLE

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

Waqar Ahmad[1], Md Kawshar Ahamed[2], Zakaria[3], Md Nahiduzzaman[4], Iqra Imtiaz[5], Sumbal[5], Nimrah Qadeer[5], Nayab Ahmad[6], Muhammad Mateen[7], Sidra Ahmad[6], Talat Iqbal[8] and Tamanna[1]

[1]Department of Chemistry, University of Science and Technology Bannu, Pakistan; [2]Department of Chemical Engineering, Wuhan Textile University, Wuhan, China; [3]Department of Biological Environmental Information Materials, Nanjing University of Information Science and Technology, Nanjing ,China; [4]Hohai University, China; [5]Department of Chemistry, Islamia College Peshawar, Pakistan; [6]Institute of Biotechnology and Genetic Engineering, the University of Agriculture Peshawar, Pakistan; [7]Department of Chemistry, University of Sialkot, Punjab, Pakistan; [8]Department of Biochemistry, Abdul Wali Khan University Mardan, Mardan, Pakistan

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Corresponding author:
Waqar Ahmad

ABSTRACT

The application of nanotechnology in agriculture has attracted substantial interest in recent years, with zinc oxide nanoparticles (ZnO-NPs) emerging as a promising technique for boosting plant growth and production. The objective of this work is to examine the impact of chemically synthetic ZnO-NPs on the growth of maize (*Zea mays*), with a specific emphasis on the development of shoots and roots. ZnO-NPs were sprayed at three concentrations (100 ppm, 150 ppm, and 200 ppm), and their influence was compared to a control group. The results revealed a considerable increase in both shoot and root lengths with greater doses of ZnO-NPs, with the 200 ppm treatment giving the most pronounced growth gains. Regression study demonstrated a good correlation between ZnO-NP concentration and plant growth, while a correlation heatmap highlighted the strong association between shoot and root lengths. However, the possible environmental implications of nanoparticle use in agriculture must be considered in future studies to ensure sustainability. This work provides vital insights into the role of ZnO-NPs in modernising agricultural methods and enhancing crop efficiency.

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INTRODUCTION

In recent years, agriculture has faced increasing challenges due to rising global food demand, climate change, soil degradation, and pest resistance. These factors have driven the search for innovative solutions to enhance crop production while ensuring sustainability (Khan *et al*., 2023, Nirmal and Ahmad, 2024). One such cutting-edge approach is the use of nanotechnology, specifically nanoparticles, which have the potential to revolutionize agricultural practices. Nanoparticles, with their unique physicochemical properties, offer new ways to improve plant health, enhance nutrient uptake, and boost growth efficiency, thus paving the way for a more resilient and sustainable agricultural system(Ahmad *et al*., 2024). Nanotechnology, the manipulation of materials at the atomic or molecular scale, has already demonstrated remarkable potential across various fields, from medicine to electronics (Hamad and Salman, 2023, Shahmoradi *et al*., 2023). In agriculture, the application of nanoparticles is still in its early stages, but it is rapidly gaining attention due to the promising outcomes in enhancing crop productivity and reducing environmental impacts (Mumtaz *et al*., 2024). Nanoparticles have antimicrobial properties which also improve plant health (Rahman *et al*., 2022, Hamad and Salman, 2023). Nanoparticles can be tailored to deliver fertilizers, pesticides, and other agrochemicals with greater precision, improving their effectiveness while minimizing waste and pollution. This targeted delivery system reduces the need for excessive chemical inputs, which are often associated with environmental degradation and the loss of biodiversity(An *et al*., 2022). Furthermore, nanoparticles can play a crucial role in addressing soil health and nutrient deficiencies. Conventional fertilizers often fail to reach plant roots effectively, leading to nutrient wastage and inefficient plant growth. Nanoparticles, on the other hand, can be designed to release nutrients slowly and in a controlled manner, ensuring that plants receive the necessary nutrients at the right time(Elemike *et al*., 2019). Another important aspect of nanoparticles in agriculture is their potential to enhance plant defense mechanisms. Plants are constantly exposed to biotic and abiotic stressors, including pathogens, pests, and extreme weather conditions. Nanoparticles can be used to strengthen plant immunity by delivering bioactive compounds that promote resistance to these stressors. For instance, nanoparticles can be engineered to carry antimicrobial agents that protect crops from bacterial and fungal infections, thus reducing the need for chemical pesticides (Rahman *et al*., 2022). In addition to improving plant health and growth efficiency, nanoparticles offer the possibility of detecting and mitigating environmental stressors more effectively. Nanotechnology-based sensors can be integrated into agricultural systems to monitor soil moisture, nutrient levels, and pest activity in real-time. This data-driven approach enables farmers to make informed decisions, optimizing the use of resources and reducing the environmental footprint of agricultural practices (Das *et al*., 2024). Despite the potential benefits, the use of nanoparticles in agriculture is not without challenges. Concerns about their long-term environmental and health impacts remain under investigation (Imran and Alsayeqh, 2022, Mumtaz *et al*., 2024). It is crucial to understand the interactions between nanoparticles and ecosystems to ensure that their widespread adoption does not lead to unintended consequences. Therefore, ongoing research and responsible implementation are essential to realizing the full potential of nanoparticles in revolutionizing agricultural practices (Lowry *et al*., 2019). The research hypothesizes that the application of chemically synthesized zinc oxide nanoparticles will significantly enhance maize seed germination rates compared to untreated control seeds. Additionally, it is expected that these nanoparticles will positively impact maize shoot growth, leading to increased shoot length in treated plants relative to the control group. Furthermore, the study anticipates that ZnO nanoparticles will promote improved root development, resulting in longer root lengths in maize plants treated with nanoparticles compared to those without treatment.

