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FOLIAR APPLICATION OF NANO IRON OXIDE ENHANCES THE GROWTH, YIELD AND OIL CONTENT OF GROUNDNUT (*Arachis hypogaea* L.) IN CALCAREOUS VERTISOLS

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ABSTRACT

Iron deficiency is a widespread nutritional problem, particularly in plants grown on calcareous and high pH soils. This study evaluated the impact of foliar-application of nano iron oxide (Fe_2O_3 NPs) on growth, yield attributes and oil content of groundnut (*Arachis hypogaea* L.) in a calcareous vertisol under controlled pot culture conditions. Treatments included soil-applied ferrous sulphate, foliar-applied conventional ferrous sulphate, and various concentrations of nano-iron oxide (100 to 1500 ppm) applied 30 days after sowing. The results revealed that foliar application of nano iron oxide significantly enhanced the growth and yield of groundnut. The foliar application of nano iron @ 1000 ppm gave higher dry matter production (69.37 g), and improved root parameters, number of pods plant^{-1} (58.0), kernels plant^{-1} (89.33), pod dry weight (30.5 g plant^{-1}), kernel dry weight (23.2 g plant^{-1}), oil content (48.1%), oil yield (11. 24 g plant^{-1}) and crude protein (26.75%) over other treatments. This treatment improved yield by 46 and 35% over the recommended practice and foliar application of $FeSO_4$, respectively. The control showed lowest performance in all the test parameters.

Keywords: Calcareous soils, groundnut, iron deficiency, nano-iron formulations, yield, oil content

INTRODUCTION

Groundnut (*Arachis hypogaea L.*), a major oilseed crop, constitutes approximately 40% of total oil-seed area in India and contributes 60% of the nation's oilseed production (Poonia *et al.*, 2018). Globally, it stands as the largest source of edible oil, ranking 13th among food crops and 4th among major oilseed crops. Despite its economic and nutritional importance, the productivity of groundnut is constrained by several agronomic and soil-related challenges. Among these, micronutrient deficiencies, especially iron (Fe) deficiency poses a major threat to sustainable production. Iron plays a crucial role in various physiological and biochemical processes in plants, including chlorophyll synthesis, respiration, and enzyme activation. In many groundnut-growing regions, particularly those with calcareous and alkaline soils, the availability of iron is limited due to its poor solubility, leading to lime-induced iron chlorosis, reduced photosynthetic efficiency, and ultimately lower yields and oil quality (John *et al.*, 2024). Most of the world's arable soils are calcareous and alkaline due to their high pH, elevated bicarbonate levels, and low temperatures, which collectively limit the availability of iron (Fe) to plants (Mitra *et al*., 2022).

The application of iron fertilizers has widely been adopted as a conventional remedy to overcome iron deficiency (Zhang *et al.*, 2018). Commonly used iron fertilizers include inorganic, organic, and chelated forms. However, these approaches often face limitations in calcareous and alkaline soils due to poor iron solubility and availability. Inorganic iron fertilizers are largely ineffective in high pH soils, while organic forms tend to bind rapidly to soil particles, reducing their efficacy (Rui *et al*., 2016). Although chelated iron fertilizers are more effective in improving Fe availability, their high cost restricts their use primarily to high-value crops ((D'Amato *et al*., 2022). Consequently, the efficiency of conventional iron fertilizers remains inadequate in mitigating iron stress in crop plants, highlighting the need for alternative, more efficient, and cost-effective solutions to enhance iron nutrition in groundnut.

