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Enhanced micronutrient management in rice and maize through nitrogen-doped zinc oxide nanoparticles

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Zinc (Zn) deficiency is a major limitation affecting cereal productivity and nutritional quality worldwide, particularly in rice and maize cultivated under Zn-deficient soils. Conventional zinc fertilizers often exhibit poor nutrient use efficiency due to fixation, leaching, and limited bioavailability. Therefore, the present study aimed to synthesize and evaluate nitrogen-doped zinc oxide nanoparticles (N–ZnO NPs) as an efficient nanofertilizer for improving crop growth under zinc-deficient conditions. Nitrogen-doped ZnO nanoparticles were synthesized using an imidazole-based precursor method followed by calcination at 900°C for 30 min. Scanning electron microscopy (SEM) analysis confirmed the formation of predominantly spherical nanoparticles with an average particle size of approximately 51 nm. The growth-promoting potential of N–ZnO nanoparticles was evaluated through a controlled pot experiment using rice (*Oryza sativa* L.) and maize (*Zea mays* L.) under nutrient-deficient conditions with Hoagland nutrient solution. Nanoparticles were applied at concentrations of 2, 5, and 10 ppm. Application of N–ZnO nanoparticles significantly enhanced shoot and root length, biomass accumulation, and chlorophyll content compared with zinc-deficient controls and undoped ZnO nanoparticles. The maximum growth response was observed at 10 ppm, indicating improved agronomic efficiency and bioavailability of N–ZnO nanoparticles under zinc-deficient conditions.Keywords: Nitrogen-doped ZnO nanoparticles, zinc deficiency, nanofertilizer, rice, maize, micronutrient management, sustainable agriculture.

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INTRODUCTION

Zinc (Zn) deficiency is one of the most widespread micronutrient disorders affecting agricultural productivity and human nutrition worldwide[1]. In plants, zinc plays an essential role as a structural and catalytic component of numerous enzymes involved in photosynthesis, antioxidant defence, protein synthesis, membrane stability, pollen development, and disease resistance[2,3]. Insufficient zinc availability in soil disrupts these physiological processes, leading to impaired growth, reduced yield, and poor grain nutritional quality[4]. Globally, a substantial proportion of arable soils—particularly calcareous and alkaline soils—are zinc-deficient, making zinc limitation a persistent constraint in cereal-based cropping systems[5,6]. Rice and maize, two of the most important staple crops globally, are highly sensitive to zinc deficiency. In rice, zinc deficiency manifests as delayed maturity, bronzing of leaves, reduced tillering, and poor grain filling, ultimately resulting in lower yields and grain quality[7,8]. In maize, zinc deficiency causes interveinal chlorosis, shortened internodes, stunted

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growth, and impaired reproductive development, including reduced pollen viability and male sterility under severe deficiency[9]. Beyond agronomic losses, zinc deficiency in crops contributes directly to zinc malnutrition in humans, a condition affecting more than three billion people worldwide and commonly referred to as "hidden hunger," particularly in populations dependent on cereal-based diets[10]. Conventional zinc fertilisers, such as zinc sulfate and bulk zinc oxide, are widely used to address zinc deficiency; however, their agronomic efficiency is often limited due to poor solubility, rapid fixation in the soil, leaching losses, and low bioavailability to plants[11,12]. These limitations necessitate improved nutrient delivery strategies that enhance zinc use efficiency while minimising environmental impacts. In this context, nanotechnology has emerged as a promising approach for sustainable nutrient management. Zinc oxide nanoparticles (ZnO NPs), owing to their high surface area, controlled release behaviour, and improved plant uptake, have demonstrated potential as nanofertilizers in several crop systems[13]. Previous studies have reported that ZnO nanoparticles enhance growth, biomass accumulation, chlorophyll content, photosynthetic efficiency, and stress tolerance in rice and maize, while also reducing the accumulation of toxic elements such as arsenic in plants[14,15,16]. Despite these advances, the performance of ZnO nanoparticles as nanofertilizers can still be limited by aggregation, instability, and suboptimal nutrient availability under stress or deficiency conditions. Material modification strategies, particularly elemental doping, offer a rational approach to improving the physicochemical and functional properties of nanoparticles. Doping can alter the crystal structure, surface charge, dispersibility, and reactivity of nanomaterials, thereby influencing their interaction with biological systems[17,18]. In agricultural contexts, doped nanoparticles have been proposed to enhance nutrient retention, improve absorption efficiency, and increase plant responsiveness under adverse conditions[19]. Nitrogen is a key macronutrient for plant growth and has been widely reported to interact synergistically with zinc in conventional fertilisation systems. The combined application of nitrogen and zinc enhances zinc bioavailability in soil, improves nutrient use efficiency, stimulates antioxidant activity, and increases yield and nutritional quality in cereals such as wheat, rice, and maize[20,21]. However, these synergistic effects have largely been investigated using bulk fertilisers, and the potential of nitrogen-doped zinc-based nanomaterials for agricultural applications remains unexplored. In particular, we have not found any previous studies that have examined whether nitrogen doping of ZnO nanoparticles can enhance their agronomic efficiency under zinc-deficient conditions. In this context, the present study aims to synthesise nitrogen-doped ZnO nanoparticles, characterise their physicochemical properties, and evaluate their effectiveness as a nanofertilizer for improving the growth performance of rice and maize under zinc-deficient conditions. By integrating nanomaterial design with plant nutrient management, this work seeks to provide experimental evidence for the potential of nitrogen-doped ZnO nanoparticles as a sustainable strategy to alleviate zinc deficiency in cereal crops.

MATERIALS AND METHODS

Synthesis of nitrogen-doped zinc oxide nanoparticles

Nitrogen-doped zinc oxide (N–ZnO) nanoparticles were synthesised using an imidazole-based precursor route with subsequent calcination, following a modified protocol reported earlier[22].

Imidazole derivatives are known as precursors to zinc oxide nanoparticles. Imidazole is an organic compound with the formula $C_3H_4N_2$. It is a five-membered heterocyclic aromatic compound containing two annular nitrogen atoms; one nitrogen behaves like pyrrole-type nitrogen, and the other resembles pyridine-type nitrogen. This ring system is present in various important biological building blocks like histidine and histamine, which have been efficiently utilised in biological activities and pharmaceutical applications[23,24]. Initially, 0.02 mol of diacetylmonoxime (DAM) was dissolved in 20 mL of glacial acetic acid in a round-bottom flask, under continuous magnetic stirring at 250 rpm. Subsequently, 4 g ammonium acetate was added, and the reaction mixture was stirred for 20 min. Thereafter, 0.02 mol 4-hydroxybenzaldehyde was added to the mixture, and the reaction was allowed to proceed for 24 h under constant stirring.

Neutralisation and isolation of imidazole product

After the reaction was completed, the mixture was transferred to a beaker and diluted with distilled water. The beaker was placed on an ice bath, and aqueous ammonia solution was added dropwise with continuous stirring until the reaction mixture reached neutral pH[22](pH 7). The neutralised product was collected by vacuum filtration using a suction pump, transferred to a Petri dish, and dried at room temperature. The dried product was weighed, and its melting point and percentage yield were determined.

