

# Comparative effects of nano and chelated micronutrient fertilizers on growth, yield, and nutritional value of common bean (*Phaseolus vulgaris* L.) under sandy soil conditions

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## Abstract

This two-season field study evaluated the impact of foliar-applied nano and chelated micronutrient fertilizers (iron, zinc, and manganese), combined with standard NPK, on common bean (*Phaseolus vulgaris* L.) growth, yield, and nutritional quality under sandy soil conditions in Egypt. Using a randomized complete block design, nine treatments were assessed during 2022 and 2023. Results consistently showed that nano-fertilizer applications significantly enhanced vegetative growth parameters, including plant height, leaf count, and shoot fresh weight. Specifically, the combined nano (Fe+Zn+Mn) treatment proved most effective, leading to the highest total green pod yield (5.77 tons/fed in 2022; 6.33 tons/fed in 2023) and improved total soluble solids (TSS). Furthermore, nano-fertilizers notably increased the concentrations of macronutrients (N, P, K) and micronutrients (Fe, Zn, Mn) in both leaves and pods, indicating superior nutrient uptake and translocation efficiency. The study also revealed the positive effects of nano-fertilizers on key biochemical quality traits, including protein, fibre, fat, and ascorbic acid content. These benefits are attributed to the unique properties of nanoparticles, including their small size and high surface area, which facilitate enhanced nutrient bioavailability. This research highlights the promising potential of integrating nano-fertilizers into agricultural practices to significantly boost common bean productivity and nutritional value, thereby supporting more sustainable farming systems.

**Key words:** Snap bean, nano micronutrient fertilizers, growth, yield and nutritional value

## Introduction

Common bean (*Phaseolus vulgaris* L.) is a globally significant legume crop, cultivated for its edible dry seeds and fresh pods. It serves as a primary food source for human consumption worldwide, making its enhanced production crucial. Conventional agricultural practices heavily rely on chemical fertilizers containing nitrogen, phosphorus, and potassium (NPK) due to their rapid availability and ease of application, which significantly boost crop yields (Al-Tawarah *et al.*, 2024). Micronutrient deficiencies are a common constraint in crop production, particularly in alkaline soils characterized by low element solubility, the presence of carbonate and bicarbonate ions in irrigation water, and excessive phosphorus intake. Iron (Fe), zinc (Zn), and manganese (Mn) are essential micronutrients vital for crop growth, and their deficiencies can severely impact yields or even lead to plant death. For instance, Fe can accumulate in plant vessels, hindering its translocation to other plant parts. Foliar application of micronutrients provides an effective solution to overcome soil absorption limitations and enhance nutrient availability to plant roots, compared to soil application (Roosta and Hamidpour, 2013). These fertilizers are manufactured by formulating nutrient materials into extremely small particles (1–100 nm), which allows for distinct characteristics compared to macro-scale nutrients. Nano-fertilizers offer several advantages, including the controlled and slow release of nutrients over an extended period, which minimizes nutrient loss from the soil and reduces soil and groundwater pollution (Mandal and Lalrinchani, 2021). Nano-fertilizers, developed through various processes, are considered comparable to or superior to traditional

chemical fertilizers in terms of nutrient content and application efficiency. Nanoparticles can enhance nutrient management through controlled release mechanisms and increased plant stress resistance (Mohamed, *et al.*, 2025; Mahdy *et al.*, 2024a; 2024b). They contribute to improved nutrient uptake efficiency, promoting plant growth and yield when applied at optimal concentrations, although excessive dosages can have negative impacts (Singh, 2017). Integrating nano-fertilizers with conventional fertilizers can lead to reduced input costs, minimized waste, and the prevention of nutrient losses by aligning nutrient release with plant needs, thereby supporting sustainable agricultural development (Abdel-Aziz and Taha, 2018). Unlike conventional fertilizers, nano-fertilizers exhibit distinct characteristics in terms of soil interactions, application methods, required dosage, and environmental impact (Abd El-Azeim *et al.*, 2020).

Given these considerations, this study aimed to investigate the influence of foliar application of iron, zinc, and manganese in nanoform and compare their effects with those of chelated forms on the vegetative growth, physical and chemical characteristics, pod quality, and green yield of common bean grown in sandy soil.

## Materials and methods

**Experimental site and agricultural practices:** Two field trials were conducted during the 2022 and 2023 growing seasons at Al Karimat - Kafr Al Dasmi, El Wahat El Bahariya, Giza Governorate, Egypt (GPS coordinates: 29.567° N, 30.567° E). The experimental soil was sandy, with characteristics in the first season of pH 7.8, EC 1.41 dSm<sup>-1</sup>, and 4.26% CaCO<sub>3</sub>, and in the

second season of pH 8.3, EC 4.78 dSm<sup>-1</sup>, and 5.02% CaCO<sub>3</sub>. Certified Bronco common bean seeds were planted on April 14, 2022, and 2023. The experiment was arranged in a Randomized Complete Block Design (RCBD) with three replicates. Each experimental unit covered a net plot area of 20 m<sup>2</sup> (0.8 m wide × 25 m long). Drip irrigation was used for all plots. Prior to planting, all experimental areas received a complete dose of organic fertilizer (compost) at a rate of 20 m<sup>3</sup> per feddan. Mineral phosphorus (P) was applied as calcium superphosphate (15.5% P<sub>2</sub>O<sub>5</sub>) at 100 kg/feddan. Mineral nitrogen (N) as ammonium sulphate (20.6% N) at 150 kg/feddan and mineral potassium (K) as potassium sulphate (48% K<sub>2</sub>O) at 50 kg/feddan were added during the growth seasons according to standard recommendations.

