PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.12722

eISSN 2348-1900

RESEARCH ARTICLE

Effect of different concentrations of iron and zinc nanoparticles on the growth and yield of groundnut (*Arachis hypogaea* L.)

Md. Mahmudul Hasan Manik[1], Aysha Siddika Jarin[2], Rashiduzzaman Emran[3], Mahbubur Rahman Khan[1], Md. Selim Reza[1] & Md Asadujjaman Rasel[4]*

[1]Bangladesh Institute of Nuclear Agriculture, Mymensingh 2202, Bangladesh
[2]Department of Agronomy, Gazipur Agricultural University, Gazipur 1706, Bangladesh
[3]Department of Agricultural Extension, Nalitabari 2110, Bangladesh
[4]Bangladesh Sugarcrop Research Institute, Ishwardi, Pabna 6620, Bangladesh

*Correspondence email - asadrasel65@gmail.com

Received: 13 November 2025; Accepted: 05 March 2026; Available online: Version 1.0: 27 April 2026

Cite this article: Manik MMH, Jarin AS, Emran R, Khan MR, Reza MS, Rasel MA. Effect of different concentrations of iron and zinc nanoparticles on the growth and yield of groundnut (*Arachis hypogaea* L.). Plant Science Today (Early Access). https://doi.org/10.14719/pst.12722

Abstract

Groundnut (*Arachis hypogaea* L.) is an important legume crop cultivated for its oil and protein content and widely used for human consumption and animal feed. However, its productivity is often limited by micronutrient deficiencies, particularly zinc (Zn) and iron (Fe), especially in calcareous soils. This investigation was conducted to determine the effect of foliar application of zinc and iron nanoparticles on the growth and yield of groundnut to identify the optimal concentration under field conditions. A field experiment was conducted at the Bangladesh Institute of Nuclear Agriculture (BINA), Sub-station Sunamganj, following a randomised complete block design (RCBD) with 17 treatments and 3 replications. The treatments consisted of different concentrations and combinations of Zn and Fe nanoparticles applied as foliar sprays. Growth parameters and yield attributes were recorded and analysed statistically. The results showed that foliar application of Zn and Fe nanoparticles significantly influenced growth and yield parameters. The combined treatment Zn_{100} + Fe_{50} mg L^{-1} (T_8) produced the highest biomass accumulation, pod number and grain yield compared to other treatments. Higher concentrations did not result in further yield improvement, indicating a concentration-dependent response. These findings suggest that moderate combined application of Zn and Fe nanoparticles may enhance growth and yield performance of groundnut under the tested conditions. Further studies incorporating detailed soil and nanoparticle characterisation are recommended to strengthen mechanistic understanding.

Keywords: groundnut; iron nanoparticles; micronutrient deficiency; nanofertilisers; plant biomass; pod yield; zinc nanoparticles

Introduction

Groundnut (*Arachis hypogaea* L.) is an important oilseed and protein-rich legume widely cultivated in tropical and subtropical regions (1). Peanut kernels are rich in oil (44–55 %), protein (22–30 %), carbohydrate (20 %) and fiber content (5 %) which make an excellent source of nutritional value for both human and animal consumption (2). Its productivity is frequently limited by micronutrient deficiencies, particularly zinc (Zn) and iron (Fe), which are common in calcareous and alkaline soils. Moreover, groundnut restores nitrogen into the soil by fixing it without affecting unrenewable resources or troubling balance in the environment and thus is predicted as one of the most crucial legume crops (3). Worldwide, groundnut is cultivated in 30.54 Mt ha with a total production of 54.23 Mt and average productivity of 1.7 t ha^{-1} (4). In Bangladesh, according to BBS 2021–2022, 97874.91 acres land used to produce 75030.85 Mt of groundnuts (5).

Micronutrient deficiency is one of the important reasons for poor groundnut yield. For calcareous soils, the restricted use of fertiliser and poor organic matter condition, soil salinity and drought stress are key factors causing nutrient deficiency in many arid regions where alkaline pH is common (6, 7). Micronutrients are essential for physiological processes for many functions such as respiration, cell elongation, cell maturity, meristematic tissue formation and protein synthesis (8). Zinc is a vital element for biomass production, which necessitates it to enable the production of chlorophyll, functionality and fertilisation of pollen (9). Zinc is involved in auxin metabolism, membrane stabilisation and enzyme activation, while iron is essential for chlorophyll synthesis, electron transport and nitrogen metabolism. Like Zn, Fe is necessary for all forms of life and required in many processes (10). Deficiency of these micronutrients in groundnut results in reduced growth, chlorosis, impaired pod development and ultimately lower yield. Iron is an essential component of numerous proteins, plant pigments (11) and cellular functions such as chlorophyll synthesis, photosynthesis, chloroplast development and dark respiration. Iron activates several metabolic pathways and it is a central element in electron chains and co-factor of numerous essential enzymes. The iron starvation induces structural and functional modifications of the entire photosynthetic apparatus in higher plants with disturbance in photosystems stoichiometry and lipid composition, as well as modification of chlorophyll a:b ratio (12). Iron is also required for the function of rubisco and functions in stomatal closure (13). Restricted Fe availability in the soil is a primary restriction to yield and quality of agricultural crops all over the world, especially in alkaline and calcareous soils in semi-arid regions (14). To address the rising food requirements for rising population, production and productivity need to be enhanced. Improving micronutrient use efficiency is therefore critical for enhancing groundnut productivity.

