

## Role of nano-mineral fertilizers in sugar beet growth and environmental sustainability in sandy soils

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### ABSTRACT

This study aimed to evaluate the effects of nitrogen (N), phosphorus (P), potassium (K), and micronutrient fertilizers in nanoparticle form on sandy soil properties, fertility, and the growth of sugar beet (*Beta vulgaris* L.) under greenhouse conditions. Five treatments were studied using pot experiments conducted in the greenhouse at Menoufia University, Egypt, to study the effect of the combined application of nano-form fertilizers and/or conventional fertilizers. Seeds were treated before planting either with or without soaking in a nano-micronutrient solution. Soil properties, nutrient availability, and plant growth parameters, such as chlorophyll content, leaf area index, and fresh and dry weights, were measured. The results indicated that applying low concentrations of nano-mineral fertilizers (NMFs) (T2, T3, T4, and T5) showed no significant changes in soil pH and electrical conductivity (EC, dS m<sup>-1</sup>) compared to conventional mineral fertilizers (CMFs) (T1). Soaking treatments combined with the application of T2 led to a marked increase in the available N and K content in the sandy soil compared to T1. Moreover, nano-fertilizer application enhanced chlorophyll content, leaf area index, and both fresh and dry weights of sugar beet roots and foliage. Significant increases were also observed in root and shoot concentrations of N, P, K, and micronutrients, with the soaking treatment yielding the most substantial improvements. The findings underscore the effectiveness of nano-mineral fertilizers (both macro- and micronutrients) in enhancing soil fertility and plant growth under sandy soil conditions.

**Key Words:** micronutrients, nano-fertilizers, sandy soil, soil fertility, sugar beet growth

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### INTRODUCTION

Currently, the extensive use of mineral fertilizers has led to nutrient accumulation in soils and runoff into aquatic systems, contributing to eutrophication in lakes and enhanced soil salinity (Ahmadi and Souri, 2020; Zargar Shooshtari *et al.*, 2020). These fertilizers exhibit low nutrient use efficiency, with rates as low as 30–35% for nitrogen (N), 18–20% for phosphorus (P), and 35–40% for potassium (K). Bhardwaj *et al.* (2022) demonstrated that nano-fertilizers (NF) significantly enhance nutrient use efficiency by reducing nutrient loading due to their high surface area and effectiveness in foliar applications that minimize environmental losses. Consequently, improving nutrient use efficiency through nanotechnology is essential (Yaswanth *et al.*, 2021). By adopting sustainable solutions such as nanotechnology in agriculture,

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particularly in plant nutrition and soil fertility, crop productivity can be improved. Nano-fertilizers, as opposed to conventional fertilizers, address challenges related to nutrient bioavailability and uptake, reduce fertilizer waste, and help protect the environment (Abd-Elrahman and Mostafa, 2015; Adhikari and Ramana, 2019). According to the Nano-Fertilizers Market Size, Share, and Trends Report (Bidwai, 2024), the global nano-fertilizers market size was estimated at USD 2,705.5 million in 2021, with an expected compound annual growth rate (CAGR) of 14.8% from 2022 to 2030. The market is projected to grow from USD 532.77 million in 2024 to USD 614.81 million in 2025. By 2034, the market is expected to reach approximately USD 2,231.49 million. In North America, the market size was approximately USD 223.76 million in 2024, with a projected growth rate of 15.52%.

Both conventional and nano fertilizers play a vital role in improving crop yield and nutritional quality by increasing soil fertility (Banotra *et al.*, 2017). However, nano-structured materials exhibit higher N use efficiency because plant cell walls contain very small pore sizes (5–20 nm), leading to increased nutrient absorption and enhanced plant growth.

In contrast to conventional fertilizers, applying lower quantities of NF is effective in supplying plants with essential nutrients and enhancing both the biochemical composition and quality of crops (Rezk *et al.*, 2021). Moreover, NF provide nutrients over an extended period (40–50 days), compared to the shorter release duration of conventional fertilizers (4–10 days). To maximize environmental benefits, the NF industry should prioritize the development of nano-forms of key macroelements (N, P, K), as this shift can significantly reduce the ecological footprint of traditional fertilizers (Bhardwaj *et al.*, 2022). Research by Kottogoda *et al.* (2017) further supports this by demonstrating that NF release nutrients at a rate approximately 12 times slower than conventional fertilizers, offering sustained nutrient availability.

Sugar beet (*Beta vulgaris* L.) is an edible plant belonging to the Amaranthaceae family, primarily utilized for sugar production worldwide (Kumar *et al.*, 2016). Sugar beet is recognized as a moderate climate crop and has emerged as a promising cash crop for tropical and subtropical regions (Cosyn *et al.*, 2011).

In countries such as Egypt, the sugar beet production is increasing and has become a crucial component of the sugar manufacturing sector (Abou-Elwafa *et al.*, 2020; Alotaibi *et al.*, 2021). It ranks second in importance after sugarcane, contributes approximately 40% to global sugar production annually, and is known for its adaptability to various environmental conditions (Abo-Elwafa *et al.*, 2013). Given Egypt's increasing population, as noted by Abofard *et al.* (2021) and Aljabri *et al.* (2021), there is a growing disparity between sugar production and consumption due to rising sugar demand. One significant advantage of sugar beet is its ability to grow in a wide range of soil types, both old and newly reclaimed, without competing with other winter crops. Furthermore, it can be cultivated under various stress conditions while requiring less water compared to sugarcane.

The objective of this research is to study the effect of individual and/or combined application of nano fertilizers and conventional fertilizer through reducing NPK and micronutrient concentrations compared to conventional fertilizers in enhancing the crop yield of sugar beet (*Beta vulgaris* L.). This approach enables the reduction of conventional fertilizer application rates while maintaining or even improving crop yield.

## MATERIALS AND METHODS

A pot experiment was conducted in the greenhouse at Menoufia University, Egypt (30°33'29.8"N, 31°00'51.2"E). The objective was to investigate the effects of various conventional fertilizers and NFs, along with seed pre-treatment, on the growth and chemical composition of sugar beet (*Beta vulgaris* L. cv. BTS 645).

### *soil sampling and characteristics*

Surface soil samples (0-20 cm) were collected from a sandy soil site in Alkhatatba Village, El Sadat City, Menoufia Governorate, Egypt (30°22'11.0"N, 30°47'41.3"E). These samples were air-dried, ground, mixed, and sieved through a 2 mm mesh. A portion of the resulting fine soil was analyzed for selected physicochemical properties and the availability of macro- and micronutrients, following the methods outlined by Klute (1986) for physical properties, and Cottenie *et al.* (1982) and Page *et al.* (1982) for chemical properties and nutrient availability. The results of these analyses are presented in Table I.

