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Comparative Efficiency of Nano and Chelated Forms of Iron, Zinc and Manganese for Improvement Yield and Water Use Efficiency of Faba Bean Grown under Drought Stress

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DROUGHT is a highly damaging abiotic stress that affects crops' development, functioning, productivity, and quality. In contemporary farming, nanoparticles are advantageous because of their extensive surface area and enhanced ability to penetrate plant leaves when applied as a spray. Lately, nano-fertilizers have been employed in agriculture to help reduce the negative impacts of drought stress. This study aims to investigate the effects of different forms (nano and chelated) of iron (Fe), zinc (Zn), and manganese (Mn) foliar application, as well as their combinations, on the growth, yield, and water productivity of faba bean plants under different soil moisture levels (100, 80, and 60% of field capacity, FC). The results indicated the best readings of traits studied in the faba bean plant were observed under soil moisture at 100% of FC (control) compared to 60% of FC. On the other hand, results showed that the combined foliar application (FA) of FeZnMn-nanofertilizers (FeZnMn-NFs) to faba bean plants yielded the most favorable growth characteristics and chlorophyll content compared to the untreated plants (control). Also, the FA of FeZnMn-NFs treatment resulted in the highest seed yield and macronutrient (NPK) content in both straw and seed. The seed yield under FeZnMn-NFs treatment (21.24 g pot^{-1}) was significantly more significant than the control (15.47 g pot^{-1}). Regarding water use efficiency (WUE), the FeZnMn-NFs treatment achieved the highest WUE for the faba bean (2.44 kg m^{-3}) compared to the control (1.60 kg m^{-3}). Conversely, the amount of irrigation water applied (IWA) was lowest with the FeZnMn-NFs treatment (8.72 L pot^{-1}) compared to the control (9.64 L pot^{-1}). Concerning the interaction between irrigation levels and foliar spray treatments of faba bean plants, there were no significant differences in seed yield between the 100% irrigation level and the 80% level when foliar application of FeZnMn-NFs. Additionally, nano-fertilizers (NFs) demonstrate greater effectiveness than chelated fertilizers (EDTA), significantly enhancing yield and macronutrient content. Thus, the results highlight the crucial role of NFs in mitigating damage from drought stress, improving growth characteristics, and saving 20% of the amount of IWA for faba bean plants, allowing it to be used elsewhere in agriculture. Consequently, these findings suggest that using NFs of Fe, Zn, and Mn as foliar applications (FA) could be a promising approach to boost the growth parameters, seed yield, and WUE of faba bean plants in arid and semi-arid regions.

Keywords: Water deficit; Micronutrients; Nano-fertilizers; Nanotechnology; Water use efficiency; and *Vicia faba*.

1. Introduction

The faba bean is a prevalent leguminous crop in Egypt, primarily utilized for human nutrition due to its rich vitamins, minerals, and starch (Fayed et al., 2021; Aboseif et al., 2022; Faiyad & Abd EL-Azeiz, 2024). Additionally, it serves as an alternative protein source (Elsherpiny & Kaney, 2023). This versatile crop is used for food and as fodder and green manure because of its high nitrogen content (Abou Khater et al., 2024). Furthermore, it is an adaptable plant that thrives in various climatic conditions and is resistant to biotic and abiotic stresses (Afreen et al., 2024). Its exceptional ability to fix nitrogen biologically enhances soil fertility, making it a valuable component of cropping systems (Bamber et al., 2024; Gu et al., 2024). Farmers growing faba beans require less nitrogen fertilizer than other crops (El-Badry et al., 2023; Simon-Miquel et al., 2024).

Abiotic stress factors like drought significantly reduce crop productivity (Kopecká et al., 2023; Moustafa et al., 2024a). Drought is a crucial method for reducing irrigation water usage and addressing the water-deficit crisis (Kandhol et al., 2022; Moustafa et al., 2024b), which negatively impacts nutritional quality, yield, and seed growth (Naumann et al., 2018). This stress factor affects approximately 25% of agricultural production (Ahmad et al., 2022), influencing various biochemical, molecular, morphological, ecological, and physiological traits and processes throughout all growth stages (Fathi & Tari, 2016). Climate change, a major global issue, has recently led to more frequent and severe drought conditions (Ali et al., 2022).