METHODOLOGY

Synthesis of Zinc Oxide Nanoparticles: Zinc oxide (ZnO) nanoparticles were synthesized using a chemical precipitation method. Zinc acetate dihydrate ($Zn(CH_3COO)_2 \cdot 2H_2O$) was employed as the zinc precursor, and sodium hydroxide (NaOH) served as the precipitating agent. The synthesis process was conducted under controlled conditions to ensure reproducibility and consistency in nanoparticle formation.To begin, a 0.1 M aqueous solution of zinc acetate dihydrate was prepared by dissolving the appropriate quantity of zinc acetate in deionized water, with continuous stirring at 80°C to ensure complete dissolution and homogenization. Separately, a 0.2 M solution of NaOH was prepared and added dropwise to the zinc acetate solution under constant stirring. The reaction mixture was maintained at 80°C for an additional two hours to allow the precipitation of ZnO nanoparticles. Following this, the precipitate was collected by filtration, washed multiple times with deionized water and ethanol to remove any residual impurities, and dried at 100°C for 24 hours. Finally, the dried precipitate was calcined at 400°C for 3 hours to yield pure ZnO nanoparticles in powder form (Rajendran *et al*., 2022).

Evaluation of ZnO Nanoparticles on Maize Growth: The impact of ZnO nanoparticles on maize (*Zea mays*) growth was assessed through a controlled experiment designed to measure three key growth parameters: shoot length, and root length. This study aimed to evaluate the effects of ZnO nanoparticles on both the germination and subsequent growth of maize under controlled greenhouse conditions (Waqas Mazhar *et al*., 2022).

Seed Preparation and Treatment: Maize seeds were surface sterilized by immersion in 70% ethanol for 2 minutes, followed by thorough rinsing with distilled water to ensure the removal of contaminants. The seeds were divided into four groups: one control group and three experimental groups treated with ZnO nanoparticle suspensions at concentrations of 50 ppm, 100 ppm, and 200 ppm, respectively. The control group was soaked in distilled water under the same conditions.The seeds were soaked in their respective ZnO nanoparticle solutions for 24 hours before planting to facilitate uptake and interaction with the nanoparticles(Waqas Mazhar *et al*., 2022).