Formation of zinc–imidazole complex

For complexation, 11 g zinc acetate was dissolved in 15 mL of methanol in a round-bottom flask and stirred for 20 min. In a separate beaker, 15 mL of methanol containing a few drops of ammonia was prepared, to which 5.26 g of the previously synthesised imidazole derivative was added and mixed thoroughly. This solution was then added dropwise to the zinc acetate solution under continuous stirring, and the reaction was allowed to proceed for 2 h. Following completion, methanol was removed using a rotary evaporator. The flask was covered with aluminium foil and kept undisturbed for several hours. The resulting zinc–imidazole complex (zinc salt) was scraped from the flask, collected, weighed, and divided into six equal portions for calcination.

Calcination

Calcination was performed by placing the zinc–imidazole complex in a silica crucible and heating it in a muffle furnace at 900 °C for 30 minutes to obtain nitrogen-doped

ZnO nanoparticles

Characterisation of nitrogen-doped ZnO nanoparticles

The morphology and particle size of the synthesised nanoparticles were analysed using scanning electron microscopy (SEM). SEM images revealed that the N–ZnO nanoparticles were predominantly spherical, with an average particle size of approximately 51 nm.

Plant growth experiment

Seed material and surface sterilisation

Certified seeds of rice (*Oryza sativa* L., cv. Ranbir Basmati) and maize (*Zea mays* L., cv. P3377) were used in this study. Seeds were surface-sterilised with a 0.1 % sodium hypochlorite solution for 5 min and then rinsed thoroughly with sterile distilled water [25].

Preparation of nanoparticle suspension and seed treatment

The synthesised N–ZnO nanoparticles were dispersed in deionised water using a sonicator (100 W, 40 kHz) for 10 min to obtain a uniform nanosuspension. Surface-sterilised seeds used in all treatments were initially nanoprimed with N-doped ZnO NPs at 10 ppm. For nanopriming, surface-sterilised seeds were immersed in 50 ml 10 ppm N– N-doped ZnO nanoparticles and constantly agitated by shaking at 160 rpm for 12 h at room temperature26. For treatments 1 and 3, the recommended zinc level was used as zinc sulphate. For treatment 5 (T5), a 1 mM solution of commercial ZnO NPs was prepared in 20 mL of water. Further, we made a 10 ppm solution. Again 1 mM solution of N- doped ZnO NPs was made in 20 ml water. Further, we prepared its 2 ppm, 5 ppm, and 10 ppm solutions for T6, T7, and T8, respectively.

Pot setup and experimental design

Sand was thoroughly washed with tap water to remove dust particles, followed by washing with 1 M NaOH and 1 M HCl solutions to eliminate residual contaminants. The sand was then rinsed with distilled water until it reached a neutral pH and air-dried at room temperature. Sterile plastic pots were filled with 200 g of treated sand. After soaking, the seeds were transferred to Petri plates for germination. After 6 days of germination, the seedlings were transplanted into the pots. Each pot contained two maize seedlings or fifteen rice seedlings. Plants were irrigated with 70 mL of modified Hoagland nutrient solution. To maintain appropriate moisture conditions, rice pots were kept flooded, while maize pots were kept moist by adding 20 mL of Hoagland solution every other day.

Eight treatment groups were established

- T1 (Control): Plants supplied with complete Hoagland nutrient solution containing the recommended zinc concentration in the form of $ZnSO_4$.
- T2 (Zinc-deficient): Plants grown in modified Hoagland nutrient solution devoid of zinc (Zn).
- T3 (Nitrogen-deficient): Plants grown in modified Hoagland nutrient solution lacking nitrogen (N).
- T4 (Combined nitrogen and zinc deficiency): Plants cultivated under simultaneous nitrogen- and zinc-deficient conditions.
- T5 (ZnO NP treatment): Plants treated with undoped zinc oxide nanoparticles (ZnO NPs) at a concentration of 10 ppm.
- T6 (N–ZnO NP treatment, 2 ppm): Plants treated with nitrogen-doped zinc oxide nanoparticles (N–ZnO NPs) at 2 ppm.
- T7 (N–ZnO NP treatment, 5 ppm): Plants treated with nitrogen-doped zinc oxide nanoparticles (N–ZnO NPs) at 5 ppm.
- T8 (N–ZnO NP treatment, 10 ppm): Plants treated with nitrogen-doped zinc oxide nanoparticles (N–ZnO NPs) at 10 ppm.Each treatment was conducted in triplicate.

Growth conditions and morphological measurements

Plants were grown for 21 days under controlled environmental conditions (25 ± 2 °C, 12 h photoperiod). At harvest, plants were gently removed from the sand, washed, and analysed for growth parameters. Root and shoot lengths were measured using a measuring scale, with root length measured from the root tip to the shoot base and shoot length from the base to the shoot apex. Fresh biomass was determined immediately after harvest using an analytical balance. Subsequently, plant samples were dried in a hot-air oven at 65 °C until constant weight was achieved, and the dry biomass was recorded separately for roots and shoots.

Chlorophyll estimation

Chlorophyll a and b contents were estimated following a standard acetone extraction method[27]. Fresh leaf tissue (0.1 g) was homogenised in 2 mL of 80% acetone and transferred to a test tube. An additional 8 mL of 80% acetone was added, and samples were kept overnight in the dark. Absorbance was recorded at 663 nm and 645 nm using a UV–visible spectrophotometer. Chlorophyll concentrations were calculated and expressed as mg g^{-1} fresh weight.

Visual assessment of deficiency symptoms

Plants were visually examined for symptoms of zinc and nitrogen deficiency, including chlorosis, stunting, and leaf deformities, throughout the experimental period.

Statistical analysis

All experiments were conducted in triplicate, and the data were expressed as mean ± standard error (SE). Statistical analysis was performed using one-way analysis of variance (ANOVA), followed by appropriate post hoc comparison tests to determine significant differences among treatments at $p \leq 0.05$.

RESULTS AND DISCUSSION

Effect of N–ZnO nanoparticles on growth performance of rice and maize

Shoot and root length

Significant variations in shoot and root lengths were observed among different treatments in both rice and maize, as evidenced by corresponding image-based documentation of the experimental setup and plant morphology. Representative images of the pot experiment illustrated clear treatment-wise differences in overall plant vigour, canopy development, and shoot system architecture (Figures 1 & 2). Root length images were not recorded during the experiment and are therefore not included in this figure.

Maize plants exhibited the highest shoot length, and biomass accumulation following the application of nitrogen-doped zinc oxide nanoparticles (N-doped ZnO NPs) at 10 ppm (T8). Application of N-doped ZnO NPs even at lower concentrations significantly enhanced shoot length, root dry biomass, shoot fresh biomass, and chlorophyll content compared with zinc-deficient conditions and undoped ZnO nanoparticles, although these effects were less pronounced than in T8. Overall, a clear dose-dependent increase was observed across all measured growth and physiological parameters. In addition, N-doped ZnO NPs effectively alleviated zinc deficiency symptoms such as stunted growth and interveinal chlorosis, collectively demonstrating their agronomic effectiveness in maize.