TABLE I

Physical and chemical characteristics and nutrient availability of the examined sandy soil

Physicochemical characteristics of soil						
Proportion of particle sizes (%)			Textural category *	pH	EC dSm <sup>-1</sup>	OM (%)
Sand	Silt	Clay				
86.50	8.30	5.20	Sand	8.10	2.10	0.51
Available nutrients in soil (mg kg <sup>-1</sup> )						
Macronutrient availability			Micronutrients availability			
N	P	K	Fe	Zn	Mn	Cu
18.52	3.20	63.60	4.25	2.35	3.88	1.02

\*According to International Society of Soil Science (ISSS) Texture triangle

### Tested plant

This study focused on sugar beet (*Beta vulgaris* L. cv. BTS-645). The seeds were procured from the Sugar Crops Research Institute, Agricultural Research Centre (ARC), Egypt.

### Study treatments

In all treatments, P was applied—both in conventional and nanosized forms—prior to the planting of sugar beet seeds and was thoroughly mixed into the soil (Table II). N and K were applied 30 days after planting, with the nano-K incorporated into the irrigation water for all treatments. Ninety days after planting, micronutrients—also in both conventional and nanosized forms—were applied as a foliar treatment in two equal doses.

TABLE II

Applied treatments of conventional and nano fertilizers

Treatments	N	P	K	MN	
T1	100% conventional fertilizers at Recommended dose	100 kg N fed <sup>-1</sup> (represents 298.5 kg ammonium nitrate fed <sup>-1</sup> )	31 kg P fed <sup>-1</sup> (represents 200 kg superphosphate fed <sup>-1</sup> )	25 kg K fed <sup>-1</sup> (represents 52 kg potassium sulphate fed <sup>-1</sup> )	100% RD (800 ml fed <sup>-1</sup> )
T2	Nano NPK + Nano MN	29.8 kg Nano N fed <sup>-1</sup> (Represent 10% Nano from RD)	20 kg Nano P fed <sup>-1</sup> (Represent 10% Nano from RD)	5.2 kg Nano K fed <sup>-1</sup> (Represent 10% Nano from RD)	80 ml fed <sup>-1</sup> Represent 10% Nano from RD
T3	Nano K	100 kg N fed <sup>-1</sup> (represents 298.5 kg ammonium nitrate fed <sup>-1</sup> )	31 kg P fed <sup>-1</sup> (represents 200 kg superphosphate fed <sup>-1</sup> )	5.2 kg Nano K fed <sup>-1</sup> (Represent 10% Nano from RD)	100% RD (800 ml fed <sup>-1</sup> )
T4	Nano MN	100 kg N fed <sup>-1</sup> (represents 298.5 kg ammonium nitrate fed <sup>-1</sup> )	31 kg P fed <sup>-1</sup> (represents 200 kg superphosphate fed <sup>-1</sup> )	25 kg K fed <sup>-1</sup> (represents 52 kg potassium sulphate fed <sup>-1</sup> )	80 ml fed <sup>-1</sup> Represent 10% Nano from RD
T5	Nano K + Nano MN	100 kg N fed <sup>-1</sup> (represents 298.5 kg ammonium nitrate fed <sup>-1</sup> )	31 kg P fed <sup>-1</sup> (represents 200 kg superphosphate fed <sup>-1</sup> )	5.2 kg Nano K fed <sup>-1</sup> (Represent 10% Nano from RD)	80 ml fed <sup>-1</sup> Represent 10% Nano from RD

#### \*Remark:

\*Applications of macronutrients were carried out as soil applications, while the applications of micronutrients were carried out as foliar applications.

\*Nano-form fertilizers were applied at a concentration of 10% from the recommended dose of conventional fertilizers and prepared from nano solution, which contained 20% of nanoform, which, considered by volume, represents about 50% of the total amount of conventional fertilizers.

### Preparation of NF solutions

All NFs used in this study were sourced from Nanotech for Photo Electronics (Giza, Egypt) with a concentration of 20%. Rutin-loaded chitosan nanoparticles were created by dissolving rutin in 70% ethanol and mixing it with a chitosan solution, followed by the incorporation of NF containing N, P, and K. The resulting colloidal suspension was stirred for two hours to facilitate particle hardening (Makvandi *et al.*, 2020; Abdel-Hakim *et al.*, 2023). The size and shape of the nanomineral fertilizers (NMFs) were characterized using transmission electron microscopy (TEM), which revealed average nanoparticle sizes of 34 nm for ammonium nitrate, 30 nm for phosphoric acid, and 31 nm for potassium sulfate (Fig. 1).