Nanotechnology has been extensively used for the source of fertilisers due to the high competency and homogenous settlement of nano form of the nutrients within the plants. Nanoparticles are being widely applied to enhance crop resistance to abiotic and biotic stresses and are used in nano fertilisers. They influence plants on morphological, physiological, biochemical, genetic and molecular level (15). Nanotechnology boosts crop yields by improving water use, nutrient uptake, pest and disease resistance, pathogen detection and environmental protection (16). Furthermore, nanoparticles improve the uptake and transport of K, P and N, highlighting nanotechnology's potential to advance agriculture rapidly (17). Nanotechnology can address nutrient deficiencies by converting chemicals into more bioavailable form (18). Zinc application significantly increases plant height, dry matter accumulation and overall growth in groundnut (19, 20). Foliar and soil Zn application improves leaf chlorophyll content and physiological performance (13). Therefore, nano fertilisers can boost crop yields and enhance nutrient content in edible parts by improving the absorption of ions, water and nutrients (21). Zinc significantly improves pod yield, kernel weight, oil content and protein content (22, 23). Iron increases nodulation and supports nitrogen fixation in groundnut (24–26). The use of nanoparticles can enhance agricultural productivity by reducing fertiliser overuse and improving resource efficiency. Metallic nanoparticles have been shown to boost photosynthesis, stress tolerance and increase redox potential, proline, chlorophyll and photosynthesis levels (27). Although several studies have examined individual applications of Zn and Fe nanoparticles in different crops, limited field-based evidence exists regarding their combined dose-dependent effects on groundnut under Bangladesh agro-ecological conditions. Therefore, the present study was conducted to evaluate the effects of different concentrations of foliar-applied zinc and iron nanoparticles on growth and yield attributes of groundnut (*Arachis hypogaea* L.) under field conditions, with the objective of identifying an optimal concentration range.

Materials and Methods

A field experiment was done at the experimental farm of the Bangladesh Institute of Nuclear Agriculture (BINA), Sub-station Sunamganj. The experiment aimed to assess the outcome of foliar-applied Fe and Zn nanoparticles on the growth and yield of groundnut. The plot size was 3 × 2 m. The experiment was carried out with the variety Binachinabadam-8. Groundnut variety Binachinabadam-8 was sown on 26 January 2025 during the rabi season under typical subtropical climatic conditions. During the crop growth period, average temperatures ranged approximately between 18–30 °C with relatively low rainfall, which is characteristic of the dry winter season. Seeds were planted at a spacing of 30 cm between rows and 15 cm between plants. The recommended dose of fertilisers (RDF) was applied as basal dose at the rate of 18 kg N ha^{-1}, 79 kg P_2O_5 ha^{-1} and 78 kg K_2O ha^{-1}. Irrigation was provided as required, with major irrigations applied at flowering and pod development stages to ensure optimal crop growth. Standard intercultural operations such as weeding and pest management were performed uniformly across all treatments. The study was conducted using a randomised complete block design (RCBD) with 3 replications and 17 treatments, including various concentrations and combinations of Fe and Zn nanoparticles. Randomised complete block design was chosen to minimise the effects of field variability on treatment comparison. Total plots were (17 × 3): 51 and treatments were T_0 = Control, T_1 = RDF, T_2 = RDF + Zn_{100} mg L^{-1} foliar spray, T_3 = RDF + Zn_{150} mg L^{-1} foliar spray, T_4 = RDF + Zn_{200} mg L^{-1} foliar spray, T_5 = RDF + Fe_{50} mg L^{-1} foliar spray, T_6 = RDF + Fe_{100} mg L^{-1} foliar spray, T_7 = RDF + Fe_{150} mg L^{-1} foliar spray, T_8 = RDF + Zn_{100}+ Fe_{50} mg L^{-1} foliar spray, T_9 = RDF + Zn_{100}+ Fe_{100} mg L^{-1} foliar spray, T_{10}= RDF + Zn_{100}+ Fe_{150} mg L^{-1} foliar spray, T_{11} = RDF + Zn_{150}+ Fe_{50} mg L^{-1} foliar spray, T_{12} = RDF + Zn_{150}+ Fe_{100} mg L^{-1} foliar spray, T_{13} = RDF + Zn_{150}+ Fe_{150} mg L^{-1} foliar spray, T_{14} = RDF + Zn_{200}+ Fe_{50} mg L^{-1} foliar spray, T_{15} = RDF + Zn_{200}+ Fe_{100} mg L^{-1} foliar spray, T_{16} = RDF + Zn_{200}+ Fe_{150} mg L^{-1} foliar spray.

Growth parameters such as plant height, branches per plant, number of leaves, root length, plant fresh weight, plant dry weight and yield parameters including number of pods per plant, pod length and yield were recorded and analysed. Iron and zinc nanoparticles were prepared at BINA Sub-station Sunamganj. Iron oxide (FeO) or zinc oxide (ZnO) nanoparticles were prepared by dissolving 0.1 M ferrous sulfate ($FeSO_4$ for iron oxide) or zinc sulfate ($ZnSO_4$ for zinc oxide) in 25 mL of distilled water. To this solution, 0.1 M polyethylene glycol (PEG) was added, followed by the addition of 25 mL of 0.2 M sodium hydroxide and 0.1 mL of 0.1 M sodium borohydride (28). The mixture was vigorously stirred at room temperature, resulting in the formation of a black precipitate for FeO and a white precipitate for ZnO. The precipitates were then washed with distilled water and dried in a vacuum oven at 70 °C. The resulting nanoparticle samples were stored in distilled water. The concentration of the nanoparticles was determined through differential weight analysis. Foliar sprays of Zn and Fe nanoparticles were applied during the active vegetative and early reproductive growth stages. Two foliar applications were conducted at 15 days intervals, starting from the early vegetative phase through to the onset of flowering. Sprays were applied in the morning (8:00–10:00 AM) to minimise evaporation and maximise leaf uptake, using a hand sprayer to ensure uniform foliar coverage.

Nanoparticle size distribution and surface charge (zeta potential) could not be measured due to limited access to DLS/SEM/TEM facilities during the experimental period. Therefore, detailed physicochemical characterisation (particle size, morphology and zeta potential) was not performed. Similarly, initial physico-chemical properties of the experimental soil, including pH, texture, organic matter content and baseline available Zn and Fe, were not analysed prior to treatment application due to unavailability of soil-testing facilities. These limitations are acknowledged in the present study and future experiments will include comprehensive nanoparticle characterisation and complete baseline soil analysis to strengthen interpretation and reproducibility of results.