Recent advances in nanotechnology offer promising alternatives to overcome the limitations of conventional iron fertilization methods. Nanomaterials, owing to their unique physicochemical properties such as high surface area, enhanced reactivity, and controlled release capabilities, are being increasingly explored in agriculture to improve nutrient delivery and uptake efficiency (Rodrigues *et al.,* 2017; Lowry *et al.,* 2019). Nano-fertilizers, particularly iron-based nanoparticles (Fe-NPs), have demonstrated potential in enhancing Fe availability in soils with high pH, thereby mitigating iron deficiency in plants (Natarajan *et al.,* 2019). Moreover, Fe-NPs have been reported to promote better physiological performance, including higher chlorophyll content, enhanced photosynthetic efficiency, and improved relative water content under both stress and non-stress conditions (Deepa *et al.,* 2015; Cui *et al.,* 2022). The foliar application of iron nano particles avoids the issue of nutrient fixation in soil, improves to availability of essential nutrients to the crops, enables rapid bio-fortification, and effectively mitigates iron deficiency (Reshma and Meenal, 2022). In view of above facts, the present study was aimed to assess the effectiveness of foliar-applied Fe_2O_3 nanoparticles in improving the growth, yield, and oil content of groundnut in calcareous vertisols.

MATERIALS AND METHODS

Pot culture experiment

The pot culture experiment on groundnut variety "GPBD - 4" was conducted in a greenhouse at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dharwad, Karnataka (India). The soil for the study was collected from iron-deficient calcareous soils in groundnut-growing region of Dharwad district. The study was conducted in a completely randomized design with eleven treatments and each treatment replicated three times. The treatments included: T_1 = absolute control [(no fertilizer application, only water spray at 30 days after sowing (DAS)]; T_2 = recommended package of practices which includes farm yard manure (FYM) @ 7.5 t + 25 kg N + 50 kg P_2O_5 + 25 kg K_2O + 500 kg gypsum + 25 kg $ZnSO_4 \cdot 7H_2O$ + $FeSO_4 \cdot 7H_2O$ ha^{-1}); T3: RPP + foliar spray of $FeSO_4$ @ 0.5% 30 DAS; T_4 - T_{10}: RPP + foliar spray of nano Fe @ 100, 250, 500, 750, 1000, 1250, and 1500 ppm, respectively; and T_{11}: control (RPP + water spray 30 DAS). Nano iron (Fe_2O_3 < 50 nm) were procured from Sigma-Aldrich and characterization was performed using UV-visible spectrophotometry, field emission scanning electron microscopy (FESEM), and X-ray diffraction (XRD) techniques. As per the treatments, the nano Fe solutions were prepared and sonicated to ensure uniform dispersion, then applied using calibrated foliar spray equipment. The volume was standardized per plant, and pot positions were randomized periodically to minimize environmental variability.

Physicochemical properties of soil

The initial soil properties were determined using standard methods *viz*., pH by potentiometric method (Sparks, 1996), electrical conductivity by conductometric method (Sparks, 1996), organic carbon by Walkley and Black's wet oxidation (Sparks, 1996), available nitrogen by modified alkaline permanganate method (Sharawat and Burford, 1982), available phosphorus by Olsen's method (Sparks, 1996), available potassium by neutral ammonium acetate and flame photometer (Sparks, 1996) and micronutrients (Fe, Zn, Cu and Mn by DTPA extraction method (Lindsay and Norvell, 1978) using AAS (PinAAcle 900F). The soil was clayey in texture, slightly alkaline (pH 7.6), and exhibited low electrical conductivity (0.17 dS m^{-1}). The organic carbon content was medium (5.8 g kg^{-1}), and soil was calcareous in nature ($CaCO_3$, 10.5%), low in available nitrogen (210 kg N ha^{-1}), medium in phosphorus (41.60 kg P_2O_5 ha^{-1}), and high in potassium (485 kg K_2O ha^{-1}). Micronutrient analysis of soil showed sufficient levels of copper (1.61 mg kg^{-1}) and manganese (6.60 mg kg^{-1}), but deficiencies of zinc (0.44 mg kg^{-1}) and iron (4.13 mg kg^{-1}) making the soil suitable for Fe-deficiency studies.