**Nano and chelated micronutrient treatments:** The experiment included eight micronutrient treatments, in addition to a control (recommended NPK fertilizers only), totalling nine treatments. All treatments, except the control, received foliar applications of micronutrients. The treatments were as following:

Control: NPK fertilizers (recommended doses); Nano Fe: 25 ppm; Chelate Fe: 13% Fe (equivalent to 2.5 g/L); Nano Zn: 30 ppm; Chelate Zn: 13% Zn (equivalent to 2.5 g/L); Nano Mn: 20 ppm; Chelate Mn: 13% Mn (equivalent to 2.5 g/L); Nano Mix: Fe (25 ppm) + Zn (30 ppm) + Mn (20 ppm); Chelate Mix: Fe (13%) + Zn (13%) + Mn (13%).

Nano-microelement doses (Zn, Fe, Mn) applied were equivalent to mg cm<sup>-3</sup> of nanoparticles per liter. Foliar applications were performed three times at 15-day intervals, starting 20 days after sowing.

**Nanoparticle preparation:** All reagents used were of analytical grade. Nanoparticles were prepared using a top-down molecular chemical method. Zinc chloride (ZnCl<sub>2</sub>), magnetite (Fe<sub>3</sub>O<sub>4</sub>), and manganese chloride (MnCl<sub>2</sub>) were purchased from Sigma Chemical Co. (St. Louis, USA).

**Nano zinc:** Prepared from an aqueous solution of ZnCl<sub>2</sub>. Sodium hydroxide solution was slowly added (1:2 molar ratio) under vigorous stirring for 8 hours. The precipitate was filtered, thoroughly washed with a mixed water/toluene system, and then washed again with deionized water for 3 hours. The precipitate was dried at 100°C and then exposed to 1.5 psi pressure discontinuously (7 hours/day) for 3 days (Mahmoud *et al.*, 2022).

**Nano iron (FeO):** Prepared with slight modifications from

magnetite (Fe<sub>3</sub>O<sub>4</sub>) of Fe<sup>3+</sup> and Fe<sup>2+</sup> by reduction-precipitation in aqueous ammonia (0.3 mol/L), tetramethylammonium hydroxide, and 98% sulfuric acid. The mixture was vigorously stirred for 4 hours. The precipitate was separated by magnetic filtration, washed with distilled water until the pH reached neutrality, and then centrifuged at 1200 rpm for 40 minutes. It was subsequently further washed with deionized water. Finally, the precipitate was dried at 100°C for 3 days, then exposed to 1.5 psi pressure discontinuously (5 hours/day) for 2 days (Mahmoud *et al.*, 2022).

**Nano manganese:** Synthesized using aqueous solutions of calcium hydroxide [Ca(OH)<sub>2</sub>], 85% orthophosphoric acid (H<sub>3</sub>PO<sub>4</sub>), and MnCl<sub>2</sub>·4H<sub>2</sub>O (99%). A molar ratio of 1:1:2 (Ca(OH)<sub>2</sub>, H<sub>3</sub>PO<sub>4</sub>, and MnCl<sub>2</sub>·4H<sub>2</sub>O, respectively) was added dropwise to 50 mL of deionized water and dissolved slowly. This mixture was then slowly added to a 3M NaOH (95%) solution at 95°C, with vigorous stirring in a water bath, for 3 hours. The reaction mixture underwent triple washing with deionized water and absolute ethanol (98%), followed by centrifugation at 4000 × g for 14 minutes. The resulting powder was dried at 70°C for 36 hours, subsequently exposed to discontinuous pressure of 2 psi (3 hours/day) for 3 days, and finally finely ground after cooling to room temperature (Hong *et al.*, 2021).

The structural morphology and approximate particle size of the synthesized micronutrients were confirmed prior to agricultural application, as depicted in Fig. 1.

**Growth characteristics assessment:** Forty-five days after sowing, nine plants were randomly selected from each treatment to measure growth characteristics: plant height (from ground level to apical meristem), number of shoots per plant, number of leaves per plant, fresh weight, and dry weight. Relative chlorophyll content (SPAD reading) was measured in the fresh third top fully expanded leaf using a SPAD-502 meter.

**Yield and quality:** Parameters: Green pods were harvested from the two external rows of each experimental unit, starting 70 days after sowing over three rounds. The following determinations were recorded: number of green pods per plant, green pod yield per plant, fresh weight per green pod (calculated), and total green pod yield per feddan (0.42 ha). Ten randomly selected pods were weighed and then dried at 70°C to determine pod dry weight. Total soluble solids (TSS) were evaluated using a digital refractometer. The fibre, protein and fat content were determined according to the AOAC (2005) method.