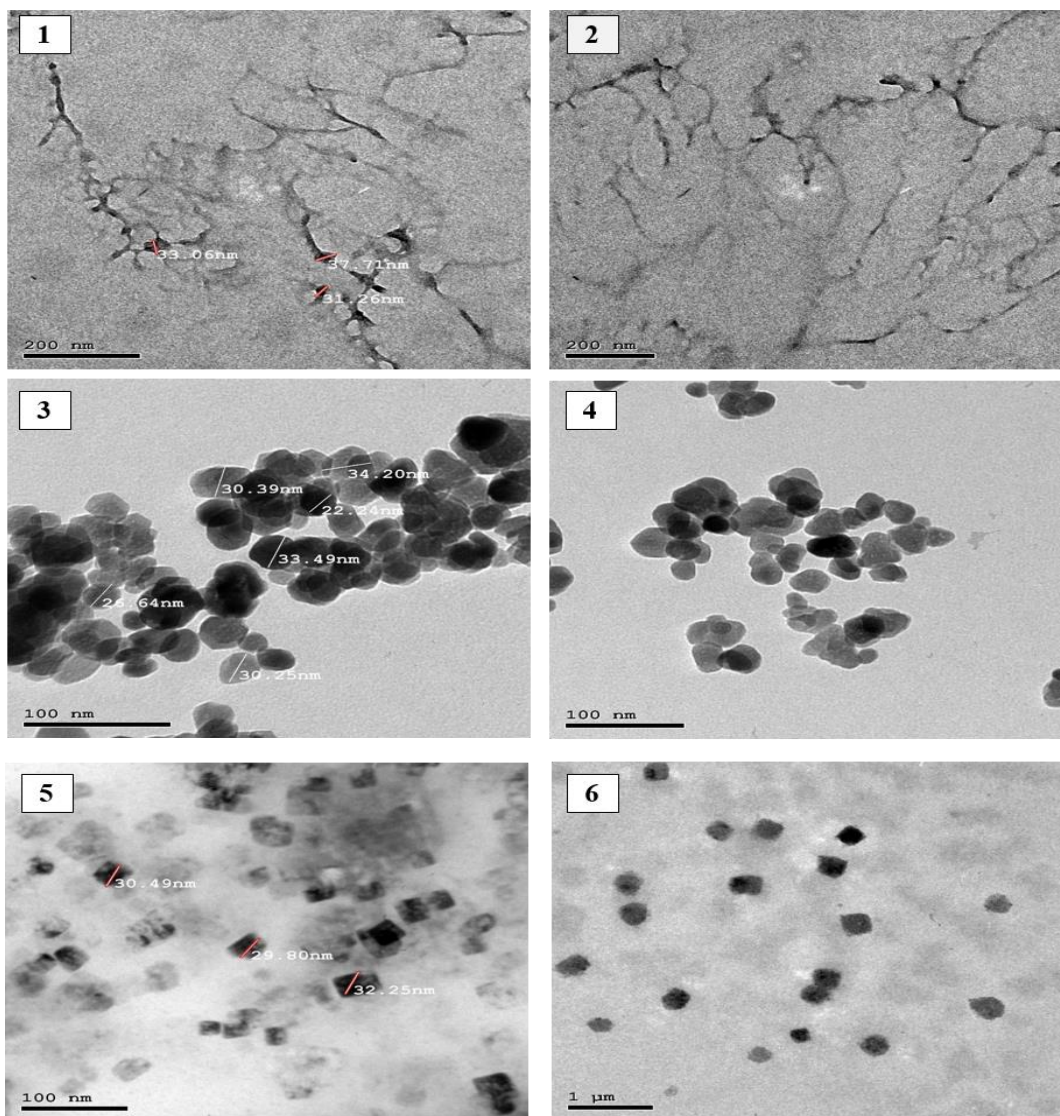


Fig. 1 Transmission electron microscope (TEM) of NMFs; ammonium nitrate (1 and 2), phosphoric acid (3 and 4) and potassium sulphate (5 and 6).

### Greenhouse experiment

This study was conducted in a greenhouse using 40 plastic pots, each with an inner diameter and depth of 40 cm. Each pot was filled with 15 kg of prepared sandy soil. The pots were divided into two main groups, with 20 pots per group, representing soaking treatments (non-soaking and soaking) applied to sugar beet seeds prior to planting. Each main group was further subdivided into five subgroups (4 pots per subgroup) corresponding to the fertilization treatments (T1, T2, T3, T4, and T5) described earlier. The soaking treatment was applied to half of the sugar beet seeds, using a soaking solution that contained 1 mL of 4% (Cu) and 1 mL of a 20% mixture of micronutrient solutions in nanosized forms per liter.

A total of 0.25 kg of sugar beet seeds (*Beta vulgaris* L., cv. BTS-645) were soaked in 1 L of a soaking solution for 4 hours. For the planting process, three non-soaked seeds were planted in each pot of the first group, while three soaked seeds were planted in each pot of the second group. The experimental design

followed a completely randomized block design with two treatment approaches and four replicates. All pots were irrigated using tap water to maintain the soil moisture content at field capacity (16%), with irrigation occurring every three days, based on weight, to sustain this moisture level.

After 15 days, seedlings were thinned to one plant per pot. At harvest (conducted 120 days after planting), each plant was separated into foliage and roots, and several growth parameters were measured, including leaf chlorophyll content ( $\text{mg m}^{-2}$ ), which was calculated by converting SPAD readings using the method of Monje and Bugbee (1992), fresh weight (g) of foliage and root, leaf area index (LAI), and dry weight (g) of foliage and root.

Foliage and root samples were air-dried, then oven-dried at  $70^{\circ}\text{C}$  for 48 hours, weighed (g/plant), ground, and analyzed for chemical composition. A 0.5 g sample of oven-dried plant material (foliage and root) was digested with 5 ml of concentrated  $\text{H}_2\text{SO}_4$  and  $\text{HClO}_4$  (3:1) until the solution became colorless (Chapman and Pratt, 1961). The digest was then diluted with distilled water to a volume of 100 ml, and the resulting solution was analyzed for macronutrients (N, P, K) and micronutrients (Fe, Zn, Mn, Cu) following the methods outlined by Cottenie *et al.* (1982) and Page *et al.* (1982).

After harvest, soil samples from each pot were collected, prepared, and analyzed for chemical properties and the availability of macro- and micronutrients, using the procedures described by Cottenie *et al.* (1982).

In addition, relative changes "RC" (%) in soil and plant measurements were calculated using (Eq. 1)

$$RC (\%) = \frac{DT-DC}{DC} \times 100 \quad (\text{Eq.1})$$

Where the *DT* and *DC* represent fertilizer treatments (T2, T3, T4 and T5) and control (T1), respectively.

### Statistical analysis

Data obtained from the plant was statistically analyzed according to Gomez and Gomez (1984). Significance was calculated at a 5% level of probability.

## RESULTS

### Soil pH and electrical conductivity (EC, $\text{dS m}^{-1}$ )

Under greenhouse conditions, the application of NMFs (T2, T3, T4, and T5) did not affect soil pH and electrical conductivity (EC,  $\text{dS m}^{-1}$ ) compared to conventional mineral fertilizers (CMFs) (T1), as shown in Table III. This trend was observed in both the non-soaking and soaking seed treatments. Consequently, the relative changes (RC%) for both soil pH and EC in relation to NMF applications were negative.

TABLE III

Effect of conventional and nano-mineral fertilizer applications on sandy soil pH and EC ( $\text{dS m}^{-1}$ ) and their relative change "RC (%)" affected by nano-fertilizer applications

Fertilizer treatment		pH 1:2.5 (soil : water) susp.		EC 1:5 (soil : water) extract	
Seeds soaking "a"	Soil and foliar "b"	Value	RC%	( $\text{dS m}^{-1}$ )	RC%
Non-soaking	T1	7.88	0	1.59 <sup>a</sup>	0
	T2	7.58	-3.81	1.40 <sup>ab</sup>	-11.95
	T3	7.70	-2.28	1.52 <sup>ab</sup>	-4.40
	T4	7.79	-1.14	1.56 <sup>a</sup>	-1.89
	T5	7.65	-2.92	1.50 <sup>ab</sup>	-5.66
	Mean		7.72		1.51
Soakin	T1	7.83	0	1.55 <sup>a</sup>	0
	T2	7.50	-4.21	1.33 <sup>b</sup>	-14.19

	T3	7.67	-2.04	1.46 <sup>ab</sup>	-5.81
	T4	7.75	-1.02	1.52 <sup>ab</sup>	-1.94
	T5	7.65	-2.30	1.43 <sup>ab</sup>	-7.74
	Mean	7.69		1.47	
General mean		7.70		1.44	

**T1**=Control (100% conventional fertilizers), **T2**= 100% Nano Macro and micronutrients, **T3**=Nano-potassium, **T4**= Nano micronutrients, **T5**= Nano potassium+ Nano micronutrients

### Soil content of available nutrients

Data presented in Table IV illustrate the effects of various mineral fertilizers (N, P, K, and micronutrients) and seed-soaking treatments using a nano-micronutrient mixture on the available N, P, and K content in sandy soil. The non-soaking treatments revealed no significant differences in the soil nutrient content (mg kg<sup>-1</sup>) among the treatments.