Observations

For dry matter production, the whole plants sampled at 60 DAS and at harvest were oven-dried at 65°C to a constant weight. Dry matter per plant was calculated by summing the weights of leaves, stems, and pods. Also, the harvested roots were washed using 0.5% sodium hexametaphosphate and scanned by using the WinRHIZO™ Root Analysis System (STD 1600+, Regent Instruments, Canada). The root parameters measured included root length, diameter, volume, length density, and surface area. The plants were harvested at physiological maturity and sun-dried. Pod and haulm yields were recorded per plant. The oil content in groundnut seeds was estimated by using nuclear magnetic resonance [NMR (Oxford 400 series)] technique, a rapid and non-destructive method based on the detection of hydrogen nuclei in oil molecules. Clean and dried seeds were weighed and placed in NMR sample tubes. The instrument was calibrated using groundnut seed standards with known oil content to generate a calibration curve. Each sample was analysed in triplicate, and the oil percentage was obtained directly from the instrument output. The oil yield was computed by using the formula:

$$\text{Oil yield (kg/ha)} = \frac{\text{Oil content (\%) x Kernel yield } \left(\frac{kg}{ha}\right)}{100}$$

Statistical analysis

The data generated was subjected to the analysis of variance (ANOVA) following Gomez and Gomez (1984). Treatment means were compared using Duncan's multiple range test (DMRT) at 5% significance level ($p < 0.05$).

RESULTS AND DISCUSSION

Characterization of iron oxide nanoparticles

The iron oxide nanoparticles (Fe_2O_3 < 50 nm) on characterization by X-ray diffraction displayed a series of sharp strong diffraction peaks at regular intervals (Fig. 1). The high intensity and sharpness of peaks indicated high crystallinity, well-defined crystal structure and small particle size. Sharper peaks are typically associated with nanocrystals of Fe_2O_3. Similar X-ray diffraction patterns have previously been reported (Dehbi *et al.*, 2020; John *et al.*, 2024). The field emission scanning electron microscopic images

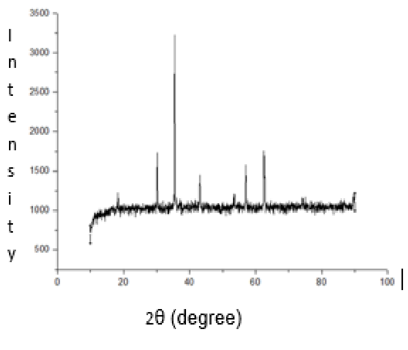

Fig. 1: XRD images of nano Fe

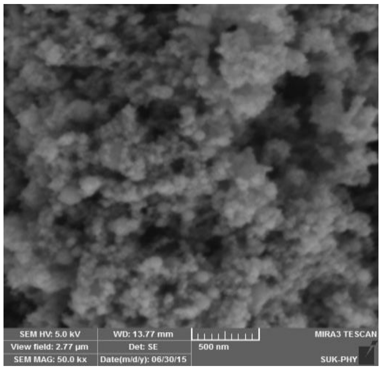

Fig. 2: FESEM images of nano Fe

revealed that particles were cubic, highly uniform in nature with average size of 20 - 45 nm (Fig. 2). The surface appeared rough and porous**,** which can be beneficial for nutrient delivery in agriculture.

Dry matter accumulation and partitioning

The pattern of dry matter accumulation in groundnut plants was distinctly influenced by different foliar iron treatments, as reflected in the partitioning into leaf, stem, and pod components (Fig. 3). Across the treatments, dry matter increased from 60 DAS to harvest, with pods contributing the largest proportion at harvest, indicative of efficient source-to-sink translocation during reproductive phase. Among the treatments foliar spray of nano Fe @ 1000 ppm gave highest total dry matter production (TDMP) at both 60 DAS (28.60 g plant^{-1}) and at harvest (69.37 g plant^{-1}) which was followed by foliar spray of nano Fe @ 1250 ppm (66.30 g plant^{-1}), and nano Fe @ 1500 ppm (65.33 g plant^{-1}) at harvest. These values were significantly superior to all other treatments, including the recommended farmer practice (foliar $FeSO_4$ @ 0.5%), which produced 23.45 g plant^{-1} at 60 DAS and 59.25 g plant^{-1} at harvest. Notably, the 1000 ppm nano Fe treatment enhanced TDMP by 17% over the farmer practice.