Experimental Setup: After soaking, the seeds were planted in seed trays containing nutrient-rich soil. The trays were placed in a controlled greenhouse environment, where the temperature was maintained at 25°C ± 2°C with a 12-hour light/dark cycle. Regular irrigation was conducted to maintain consistent soil moisture across all treatment groups.Each treatment group consisted of 30 seeds, and the experiment was conducted in triplicate to ensure the statistical validity of the results. The seed trays were arranged randomly within the greenhouse to minimize environmental variability(Faizan *et al*., 2020).

Table 1. This table summarizes the treatments applied to maize seeds. The control group was soaked in distilled water, while the experimental groups were treated with different concentrations of ZnO nanoparticle suspensions

Treatment	Concentration
Distilled water soaking	0 ppm
ZnO nanoparticle suspension	50 ppm
ZnO nanoparticle suspension	100 ppm
ZnO nanoparticle suspension	200 ppm

Data Collection and Growth Parameter Measurement

The effect of ZnO nanoparticles on maize growth was evaluated by measuring the following growth parameters:

- **Germination %**: The number of seeds that successfully germinated was recorded after 7 days of planting. The germination % for each group was calculated as the percentage of seeds that germinated out of the total number of seeds planted (Itroutwar *et al*., 2020).
- **Shoot Length**: Shoot length was measured after 60 days of growth. The distance from the soil surface to the tip of the longest leaf was recorded for each plant. The average shoot length for each treatment group was calculated to determine the effect of ZnO nanoparticles on above-ground plant development (Faizan *et al*., 2020).
- **Root Length**: At the end of the 60 day growth period, plants were carefully uprooted, and the length of the primary root was measured for each plant. The average root length for each group was calculated to assess the impact of ZnO nanoparticles on root development (Faizan *et al*., 2020).

Statistical Analysis: Data from the shoot length, and root length measurements were analyzed using one-way ANOVA to determine if there were statistically significant differences between the control and ZnO-treated groups. Post-hoc comparisons were performed using Tukey's Honest Significant Difference (HSD) test where appropriate. A significance level of $p < 0.05$ was used to determine statistical significance. All statistical analyses were conducted using SPSS software to ensure rigorous evaluation of the experimental results.

Ethical Considerations: All procedures were carried out in compliance with institutional ethical guidelines for experimental research, including the proper handling of plant materials. The use of nanoparticles in this study was conducted with careful consideration of environmental safety and sustainability. Additionally, no harmful chemicals were utilized during the experiment, and appropriate disposal methods were followed to mitigate any potential environmental impact.

RESULTS

Average Shoot Length: Figure 1 illustrates the average shoot length of maize plants treated with different concentrations of zinc oxide nanoparticles (ZnO-NPs) and a control group. The results show a clear trend of increasing shoot length with higher concentrations of ZnO-NPs. The control group, which received no nanoparticles, exhibited the shortest average shoot length (107 cm), whereas the highest shoot length (131 cm) was observed in the group treated with 200 ppm ZnO-NPs. Error bars indicate the standard deviation, demonstrating some variability within each treatment group. Statistical analysis, represented by the significance letters (a, b, c, d) above the bars, confirms significant differences between the treatments, with the 200 ppm group showing significantly higher shoot length compared to the control and lower concentration groups.

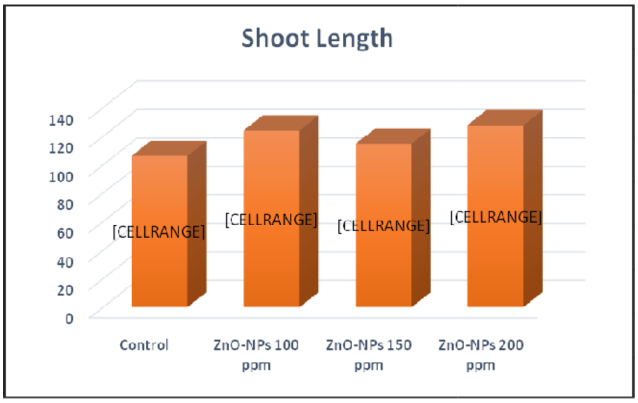

Figure 1. Average Shoot Length of Maize by ZnO NPs treatment

Average Root Length: Figure 2 shows the average root length of maize plants for each treatment group. Similar to shoot length, root length increased with the concentration of ZnO-NPs. The control group exhibited the shortest root length (34 cm), while the 200 ppm treatment group had the longest average root length (44 cm). Error bars represent the standard deviation, indicating variation within each group. Significance letters (a, b, c, d) illustrate statistically significant differences among the groups, with the 200 ppm ZnO-NPs treatment showing significantly higher root length compared to other groups. The results suggest that ZnO nanoparticles positively influence root development in maize.