TABLE IV

Effect of conventional and nano-mineral fertilizers applications on sandy soil content of available N, P and K and their relative change RC affected by soil applications of mineral fertilizers

Fertilizer treatment		Available N		Available P		Available K	
Seeds soaking "a"	Soil and foliar "b"	mg kg <sup>-1</sup>	RC%	mg kg <sup>-1</sup>	RC%	mg kg <sup>-1</sup>	RC%
Non-soaking	T1	18.50 <sup>c</sup>	0	3.22 <sup>b</sup>	0	63.40 <sup>c</sup>	0
	T2	21.12 <sup>abc</sup>	14	3.67 <sup>ab</sup>	14	70.20 <sup>abc</sup>	11
	T3	19.95 <sup>abc</sup>	8	3.49 <sup>ab</sup>	8	67.17 <sup>abc</sup>	6
	T4	19.50 <sup>bc</sup>	5	3.31 <sup>ab</sup>	3	65.13 <sup>bc</sup>	3
	T5	20.66 <sup>abc</sup>	12	3.55 <sup>ab</sup>	10	68.91 <sup>abc</sup>	9
	Mean	19.95		3.45		66.96	
Soaking	T1	19.25 <sup>bc</sup>	0	3.32 <sup>ab</sup>	0	65.15 <sup>bc</sup>	0
	T2	22.05 <sup>a</sup>	15	3.85 <sup>a</sup>	16	73.55 <sup>a</sup>	13
	T3	20.75 <sup>abc</sup>	8	3.63 <sup>ab</sup>	9	70.35 <sup>abc</sup>	8
	T4	20.35 <sup>abc</sup>	6	3.41 <sup>ab</sup>	3	67.92 <sup>abc</sup>	4
	T5	21.48 <sup>ab</sup>	12	3.70 <sup>ab</sup>	11	71.35 <sup>ab</sup>	10
	Mean	20.78		3.58		69.66	
General mean		20.36		3.52		68.31	

**T1**=Control (100% conventional fertilizers), **T2**= 100% Nano Macro and micronutrients, **T3**=Nano-potassium, **T4**= Nano micronutrients, **T5**= Nano potassium+ Nano micronutrients.

Furthermore, soaking treatments combined with the application of T2 led to a marked increase in the available N and K content in the sandy soil compared to T1, with no significant differences among other treatments. However, there were no significant differences between any treatments in the P content.

The data in Table V highlight the effects of different mineral fertilizers (N, P, K, and micronutrients), applied in both conventional and nano forms, with and without seed soaking, on the available Fe, Zn, Mn, and Cu content (mg kg<sup>-1</sup>) in sandy soil. The results show no variations between the nano-fertilizer treatments (T2, T3, T4, and T5) compared to the conventional fertilizer treatment (T1). Zn concentration showed a significant difference with nano fertilizer treatment (T2) compared to conventional fertilizer under both soaking and non-soaking treatments.

TABLE V

Effect of conventional and nano-mineral fertilizers applications on sandy soil content of Available Fe, Zn, Mn and Cu and their relative change RC affected by soil applications of mineral fertilizers

Fertilizer treatment		Available Fe		Available Zn		Available Mn		Available Cu	
Seeds soaking "a"	Soil and foliar "b"	mg kg <sup>-1</sup>	RC%	mg kg <sup>-1</sup>	RC%	mg kg <sup>-1</sup>	RC%	mg kg <sup>-1</sup>	RC%
Non-soaking	T1	4.18 <sup>ab</sup>	0	2.38 <sup>b</sup>	0	3.05 <sup>b</sup>	0	1.05 <sup>ab</sup>	0
	T2	4.65 <sup>ab</sup>	11	2.69 <sup>ab</sup>	13	3.42 <sup>ab</sup>	12	1.23 <sup>ab</sup>	17
	T3	4.45 <sup>ab</sup>	6	2.55 <sup>ab</sup>	7	3.23 <sup>ab</sup>	6	1.15 <sup>ab</sup>	10
	T4	4.32 <sup>ab</sup>	3	2.50 <sup>ab</sup>	5	3.17 <sup>ab</sup>	4	1.10 <sup>ab</sup>	5
	T5	4.56 <sup>ab</sup>	9	2.60 <sup>ab</sup>	9	3.27 <sup>ab</sup>	7	1.19 <sup>ab</sup>	13
	Mean	4.43		2.54		3.23		1.14	
Soaking	T1	4.27 <sup>ab</sup>	0	2.44 <sup>b</sup>	0	3.14 <sup>ab</sup>	0	1.09 <sup>ab</sup>	0
	T2	4.80 <sup>a</sup>	12	2.81 <sup>a</sup>	15	3.56 <sup>a</sup>	13	1.30 <sup>a</sup>	19
	T3	4.55 <sup>ab</sup>	7	2.64 <sup>ab</sup>	8	3.40 <sup>ab</sup>	8	1.20 <sup>ab</sup>	10
	T4	4.43 <sup>ab</sup>	4	2.55 <sup>ab</sup>	5	3.31 <sup>ab</sup>	5	1.15 <sup>ab</sup>	6
	T5	4.70 <sup>ab</sup>	10	2.68 <sup>ab</sup>	10	3.36 <sup>ab</sup>	7	1.23 <sup>ab</sup>	13
	Mean	4.55		2.62		3.35		1.19	
General mean		4.49		2.58		3.29		1.17	

**T1**=Control (100% conventional fertilizers), **T2**= 100% Nano Macro and micronutrients, **T3**=Nano-potassium, **T4**= Nano micronutrients, **T5**= Nano potassium+ Nano micronutrients.

T2 exhibited the highest Fe, Zn, Mn, and Cu concentrations, while T1 exhibited the lowest. This trend persisted under both non-soaking and soaking treatments, demonstrating the superior effectiveness of NF in increasing the availability of micronutrients in sandy soil compared to conventional fertilizers.

#### Leaf characteristics

Data in Table VI illustrate the effects of NMFs and CMFs on several leaf characteristics of sugar beet grown under sandy soil conditions. These characteristics include leaf chlorophyll content (mg m<sup>-3</sup>), leaf area index (LAI), fresh leaf weight (g plant<sup>-1</sup>), and dry leaf weight (g plant<sup>-1</sup>). The results indicate significant increases in all parameters with NMFs compared to CMFs. Additionally, soaking treatments further enhanced these leaf characteristics compared to non-soaking treatments, and all relative change (RC%) values were positive.

TABLE VI

Leaf characters of sugar beet plant growth in sandy soil affected by conventional and nano-mineral fertilizer applications and their relative change RC affected by nano-mineral fertilizer applications