Data were analysed using R software (version 4.5.2). Analysis of variance (ANOVA) was performed following the RCBD model to determine the effects of treatments on growth and yield parameters. Treatment means were compared using the least significant difference (LSD) test at the 5 % level of significance ($p \leq 0.05$). Results are presented as mean values of 3 replications. Coefficient of variation (CV %) was calculated to assess experimental precision.

Results

Growth parameter

The growth parameters of groundnut exhibited considerable variance under different treatments involving various concentrations of iron (Fe) and zinc (Zn) nanoparticles (Table 1). Values presented in Tables 1 and 2 represent means of 3 replications and treatment differences were determined using LSD at $p \leq 0.05$. The results showed that the tallest plants were observed in treatment T_1 (RDF), with a height of 63.20 cm, which was statistically comparable to T_9 and T_3 according to LSD grouping at $p \leq 0.05$. The number of branches per plant was highest in treatment T_{14} (Zn_{200} + Fe_{50} mg L^{-1}), with 12.67 branches, followed by T_8 (11.90 branches). The control treatment (T_0) had the highest leaf count (100 leaves plant^{-1}), though this was associated with lower fresh and dry weights, indicating nutrient stress. In contrast, treatment T_8 exhibited fewer leaves but higher biomass production, suggesting more efficient nutrient utilisation. Root length was significantly greater in Treatments T_6 (17.60 cm) and T_{13} (17.40 cm), indicating enhanced root development under specific nanoparticle applications. Treatment T_8 also recorded the highest fresh weight (194.67 g) and dry weight (93.33 g), which were significantly superior to most other treatments based on LSD comparison. These findings suggest that foliar application of zinc and iron nanoparticles, particularly in combination (T_8), can significantly enhance growth parameters, contributing to better nutrient uptake and efficient biomass partitioning in groundnut cultivation.

Yield and yield contributing characters

Iron and zinc nanoparticles at different doses influence the yield parameters of groundnut in different treatments (Table 2). The highest number of pods per plant was recorded in T_8 (RDF + Zn_{100} + Fe_{50} mg L^{-1}), followed by T_6 33.90 pods) and T_{11} (33.77 pods). The longest pod length recorded was in treatments T_2 and T_{14} with a value of 3.17 cm each, whereas the lowest pod length was observed under control treatment (T_0= 2.67 cm). In yield terms, treatment T_8 also presented with the highest yield (3.00 t ha^{-1}), which was significantly higher compared to all other treatments. The second optimal results were in the treatments T_2 (2.73 t ha^{-1}) and T_{13} (2.70 t ha^{-1}). The enhancements in pod number, pod length and total yield of T_8 are probably due to the combinational effect of Fe and Zn nanoparticles application that promoted plant growth and nutrient uptake. These findings further highlight the possibility of utilising nanoparticle-based fertilisers for enhancing growth and yield of groundnut crops, which might provide an innovative alternative for enhancing crop yields by nanotechnology.

Table 2. Effect of iron and zinc nanoparticles on different yield parameter

Treatment	No. of pod plant^{-1}	Pod length (cm)	Yield (t ha^{-1})
T_0	27.80	2.67 d	2.50 efg
T_1	28.90	2.93 abcd	2.70 bc
T_2	30.87	3.17 a	2.73 b
T_3	28.67	2.97 abcd	2.33 hi
T_4	26.10	2.70 cd	2.23 i
T_5	25.00	2.87 abcd	2.53 ef
T_6	33.90	2.97 abcd	2.57 de
T_7	31.43	2.70 cd	2.67 bcd
T_8	34.00	2.73 bcd	3.00 a
T_9	26.10	3.10 abc	2.43 fgh
T_{10}	33.67	2.83 abcd	2.43 fgh
T_{11}	33.77	3.13 ab	2.53 ef
T_{12}	32.43	2.83 abcd	2.60 cde
T_{13}	31.90	2.93 abcd	2.70 bc
T_{14}	32.33	3.17 a	2.37 h
T_{15}	26.20	3.00 abcd	2.37 h
T_{16}	29.90	3.13 ab	2.40 gh
CV (%)	9.98	8.75	2.78

Means within a column followed by the same letter(s) do not differ significantly according to the LSD test at $p \leq 0.05$. Where no letters are shown, treatment effects were non-significant (NS).

Analysis of multivariate data

The cluster heatmap representing the associations between different treatments (T_0 to T_{16}) and the growth/yield parameters of groundnut is shown in Fig. 1. Hierarchical clustering grouped treatments according to similarity in trait responses. Fresh weight, dry weight, pod number and grain yield clustered closely together, indicating positive associations among these parameters. T_8 clustered with treatments showing higher biomass and yield traits, whereas higher concentration treatments formed separate clusters, reflecting distinct response patterns. The colour scale is