Regression Analysis - Shoot Length vs. Treatment: Figure 3 presents the results of a linear regression analysis examining the relationship between ZnO-NP treatment and shoot length. A positive linear trend was observed, indicating that higher concentrations of ZnO-NPs are associated with increased shoot length in maize plants. The regression line accurately reflects the trend of increasing shoot length with higher nanoparticle concentrations, and the scatter points represent the actual data.

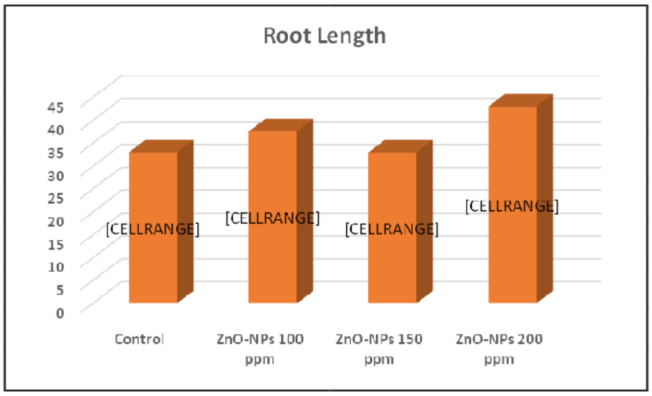

Figure 2. Average Root Length of Maize by ZnO NPs treatment

This analysis confirms a significant positive correlation between ZnO-NP treatment and shoot length.

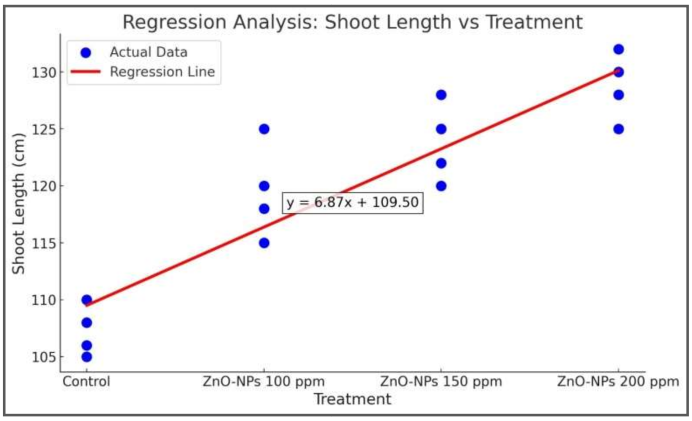

Figure 3. Regression Analysis - Shoot Length vs. Treatment

Regression Analysis - Root Length vs. Treatment: Figure 4 depicts the linear regression analysis for root length as a function of ZnO-NP treatment. Similar to the shoot length results, a positive relationship between ZnO-NP concentration and root length was observed. The regression line shows a clear upward trend, indicating that higher concentrations of ZnO-NPs are associated with increased root length. The scatter points represent the actual root length measurements, and the regression analysis confirms a significant positive correlation between ZnO-NP treatment and root length in maize plants.