Fertilizers treatment		Leaf chlorophyll content	LAI	Foliage fresh weight		Foliage dry weight	
Seeds soaking "a"	Soil and foliar "b"	mg m <sup>-2</sup>	Value	RC%	g plant <sup>-1</sup>	RC%	g plant <sup>-1</sup>
Non-soaking	T1	558.45 <sup>c</sup>	3.95 <sup>b</sup>	0	283.91 <sup>c</sup>	0	115.13 <sup>b</sup>
	T2	645.81 <sup>abc</sup>	4.75 <sup>ab</sup>	16	361.44 <sup>abc</sup>	27	187.54 <sup>ab</sup>
	T3	599.49 <sup>abc</sup>	4.31 <sup>ab</sup>	7	331.45 <sup>abc</sup>	17	129.53 <sup>ab</sup>
	T4	590.01 <sup>bc</sup>	4.15 <sup>b</sup>	6	306.51 <sup>bc</sup>	8	125.67 <sup>ab</sup>
	T5	610.37 <sup>abc</sup>	4.53 <sup>ab</sup>	9	344.15 <sup>abc</sup>	21	139.78 <sup>ab</sup>
	Mean	600.83	4.34		325.49		139.53
Soaking	T1	586.80 <sup>bc</sup>	4.18 <sup>b</sup>	0	302.27 <sup>bc</sup>	0	123.53 <sup>b</sup>
	T2	689.75 <sup>a</sup>	5.16 <sup>a</sup>	18	389.01 <sup>a</sup>	29	204.61 <sup>a</sup>
	T3	637.25 <sup>abc</sup>	4.58 <sup>ab</sup>	9	355.61 <sup>abc</sup>	18	140.59 <sup>ab</sup>
	T4	621.39 <sup>abc</sup>	4.41 <sup>ab</sup>	6	330.13 <sup>abc</sup>	9	135.55 <sup>ab</sup>
	T5	651.01 <sup>ab</sup>	4.88 <sup>ab</sup>	11	369.51 <sup>ab</sup>	22	151.76 <sup>ab</sup>
	Mean						

Mean	637.24	4.64	349.31	151.21
General Mean	619.03	4.49	337.40	145.37

**T1**=Control (100% conventional fertilizers), **T2**= 100% Nano Macro and micronutrients, **T3**=Nano-potassium, **T4**= Nano micronutrients, **T5**= Nano potassium+ Nano micronutrients.

Under non-soaking treatments, leaf chlorophyll content, LAI, leaf fresh and dry weight ranged from 558.45 to 645.81 mg m<sup>-3</sup>, 3.95 to 4.75, 283.91 to 361.44 g plant<sup>-1</sup>, and 115.13 to 187.54 g plant<sup>-1</sup>, respectively, corresponding to RC values of 16%, 20%, 27%, and 63%. Under soaking treatments, these values increased to ranges of 586.80 to 689.75 mg m<sup>-3</sup> for chlorophyll content, 4.18 to 5.16 for LAI, 302.27 to 389.01 g plant<sup>-1</sup> for fresh weight, and 123.53 to 204.61 g plant<sup>-1</sup> for dry weight, with respective RC values of 18%, 23%, 29%, and 66%.

The use of seed soaking treatments with a nano-micronutrient mixture further amplified the leaf improvements under both CMFs and NMFs applications. For example, under soaking treatments, RC values for leaf chlorophyll content, LAI, leaf fresh and dry weight increased by 5.08%, 5.82%, 6.47%, and 7.30%, respectively, with T1. These improvements were more pronounced with T2, showing respective increases of 6.80%, 8.63%, 7.63%, and 9.10%, respectively. These findings suggest that NMFs, especially in combination with seed soaking, significantly enhance leaf growth and development in sugar beet.

#### *Fresh and dry weight of root and foliage*

The fresh and dry weights of sugar beet root and foliage (g plant<sup>-1</sup>), grown under greenhouse conditions in sandy soil, varied slightly among the different fertilizer treatments, as shown in Table VII. Soaking treatments do not affect the fresh and dry weights of sugar beet root and foliage. Both non-soaking and soaking treatments demonstrated that the highest root and shoot weights were observed in plants treated with T2 compared to T1.

TABLE VII

Root and foliage yield of sugar beet plants planted on sandy soil affected by some applications of mineral fertilizers, as well as their relative change RC, following nano-fertilizers applications

Fertilizer treatment		Fresh weight				Dry weight			
		Root		Foliage		Root		Foliage	
Seeds soaking "a"	Soil and foliar "b"	(g plant <sup>-1</sup> )	RC %	(g plant <sup>-1</sup> )	RC %	(g plant <sup>-1</sup> )	RC %	(g plant <sup>-1</sup> )	RC %
Non-soaking	T1	201.19 <sup>b</sup>	0	283.91 <sup>c</sup>	0	95.97 <sup>b</sup>	0	115.13 <sup>b</sup>	0
	T2	256.65 <sup>ab</sup>	28	361.44 <sup>abc</sup>	27	148.27 <sup>ab</sup>	54	187.54 <sup>ab</sup>	63
	T3	229.63 <sup>ab</sup>	14	331.45 <sup>abc</sup>	17	110.44 <sup>ab</sup>	15	129.53 <sup>ab</sup>	13
	T4	218.90 <sup>ab</sup>	9	306.51 <sup>bc</sup>	8	102.90 <sup>ab</sup>	7	125.67 <sup>ab</sup>	9
	T5	240.72 <sup>ab</sup>	20	344.15 <sup>abc</sup>	21	114.39 <sup>ab</sup>	19	139.78 <sup>ab</sup>	21
	Mean		229.42		325.49		114.39		139.53
Soaking	T1	212.14 <sup>b</sup>	0	302.27 <sup>bc</sup>	0	101.79 <sup>b</sup>	0	123.53 <sup>b</sup>	0
	T2	277.83 <sup>a</sup>	31	389.01 <sup>a</sup>	29	159.81 <sup>a</sup>	57	204.61 <sup>a</sup>	66
	T3	244.78 <sup>ab</sup>	15	355.61 <sup>abc</sup>	18	118.13 <sup>ab</sup>	16	140.59 <sup>ab</sup>	14
	T4	232.30 <sup>ab</sup>	10	330.13 <sup>abc</sup>	9	110.02 <sup>ab</sup>	8	135.55 <sup>ab</sup>	10
	T5	258.92 <sup>ab</sup>	22	369.51 <sup>ab</sup>	22	122.161 <sup>ab</sup>	20	151.76 <sup>ab</sup>	23
	Mean		245.19		349.31		122.38		151.21
General Mean		237.31		337.40		118.39		145.37	

**T1**=Control (100% conventional fertilizers), **T2**= 100% Nano Macro and micronutrients, **T3**=Nano-potassium, **T4**= Nano micronutrients, **T5**= Nano potassium+ Nano micronutrients.

For the non-soaking treatment, the fresh weight of root and foliage ranged from 201.19 to 256.65 g plant<sup>-1</sup> and from 283.91 to 361.44 g plant<sup>-1</sup>, respectively, with relative change (RC) values of 28% and

27%. The dry weights of root and foliage under non-soaking conditions ranged from 95.97 to 148.27 g plant<sup>-1</sup> for root, and from 115.13 to 187.54 g plant<sup>-1</sup> for foliage, with RC values of 54% and 63%, respectively.

Based on the observed fresh and dry weights of root and foliage, and the calculated RC%, the ranking of treatments in terms of effectiveness was as follows: T2 > T5 > T3 > T4 > T1. This trend was consistent across both non-soaking and soaking treatments.

### Nutrient content

The uptake of N, P, and K by sugar beet root and foliage (mg plant<sup>-1</sup>) grown in sandy soil was evaluated following the application of mineral fertilizers, both in conventional and nano forms, as well as seed soaking treatments using a mixture of nano-micronutrients. The results, presented in Figures 2 and 3, reveal the impact of these treatments on nutrient uptake under greenhouse conditions.