At 60 DAS, greater allocation was observed, especially to leaves and stems as compared to the control and other treatments, which supports better canopy development and photosynthetic capacity early in growth. By harvest, T_9 exhibited markedly higher pod biomass, showing superior reproductive efficiency. This suggested that nano Fe at optimal concentration not only enhanced vegetative growth but also facilitated efficient assimilate partitioning towards economic yield components. The positive impact of nano Fe on biomass may be attributed to the increased photosynthetic activity, possibly due to vital role of elemental iron in chloroplast development and stabilization of photosynthetic pigments (John *et al.*, 2024). The results are consistent with Rui *et al.* (2016) and Ghafariyan *et al.* (2013)**,** who reported enhanced dry matter production and yield components in leguminous crops with nano iron application. The beneficial effects are likely due to the improved Fe availability and better uptake efficiency, perhaps due to nanoscale size which facilitates better translocation and metabolic functioning. Iron is critical in chlorophyll synthesis, photosynthetic electron transport, and respiratory pathways, which directly contribute to biomass production. Nanoparticles, owing to their high surface area and reactivity, facilitate faster uptake and efficient translocation, leading to improved photosynthate production and dry matter accumulation (Kumar *et al.*, 2021). Similar results were reported by Ghafariyan *et al.*, (2013) in soybean and Muhammadi *et al.*, (2018) in peppermint.

The increase in the concentration beyond 1000 ppm (i.e., 1250 and 1500 ppm) did not result in a significant improvement in biomass and slightly decreased TDMP, indicating potential phytotoxicity. Excessive nanoparticle accumulation can impair plant growth due to oxidative stress or interference with nutrient homeostasis (Rui *et al.*, 2018; Alhammad *et al.*, 2023).