Rice plants showed the highest shoot length, and biomass accumulation following the application of nitrogen-doped zinc oxide nanoparticles (N-doped ZnO NPs) at 10 ppm (T8). Application of N-doped ZnO NPs even at lower concentrations significantly enhanced shoot length, root dry biomass, shoot fresh biomass, and chlorophyll content compared with zinc-deficient conditions and undoped ZnO

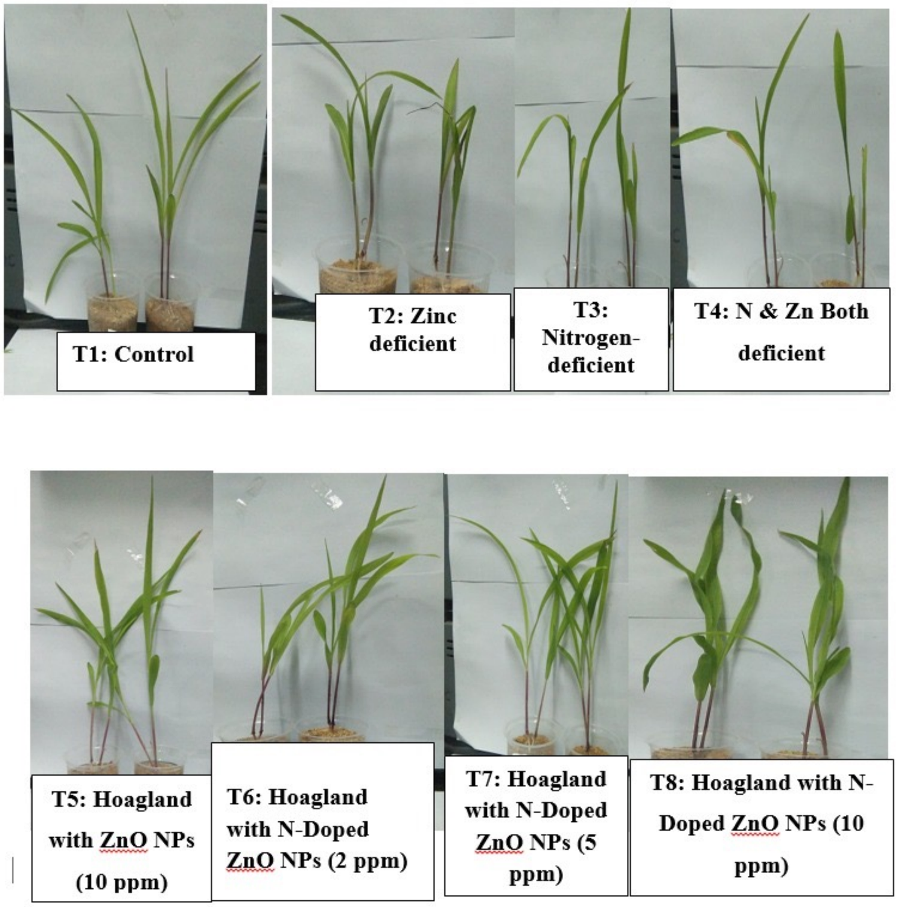

Figure 1. Growth response of maize under different treatments

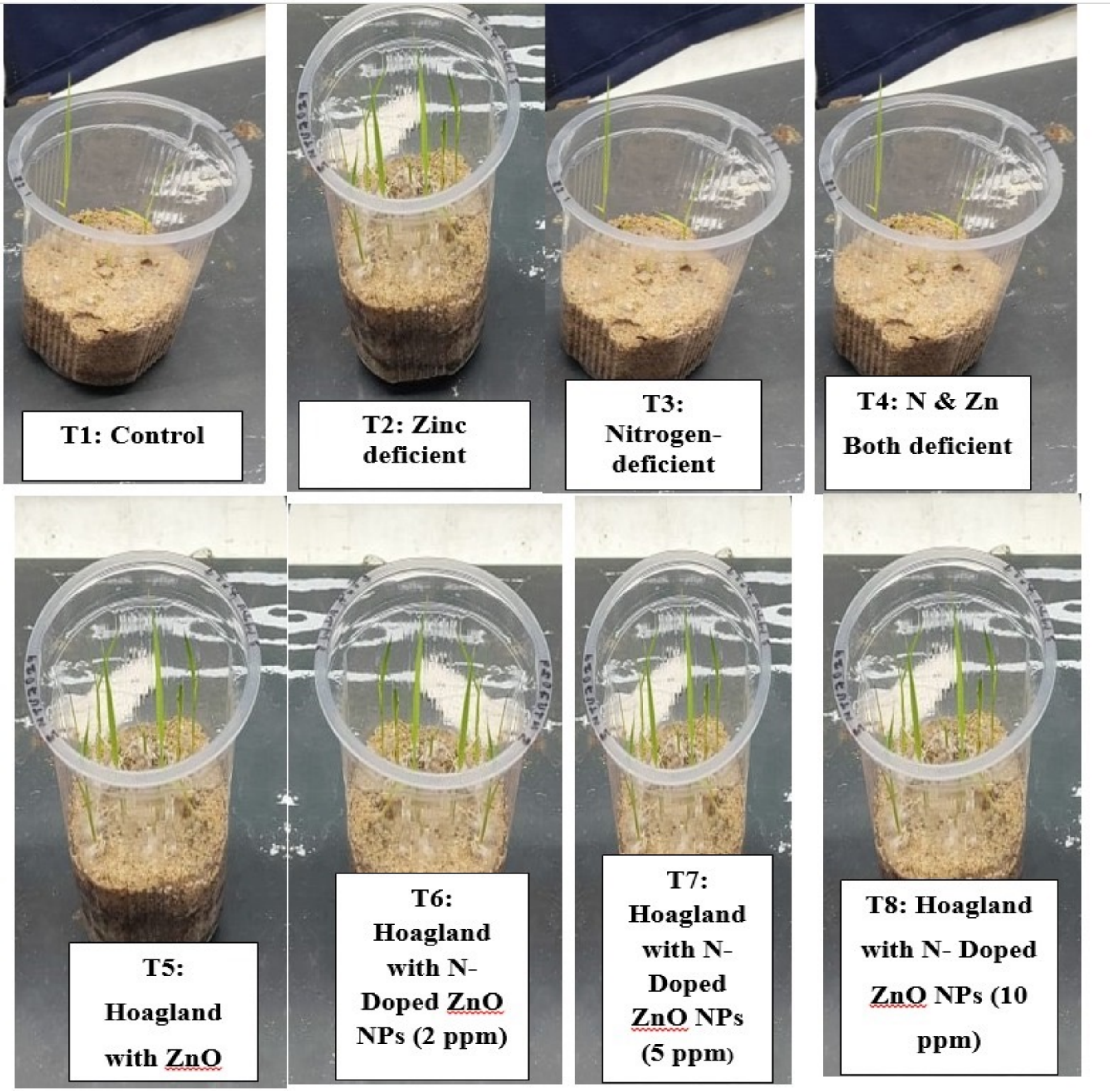

Figure 2. Growth response of rice under different treatments

nanoparticles, although these responses were lower than those observed in T8. A clear dose-dependent increase was evident across all evaluated growth and physiological parameters. Furthermore, N-doped ZnO NPs effectively alleviated zinc deficiency symptoms such as stunted growth and interveinal chlorosis, collectively indicating their agronomic effectiveness in rice.