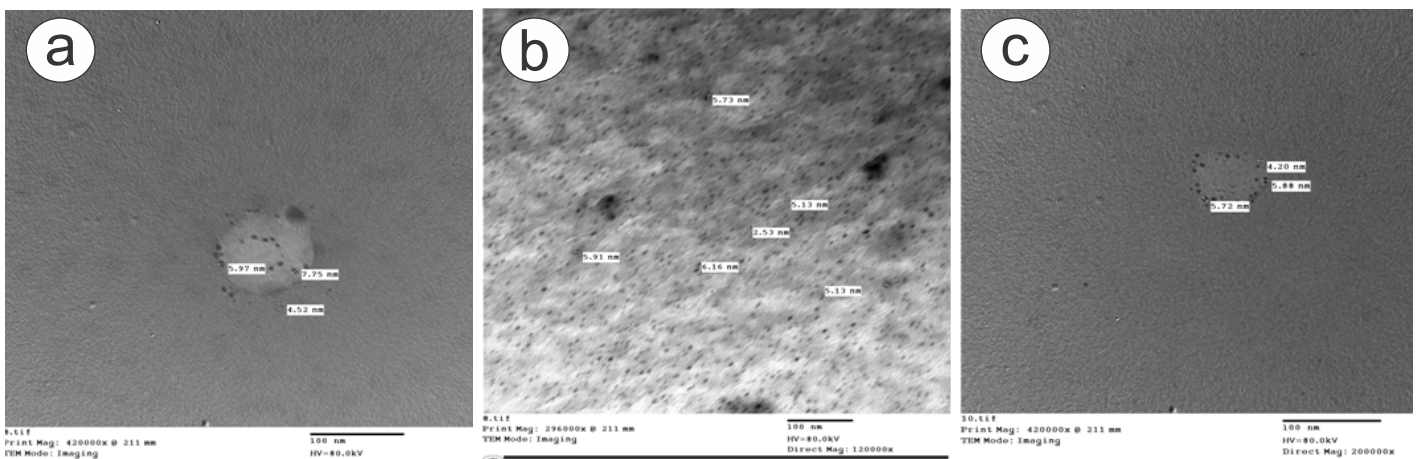


Fig.1. Image of nano Zn (a), nano Fe (b) and nano Mn (c)

**Leaf and pod elemental contents:** Leaf and pod samples were collected from five randomly selected plants per experimental unit, washed, and rinsed three times with distilled water. They were then dried at 70°C to a constant weight. Samples were then finely ground. A 0.2 g dried sample (leaves and pods) was digested with 5 mL of sulfuric acid and perchloric acid, heated for 10 minutes, followed by the addition of 0.5 mL of perchloric acid and continued heating until a clear solution was obtained (AOAC, 1990). Total nitrogen (N) content was determined using a modified micro-Kjeldahl technique (AOAC, 1990). The total protein content in pods was calculated by multiplying the nitrogen content by a conversion factor of 6.25 (Mahmoud *et al.*, 2019). Phosphorus (P) levels were measured colorimetrically using the chlorostannous molybdophosphoric blue colour method (AOAC, 1990). Potassium (K) concentrations were analyzed using a flame photometer (CORNING M410, Halstead, UK). Iron (Fe), zinc (Zn), and manganese (Mn) levels were determined with an atomic absorption spectrophotometer (Pye Unicam, model SP-1900, Cambridge, UK) using an air-acetylene flame (Antunes *et al.*, 2017).

**Statistical analysis:** The experiment utilized an RCBD, where nine treatments were randomly assigned to three replications. The Least Significant Difference (LSD) test at a 0.05 significance level was applied to compare mean values, following the statistical methodology by Snedecor and Cochran (1980).

## Result and discussion

The application of various nano and chelated micronutrient treatments significantly enhanced the growth parameters of common bean (Bronco cv.) in both the 2022 and 2023 seasons (Table 1). All single nano (Fe, Zn, or Mn) treatments, as well as chelated Fe and chelated Zn treatments, significantly increased plant height compared to the control in the first season. In the second season, most foliar applications resulted in taller plants than the control, except for nano Mn. Notably, Chelate Fe (67.57 cm) produced the tallest plants in the second season, while Nano Zn (48.13 cm) and Nano Mn (48.30 cm) were among the highest in the first season. The superior plant height observed with Chelate Fe can be attributed to iron's crucial role in chlorophyll biosynthesis and overall photosynthetic efficiency, which drives plant growth.