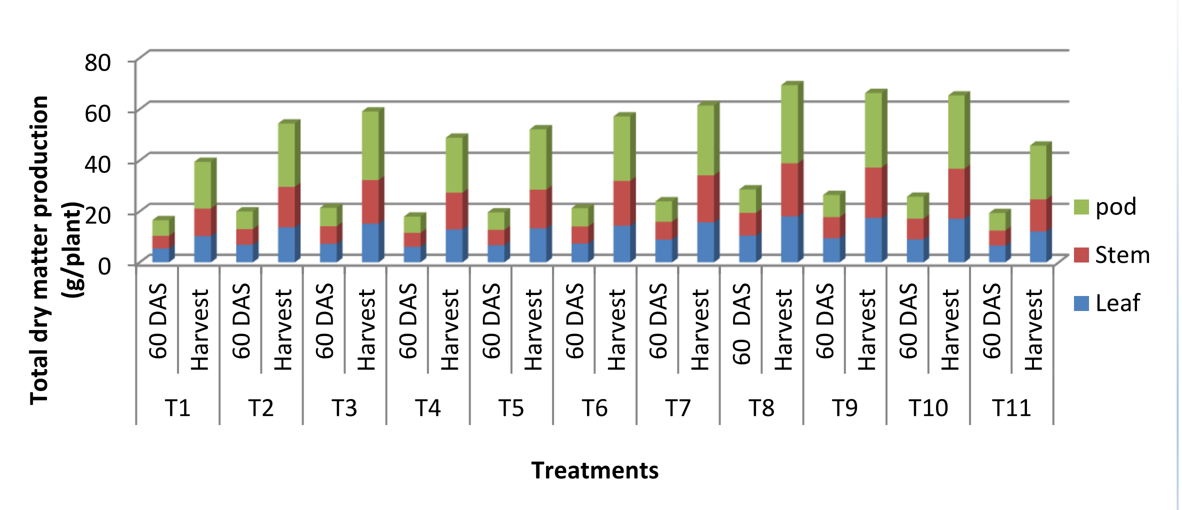

Fig. 3: Dry matter partitioning in groundnut at different growth stages

Root morphological characteristics

Root morphological traits including length, surface area, and average diameter, responded significantly to the nano Fe treatments (Table 1; Fig. 4). The treatment with foliar nano Fe @ 1000 ppm gave the highest root length (385 cm), surface area (88.50 cm^2), and average diameter (0.95 mm). The improvements over conventional $FeSO_4$ treatment underscore the efficiency of nano Fe in stimulating root architecture. Enhanced root growth may be attributed to the improved availability and mobility of Fe in nano form, which facilitates cellular uptake via aquaporins and ion channels (Li *et al.*, 2018). Rui *et al.* (2016) and Alidoust and Isoda (2013) demonstrated similar findings, like increased root elongation and biomass in peanut and soybean with nano Fe applications. Improved root systems support better water and nutrient absorption, contributing to higher overall plant performance. Application of γ Fe_2O_3 NPs @ 20 mg L^{-1} significantly enhanced root length by 11.5% as

Table 1: Root parameters of groundnut as influenced by foliar application of nano iron oxide formulations

Treatment details	Root parameters at harvest		
	Root length (cm)	Surface area (cm^2)	Average diameter (mm)
T_1: Absolute control (No fertilizer (only water spray at 30 DAS)	235.9^{g}	44.79^{i}	0.54^{f}
T_2: RPP (water spray at 30 DAS)	308.0^{cd}	72.70^{de}	0.82^{c}
T_3: Foliar $FeSO_4$ @ 0.5 % at 30 DAS	368.6^{ab}	80.70^{bc}	0.93^{ab}
T_4: Foliar nano Fe @ 100 ppm at 30 DAS	273.0^{ef}	56.90^{g}	0.67^{de}
T_5: Foliar nano Fe @ 250 ppm at 30 DAS	297.0^{de}	63.90^{f}	0.72^{d}
T_6: Foliar nano Fe @ 500 ppm at 30 DAS	327.0^{c}	68.20^{ef}	0.79^{c}
T_7: Foliar nano Fe @ 750 ppm at 30 DAS	354.0^{b}	76.40^{cd}	0.86^{bc}
T_8: Foliar nano Fe @ 1000 ppm at 30 DAS	385.0^{a}	88.50^{a}	0.95^{a}
T_9: Foliar nano Fe @ 1250 ppm at 30 DAS	378.0^{ab}	85.20^{ab}	0.93^{ab}
T_{10}: Foliar nano Fe @ 1500 ppm at 30 DAS	371.3^{ab}	82.50^{b}	0.90^{ab}
T_{11}: Control (water spray at 30 DAS)	261.0^{fg}	49.53^{h}	0.62^{e}
SEM $\pm$	8.74	1.63	0.02

Note: RPP - FYM @ 7.5 t + 25 kg N +50 kg P_2O_5 + 25 kg K_2O + 500 kg Gypsum + 25 kg $ZnSO_4.7H_2O$ + $FeSO_4.7H_2O$ ha^{-1}; Treatments T_3 to T_{11}, RPP is common except soil application of $FeSO_4.7H_2O$; Control (RPP without $FeSO_4.7H_2O$ representing the Iron control treatment)