Zinc-deficient (T2) and combined nitrogen- and zinc-deficient (T4) treatments resulted in marked reductions in shoot and root growth, indicating severe nutrient stress. In contrast, supplementation with ZnO nanoparticles (T5) partially restored plant growth compared to zinc-deficient plants. Among all treatments, application of nitrogen-doped ZnO nanoparticles at 10 ppm (T8) resulted in the highest shoot and root lengths in both crops. In rice, shoot length increased by approximately 59% relative to the zinc-deficient treatment, while maize exhibited an increase of approximately 32% under the same treatment. Lower concentrations of N–ZnO nanoparticles (2 and 5 ppm; T6 and T7) also promoted growth compared to zinc-deficient plants, though the effect was less pronounced than at 10 ppm. These results indicate a dose-dependent improvement in vegetative growth following N–ZnO nanoparticle application (Figures 3 & 4).

Application of N-doped ZnO NPs at 10 ppm enhanced approximately 59% & 32% shoot length in rice and maize, respectively, compared to Zn-deficient and nitrogen-deficient conditions. Even the lesser concentration of N-doped ZnO Nps, like 2 and 5 ppm (T6 & T7), showed a significant increase in shoot length in both crops as compared to Zn-deficient (T2) and undoped treatment (T5). Application of N-doped ZnO nanoparticles showed 31&15% increase in root length of rice and maize, respectively, compared to zinc-deficient, nitrogen, and sole undoped nanoparticles. There is a significant increase in root length at T6 and T7 as compared to zinc-deficient (T2) and undoped nanoparticle (T5) application.

Fresh and dry biomass accumulation

Fresh and dry biomass accumulation followed trends similar to those observed for shoot and root length. The lowest biomass values were recorded in zinc-deficient (T2) and nitrogen-plus zinc-deficient (T4) treatments, where plants exhibited stunted growth and pale foliage. Application of ZnO nanoparticles (T5) significantly improved biomass accumulation compared to zinc-deficient plants. However, the highest fresh and dry biomass in both rice and maize was recorded in plants treated with 10 ppm N–ZnO nanoparticles (T8). Treatments with 2 and 5 ppm N–ZnO nanoparticles yielded intermediate biomass values, indicating a concentration-dependent response. Overall, nitrogen doping of ZnO nanoparticles enhanced biomass production more effectively than undoped ZnO nanoparticles under zinc-deficient conditions (Figures 5 & 6).

Application of N-doped ZnO nanoparticles showed 65&78 % increase in root dry biomass of rice and maize, respectively, compared to zinc-deficient and sole undoped nanoparticles. There is a significant increase in root dry wt. at T6 and T7 as compare to zinc deficient (T2) and undoped nanoparticle application (T5).

Application of N-doped ZnO nanoparticles showed a 65% increase in shoot fresh biomass of rice and maize compared to zinc-deficient and sole undoped nanoparticles.

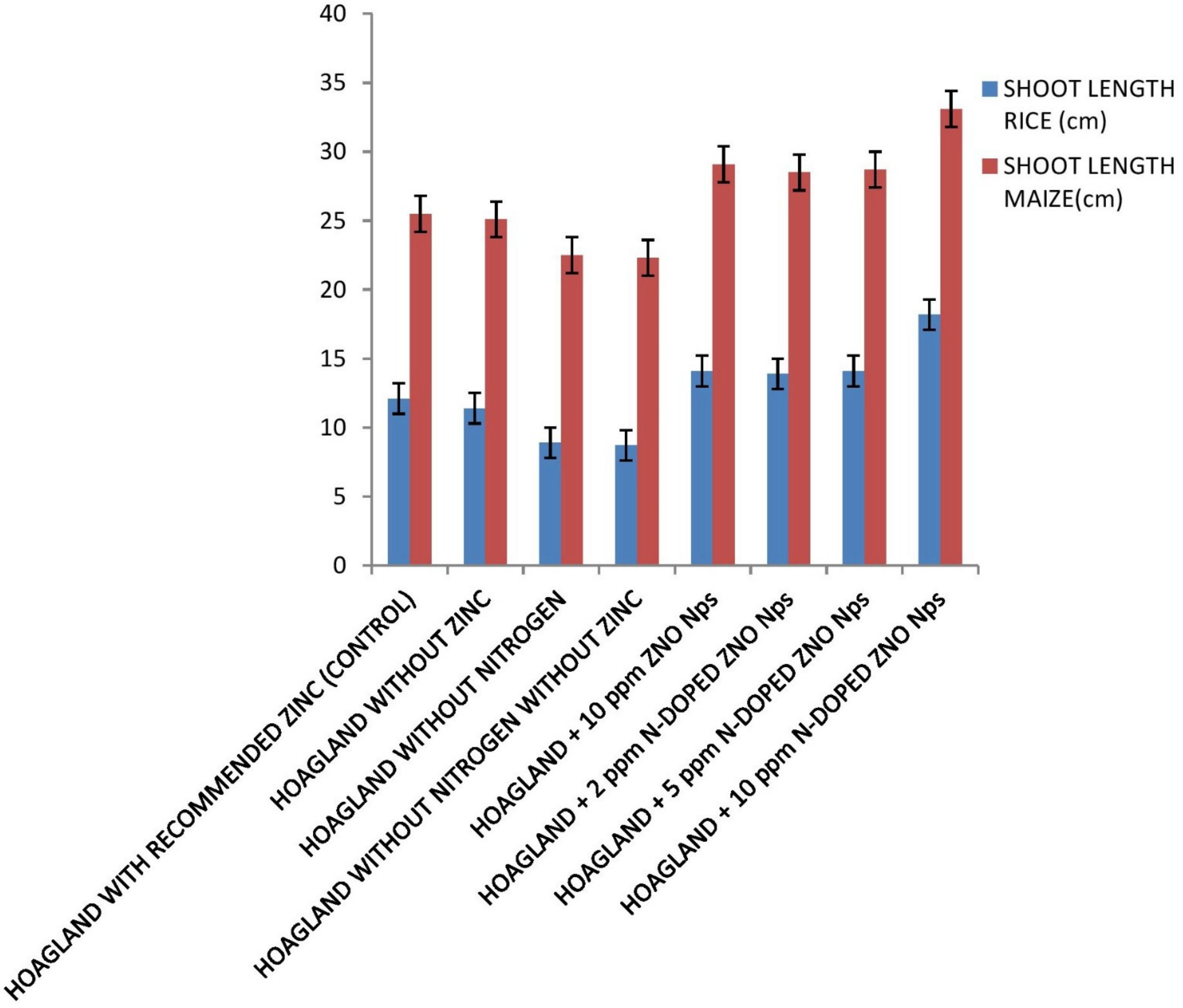

Figure 3. Showing an increase in shoot length in rice and maize in T8. Data are presented as mean ± SE (n = 3); Different letters indicate significant differences among treatments (one-way ANOVA, Tukey's test, $p \leq 0.05$)