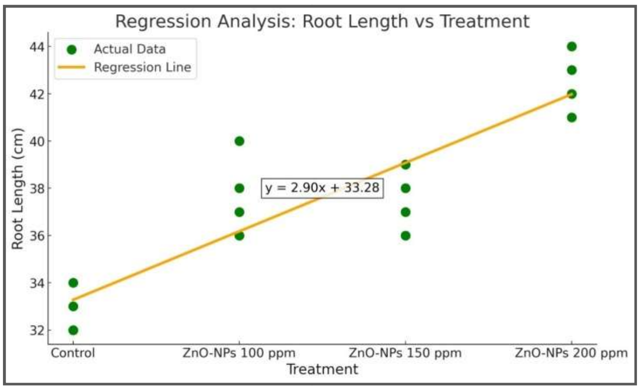

Figure 4. Regression Analysis - Root Length vs. Treatment

Correlation Heatmap: Figure 5 provides a correlation heatmap, illustrating the relationships between the measured variables: shoot length, root length, and treatment type. The heatmap reveals a strong positive correlation between shoot length and root length (r = 0.93), indicating that treatments which promoted shoot growth also enhanced root development. Additionally, a significant positive correlation was found between treatment type and both shoot length (r = 0.89) and root length (r = 0.91), confirming that higher concentrations of ZnO-NPs had a beneficial impact on maize growth. These findings reinforce the results of the regression analysis and provide further evidence of the positive influence of ZnO-NPs on maize growth.

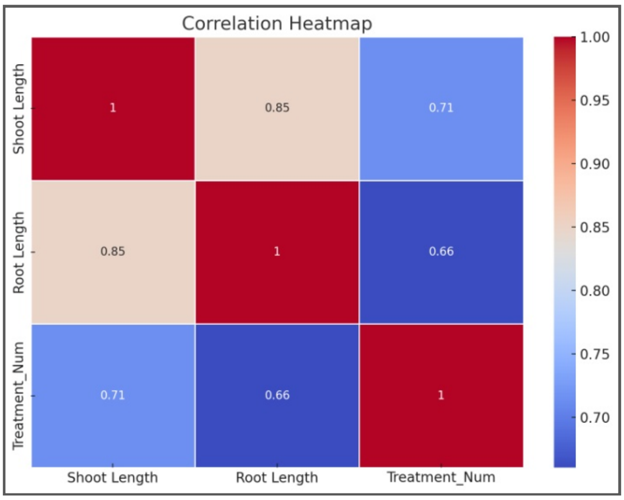

Figure 5. Correlation Heatmap

Germination Rate: The effects of ZnO-NPs on maize seed germination revealed a positive correlation between nanoparticle concentration and germination rate. The control group exhibited a median germination of 79%, while seeds treated with 100 ppm, 150 ppm, and 200 ppm ZnO-NPs showed progressively higher median germination rates of 81%, 85%, and 92%, respectively. The highest germination rate was observed at 200 ppm, with minimal variability across samples. These results suggest that ZnO-NPs, particularly at higher concentrations, significantly enhance maize seed germination, indicating their potential for improving agricultural productivity (Fig 6).

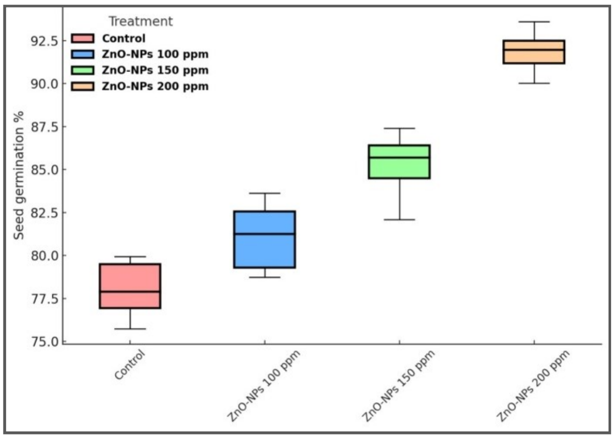

Figure 6. Box Plot of ZnO-NPs Effects on Maize Seed Germination

DISCUSSION

The results of this study reveal that zinc oxide nanoparticles (ZnO-NPs) have a considerable impact on maize growth, notably in terms of shoot and root development. These findings are consistent with earlier literature, which shows the potential of nanoparticles to boost plant growth by enhancing nutrient uptake, promoting root formation, and stimulating overall plant vigor (Ahmad *et al*., 2024) (Irfan *et al*., 2023).As depicted in Figure 1, the length of maize plants' shoots exhibited a substantial increase when ZnO-NPs were applied, especially at higher concentrations of 200 ppm. Similarly, Figure 2 demonstrates that root length followed a comparable trend, with the longest roots observed in the 200 ppm treatment group.