Table 1. Effect of iron and zinc nanoparticles on different growth parameter

Treatment	Plant height (cm)	Branches plant^{-1}	No. of leaves plant^{-1}	Root length (cm)	Plant fresh weight (g)	Plant dry weight (g)
T_0	59.03	9.80 b	100.00 a	15.63 ab	148.77 b	80.00 abc
T_1	63.20	11.53 ab	97.67 ab	16.00 ab	173.47 ab	90.00 ab
T_2	59.67	10.77 ab	69.00 cd	15.97 ab	165.37 ab	70.00 bc
T_3	60.80	10.53 ab	75.33 bcd	17.07 ab	163.77 ab	86.67 abc
T_4	57.43	10.10 ab	73.00 cd	16.10 ab	147.47 b	80.00 abc
T_5	60.30	9.70 b	78.00 abcd	14.70 b	144.13 b	66.67 c
T_6	59.90	11.53 ab	77.67 abcd	17.60 a	178.53 ab	86.67 abc
T_7	56.17	11.47 ab	91.33 abc	16.40 ab	165.67 ab	86.67 abc
T_8	59.10	11.90 ab	85.00 abcd	15.50 ab	194.67 a	93.33 a
T_9	61.57	10.47 ab	67.00 d	15.77 ab	157.23 ab	80.00 abc
T_{10}	59.23	11.00 ab	84.33 abcd	15.67 ab	178.97 ab	90.00 ab
T_{11}	59.57	10.57 ab	83.00 abcd	16.00 ab	174.57 ab	83.33 abc
T_{12}	58.43	10.00 ab	66.33 d	16.67 ab	158.57 ab	76.67 abc
T_{13}	60.73	11.43 ab	77.00 bcd	17.40 a	169.13 ab	80.00 abc
T_{14}	60.13	12.67 a	90.33 abc	16.77 ab	171.10 ab	90.00 ab
T_{15}	59.30	9.53 b	69.33 cd	16.50 ab	156.00 ab	73.33 abc
T_{16}	56.63	10.33 ab	74.33 cd	16.33 ab	163.20 ab	76.67 abc
CV (%)	8.12	15.66	16.87	8.94	14.32	16.89

Means within a column followed by the same letter(s) do not differ significantly according to the LSD test at $p \leq 0.05$ Where no letters are shown, treatment effects were non-significant (NS).

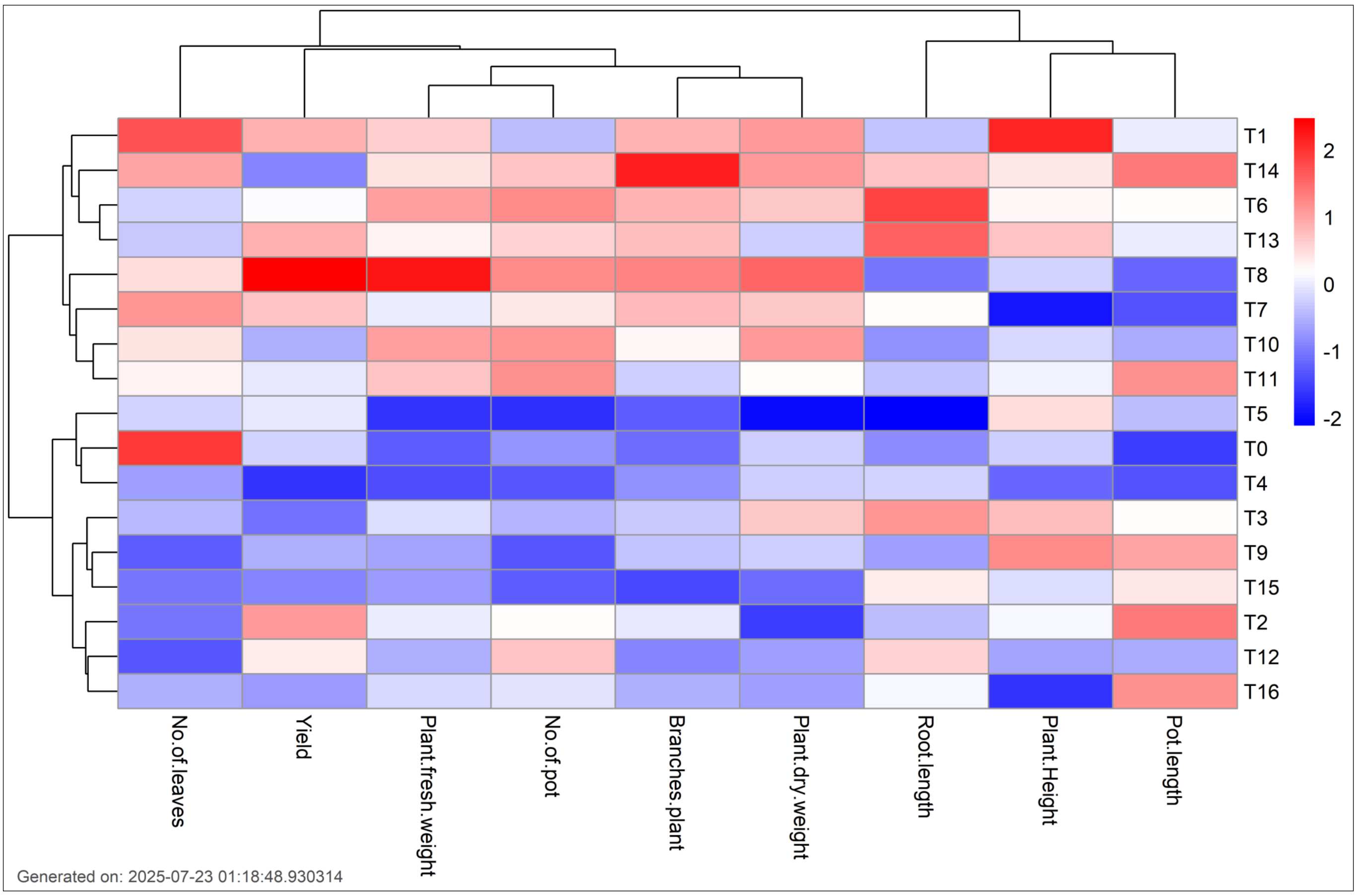

Fig. 1. Heatmap visualisation of treatment responses across growth and yield variables.

relative from blue to red and represents poor-to-good performance of a treatment on each parameter which denotes the lower and higher values being displayed by blue and red, respectively. It can be seen from the heatmap that T_8 treatment (RDF + Zn_{100} + Fe_{50} mg L^{-1}) exhibited same behaviour and has repeatedly performed well in most of the parameters having the deeper red colour especially in yield, plant fresh weight and number of pods per plant. This indicates that T_8 brings important advances with respect to vegetative and reproductive traits. T_0 and T_2 (on the other extreme) appear more blue, in which there is lower mean performance compared to others particularly for the plant fresh weight and number of pods per plant. The clustering of treatments also provides insight into how different nanoparticle combinations (Zn and Fe) affect the plants. Treatments like T_1 (RDF), T_6 and T_{13} also show promising results in certain parameters, but T_8 stands out as the most effective across the majority of traits. The hierarchical clustering further emphasises the relationships between the treatments and parameters, with treatments that share similar nanoparticle combinations or concentrations clustering together. Overall, the heatmap reinforces the potential benefits of optimising the concentration of Fe and Zn nanoparticles for enhancing groundnut growth and yield.