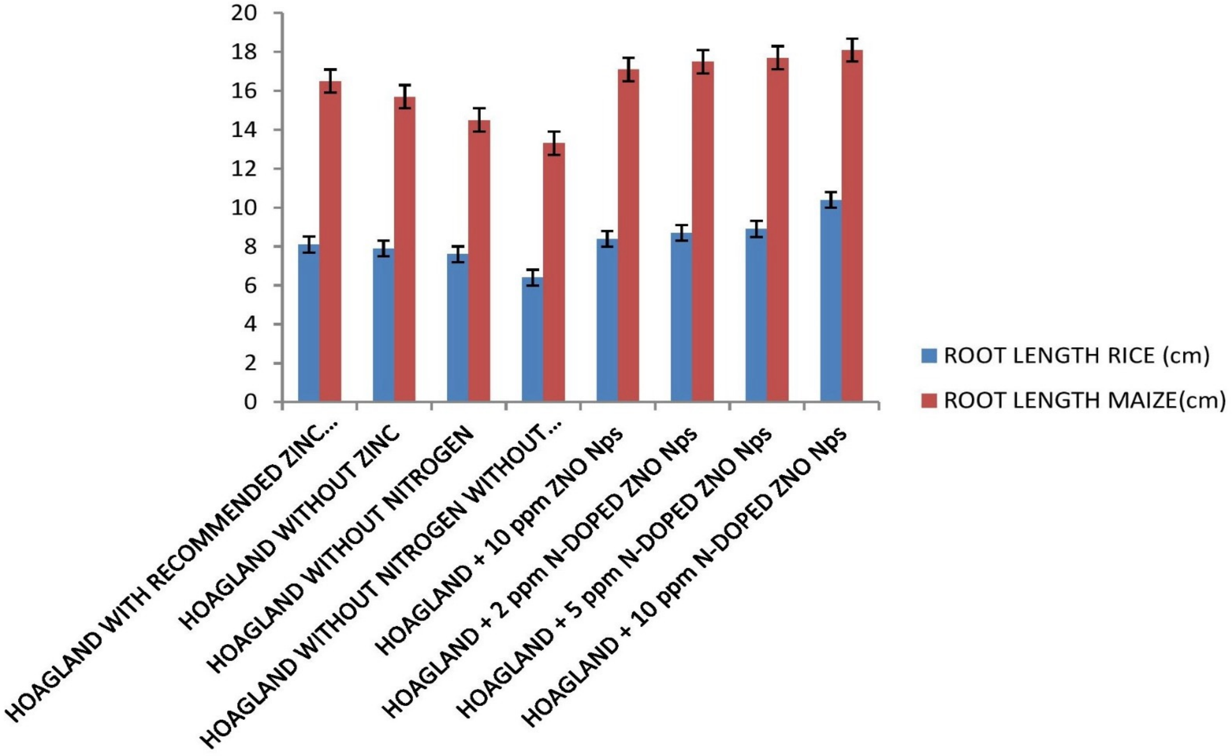

Figure 4. Showing an increase in root length in rice and maize in T8. Data are presented as mean ± SE (n = 3). Different letters indicate significant differences among treatments (one-way ANOVA, Tukey's test, $p \leq 0.05$)

There is a significant increase in shoot fresh biomass at T6 and T7 compared to zinc-deficient (T2) and undoped nanoparticle application (T5).

Chlorophyll content

The chlorophyll content of rice and maize leaves was significantly influenced by the nutrient treatments. Zinc-deficient plants exhibited reduced chlorophyll levels, reflecting impaired photosynthetic capacity. In contrast, plants treated with N–ZnO nanoparticles showed significantly higher chlorophyll content compared to zinc-deficient and nitrogen-plus-zinc-deficient treatments. The highest chlorophyll content was recorded in plants treated with 10 ppm N–ZnO nanoparticles (T8), followed by the treatment with ZnO nanoparticles (T5). These results indicate that nitrogen-doped ZnO nanoparticles effectively mitigated zinc deficiency–induced chlorophyll reduction in both crops (Figure 7).

Application of N-doped ZnO nanoparticles showed a 91%increase in chlorophyll content of rice and maize compared to zinc-deficient and sole undoped nanoparticles. There is a significant increase in Chlorophyll content at T6 and T7 as compared to zinc-deficient (T2) and undoped nanoparticle application (T5).

Visual assessment of deficiency symptoms

Clear visual differences were observed among treatments throughout the experimental period. Zinc-deficient and nitrogen-plus zinc-deficient plants exhibited characteristic deficiency symptoms, including interveinal chlorosis, reduced leaf expansion, and stunted growth. In contrast, plants treated with N–ZnO nanoparticles showed healthy green leaves and normal growth patterns. Notably, visible zinc deficiency symptoms were largely absent in plants receiving a 10 ppm N–ZnO nanoparticle treatment, further supporting the treatment's effectiveness in alleviating zinc deficiency stress.

The present study demonstrates that nitrogen-doped zinc oxide nanoparticles (N–ZnO NPs) significantly enhanced the growth performance of rice and maize under zinc-deficient conditions, compared with zinc-deficient controls and plants treated with undoped ZnO NPs. Improvements in shoot and root length, biomass accumulation, chlorophyll content, and visible alleviation of deficiency symptoms collectively indicate that nitrogen doping enhances the agronomic effectiveness of ZnO nanoparticles. Zinc deficiency is known to impair photosynthesis, enzyme activation, hormone regulation, and overall metabolic activity in plants, leading to stunted growth and reduced biomass. In agreement with earlier studies reporting the beneficial effects of ZnO nanoparticles in cereals, the application of ZnO NPs in the present study partially restored growth and physiological parameters under zinc-deficient conditions. However, the superior performance