For the number of branches, foliar spraying with Nano Mn was consistently superior in both seasons (3.43 and 3.47 branches/

Table 1. Plant growth parameters affected by nano- and chelate micronutrient foliar application during the 2022 and 2023 seasons in common bean

Treatment	Plant height (cm)		Number of branches plant <sup>-1</sup>		No. leaves plant <sup>-1</sup>		Fw. shoots (g) plant <sup>-1</sup>		Dw. shoots (g) plant <sup>-1</sup>	
	1 <sup>st</sup> Season	2 <sup>nd</sup> Season	1 <sup>st</sup> Season	2 <sup>nd</sup> Season	1 <sup>st</sup> Season	2 <sup>nd</sup> Season	1 <sup>st</sup> Season	2 <sup>nd</sup> Season	1 <sup>st</sup> Season	2 <sup>nd</sup> Season
Control	36.13c	40.2c	2.76bc	2.97d	14.07de	12.60c	155.57bc	83.03e	9.65bc	14.44e
Nano Fe	44.90ab	51.97abc	2.70bc	3.30c	11.50e	13.80bc	165.97abc	139.1cd	11.47abc	24.20cd
Chelate Fe	44.47ab	67.57a	2.40c	3.27cd	13.60de	14.17bc	178.10a	125.5d	12.54ab	21.83d
Nano Zn	48.13a	55.93abc	2.83abc	3.70b	21.57cd	18.50ab	185.90a	173.9ab	14.42a	30.25ab
Chelate Zn	49.17a	55.43abc	2.93abc	3.30c	28.83abc	17.53abc	181.53a	155.8abc	14.18a	27.11bc
Nano Mn	48.30a	50.37bc	3.43a	3.47bc	30.83ab	16.00abc	174.13ab	136.8cd	12.9ab	23.80cd
Chelate Mn	39.87bc	52.87abc	2.93abc	4.03a	23.27bc	17.57abc	148.83c	142.3cd	8.49c	24.75cd
Nano (Fe+Zn + Mn)	46.23a	54.87abc	3.30ab	3.27cd	31.40ab	21.60a	186.37a	182.2a	15.02a	31.70a
Chelate (Fe+Zn+Mn)	40.57bc	61.80ab	3.23ab	3.17cd	32.27a	18.13abc	177.87a	139.1cd	13.53a	24.21cd
LSD (0.05)	5.04	15.99	0.65	0.32	8.50	5.73	21.82	19.74	3.82	3.43

plant, respectively). This reflects manganese's involvement in cell division and the development of meristematic tissue, leading to increased branching. While individual applications showed specific strengths, the combined micronutrient treatments demonstrated a broader positive effect across most vegetative growth measurements.

The highest number of leaves (32.27 leaves) was observed in chelate (Fe+Zn+Mn), during the first season. Conversely, Nano (Fe+Zn+Mn) achieved the highest leaf number in the second season (21.60 leaves). Nano (Fe+Zn+Mn) treatment consistently produced the highest fresh and dry shoot weights per plant in both seasons (*e.g.*, 186.37 g fresh weight and 15.02 g dry weight in 2022; 182.2 g fresh weight and 31.70 g dry weight in 2023). This strong synergistic effect, particularly from the nano-combination, highlights the integrated roles of zinc in regulating hormonal activity, iron in supporting chloroplast development, and manganese in contributing to enzymatic activation and photosynthesis. The enhanced growth observed with nano-fertilizers can be attributed to their increased surface area and reactivity, which facilitate better nutrient uptake and utilization by plants (Kumar *et al.*, 2021). Chelated forms also improve nutrient availability and mobility. These findings highlight the potential of both nano- and chelated micronutrient fertilizers to enhance the vegetative growth of common beans significantly.

Vegetative growth increments are largely due to the stimulatory effects of micronutrients on chlorophyll production, mitochondrial respiration, and photosynthesis. Our results align with several studies that have reported similar positive effects of micronutrient and nano-fertilizer applications on snap beans (Mahmoud *et al.*, 2022; Salama *et al.*, 2022).

Foliar application of micronutrients significantly improved pod physical quality and green pod yield (Table 2). The Nano (Fe+Zn+Mn) treatment consistently outperformed all other treatments, including the chelated combination and the control, across both seasons for most yield parameters. This integrative nano application led to significantly higher pods per plant, green pod fresh weight per plant, dry weight per plant, and total yield per feddan.

Specifically, in the first season, Nano (Fe+Zn+Mn) yielded 29.13 pods/plant, 125.20 g of fresh pods/plant, 17.54 g of dry pods/plant, and 5.77 tons/feddan of total yield. In the second season, these values were even higher: 62.60 pods/plant, 165.00 g fresh pods/plant, 23.10 g dry pods/plant, and 6.33 tons/feddan total

Table 2. Pod physical quality and green pod yield as affected by nano and chelate micronutrients foliar application during the 2022 and 2023 seasons in common bean