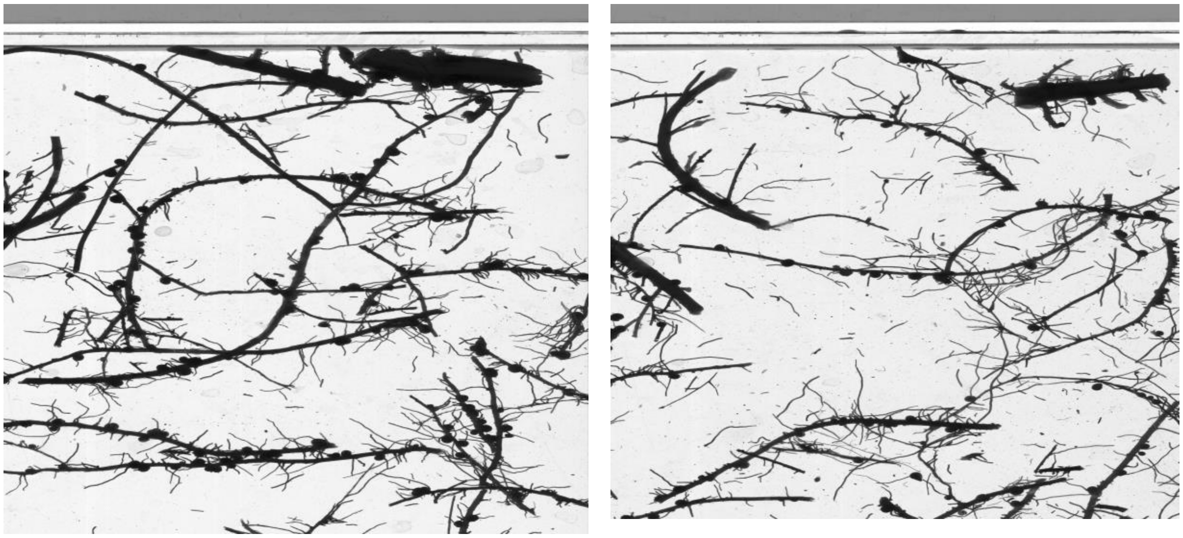

Fig. 4: Foliar application of nano Fe @ 1000 ppm and foliar application of $FeSO_4$ @ 0.5%

compared to control indicating that cell elongation in the root system could lead to faster root growth (Li *et al.,* 2016).

Yield and yield related components

Foliar application of nano Fe formulations significantly influenced the yield and its components (Table 2). The 1000 ppm nano Fe treatment yielded highest number of pods (58 plant^{-1}) and kernels (89.33 plant^{-1}), representing the yield increases of 28 and 33%, respectively, over conventional foliar $FeSO_4$ spray. Pod and kernel dry weights were also highest in this treatment (30.5 and 23.2 g plant^{-1}, respectively), indicating superior assimilate partitioning towards reproductive structures. Even nano Fe @ 750 ppm outperformed conventional treatments, *viz*. T_2 and T_3 (Fig. 5). This may be due to better supply of iron in nano form as they are highly reactive because of more specific surface area and more density of reactive areas on the particle surfaces. Through foliar application, nutrients can enter the plant via stomata and are then transported efficiently throughout the plant via the phloem or xylem, ensuring effective nutrient delivery. (Garg *et al*., 2023; Faizan *et al.,* 2024).

Fig. 5: Response of groundnut to foliar application of nano iron formulations

The increase in yield can be explained by the enhanced iron availability during critical reproductive stages, leading to increased photosynthetic efficiency and pod formation. The reduced particle size facilitates greater interaction with plant surfaces and cellular uptake, resulting in improved nutrient absorption and translocation (Kumbhakar *et al.,* 2014; Shirsat and Suthindhiran, 2024). These results corroborate with the findings of Sheykhbaglou *et al*. (2010) who reported 48% increase in grain yield in soybean due to 0.5 g L^{-1} iron oxide nanoparticles over control. Further, Fe_3O_4 nanoparticle significantly improved grain yield (37.43%), biological yield (22.91%), and harvest index (3.86%) under drought stress. Chen *et al*. (2023) reported that nano-iron fertilizers show better adhesion and lower leaching and overall effectiveness in iron delivery than conventional iron sources. Benzon *et al*. (2015) reported that applying Fe and Zn nano-chelates typically raised soybean grain production by 43.8%. Monjezi *et al.* (2013) suggested that the increase in seed yield was due to the presence of Fe which enhanced photosynthesis and consequently yield of wheat. Beyond 1000 ppm, no further yield improvement was observed, corroborating the findings on dry matter production.