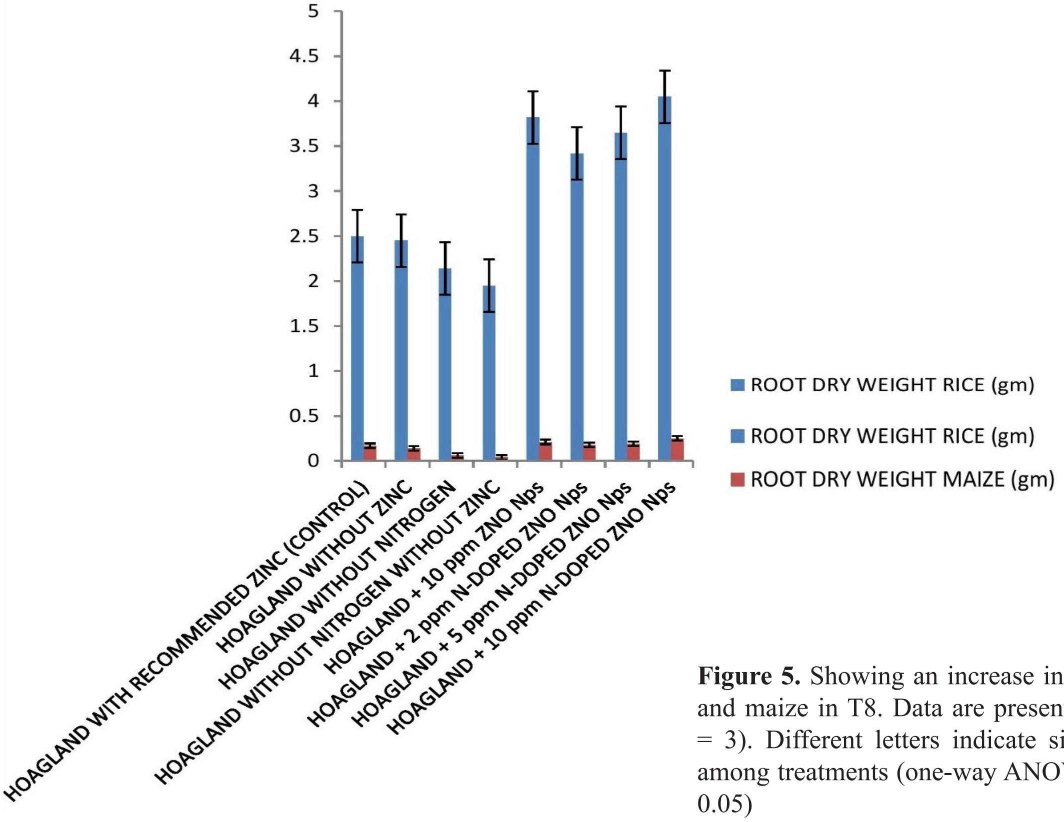

Figure 5. Showing an increase in root biomass in rice and maize in T8. Data are presented as mean ± SE (n = 3). Different letters indicate significant differences among treatments (one-way ANOVA, Tukey's test, $p \leq 0.05$)

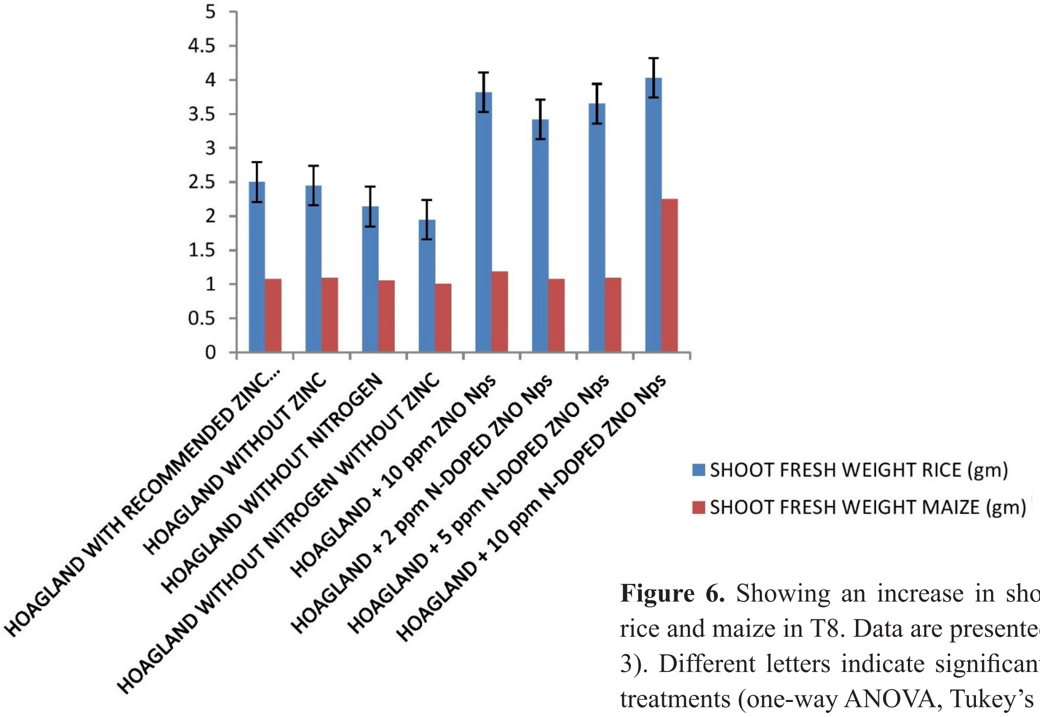

Figure 6. Showing an increase in shoot fresh biomass in rice and maize in T8. Data are presented as mean ± SE (n = 3). Different letters indicate significant differences among treatments (one-way ANOVA, Tukey's test, $p \leq 0.05$)

observed with N–ZnO nanoparticles suggests that nitrogen doping can further enhance the functional properties of ZnO-based nanofertilizers. The enhanced growth response in plants treated with N–ZnO nanoparticles may be attributed to improved physicochemical properties resulting from nitrogen incorporation into the ZnO lattice, including

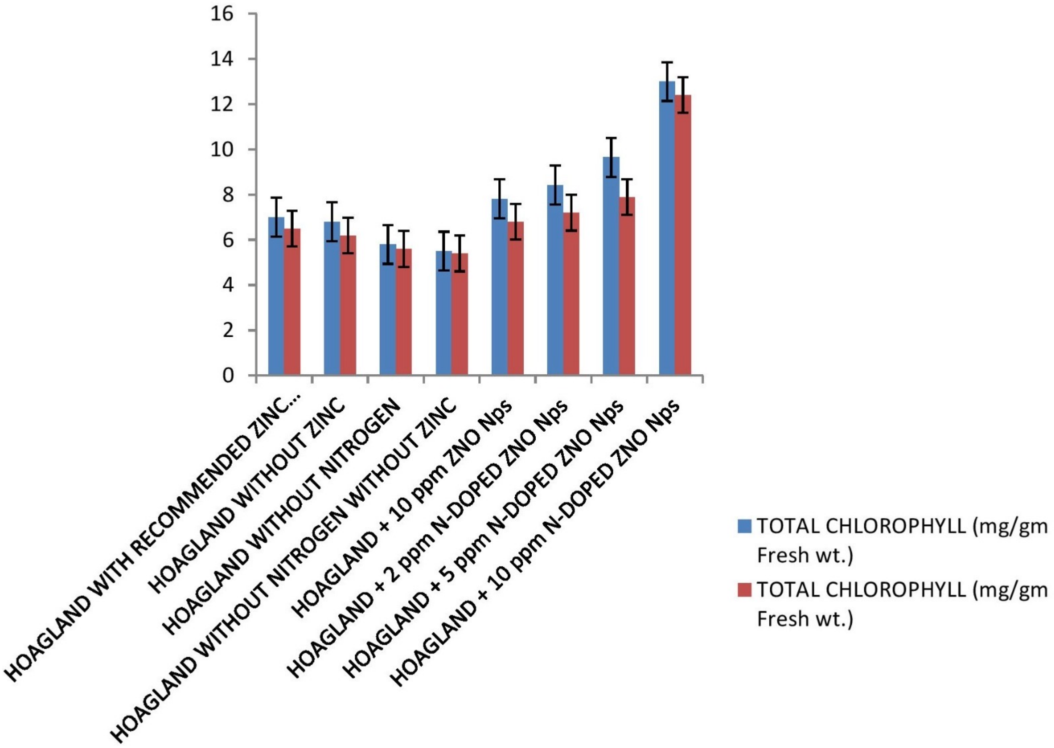

Figure 7. Showing an increase in chlorophyll content in rice and maize in T8. Data are presented as mean ± SE (n = 3). Different letters indicate significant differences among treatments (one-way ANOVA, Tukey's test, $p \leq 0.05$)