Treatment	Number of Pods		FW Pod (gm)		DW Pod		Total yield (ton)/fed		TSS (%)	
	1 <sup>st</sup> Season	2 <sup>nd</sup> Season	1 <sup>st</sup> Season	2 <sup>nd</sup> Season	1 <sup>st</sup> Season	2 <sup>nd</sup> Season	1 <sup>st</sup> Season	2 <sup>nd</sup> Season	1 <sup>st</sup> Season	2 <sup>nd</sup> Season
Control	22.17bc	23.20e	98.50cd	96.17e	13.79cd	13.46e	3.97d	4.20c	3.73c	4.40b
Nano Fe	23.83ab	50.23abc	111.90a-d	127.20cd	15.66a-d	17.80cd	4.93bc	5.07abc	4.20b	4.30b
Chelate Fe	23.17abc	40.50bcd	103.10bcd	123.70d	14.43bcd	17.32d	4.43cd	4.90bc	4.10b	4.17bc
Nano Zn	28.90a	58.57a	125.10a	149.50ab	17.51a	20.92ab	5.13b	6.20ab	4.23b	3.97c
Chelate Zn	29.23a	51.50ab	113.50abc	132.90bcd	15.89abc	18.60bcd	5.13b	5.20abc	3.73c	3.37d
Nano Mn	26.93ab	37.90bcd	120.50ab	140.30bcd	16.86ab	19.64bcd	4.80bc	5.83ab	4.10b	4.20bc
Chelate Mn	17.60c	29.50de	91.27d	133.90bcd	12.77d	18.75bcd	4.20d	5.53abc	4.17b	4.40b
Nano (Fe+Zn + Mn)	29.13a	62.60a	125.20a	165.00a	17.54a	23.10a	5.77a	6.33a	4.57a	5.00a
Chelate (Fe+Zn+Mn)	26.77ab	36.60cde	110.80a-d	143.90bc	15.51a-d	20.15bc	5.30ab	5.93ab	4.17b	4.20bc
LSD 0.05	6.18	13.94	21.92	17.6	3.06	2.46	0.57	1.41	0.29	0.24

yield. This represents a substantial increase over the control (e.g., 31.4–170% increase in pods/plant, and 45.4–50.7% increase in total yield). The results unequivocally demonstrate that the combined nano-formulation is the most effective treatment for enhancing both the quantity and quality of common bean yield (Bronco cv.).

The superior performance of nanoformulations over chelated forms is consistent with the literature (Kumar *et al.*, 2021), which attributes this to their smaller particle size, higher surface area, and improved penetration and translocation within plant tissues. The vigorous vegetative growth observed with Nano (Fe+Zn+Mn) (Table 1) directly translated into significantly improved yield attributes, indicating efficient photosynthesis and healthy canopy development, which supports higher productivity. Nano-fertilizers enhance the bioavailability of micronutrients, leading to increased photosynthetic efficiency, improved flowering, and ultimately higher fruit yields (Dimkpa *et al.*, 2017). The combined application of Fe, Zn, and Mn in nanoform likely created a synergistic effect, optimizing enzymatic and hormonal processes critical for fruit development. Previous studies have similarly demonstrated that nano-Zn and nano-Fe significantly enhance fruit yield in green beans by improving nutrient absorption and physiological efficiency (Azimi *et al.*, 2022). This foliar approach is particularly effective for direct nutrient absorption by leaves, especially when soil conditions are unfavourable for root uptake.

Table 3. Macronutrients NPK and Chlorophyll % in both leaves and pods as affected by nano and chelate micronutrients foliar application during the 2022 and 2023 seasons in common bean

Treatment	Season 1				Season 2				Season 1				Season 2			
	Chlor	N	P	K	Chlor	N	P	K	Chlor	N	P	K	Chlor	N	P	K
	Leaf								Pod							
Control	40.90e	3.15b	0.36a	2.81a	38.60d	3.49bc	0.38a	2.68a	77.6g	1.16d	0.72ef	1.54d	76.90g	1.24c	0.7bc	1.55a
Nano Fe	42.24de	4.50ab	0.47a	3.26a	43.59bc	5.10ab	0.53a	3.56a	87.20cd	1.33c	0.75cde	1.68c	88.55c	1.41abc	0.83b	1.76a
Chelate Fe	43.49cde	3.16b	0.43a	3.10a	44.84bc	3.76bc	0.49a	3.40a	86.50de	1.27cd	0.73def	1.55d	87.85c	1.35bc	0.81bc	1.63a
Nano Zn	45.60c	4.77ab	0.48a	3.14a	43.50c	4.79abc	0.49a	3.16a	90.51b	1.39c	0.78bcd	1.66c	90.50b	1.41abc	0.79bc	1.72a
Chelate Zn	41.90de	4.51ab	0.45a	3.09a	37.60d	4.48abc	0.44a	3.07a	81.43f	1.28cd	0.68f	1.63cd	82.50e	1.25c	0.67c	1.55a
Nano Mn	44.30cd	4.93ab	0.41a	2.91a	42.50c	4.95abc	0.45a	3.06a	88.30c	1.89b	0.82b	1.65c	85.20d	1.86abc	0.8bc	1.68a
Chelate Mn	43.80cd	4.96a	0.40a	2.72a	39.60d	3.24c	0.37a	2.18a	82.60f	1.38c	0.75cde	1.63cd	80.50f	1.36bc	0.72bc	1.50a
Nano FZM)	52.40a	6.10a	0.48a	3.27a	51.30a	5.92a	0.50a	3.25a	98.60a	2.15a	1.06a	2.03a	96.50a	2.14a	1.02a	2.00a
Chelate FZM	48.80b	4.70ab	0.42a	3.19a	46.20b	4.70abc	0.40a	3.14a	85.67e	2.02ab	0.79bc	1.92b	82.50e	2.05ab	0.76bc	1.84a
LSD 0.05	2.73	1.79	NS	NS	2.71	1.74	NS	NS	1.46	0.15	0.145	0.12	1.80	0.75	0.055	NS