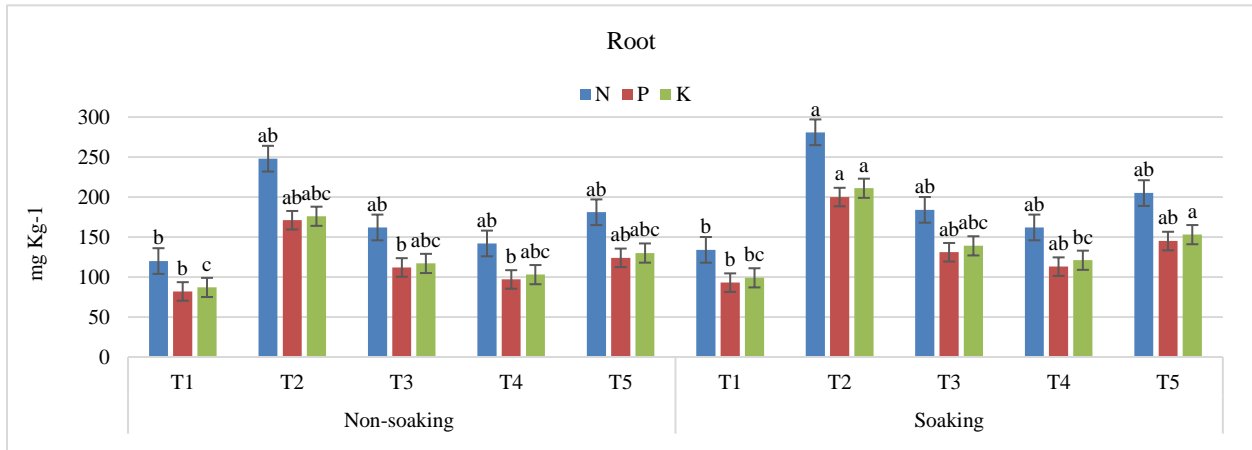


Fig. 2 Effect of mineral fertilizers (conventional and nano forms) applications and soaking treatment on NPK uptake (mg plant<sup>-1</sup>) by the root of sugar beet.

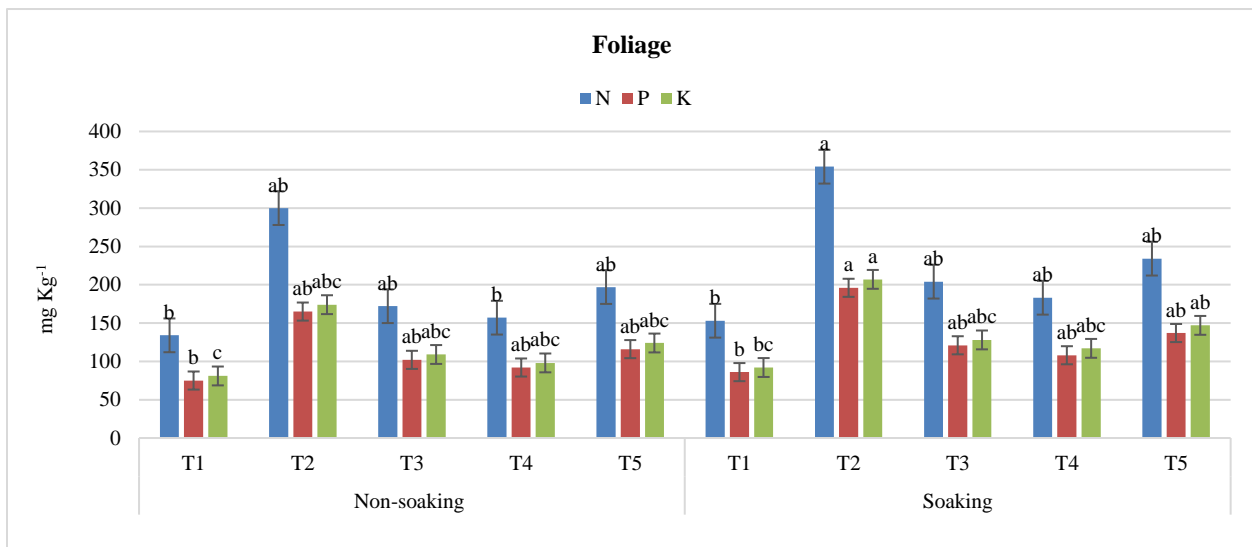


Fig. 3 Effect of mineral fertilizers (conventional and nano forms) applications and soaking treatment on NPK uptake (mg plant<sup>-1</sup>) by the foliage of sugar beet.

N uptake (mg plant<sup>-1</sup>) by sugar beet root and foliage significantly increased with the application of NMFs compared to CMFs (Figs. 2 and 3). This trend persisted under both non-soaking and soaking treatments. All RC values for N uptake by root and foliage under NMF applications were positive. Based on the data, the ranking of N uptake by sugar beet root and foliage, for both soaking and non-soaking treatments, was as follows: T2 > T5 > T4 > T3 > T1.

Additionally, seed soaking in the nano-micronutrient mixture further enhanced N uptake in both root and foliage compared to non-soaking treatments (Figs. 2 and 3). For example, N uptake by sugar beet foliage increased from 134, 300, 172, 157, and 197 mg plant<sup>-1</sup> under non-soaking treatments to 153, 354, 204, 183, and 234 mg plant<sup>-1</sup> under soaking treatments for T1, T2, T3, T4, and T5, respectively. These values represent relative increases of 15%, 18%, 18%, 16%, and 19%, respectively.

Similarly, P uptake (mg plant<sup>-1</sup>) by sugar beet root and foliage increased significantly with the application of NMFs (T2, T3, T4, and T5) compared to CMFs (T1) (Figs. 2 and 3). All RC values for P uptake were positive, indicating an enhanced effect of NMFs. The ranking of P uptake for both root and foliage under NMF treatments, across non-soaking and soaking treatments, was as follows: T2 > T5 > T3 > T4 > T1. This order highlights the significant influence of NK and nano-micronutrients on P absorption by sugar beet plants.

P uptake (mg plant<sup>-1</sup>) in sugar beet root and foliage increased further with the soaking of seeds in a nano-micronutrient mixture, as demonstrated in Figures 2 and 3. This increase was observed across both CMFs and NMFs treatments. For instance, P uptake by foliage increased from 75, 165, 102, 92, and 116 mg plant<sup>-1</sup> in the non-soaking treatment to 86, 196, 121, 108, and 137 mg plant<sup>-1</sup> in the soaking treatment, reflecting relative increases of 16%, 19%, 18%, 18%, and 18% for T1, T2, T3, T4, and T5, respectively.

Figures 2 and 3 also show the effect of NMF application methods on K uptake (mg plant<sup>-1</sup>) by sugar beet root and foliage. Similar to the trends observed for N and P, K uptake increased significantly in response to NMF treatments. All RC values for K uptake were positive across all treatments. For example, K uptake by foliage in the non-soaking treatment increased from 81 mg plant<sup>-1</sup> in T1 to 174, 109, 98, and 124 mg plant<sup>-1</sup> in T2, T3, T4, and T5, respectively, with corresponding RC values of 33%, 21%, 11%, and 27%.