enhanced dispersibility, stability, and surface reactivity. Although the present study did not directly quantify zinc or nitrogen uptake, the observed improvements in biomass and chlorophyll content suggest a more effective alleviation of zinc deficiency stress compared to undoped ZnO nanoparticles. Similar enhancements in plant performance have been reported with other doped or modified nanomaterials, including calcium-doped zinc oxide nanoparticles in maize and wheat, metal-doped iron oxide nanoparticles in barley, and nitrogen-doped TiO_2 nanoparticles in legume crops, which support the concept that material engineering can improve nanofertilizer efficiency[28,29,30]. Previous studies investigating zinc nutrition in cereals have primarily focused on bulk fertilisers or undoped ZnO nanoparticles. In contrast, the present work explores nitrogen-doped ZnO nanoparticles as a modified nanofertilizer, representing a novel approach for addressing zinc deficiency in rice and maize. The findings indicate that nitrogen doping offers a potential strategy to enhance the performance of ZnO nanomaterials without increasing fertiliser dosage, which is advantageous from both agronomic and environmental perspectives. Despite the promising results observed under controlled conditions, this study has certain limitations. The experiments were conducted in a sand-based pot system, which does not fully replicate the complexity of field soils. Furthermore, the long-term impacts of nanoparticle application on soil microbial communities, nutrient cycling, and food safety have not been evaluated. Therefore, future research should focus on field-level validation, detailed nutrient uptake studies, and comprehensive biosafety assessments to establish the practical feasibility and sustainability of nitrogen-doped ZnO nanoparticles as agricultural inputs.

Nitrogen-doped zinc oxide nanoparticles (N–ZnO NPs) were successfully synthesised and evaluated for their potential as nanofertilizers under zinc-deficient conditions. The application of N–ZnO nanoparticles significantly improved shoot and root growth, biomass accumulation, and chlorophyll content in rice and maize compared to zinc-deficient treatments and undoped ZnO nanoparticles. These results indicate that nitrogen doping enhances the agronomic effectiveness of ZnO nanoparticles in alleviating zinc deficiency–induced growth limitations in cereal crops. Compared to conventional ZnO nanoparticles, N–ZnO nanoparticles exhibited superior growth-promoting effects, suggesting that material modification through nitrogen doping can improve the functional performance of zinc-based nanofertilizers. Although the present study was conducted under controlled pot conditions, the findings provide proof-of-concept evidence for the use of doped nanomaterials as an alternative strategy to improve micronutrient management in cereals. Overall, this study highlights the potential of nitrogen-doped ZnO nanoparticles as an effective nanofertilizer for mitigating zinc deficiency in rice and maize. Further investigations under field conditions, along with detailed assessments of nutrient uptake and long-term biosafety, are required to validate the agronomic feasibility and environmental sustainability of these approaches.

The synergistic interaction between microbial inoculants and zinc-based nanomaterials, particularly nitrogen-coated zinc oxide nanoparticles (N-ZnO NPs), has emerged as a promising strategy for enhancing nutrient use efficiency and sustainable crop production. Such integrated approaches can improve zinc availability, stimulate plant growth–promoting activities, and simultaneously reduce the required dosage of nanoparticles, thereby minimizing potential environmental toxicity and accumulation in soil ecosystems[31,32]. Beneficial rhizospheric microorganisms, including plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, can further regulate nanoparticle transformation, dissolution, stability, and bioavailability within the rhizosphere, influencing nutrient uptake dynamics in crops such as rice and maize. Moreover, microbial-mediated biotransformation of nanoparticles may reduce oxidative stress and improve soil biological health under zinc-deficient conditions[33]. However, despite these promising outcomes, comprehensive investigations on nano–microbe interactions, long-term biosafety, ecotoxicological implications, and field-scale validation remain limited. Therefore, future research should prioritize the development of eco-friendly integrated nutrient management systems combining microbial inoculants with engineered nanomaterials to achieve sustainable zinc nutrition, enhanced crop productivity, and environmental safety in agricultural systems[34].

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

1. **Cakmak, I., McLaughlin, M.J., White, P. (2017).** Generating demand for zinc for better crop production and human health. Plant Soil. 411: 1. https://doi.org/10.1007/s11104-016-3166-9
2. **Hafeez, B., Khanif, Y.M., Saleem, M. (2013).** Role of zinc in plant nutrition: A review. Am. J. Exp. Agric. 3:2. https://doi.org/10.9734/AJEA/2013/2746
3. **Zewide, I., Shiferaw, A. (2021).** Review on effect of micronutrients for crop production. Nutr. Food Process. 4: 7. https://doi.org/10.31579/2637-8914/063
4. **Natasha, N., Shahid, M., Bibi, I., et al. (2022).** Zinc in soil–plant–human system: A data-analysis review. Sci. Total Environ. 808: 152024. https://doi.org/10.1016/j.scitotenv.2021.152024
5. **Kumar, D., Patel, K.P., Ramani, V.P., Shukla, A.K., Meena, R.S. (2020).** Management of micronutrients in soil for nutritional security. In R.S. Meena (Ed.), Nutr. Dyn. Sustain. for Sustain. Crop Prod. Springer, Singapore. https://doi.org/10.1007/978-981-13-8660-2_4
6. **Adhikary, S., Bihari, B., Kundu, R., Dutta, J., Mukherjee, A.K. (2019).** Essentiality with factor influencing accessibility of zinc in crops and human. Int. J. Curr. Microbiol. App. Sci. 8: 11. https://doi.org/10.20546/ijcmas.2019.811.250
7. **Zinzala, V.N., Narwade, A.V. (2019).** Effect of zinc applications on grain yield, straw yield and harvest index in kharif rice (*Oryza sativa* L.) genotypes. Int. J. Curr. Microbiol. App. Sci. 8: 11 https://doi.org/10.20546/ijcmas.2019.811.004
8. **Wissuwa, M., Ismail, A.M., Yanagihara, S. (2006).** Effects of zinc deficiency on rice growth and genetic factors contributing to tolerance. Plant Physiol. 142: 2. https://doi.org/10.1104/pp.106.085225
9. **Mattiello, E.M., Ruiz, H.A., Neves, J.C.L., Ventrella, M.C., Araújo, W.L. (2015).** Zinc deficiency affects physiological and anatomical characteristics in maize leaves. J. Plant Physiol. 183: 138.
10. **Silva, A.B.P., Borges, L.F.S., Lucini, F., Gutiérrez, N., Santos, E.F. (2025).** Technologies in agronomic biofortification with zinc in Brazil: A rev. Plants. 14: 12. https://doi.org/10.3390/plants14121828
11. **Yadav, A., Yadav, K., Abd-Elsalam, K.A. (2023).** Nanofertilizers: Types, delivery and advantages in agricultural sustainability. Agrochem. 2: 2. https://doi.org/10.3390/agrochemicals2020019
12. **Minello, L.V.P., Kuntzler, S.G., Berghahn, E., Dorneles, L.T., Ricachenevsky, F.K., Sperotto, R.A. (2025).** Nanotechnology-driven biofortification of Fe, Zn, and Se in edible plants. J. Nanobiotechnol. 23: 1. https://doi.org/10.1186/s12951-025-03746-8
13. **Khan, S., Zahoor, M., Ullah, R., Khan, R.S. (2025).** The uptake and mechanism of action of nanoparticles and doped nanoparticles on plant growth and metabolite enrichment. Environ. Technol. Rev. 14: 1.
14. **Yan, S., Wu, F., Zhou, S., Yang, J., Tang, X., Ye, W. (2021).** Zinc oxide nanoparticles alleviate the arsenic toxicity and decrease the accumulation of arsenic in rice (*Oryza sativa* L.). BMC Plant Biol. 21: 1. https://doi.org/10.1186/s12870-021-02929-3
15. **Wang, P., Menzies, N.W., Lombi, E., et al. (2013).** Fate of ZnO nanoparticles in soils and cowpea (*Vigna unguiculata*). Environ. Sci. and Technol. 47: 23. https://doi.org/10.1021/es403466p
16. **Zhang, H., Wang, R., Chen, Z., et al. (2021).** The effect of zinc oxide nanoparticles for enhancing rice (*Oryza sativa* L.) yield and quality. Agric. 11: 12. https://doi.org/10.3390/agriculture11121247
17. **Stoleriu, S., Lungu, C., Ghituica, C.D., et al. (2020).** Influence of dopant nature on biological properties of ZnO thin-film coatings on Ti alloy substrate. Nanomater. 10: 1. https://doi.org/10.3390/nano10010129
18. **Shenoy, R.U.K., Rama, A., Govindan, I., Naha, A. (2022).** The purview of doped nanoparticles: Insights into their biomedical applications. OpenNano. 100070. https://doi.