Chlor (%)=Chlorophyll %; Nano FZM= Nano (Fe+Zn + Mn); Chelate FZM=Chelate (Fe+Zn+Mn)

content, emphasizing the essential role of micronutrients (Fe, Zn, Mn) as critical cofactors in chlorophyll production, without which chlorosis and reduced photosynthetic efficiency occur. The higher chlorophyll content in pod tissues suggests a significant contribution to photosynthesis by pods during the reproductive phase (Azimi *et al.*, 2022).

Regarding macronutrient content, the Nano (Fe+Zn+Mn) treatment significantly increased nitrogen (N), phosphorus (P), and potassium (K) in both leaves and pods in both seasons compared to the control. In leaves, N levels reached 6.10% (2022) and 5.92% (2023), and in pods, 2.15% (2022) and 2.14% (2023). This confirms the superior efficiency of nano-fertilizers in enhancing nutrient uptake and translocation, likely due to their small particle size and higher surface reactivity, which improves solubility and bioavailability (Sheta *et al.*, 2025).

Individual nano treatments (Nano Fe, Nano Zn, and Nano Mn) generally outperformed their chelated counterparts in terms of macronutrient accumulation. For instance, Nano Fe significantly increased leaf nitrogen compared to Chelate Fe. While no significant differences were observed for P and K in leaves among most treatments, the triple nano mixture recorded the highest P and K levels in pods, suggesting improved nutrient remobilization during pod development. This finding aligns with previous reports that nano-fertilization enhances nutrient partitioning (Azimi *et al.*, 2022). The chelated fertilizers, while improving the nutrient content over the control, generally lagged behind their nano counterparts, potentially due to a lower efficiency of nutrient release or absorption (Yarnia *et al.*, 2024). In summary, nano micronutrient blends (Fe, Zn, Mn) significantly enhanced macronutrient accumulation in both leaves and pods, attributed to improved nutrient availability and uptake efficiency facilitated by the nanostructure (Sheta *et al.*, 2025).

The data clearly show that applying both nano and chelated forms, individually or in combination, significantly enhanced micronutrient concentrations in common bean leaves compared to the control (Table 4). Among all treatments, Nano (Fe+Zn+Mn) consistently recorded the highest levels of Fe, Zn, and Mn in leaves during both seasons, indicating a strong synergistic effect. For example, in Season 1, this treatment resulted in 103.6 ppm Fe, 55.49 ppm Zn, and 65.38 ppm Mn, which were significantly higher than the control (79.81, 37.96, and 41.89 ppm, respectively).

Table 4. Micronutrients (ppm) in both leaves and pods as affected by nano and chelate micronutrients foliar application during the 2022 and 2023 seasons in common bean

Treatment	Season 1			Season 2			Season 1			Season 2		
	Fe	Zn	Mn	Fe	Zn	Mn	Fe	Zn	Mn	Fe	Zn	Mn
	Leaves						Pods					
Control	79.81b	37.96b	41.89f	77.62c	35.88f	36.37f	48.97de	39.62f	13.58f	48.62ef	37.70e	12.61f
Nano Fe	85.46b	42.67b	43.84de	87.81bc	44.02d	45.19bc	52.10b	44.34d	16.54bc	53.45a	45.69d	16.33bc
Chelate Fe	82.43b	40.64b	42.26ef	84.78bc	41.99d	43.61d	50.67bc	43.75d	14.32ef	52.02b	45.10d	15.67cd
Nano Zn	88.65b	40.82b	45.67c	84.72bc	43.13c	44.96c	48.25e	47.25c	17.49ab	49.1de	45.29d	17.55a
Chelate Zn	80.73b	39.72b	44.39cd	80.73bc	37.96e	42.81d	48.66de	41.19e	15.16de	48.32f	39.17e	14.19e
Nano Mn	90.64b	42.53b	43.68de	85.10bc	40.63c	45.09bc	51.69b	46.61c	16.14cd	51.15c	47.60c	17.05ab
Chelate Mn	85.10b	38.22b	43.42def	81.33bc	34.35f	41.52e	48.86de	38.66f	15.32cde	48.12f	37.81e	13.95e
Nano FZM)	103.6a	55.49a	65.38a	99.75a	52.63a	62.83a	55.62a	75.71a	18.31a	52.22b	76.91a	17.89a
Chelate FZM	89.25b	39.65b	48.23b	83.31bc	37.79b	46.13b	50.12cd	68.42b	15.62cd	49.41d	70.15b	14.81de
LSD 0.05	12.87	8.76	1.78	8.103	1.85	1.16	1.542	1.55	1.26	0.597	1.86	1.15

Similar trends observed in season 2 aligns with findings that nano-chelated combinations improve micronutrient uptake and translocation, enhancing nutritional status (Sheta *et al.*, 2025). The superiority of nano forms, especially in combination, is further supported by their enhanced bioavailability and plant absorption, which is attributed to their small particle size and high reactivity (Fatollahpour Grangah *et al.*, 2021). Individual nano treatments also performed well, but the combined nano treatment maximized uptake, suggesting positive synergistic interactions (Azimi *et al.*, 2022).