Discussion

Among a variable range of possible applications of nanotechnology in agriculture, development of novel nano-agrochemicals is one of the most prominent areas (29). Use of the nanoforms of elements, as a fertiliser, to alleviate its deficiency effects on plants is considered to be a sustainable way years for their ratio correction in plants besides betterment in quality. In general, nanoparticles performance depends on several properties including the size of particles, their chemical structure, surface coating agent and rate as well as doses of administration (30). Both Zn and Fe are critical plant growth nutrients (31). Both of the microelements are also required in activation of various enzymes which predicate in photosynthetic tissues and fundamental for chlorophyll formation (32). The present results demonstrated a clear dose-dependent response of groundnut to foliar application of Zn and Fe nanoparticles. Among all treatments, T_8 (RDF + Zn_{100} + Fe_{50} mg L^{-1}) consistently produced superior fresh weight, dry weight, pod number and yield compared to other treatments (Tables 1 and 2). This indicates that moderate concentrations of Zn and Fe nanoparticles provided an optimal balance for nutrient uptake and physiological activity. Zinc is a necessary element; however, at phytotoxic levels, it can negatively impact the health and vitality of plants. Symptoms of Zn toxicity are characterised by decreased growth and plant biomass, cell elongation/transverse cell division arrest, wilting (33), curling and rolling of young leaves, chlorotic/necrotic leaf tips (34) and root growth restriction (35). The present study observed reduced performance at higher concentrations such as T_{13} (Zn_{150} + Fe_{150} mg L^{-1}) and T_{16} (Zn_{200} + Fe_{150} mg L^{-1}) may be attributed to possible micronutrient toxicity. Excess Zn can interfere with Fe uptake and vice versa, resulting in nutrient imbalance within plant tissues. Elevated nanoparticle concentrations may also induce oxidative stress, disrupt membrane integrity or impair enzymatic functions, thereby limiting growth and yield despite increased nutrient availability. Zinc is a cofactor for carbonic anhydrase enzyme, which accumulates CO_2 in the chloroplast and consequently raises the carboxylation efficiency of rubisco enzyme (36). Zinc may influence the absorption of various macro and micronutrients (37). The superior biomass accumulation observed under T_8 may be explained by the synergistic interaction between Zn and Fe at moderate doses. Zinc supports auxin metabolism and membrane stability, while iron plays a central role in chlorophyll synthesis and electron transport in photosynthesis. Their combined application at optimal levels likely enhanced photosynthetic efficiency, assimilate production and translocation toward developing pods. The observed improvements in growth and yield under optimal nanoparticle concentration are consistent with enhanced micronutrient use efficiency and improved physiological functioning as evidenced by increased biomass and pod production.

Zinc and iron transport have been mainly described as taking place via the symplast pathway by specific transporters (38). They are also efficient to translocate into the apoplastic spaces in the roots or other organs prior to them reaching the Casparian strip (39) and then enter to the water system. Leaf of Zn uptake and translocation were also observed. Zinc nanoparticles generally, enter into the leaf system through stomata, cuticle penetration, hydathodes and wounded tissue (40). Specifically, the majority of the Zn types are taken up through cuticle and stomates. Growth parameters of the plant were significantly affected by Fe and Zn nanoparticles (Table 1). Although the control treatment recorded a higher number of leaves, it exhibited lower fresh and dry weights. This suggests that leaf proliferation alone did not translate into effective biomass accumulation. In contrast, T_8 showed improved biomass partitioning and source-sink balance, leading to enhanced reproductive performance. The treatments differed significantly with regard to growth parameters (Table 1). Maximum height of the plants was attained within RDF, which was statistically similar to T_9 (61.57 cm) and T_3 (60.80 cm). The combined effect of ZnO and FeO on plant height of carrot was also found to be significant (28). It is rather advantageous for the root's growth and shoots of plants, which can improve cell permeability, provide plant nutrients (41). The application of high dose of N could have facilitated high chlorophyll content. Thus, high chlorophyll induces biosynthesis of cell division and a greater number of tissues leading to lush vegetative growth and subsequently increased plant height. This suggests that the recommended dose of particles offered better availability and possibly a greater uptake of nutrients which consequently favored growth of shoots.

Number of branches per plant was significantly highest in T_{14} (Zn_{200} + Fe_{50} mg L^{-1}) with 12.67 branches, followed by T_8 (11.90 branches $plant^{-1}$). Also, optimum levels of Fe and Zn nanoparticles increased the number of branches in carrot, likely due to improved chlorophyll synthesis and enzymatic activity (28). Leaf production per plant was highest in T_0 (100 leaves plant), although it corresponded with lower fresh weight and dry matter accumulation, indicating a possible nutrient stress and poor translocation efficiency under control conditions. In contrast, T_8 recorded comparatively fewer leaves but higher biomass production, implying efficient nutrient utilisation and partitioning towards economic yield. A positive correlation found between agronomic traits as plant height, leaf area and root diameter and dry weight with Zn and Fe content in radish plant (42). These results established by previous studies in different crops (23, 28). Root length was significantly enhanced in T_6 (17.60 cm) and T_{13} (17.40 cm) compared to other treatments. Similar result was observed where peanut seeds were separately treated with nanoparticles and these particles (Fe, Zn) proved effective in increasing stem and root growth (23). Enhanced root development under Fe and Zn nanoparticle treatments might be attributed to better auxin metabolism as growth regulator substance in plants and cell elongation (43). Fresh weight and dry weight of plants were also significantly affected by the treatments. T_8 exhibited the maximum plant fresh weight (194.67 g) and dry weight (93.33 g), showing superior vegetative growth. These results corroborate with a report who found that nanoparticle supplementation at optimal concentration enhances photosynthetic efficiency and biomass accumulation (44). Similar result found by another report that net photosynthetic rate increased 55 % in response to Zn nanoparticles treatment at the end of experiment when compared to control along with DW increase was 28 , 85 and 20 % in roots, stems and leaves respectively (45).