An increasing trend in both pod and kernel dry weights was observed with nano Fe_2O_3 application up to a concentration of 1000 ppm, beyond which a slight decline was noted (Table 2). The maximum pod dry weight (30.5 g) and kernel dry weight (23.2 g) were recorded in the treatment receiving foliar application of nano iron at 1000 ppm. This treatment resulted in a kernel yield improvement of approximately 46% compared to the recommended soil application of $FeSO_4$, and 35% over the foliar application of $FeSO_4$ at 0.5%. These findings are in line with those of Chen *et al*. (2023), who reported that foliar-applied nano-iron particles were more effective than conventional iron fertilizers in alleviating iron chlorosis under simulated rainfall conditions, as indicated by increased SPAD values and higher leaf iron concentrations. The observed enhancement in yield parameters may be attributed to improved iron availability and uptake, which in turn may have positively influenced several physiological and reproductive processes. Enhanced iron nutrition during the reproductive stage likely contributed to increased flower fertility, peg formation, and effective seed development, thereby improving pod and kernel yields. Gohari and Nayaki. (2010) documented that enhanced iron content in groundnut plants led to increased numbers of fertile flowers and mature pods. Similarly, Sheykhbaglou *et al*. (2010) observed a significant increase in leaf and pod dry weights of soybean in response to nano iron application at a concentration of 0.75 g L^{-1}, highlighting the potential of nano iron in improving reproductive performance and overall productivity. Hu *et al.* (2017) reported that foliar application of γ-Fe_2O_3 nanoparticles on *Citrus maxima* leaves enhanced the uptake and utilization efficiency of inorganic iron, attributed to their strong adsorption capacity and gradual release when subjected to hourly water spraying over a 10 h period.

Table 2: Yield and yield components of groundnut at harvest as influenced by foliar application of nano iron oxide formulations

Treatment details	Total No. of pods plant^{-1}	Total no. of kernels plant^{-1}	Pod dry weight (g)	Kernel dry weight (g)	Sound mature kernels (%)	Oil content (%)	Oil yield (g plant^{-1})	Crude protein (%)
T_1: Absolute control (No fertilizer (only water spray at 30 DAS)	29.00^{e}	43.67^{g}	18.33^{H}	11.47^{f}	74.00^{d}	45.40^{c}	5.21^{h}	22.56^{d}
T_2: RPP (water spray at 30 DAS)	40.00^{c}	60.00^{c-e}	24.80^{de}	15.80^{cd}	81.50^{a-c}	46.50^{a-c}	7.35^{f}	25.38^{a-c}
T_3: Foliar $FeSO_4$ @ 0.5 % at 30 DAS	45.00^{b}	67.00^{bc}	26.80^{b-d}	17.10^{b}	83.30^{a-c}	47.33^{ab}	8.09^{de}	26.38^{ab}
T_4: Foliar nano Fe @ 100 ppm at 30 DAS	35.00^{d}	53.00^{ef}	21.50^{fg}	14.20^{de}	77.10^{cd}	46.45^{a-c}	6.60^{g}	23.81^{b-d}
T_5: Foliar nano Fe @ 250 ppm at 30 DAS	38.33^{cd}	57.33^{df}	23.60^{ef}	16.20c	79.50^{b-d}	46.70^{a-c}	7.57^{ef}	24.56^{a-d}
T_6: Foliar nano Fe @ 500 ppm at 30 DAS	42.67^{bc}	64.00^{b-d}	25.20^{c-e}	17.90^{b}	82.20^{a-c}	46.87^{a-c}	8.39^{cd}	25.13^{a-d}
T_7: Foliar nano Fe @ 750 ppm at 30 DAS	46.67^{b}	70.00^{b}	27.30_{bc}	19.10^{b}	83.80^{a-c}	47.10^{ab}	9.00^{c}	25.69a-c
T_8: Foliar nano Fe @ 1000 ppm at 30 DAS	58.00^{a}	89.33^{a}	30.50_{a}	23.20^{a}	88.50^{a}	48.10^{a}	11.24^{a}	26.75^{a}
T_9: Foliar nano Fe @ 1250 ppm at 30 DAS	56.33^{a}	84.67^{a}	29.10^{ab}	22.17^{a}	86.30^{ab}	47.40^{ab}	10.51^{b}	26.38^{ab}
T_{10}: Foliar nano Fe @ 1500 ppm at 30 DAS	54.67^{a}	82.83^{a}	28.60^{ab}	21.73^{a}	85.90^{ab}	47.20^{ab}	10.26^{b}	26.06^{a-c}
T_{11}: Control (water spray at 30 DAS)	34.00^{d}	51.00^{f}	21.10^{g}	13.43^{e}	78.20^{cd}	46.30^{bc}	6.22^{g}	23.44^{cd}
SEM $\pm$	1.56	2.41	0.77	0.53	0.77	2.33	0.21	0.81