The same trend was observed in pods: Nano (Fe+Zn+Mn) significantly increased Fe, Zn, and Mn concentrations over all other treatments in both seasons. For instance, in Season 1, this treatment produced 55.62 ppm Fe, 75.71 ppm Zn, and 18.31 ppm Mn in pods, whereas the control had 48.97 ppm Fe, 39.62 ppm Zn, and 13.58 ppm Mn, respectively. This increase in pod micronutrient content suggests that nano-micronutrient fertilization not only enhances uptake but also facilitates efficient translocation to sink tissues (pods), which is crucial for improving nutritional quality and seed enrichment (Ponce-García *et al.*, 2023). Individual nano applications (*e.g.*, Nano Fe, Nano Zn) also improved micronutrient levels in pod compared to their chelate counterparts, reinforcing the higher efficacy of nano formulations in reproductive tissues (Sepehri and Norimanesh, 2024). While both forms outperformed the control, nano formulations consistently led to higher nutrient concentrations in both leaves and pods, corroborating enhanced mobility and grain quality (Vaghar, 2021; Yilmaz, 2023).

Figures 2 and 3 demonstrate a clear superiority of the Nano (Fe+Zn+Mn) treatment, which recorded the highest values for both fat and ascorbic acid contents in both seasons. Specifically, fat content was 0.30% (2022) and 0.36% (2023), and ascorbic acid content was 29.53 mg/100g (2022) and 28.48 mg/100g (2023). This suggests a strong synergistic effect of the nano-form micronutrients, likely due to their enhanced uptake and bioavailability (Salama *et al.*, 2022).

The increased ascorbic acid content under nano treatments can be attributed to the role of iron, zinc, and manganese in antioxidant biosynthesis and enzymatic activity (Azimi *et al.*, 2022). These elements are known to participate in physiological pathways associated with ascorbate metabolism and reactive oxygen species detoxification, thereby enhancing the antioxidant potential of plant tissues (Dimkpa *et al.*, 2017).

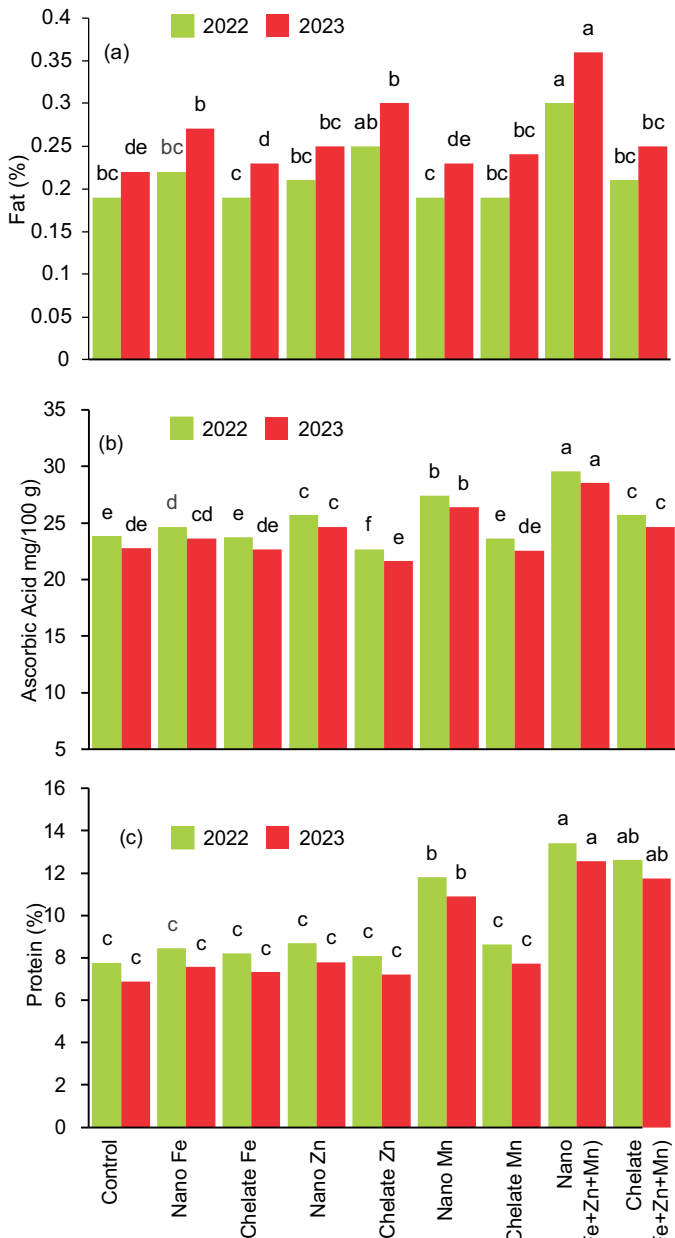


Fig. 2. Pods quality fats (a), ascorbic acid (b) and protein (c) as affected by nano and chelate micronutrients foliar application during 2022 and 2023 seasons in common bean. Letters indicate significant differences by LSD test  $P < 0.05$ . Bars with the same letter for each parameter are not significantly different at  $P < 0.05$ , according to Duncan's Multiple