Additionally, K uptake by both root and foliage was further enhanced in sugar beet plants following the soaking treatment with a nano-micronutrient mixture. For example, K uptake by roots increased from 87, 176, 117, 103, and 130 mg plant<sup>-1</sup> in the non-soaking treatment to 99, 211, 140, 121, and 153 mg plant<sup>-1</sup> in the soaking treatment, recording RC values of 14%, 20%, 19%, 17%, and 17%, respectively.

The uptake of micronutrients (Fe, Zn, Mn, and Cu) by sugar beet root and foliage (mg plant<sup>-1</sup>) under sandy soil conditions was also evaluated following the application of CMF and NMF fertilizers, as well as seed soaking with a nano-micronutrient mixture. The results are presented in Figures 4 and 5, demonstrating the positive impact of these treatments on micronutrient uptake.

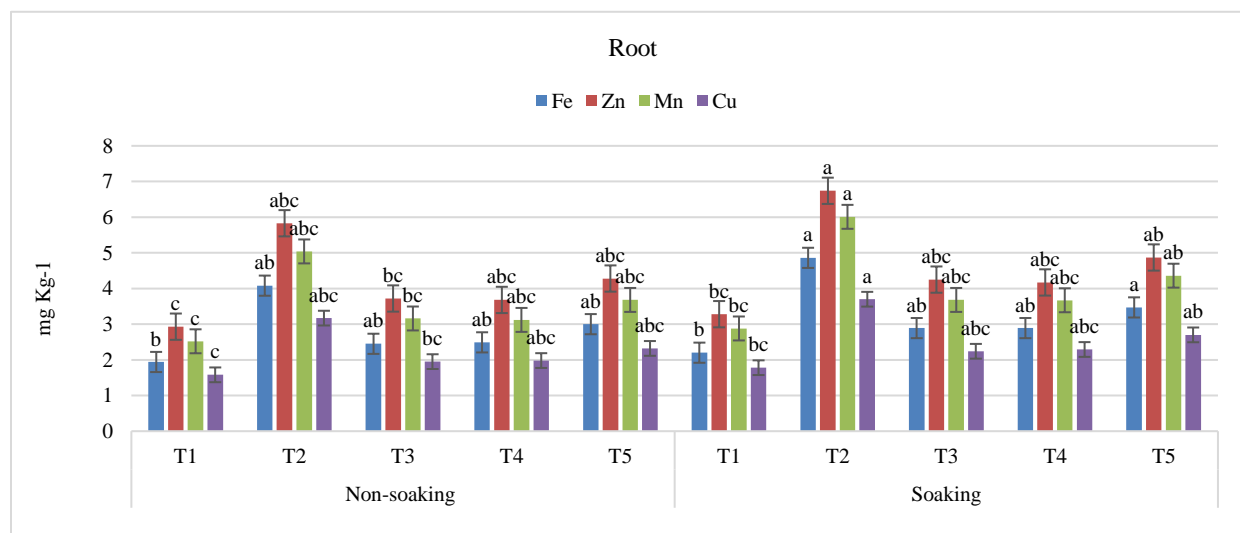


Fig. 4 Effect of mineral fertilizers (conventional and nano forms) applications and soaking treatment on micronutrients uptake (mg plant<sup>-1</sup>) by root of sugar beet.

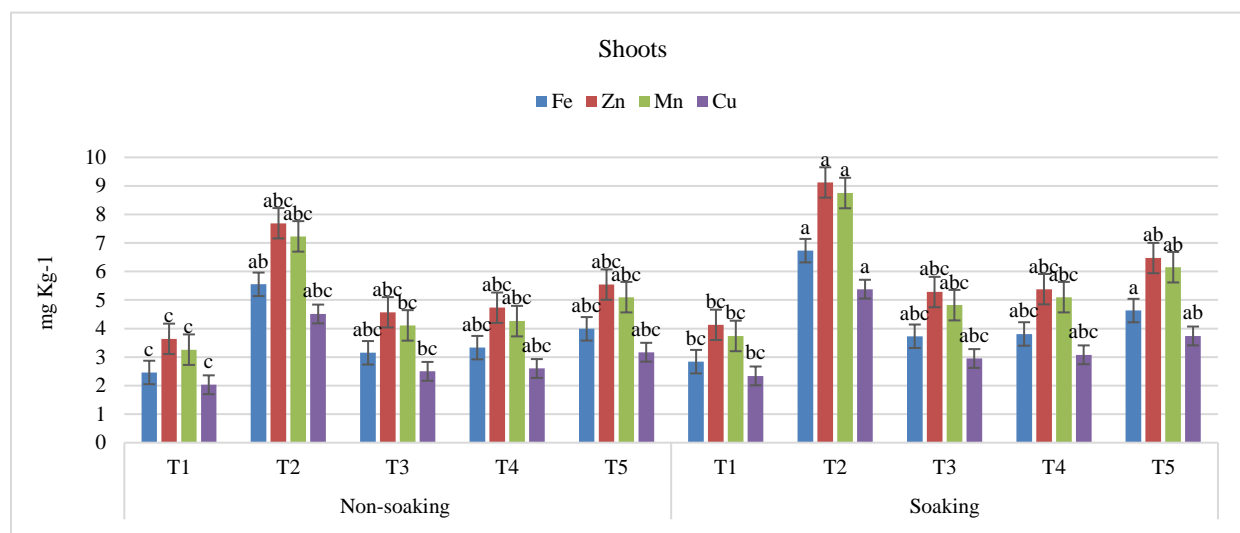


Fig. 5 Effect of mineral fertilizers (conventional and nano forms) applications and soaking treatment on micronutrient uptake ( $\text{mg plant}^{-1}$ ) by foliage of sugar beet.

Micronutrient uptake ( $\text{mg plant}^{-1}$ ) by sugar beet root and foliage was significantly increased with the application of NMFs compared to CMFs. This trend occurred in both non-soaking and soaking treatments, with all RC values for micronutrient uptake by roots and foliage being positive across treatments. Based on the data, the ranking of NMF treatments in terms of micronutrient uptake was as follows:  $T5 > T4 > T2 > T3 > T1$ .

Soaking further enhanced Fe, Zn, Mn, and Cu uptake by sugar beet roots and foliage across all fertilizer applications (T1-T5). Compared to non-soaking, soaking resulted in higher micronutrient uptake, with positive RC values for all elements. For example, Fe uptake by sugar beet roots under non-soaking conditions was 2.46, 5.55, 3.15, 3.33, and 3.99  $\text{mg plant}^{-1}$  for T1, T2, T3, T4, and T5, respectively. With soaking treatments, these values increased to 2.84, 6.73, 3.73, 3.81, and 4.63  $\text{mg plant}^{-1}$ , respectively. These results demonstrate the effectiveness of NMFs, particularly when combined with soaking treatments, in enhancing micronutrient absorption in sugar beet plants.