Note: RPP - FYM @ 7.5 t + 25 kg N + 50 kg P_2O_5 + 25 kg K_2O + 500 kg Gypsum + 25 kg $ZnSO_4.7H_2O$ + $FeSO_4.7H_2O$ ha^{-1}; Treatments T_3 to $T_{11,}$ RPP is common except soil application of $FeSO_4.7H_2O$.; Control (RPP without $FeSO_4.7H_2O$ representing the Iron control treatment)

Oil content, oil yield, and protein content

Foliar application of nano iron @ 1000 ppm resulted in highest oil content (48.1%), oil yield (11.24 g plant^{-1}), and crude protein content (26.75%), whereas lowest values were observed in absolute control, which respectively recorded 45.4%, 5.21 g plant^{-1}, and 22.56% (Table 2). Notably, foliar application of nano Fe @ 750 ppm also led to significantly higher oil yield, showing an increase of 22.4 and 11.2% over conventional soil-based and foliar $FeSO_4$ treatments, respectively.

The enhanced oil and protein content in nano Fe treatments may be attributed to the improved iron availability and rapid absorption through foliar application, which supports enhanced photosynthetic activity and nitrogen metabolism. This enhancement in quality traits is likely due to iron's role in enzymatic processes related to nitrogen metabolism and lipid biosynthesis (Marschner, 1995). These findings are consistent with Sahu *et al.* (2023) who reported increased protein (25.68%) and oil (44.31%) content in groundnut with iron oxide nanoparticles at 50 ppm. Similarly, Cao *et al.* (2022) demonstrated that foliar-applied iron oxide nanoparticles improved nodulation, nitrogen fixation, and seed nutritional quality in soybean. Souad *et al.* (2013) reported enhanced essential oil content in basil with 3 mg L^{-1} nano iron. Sheykhbaglou *et al.* (2018) documented a steady rise in soybean seed protein content with nano iron application up to 0.75 g L^{-1}.

The oil content (48.1%) and oil yield (11.24 g $plant^{-1}$) were significantly higher in nano Fe @ 1000 ppm treatment as compared to the control (45.4%, 5.21 g $plant^{-1}$) and conventional $FeSO_4$ treatments. Crude protein content increased significantly, reaching 26.75% in 1000 ppm nano Fe treatment.

Conclusion: The widespread iron deficiency in calcareous soils, coupled with low nutrient use efficiency and increasing costs of iron fertilizers demand for the development of suitable strategy. This study provides strong evidence that foliar application of nano Fe @ 1000 ppm significantly enhances growth, yield, and seed quality in groundnut. Spraying of nano Fe @ 1000 ppm recorded higher growth, yield and yield components and contributing to the yield enhancement up to 46% and 35% compared to recommended practices of soil and foliar application of $FeSO_4$. The Fe_2O_3 NPs might be an ideal substitution for the traditional Fe fertilizer to overcome iron deficiency in calcareous soils. However, further research is required to assess its potential risk to the environmental sustainability and food security.

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