In contrast, the chelate forms, especially Chelate (Fe+Zn+Mn), showed significantly lower effects compared to their nano counterparts. This is consistent with the higher efficiency of nano-fertilizers due to their small particle size, larger surface area, and controlled nutrient release (Singh, 2017). The control treatment consistently exhibited the lowest values for both fat and ascorbic acid, underscoring the essential role of micronutrient supplementation in enhancing the nutritional quality of bean crops (Gutiérrez-Ruelas *et al.*, 2021). Overall, foliar application of nano-fertilizers, particularly multi-nutrient formulations, significantly enhances the biochemical quality traits of common beans.

This two-season field study unequivocally demonstrates the significant advantages of applying nano-micronutrient fertilizers over conventional chelated forms for common bean (*Phaseolus*

*vulgaris* L.) cultivation in sandy soils. The most effective treatment was the combined foliar application of nano-iron (Fe), nano-zinc (Zn), and nano-manganese (Mn) alongside standard NPK fertilization.

This specific nano-combination consistently and significantly enhanced various critical aspects of common bean production. It resulted in superior vegetative growth, characterized by increased plant height, leaf number, and overall shoot biomass. More importantly, it resulted in a substantially higher total green pod yield and improved pod quality metrics, such as total soluble solids. The positive effects extended to the plant's nutritional profile, with marked increases in both macronutrients (N, P, K) and micronutrients (Fe, Zn, Mn) in both leaves and edible pods. Furthermore, crucial biochemical quality traits, such as protein, fat, and ascorbic acid content, were notably improved.

These benefits are primarily attributed to the unique properties of nanoparticles, including their small size and high surface area, which facilitate enhanced nutrient uptake, mobility, and bioavailability within the plant.

From a practical perspective, the integration of nano-micronutrient fertilizers presents a promising, sustainable solution for addressing micronutrient deficiencies and boosting common bean productivity in challenging sandy soil environments. This approach not only optimizes crop yield and quality but also offers a more efficient nutrient delivery system, potentially reducing nutrient losses and environmental impact.

Future research should focus on optimizing nano-fertilizer dosages, evaluating their long-term environmental impact in soil

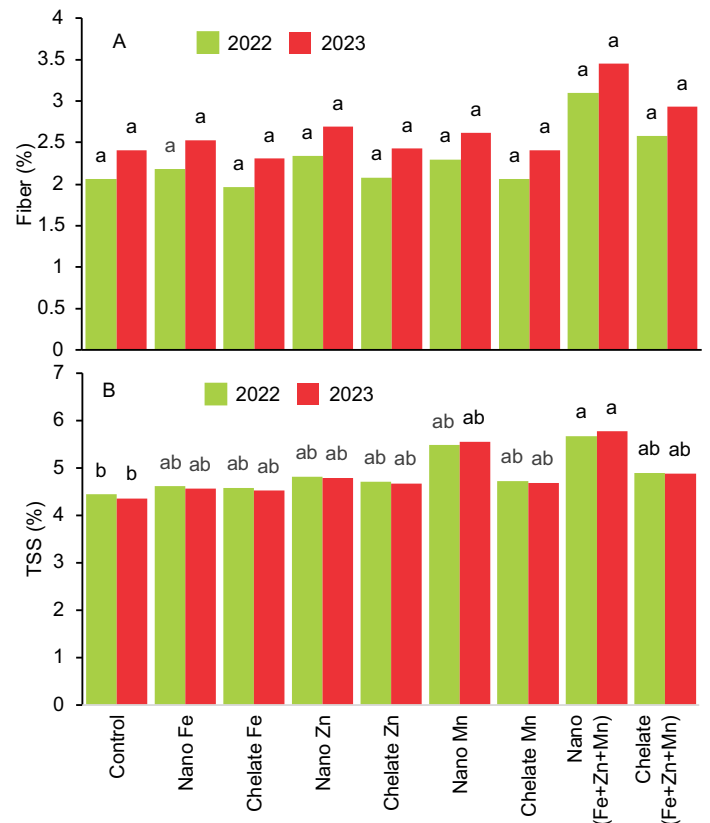


Fig. 3. Pods quality fibers (A) and total soluble solids (B) as affected by nano and chelate micronutrients foliar application during the 2022 and 2023 seasons in common bean. Letters indicate significant differences by LSD test  $P < 0.05$ . Bars with the same letter for each parameter are not significantly different at  $P < 0.05$ , according to Duncan's Multiple Range Test (DMRT).

systems, and assessing their economic viability for large-scale agricultural adoption.

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