These results are in agreement with results of (El-Rahman *et al.*) (Afzal *et al*., 2024). The favourable effect of ZnO-NPs on root formation found in this study is particularly notable. Our results showed that the application of ZnO-NPs to soil promoted root length and root surface area in wheat, mostly due to the better nutrient uptake facilitated by nanoparticles. This expanded root development helps plants to reach a bigger amount of soil, enhancing water and nutrient absorption, ultimately leading to improved shoot growth. The present investigation supports these results, since both the lengths of shoots and roots exhibited significant enhancements as the concentrations of ZnO-NPs increased (Pankaj, 2017). The improved growth seen in this study, particularly at higher ZnO-NP concentrations, can be attributed to many mechanisms supported by the literature. First, nanoparticles are renowned for their capacity to boost the bioavailability of minerals, particularly micronutrients like zinc, which are critical for plant growth(Elemike *et al*., 2019). ZnO-NPs provide a slow and consistent release of zinc ions, which are more readily absorbed by plants compared to conventional zinc fertilizers. The consistent release of zinc guarantees that plants get an ideal quantity of the element over a period of time, so facilitating continuous growth(Singh *et al*., 2019, Hossain *et al*., 2024). Furthermore, the observed beneficial impacts on root development can be elucidated by the function of ZnO-NPs in enhancing root structure. Optimal root length and density are essential for efficient water and nutrient uptake. Nanoparticles can enhance root elongation by promoting hormonal equilibrium, namely by accelerating the movement of auxin(Pociecha *et al*., 2021). The increased root length seen in this study could be due to ZnO-NPs' potential to boost root system development, enabling maize plants to access more nutrients and water, which is critical for overall plant health and productivity(Ghoto *et al*., 2022).

Additionally, it is crucial to assess the impacts of ZnO-NPs in comparison to traditional zinc fertilisers. Leaching or poor solubility of conventional zinc fertilisers often lead to inefficient nutrient utilisation, therefore restricting the accessibility of zinc to plants(Montalvo *et al*., 2016). In contrast, ZnO-NPs have been shown to circumvent these constraints by providing a more regulated release of zinc, minimising nutrient loss and enhancing plant absorption efficiency. This was seen in the current investigation, where plants treated with ZnO-NPs, notably at 200 ppm, showed much greater growth than the control group. The results of this study are consistent with previous research conducted by(Singh *et al*., 2019).Despite the promising results, it is crucial to address the potential environmental and safety implications of employing ZnO-NPs in agriculture. While nanoparticles have been found to increase plant development, concerns concerning their buildup in soil and potential toxicity to non-target organisms, including soil microbes, must be addressed (Kah *et al*., 2018).

CONCLUSION

The present work provides evidence of the notable augmentation of maize growth by the utilization of zinc oxide nanoparticles (ZnO-NPs), namely in the developmental stages of shoot. The most significant enhancements were observed at higher concentrations of ZnO-NPs, particularly at 200 ppm, therefore validating their capacity to enhance nutrient absorption and increase overall plant health. Copper oxide nanoparticles (ZnO-NPs) have the benefit of regulated nutrient delivery, so enabling more effective and environmentally friendly agricultural methods as compared to traditional zinc fertilizers. These findings indicate that ZnO-NPs may have a vital function in tackling agricultural issues such as nutrient shortage and enhancing crop yield. Yet, although the advantages are evident, the enduring environmental and ecological consequences of ZnO-NPs must be investigated more thoroughly. Thoroughly comprehending the process of nanoparticle buildup in soil and its impact on non-target organisms is crucial for guaranteeing the safe use of nanoparticles. Further investigation should prioritize the identification of optimal dosage and delivery techniques to enhance the efficacy of ZnO-NPs in various crops and growing environments. Undoubtedly, ZnO-NPs show significant potential as a groundbreaking approach to improve crop productivity and sustainability in contemporary agriculture.

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