Yield components also responded positively to nanoparticle application (Table 2). The number of pods per plant was maximum in T_8 (34.00 pods $plant^{-1}$), followed by T_6 (33.90 pods $plant^{-1}$) and T_{11} (33.77 pods $plant^{-1}$). Pod length was significantly longest in T_2 and T_{14} (3.17 cm), whereas minimum pod length (2.67 cm) was observed in T_0. Seed treatment with Fe and Zn nanoparticles promotes the number of pods per plant of groundnut, may be characterised to Fe which is known to increase the nitrogenase activity resulting in the better nodule and peg formation thereby increasing the production of number of pods per plant (46, 47). Grain yield was significantly affected by various treatments and the highest grain yield (3.00 t ha^{-1}) was produced with treatment T_8 which was statistically better than all other treatments (Table 2). T_2 (2.73 t ha^{-1}) and T_{13} (2.70 t ha^{-1}) were best next treatments. The higher yield under T_8 could be attributed to enhanced growth traits, good rooting and pod setting. These particles also demonstrated good effect on growth, development and yield of the plant (48). The highest grain yield recorded under T_8 confirms that moderate combined application of Zn and Fe nanoparticles enhances nutrient use efficiency. However, increasing concentrations beyond the optimal range did not result in proportional yield gains, reinforcing the importance of dose optimisation in nano-fertiliser applications. Bioavailability of the nanoparticle is better due to smaller size, higher surface area and less water solubility which enables increased uptake. This increased Zn uptake was responsible for high yields and biomass (48). Grain yield increased upon foliar application of Fe, which could be due to better carbon and protein synthesis and photosynthesis rate. Further, Fe is involved in the synthesis of growth hormones like auxins, seed maturation, nucleic acid metabolism and chlorophyll formation. Improved growth parameters also contributed to higher grain yield.

The interpretation of treatment effects is constrained by the absence of baseline soil physico-chemical properties and the lack of nanoparticle physicochemical characterisation. Environmental variation and within-field heterogeneity, although minimised by RCBD, may also have influenced treatment response. The observed treatment effects may vary under different seasonal or climatic conditions, as the present study was conducted during a single growing season. Therefore, while the observed dose-dependent pattern strongly suggests an optimal concentration range, future studies need to include complete soil analysis, nanoparticle characterisation and additional physiological measurements to strengthen mechanistic inference and address potential contradictory outcomes reported under different soils and climates.

Conclusion

The application of Fe and Zn nanoparticles as foliar spray significantly improved growth and yield parameters in groundnut. Among the treatments, T_8 (RDF + Zn_{100} + Fe_{50} mg L^{-1}) proved to be the most effective, indicating that moderate levels of both micronutrients in nanoparticle form provided superior results under the tested conditions. The results demonstrated a clear dose-dependent response, where moderate combined concentrations were more effective than higher levels, highlighting the importance of concentration optimisation in nano-micronutrient application. This finding provides field-based evidence supporting the combined foliar use of Zn and Fe nanoparticles in groundnut under practical cultivation conditions. Furthermore, no toxicity was observed in any treatment. Based on these findings there is potential for Zn and Fe nanoparticles to have an effect on groundnut pod number and quality. Further multi-location trials and comprehensive soil and nanoparticle characterisation studies are recommended to validate the consistency and long-term applicability of these findings.

Acknowledgements

The authors would like to extend their heartfelt gratitude to Bangladesh Institute of Nuclear Agriculture, Bangladesh for providing facilities of this work.