org/10.1016/j.onano.2022.100070

19. **Ye, J.Y., Tian, W.H., Jin, C.W. (2022).** Nitrogen in plants: From nutrition to the modulation of abiotic stress adaptation. Stress Biol. 2: 1. https://doi.org/10.1007/s44154-021-00030-1
20. **Ji, C., Li, J., Jiang, C., et al. (2022).** Zinc and nitrogen synergistic act on root-to-shoot translocation and preferential distribution in rice. J. Adv. Research. 35: 187. https://doi.org/10.1016/j.jare.2021.04.005
21. **Akram, M.A., Depar, N., Memon, M.Y. (2017).** Synergistic use of nitrogen and zinc to bio-fortify zinc in wheat grains. Eurasian J. Soil Scien. 6: 4. https://doi.org/10.18393/ejss.306698
22. Padhy, A.K., Chetia, B., Mishra, S., Pati, A., Iyer, P.K. (2010). Imidazole derivatives as the organic precursor of ZnO nanoparticles. Tetrahedron Lett. 51: 20. https://doi.org/10.1016/j.tetlet.2010.03.058
23. **Raj, B., Padhy, A.K., Singh, G.P., Dey, R.K., Oraon, R. (2020).** Imidazole framework-based metal oxide nanoparticles as photocatalysts: An approach towards degradation of environmental pollutants. In Nano-Materials as Photocatalysts for Degradation of Environmental Pollutants. Elsevier. https://doi.org/10.1016/B978-0-12-818598-8.00010-9
24. **Sharma, D., Narasimhan, B., Kumar, P., et al. (2009).** Synthesis, antimicrobial and antiviral evaluation of substituted imidazole derivatives. Eur. J. Med. Chem. 44: 6. https://doi.org/10.1016/j.ejmech.2008.08.010
25. **Geremew, A., Stovall, L., Woldesenbet, S., Ma, X., Carson, L. (2025).** Nanopriming with zinc oxide: A novel approach to enhance germination and antioxidant systems in amaranth. Front. Plant Scie. 16. https://doi.org/10.3389/fpls.2025.1599192
26. **Rai-Kalal, P., Jajoo, A. (2021).** Priming with zinc oxide nanoparticles improves germination and photosynthetic performance in wheat. Plant Physiol. Biochem. 160: 341.
27. **Lichtenthaler, H.K., and Wellburn, A.R. (1983).** Determinations of total carotenoids and chlorophylls a and b of leaf extracts in different solvents. Biochem. Soc. Trans. 11: 5. https://doi.org/10.1042/bst0110591
28. **Patil, B.M., Patil, V.L., Bhosale, S.R. (2024).** Field application of Ca-doped ZnO nanoparticles to maize and wheat plants. Plant Physiol. Biochem. 210: 108552. https://doi.org/10.1016/j.plaphy.2024.108552
29. **Vaishali, K., Nirmala, M., Pavithra, N., Balakrishnan, K. (2024).** Sol–gel synthesis of undoped and nitrogen-doped titanium dioxide nanoparticles as nano fertilizer for plant growth. Int. J. Nano Dimens. 15: 4. https://doi.org/10.57647/J.IJND.2024.1504.30
30. **Zhao, L., Peralta-Videa, J.R., Varela-Ramirez, A. (2012).** Effect of surface coating and organic matter on the uptake of CeO_2 nanoparticles by corn plants grown in soil: Insight into the uptake mechanism. J. Hazard. Mater. 225: 226, .https://doi.org/10.1016/j.jhazmat.2012.05.008
31. **Dimkpa, C.O. and Bindraban, P.S. (2018).** Nanofertilizers: New products for the industry? Journal of Agricultural and Food Chemistry. 66(26): 6462–6473. https://doi.org/10.1021/acs.jafc.8b03840
32. **Raliya, R., Saharan, V., Dimkpa, C. and Biswas, P. (2018).** Nanofertilizer for precision and sustainable agriculture: Current state and future perspectives. Journal of Agricultural and Food Chemistry. 66(26): 6487–6503. https://doi.org/10.1021/acsagscitech.4c00290
33. **Gupta, N., Yadav, K.K., Kumar, V., et al. (2022).** Nano-biofertilizer: Emerging eco-friendly approach for sustainable agriculture and environmental remediation. Environmental Research. 210: 112965. https://doi.org/10.1007/s40011-019-01133-6
34. **Rizwan, M., Ali, S., Ali, B., et al. (2019).** Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress in wheat. Chemosphere. 214: 269–277. https://doi.org/10.1016/j.chemosphere.2018.09.120
35. **Singh, D., Prasanna, R. and Saxena, A.K. (2021).** Role of microbial inoculants and nanotechnology in sustainable agriculture: Opportunities and challenges. Frontiers in Microbiology. 12: 634414.