## DISCUSSION

### *Soil pH and EC*

The application of conventional and nanosized mineral fertilizers (N, P, K, and micronutrients) to sandy soil altered the rhizosphere environment, promoting root growth and exudation. These processes, combined with enhanced microbial activity, were associated with localized soil pH reductions (El-Ghamry *et al.*, 2018; Mostafa *et al.*, 2024).

Ahmed (2023) and Khader (2023) similarly reported a comparable reduction in soil pH and EC following the application of nanosized P and Fe. The soaking treatments further enhanced microbial activity and plant growth, increasing acidic compound production and lowering soil pH. Additionally, soaking treatments improved the growth medium, supporting plant development and overall soil conditions.

### *Soil content of available nutrients*

Soil macro- and micronutrient data indicate the superior efficiency of nano-form mineral fertilizers compared to conventional forms. Hayyaw and Qusay (2019) and El-Sayed *et al.* (2020) demonstrated that the application of nano-mineral fertilizers significantly increased soil N, P, and K availability. A similar rise in soil N, P, and K was observed with the use of nitrogen NF (Shawer and Abdalla, 2019). Jithendar *et al.* (2024) and Chhikara (2020) highlighted that nano-fertilizers enable controlled nutrient release and gradual soil dispersion in alignment with plant demand, thereby improving nutrient availability.

### *Leaf characteristics*

NFs exhibit several unique features: enhanced absorption, increased production, improved photosynthesis, and greater leaf surface area. They also enhance nutrient use efficiency, reduce soil toxicity, mitigate the negative effects of excessive fertilizer use, and lower the required fertilizer application rate (Naderi and Danesh-Shahraki, 2013).

Our findings support NF benefits for plant growth parameters. Abd El-Azeim *et al.* (2020) noted that differences between conventional and NFs stem from distinct soil-plant ecosystem mechanisms, application methods, efficiency rates, and environmental impacts.

Liu and Lal (2014) also emphasized that nanoparticle application can promote plant growth due to high absorption capacity and reactivity, a conclusion similarly reported by Singh *et al.* (2021). The improvements observed with NFs in plant growth and yield likely result from their structure, which enhances nutrient uptake efficiency, ultra-high absorption rates, increased photosynthesis, soil fertility restoration, increased crop production, reduced soil toxicity, and lower fertilizer application rates, contributing to improved plant health and reduced environmental pollution (Tyagi *et al.*, 2022).

Furthermore, El-Shal *et al.* (2022) demonstrated that nano-K<sub>2</sub>SO<sub>4</sub> additives enhanced various plant growth parameters, including shoot and root dry weight, shoot and root fresh weight, plant height, flower count, tiller count, and root length, across different fertilizer concentrations.

### *Fresh and dry weight of root and foliage*

The results of this study demonstrate a significant increase in the fresh and dry weight of sugar beet roots and foliage with the application of NMFs, especially when combined with seed soaking techniques. This enhanced growth and yield can be attributed to the NFs unique structure, which improves nutrient uptake efficiency (Tyagi *et al.*, 2022).

A similar observation was noticed by Shokouhian and Omid (2021), indicating a positive impact of soaking treatments on germination, along with biochemical and metabolic processes within plant tissues. Additionally, Janmohammadi *et al.* (2016) supported these findings, reporting superior efficiency of NFs, resulting in higher nutrient uptake and utilization due to significantly reduced losses from volatilization and leaching under sandy soil conditions. These findings highlight the potential of nano-fertilizers to optimize plant growth and nutrient use efficiency in challenging soil environments.

### *Nutrient content*

Abd El-Azeim *et al.* (2020) conducted a study comparing the effects of soil and foliar-applied conventional non-nano NPK fertilizers with eco-friendly nano-NPK fertilizers at equivalent or lower levels on potato productivity, quality, and nutrient use efficiency under field conditions. They concluded that efficient NFs have the potential to enhance crop production while minimizing environmental impact, offering economically feasible options for Egyptian farmers to sustain agriculture through improved crop yield and quality. The improvement of nano fertilizers over conventional fertilizers may be attributed to the nano-scale size, which facilitates absorption and penetration into plant tissues. In addition, interactions between nano-fertilizers and soil microorganisms warrant investigation because soil microbes are essential for soil nutrient cycling and plant growth (Jithendar *et al.*, 2024). Pérez-de-Luque (2017) also reported that applying nano-fertilizers to the plant roots may promote interactions with bacteria, fungi, and other microorganisms that establish beneficial symbiotic relationships with plants. These fertilizers may also interact with humic and organic matter, enhancing their bioavailability in the rhizosphere and facilitating plant absorption and uptake.

Recent studies by Ahmed (2023) and Khader (2023) confirmed that nano-form Fe and P fertilizers significantly increased nitrogen uptake by plants. Similarly, El-Shal *et al.* (2022) reported increased nitrogen uptake in alfalfa plants fertilized with nano K<sub>2</sub>SO<sub>4</sub>. Fe<sub>2</sub>O<sub>3</sub> nanoparticles have also significantly improved growth parameters in *Catharanthus roseus*, including enhanced photosynthetic pigment and total protein content, compared to conventional Fe additives (Askary *et al.*, 2017). Additionally, Shokouhian and Omid (2021) observed that seed soaking similarly enhanced plant growth and nitrogen uptake.

The positive impact of NMFs on plant nutrient uptake is well-documented, including by El-Shal *et al.* (2022) for nano K<sub>2</sub>SO<sub>4</sub> and Khader (2023) for nano Fe. Treatment T2 showed a significant increase in phosphorus uptake due to nano-phosphorus application. Liu and Lal (2014) similarly found that

hydroxyapatite NFs  $[\text{Ca}_5(\text{PO}_4)_3\text{OH}]$  enhanced soybean growth and seed yield compared to conventional phosphorus fertilizers  $[\text{Ca}(\text{H}_2\text{PO}_4)_2]$ .

Transforming agriculture with modern technologies, such as nanotechnology, is crucial for improving nutrient use efficiency and reducing environmental impact (Sekhon, 2014). Roozbeh *et al.* (2017) highlighted the positive effects of seed soaking on plant growth and nutrient uptake. Chhikara (2020) reported that nanotechnology has been developed to immobilize nutrients and control their release into the soil, reducing leaching while enhancing nutrient uptake and availability.

## CONCLUSIONS

The findings of this study demonstrate that nanofertilizer application at reduced doses (10%) improves nutrient availability and crop productivity without significantly altering soil physical and chemical characteristics. The soaking treatments combined with the application of T2 markedly increased available N and K content in the sandy soil compared to T1. The nano-fertilizer treatments (T2, T3, T4, and T5) show no significant variations compared to the conventional fertilizer treatment (T1). Zn concentration showed a significant difference following nano fertilizer treatment (T2) compared to conventional fertilizer under soaking and non-soaking treatments.

The current study proved that applying low concentrations of nanofertilizer alongside conventional fertilizer enhances plant growth and increases nutrient use efficiency. More studies are required to determine the optimal nanofertilizer dosage before agricultural application, whereas high concentrations of nanofertilizers may accumulate in food and pose potential human risks, because not all nanomaterials are equally safe for all applications.

## DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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