Authors' contributions

MMHM and MAR conceived and designed the study. MMHM performed the methodology, validation, formal analysis, data curation and investigation and drafted the manuscript. MAR conducted data analysis and formal analysis, contributed to data visualisation and participated in manuscript drafting and editing. ASJ, RE, MRK and MSR contributed to manuscript reviewing and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used “Grammarly” in order to improve the writing style, grammar and spelling. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Sagar RMSV, Dawson J, Reddy RUK. Effect of phosphorus and gypsum on growth, yield and economics of groundnut (*Arachis hypogaea* L.). Int J Curr Microbiol Appl Sci. 2020;9(10). https://doi.org/10.20546/ijcmas.2020.910.196
2. Poonia T, Bhunia S, Choudhary R. Effect of iron fertilization on nitrogen and iron content, uptake and quality parameters of groundnut (*Arachis hypogaea* L.). Int J Curr Microbiol Appl Sci. 2018;7(3):2297–303. https://doi.org/10.20546/ijcmas.2018.703.269
3. Joshi JP, Patel AG. Influence of organic and inorganic sources of nutrients on growth, yield and economics of summer groundnut (*Arachis hypogaea* L.). Int J Curr Microbiol Appl Sci. 2020;9(8). https://doi.org/10.20546/ijcmas.2020.908.247
4. Food and Agriculture Organization of the United Nations. Crops and livestock products: Production quantity. Rome: FAO; 2022.
5. Bangladesh Bureau of Statistics. Agricultural statistics of Bangladesh 2021–22. Dhaka: Ministry of Planning, Government of Bangladesh; 2022.
6. Malakouti MJ. The effect of micronutrients in ensuring efficient use of macronutrients. Turk J Agric For. 2008;32(3):215–20.
7. Arif M, Jan MT, Marwat KB, Khan MA. Seed priming improves emergence and yield of soybean. Pak J Bot. 2008;40(3):1169–77.
8. Mengel K, Kirkby EA. Principles of plant nutrition. Dordrecht: Springer; 2001. https://doi.org/10.1007/978-94-010-1009-2
9. Pandey N, Pathak GC, Sharma CP. Zinc is critically required for pollen function and fertilisation in lentil. J Trace Elem Med Biol. 2006;20(2):89–96. https://doi.org/10.1016/j.jtemb.2005.09.006
10. Kobayashi T, Itai RN, Aung MS, Senoura T, Nakanishi H, Nishizawa NK. The rice transcription factor IDEF1 directly binds to iron and other divalent metals for sensing cellular iron status. Plant J. 2011;69(1):81–91. https://doi.org/10.1111/j.1365-313X.2011.04772.x
11. Greenshields DL, Liu G, Wei Y. Roles of iron in plant defence and fungal virulence. Plant Signal Behav. 2007;2(4):300–2. https://doi.org/10.4161/psb.2.4.4042
12. Sharma S. Adaptation of photosynthesis under iron deficiency in maize. J Plant Physiol. 2007;164(10):1261–7. https://doi.org/10.1016/j.jplph.2007.02.004
13. Shokri Z, Ashouri M, Doroudian H, Roshan NM, Sadeghi SM. Growth and yield of groundnut (*Arachis hypogaea*) under varying levels of gypsum and zinc application in Iran. Indian J Agric Sci. 2024. https://doi.org/10.56093/ijas.v94.i3.139364
14. Mohammed S, Alsafadi K, Enaruvbe GO, Harsányi E. Assessment of soil micronutrient level for vineyard production in southern Syria. Model Earth Syst Environ. 2022;8(1):407–16. https://doi.org/10.1007/s40808-021-01104-9
15. Siddiqui MH, Al-Whaibi MH. Role of nano-SiO_2 in germination of tomato (*Lycopersicum esculentum* Mill.) seeds. Saudi J Biol Sci. 2014;21(1):13–7. https://doi.org/10.1016/j.sjbs.2013.04.005
16. Ojha S, Singh D, Sett A, Chetia H, Kabiraj D, Bora U. Nanotechnology in crop protection. In: Rai M, Ribeiro C, Mattoso LHC, Duran N, editors. Nanomaterials in plants, algae and microorganisms. Cambridge (MA): Academic Press; 2018. p. 345–91. https://doi.org/10.1016/B978-0-12-811487-2.00016-5
17. Baig N, Kammakakam I, Falath W. Nanomaterials: A review of synthesis methods, properties, recent progress and challenges. Mater Adv. 2021;2(6):1821–71. https://doi.org/10.1039/D0MA00807A
18. Morales-Díaz AB, Ortega-Ortíz H, Juárez-Maldonado A, Cadenas-Pliego G, González-Morales S, Benavides-Mendoza A. Application of nanoelements in plant nutrition and its impact in ecosystems. Adv Nat Sci Nanosci Nanotechnol. 2017;8(1):013001. https://doi.org/10.1088/2043-6254/8/1/013001
19. Ariraman R, Suvain K, Vasline YA, Sowmya S, Mansingh M. Zinc application on growth, yield parameters, yield, quality, nutrient uptake and economics of groundnut. Int J Chem Stud. 2020;8 (6):892–6. https://doi.org/10.22271/chemi.2020.v8.i6m.10881
20. Dadhich SK, Yadav G, Kumawat C, Singh A. Effect of vermicompost and foliar spray of zinc on growth, quality and productivity of groundnut (*Arachis hypogaea* L.). Int J Plant Soil Sci. 2021;33(1):81–7. https://doi.org/10.9734/ijpss/2021/v33i130526
21. Venkatachalam P, Jayaraj M, Manikandan R, Geetha N, Rene ER, Sharma NC, et al. Zinc oxide nanoparticles alleviate heavy metal-induced toxicity in *Leucaena leucocephala* seedlings: A physiochemical analysis. Plant Physiol Biochem. 2017;110:59–69. https://doi.org/10.1016/j.plaphy.2016.08.022

22. Aboyeji C, Dunsin O, Adekiya A, Chinedum C, Suleiman KO, Okunlola F, et al. Zinc sulphate and boron-based foliar fertilizer effect on growth, yield, minerals and heavy metal composition of groundnut (*Arachis hypogaea* L). Int J Agron. 2019;2019:5347870. https://doi.org/10.1155/2019/5347870
23. Berhe HM, Abera D, Yemane Y. Response of groundnut (*Arachis hypogaea* L.) genotypes to combined application of phosphorus and foliar zinc fertilizers. Res Square. 2020. https://doi.org/10.21203/rs.3.rs-26091/v1
24. Gaur D, Jadav N, Maheta A, Gaur S. Effect of iron, molybdenum and rhizobium on growth, yield attributes and yield of summer groundnut (*Arachis hypogaea* L.) in loamy sand soil. Int J Plant Soil Sci. 2023;35:1–9. https://doi.org/10.9734/ijpss/2023/v35i42809
25. Barman S, Hebbara M, Bidari B. Effect of foliar spray of iron-fortified humic substances and humic acid on growth, nodulation and yield of groundnut (*Arachis hypogaea* L.) in a calcareous Vertisol. Int J Plant Soil Sci. 2023;35:1–10. https://doi.org/10.9734/ijpss/2023/v35i193706
26. Adrees M, Khan ZS, Hafeez M, Rizwan M, Hussain K, Asrar M, et al. Foliar exposure of zinc oxide nanoparticles improved the growth of wheat (*Triticum aestivum* L.) and decreased cadmium concentration in grains under simultaneous Cd and water deficient stress. Ecotoxicol Environ Saf. 2021;208:111627. https://doi.org/10.1016/j.ecoenv.2020.111627
27. Fincheira P, Tortella G, Seabra AB, Quiroz A, Diez MC, Rubilar O. Nanotechnology advances for sustainable agriculture: Current knowledge and prospects in plant growth modulation and nutrition. Planta. 2021;254:1–25. https://doi.org/10.1007/s00425-021-03714-0
28. Elizabath A, Bahadur V, Misra P, Prasad VM, Thomas T. Effect of different concentrations of iron oxide and zinc oxide nanoparticles on growth and yield of carrot (*Daucus carota* L.). J Pharmacogn Phytochem. 2017;6(4):1266–69.
29. Subramanian KS, Manikandan A, Thirunavukkarasu M, Rahale CS. Nanofertilizers for balanced crop nutrition. In: Rai M, Ribeiro C, Mattoso L, Duran N, editors. Nanotechnologies in food and agriculture. Cham: Springer International Publishing; 2015. p. 69–80. https://doi.org/10.1007/978-3-319-14024-7_3
30. Khodakovskaya MV, De Silva K, Biris AS, Dervishi E, Villagarcia H. Carbon nanotubes induce growth enhancement of tobacco cells. ACS Nano. 2012;6(3):2128–35. https://doi.org/10.1021/nn204643g
31. Fageria NK. The use of nutrients in crop plants. Boca Raton: CRC Press; 2016. https://doi.org/10.1201/9781420075113
32. Ramani S, Kannan S. Studies on Zn uptake and influence of Zn and Fe on chlorophyll development in young maize cultivars. J Plant Nutr. 1985;8(12):1183–9. https://doi.org/10.1080/01904168509363416
33. Rout GR, Sahoo S. Role of iron in plant growth and metabolism. Rev Agric Sci. 2015;3:1–24. https://doi.org/10.7831/ras.3.1
34. Nagajyoti PC, Lee KD, Sreekanth TVM. Heavy metals, occurrence and toxicity for plants: A review. Environ Chem Lett. 2010;8:199–216. https://doi.org/10.1007/s10311-010-0297-8
35. Sharma SS, Schat H, Vooijs R, Van Heerwaarden LM. Combination toxicology of copper, zinc and cadmium in binary mixtures: concentration-dependent antagonistic, nonadditive and synergistic effects on root growth in *Silene vulgaris*. Environ Toxicol Chem. 1999;18:348–55. https://doi.org/10.1002/etc.5620180235
36. Salama ZA, El-Fouly MM, Lazova G, Popova LP. Carboxylating enzymes and carbonic anhydrase functions were suppressed by zinc deficiency in maize and chickpea plants. Acta Physiol Plant. 2006;28:445–51. https://doi.org/10.1007/BF02706627
37. Peralta-Videa JR, Hernandez-Viezcas JA, Zhao L, Diaz BC, Ge Y, Priester JH, et al. Cerium dioxide and zinc oxide nanoparticles alter the nutritional value of soil cultivated soybean plants. Plant Physiol Biochem. 2014;80:128–35. https://doi.org/10.1016/j.plaphy.2014.03.028
38. González-Guerrero M, Escudero V, Saéz Á, Tejada-Jiménez M. Transition metal transport in plants and associated endosymbionts: arbuscular mycorrhizal fungi and rhizobia. Front Plant Sci. 2016;7:1088. https://doi.org/10.3389/fpls.2016.01088
39. Palmer CM, Guerinot ML. Facing the challenges of Cu, Fe and Zn homeostasis in plants. Nat Chem Biol. 2009;5(5):333. https://doi.org/10.1038/nchembio.166
40. Singh A, Singh NB, Afzal S, Singh T, Hussain I. Zinc oxide nanoparticles: A review of their biological synthesis, antimicrobial activity, uptake, translocation and biotransformation in plants. J Mater Sci. 2018;53(1):185–201. https://doi.org/10.1007/s10853-017-1544-1
41. Tyagi S. Effects of ascorbic acid and phenolic content concentrations on natural reduction of silver ions from plant extracts. Int J Curr Microbiol Appl Sci. 2016;5(11):885–90. https://doi.org/10.20546/ijcmas.2016.511.101
42. Mahmoud AWM, Abdelaziz SM, El-Mogy MM, Abdeldaym EA. Effect of foliar ZnO and FeO nanoparticles application on growth and nutritional quality of red radish and assessment of their accumulation on human health. Agriculture. 2019;65(1):16–29. https://doi.org/10.2478/agri-2019-0002
43. Der HN, Vaghasia PM, Verma HP. Effect of foliar application of potash and micronutrients on growth and yield attributes of groundnut. Ann Agric Sci. 2015;36:275–8.
44. Kumar J, Bahadur V, Prasad VM, Mishra S, Shukla PK. Effect of different concentrations of iron oxide and zinc oxide nanoparticles on growth and yield of strawberry (*Fragaria* × *ananassa* Duch.) cv. Chandler. Int J Curr Microbiol Appl Sci. 2017;6(8):2440–5. https://doi.org/10.20546/ijcmas.2017.608.288
45. Rossi L, Fedenia LN, Sharifan H, Ma X, Lombardini L. Effects of foliar application of zinc sulfate and zinc nanoparticles in coffee (*Coffea arabica* L.) plants. Plant Physiol Biochem. 2019;135:160–6. https://doi.org/10.1016/j.plaphy.2018.12.005
46. Gohari AA, Niyaki SAN. Effects of iron and nitrogen fertilizers on yield and yield components of peanut (*Arachis hypogaea* L.) in Astaneh Ashrafiyeh, Iran. Am Eurasian J Agric Environ Sci. 2010;9(3):256–62.
47. Khan TA, Ahmed ZI, Syed S, Baloch A, Malik MN, Irfan M, et al. Seed priming with iron and zinc improves growth and yield of groundnut (*Arachis hypogaea* L.). Pure Appl Biol. 2017;6(2):553–60. https://doi.org/10.19045/bspab.2017.60057
48. Harish MS, Rame Gowda RG. Effect of nanoscale zinc oxide on plant growth, seed yield and quality in groundnut. Mysore J Agric Sci. 2017;51(3):637–43.

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.