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Iron, zinc, and manganese are crucial elements for the growth of many plants, including faba bean (Mahmoud et al., 2022a). Iron (Fe) is a vital micronutrient for all organisms (Gupta et al., 2024). Plants absorb Fe^{2+} from the soil, so Fe-deficient soils result in Fe-deficient plants (Wairich et al., 2024). Plants utilize Fe in various physiological processes, such as respiration, chlorophyll biosynthesis, redox reactions, and chlorophyll production (Ahmad et al., 2024). Therefore, enhancing the efficiency of Fe fertilizer use is essential (Zhou et al., 2024). Although using Fe in its traditional form remains popular for boosting plant yields, it often proves ineffective due to poor nutrient-use efficiency (Pudhuvai et al., 2024). Zinc (Zn) is another essential micronutrient plant, and zinc deficiency is widespread in several crops (Hacisalihoglu, 2020). Zinc is necessary for the activity of various enzymes, including isomerases, aldolases, transphosphorylases, dehydrogenases, DNA and RNA polymerases, and is involved in cell division, tryptophan synthesis, photosynthesis, membrane structure maintenance, and acts as a regulatory cofactor in the synthesis of protein (Makhasha et al., 2024). Manganese (Mn), a critical micronutrient, is essential for developing pollen tubes and seeds (Lilay et al., 2024). Its role in these processes significantly impacts crop reproduction dynamics and overall yield (Obeng et al., 2024). For plants to complete their reproductive stages and form seeds and pollen tubes necessary for achieving maximum crop productivity, sufficient Mn levels are required (Pudhuvai et al., 2024). Various micronutrients have been utilized to address plant deficiencies, including synthetic chelates like ethylenediamine tetra-acetic acid (EDTA) for micronutrient enrichment in crops (Madhupriyaa et al., 2024). The response of a specific crop can vary depending on the micronutrient source due to transportation efficiency and differences in absorption within the plant (Dhaliwal et al., 2021). Synthetic micronutrient chelates such as EDTA alleviate micronutrient deficiencies and improve plant health (Almendros et al., 2019). FA, which involves spraying liquid fertilizers directly onto plant leaves, is an effective method for maximizing yield and minimizing losses (Niu et al., 2021). Foliar sprays containing micronutrients like Fe, Zn, and Mn are convenient for field use, highly effective, and elicit a rapid response from plants (Ishfaq et al., 2022). These applications are well-known for enhancing plant nutrient content (Mahmoud et al., 2022a). The use of Zn-EDTA has proven effective in boosting agricultural output under drought conditions (Wang et al., 2017).

Nanotechnology is a promising interdisciplinary research field, offering numerous opportunities in medicine, pharmaceuticals, electronics, and agriculture (Kumar et al., 2024; Singh et al., 2024a). Nanomaterials typically refer to materials sized between 1-100 nm (Saleh, 2020). Their small size and large surface area confer unique optical, physical, and biological properties (Joudeh & Linke, 2022). Recently, extensive studies have explored various nanotechnology applications in agriculture, enhancing agricultural practices (Wahab et al., 2024). Nanotechnology can revolutionize the farming and food industries by improving plant nutrient absorption (Ghorbani et al., 2024; Singh et al., 2024b). A key application in crop production is nano-fertilizers (NFs), which provide nutrients to plants slowly and in a controlled manner, unlike conventional fertilizers (Seleiman et al., 2020). These NFs are more efficient, reducing environmental risks and soil pollution associated with chemical fertilizers and increasing production stability by mitigating biotic and abiotic stresses (Kashyap et al., 2017). Nanomaterials can mimic antioxidative enzymes like catalase, superoxide dismutase, and peroxidase (Jomova et al., 2024). These enzymes and antioxidants constantly scavenge reactive oxygen species (ROS) (Rahman et al., 2024).

Nano-fertilizers (NFs) are a crucial agricultural tool for enhancing crop growth, yield, and quality while also increasing nutrient use efficiency and reducing fertilizer waste and cultivation costs (Easwaran et al., 2024; Sheta et al., 2024a; Taha et al., 2024). These fertilizers can be applied to soil or leaves (Abou-Yuoseff et al., 2022; Avila-Quezada et al., 2022). FA is beneficial under unfavorable soil and weather conditions (Faridvand et al., 2021), as it allows nutrients to enter the plant system directly, minimizing fertilizer waste (Arora et al., 2024). Consequently, FA of NFs results in higher nutrient use efficiency (NUE) and rapidly responds to crop growth (Muñoz-Márquez et al., 2022). Additionally, NFs improve growth parameters, the rate of photosynthesis, chlorophyll production, and dry matter production, leading to increased translocation and production of photosynthates to the plant's various parts than conventional fertilizers (Seleiman et al., 2020). One benefit of NFs is that they can be applied in smaller quantities than traditional fertilizers (Kumar et al., 2023). With less than 100 nm particle size and a larger surface area, NFs can easily penetrate plant leaves, ensuring higher use efficiency and nutrient availability (Mahanta et al., 2019). Nano-fertilizers can enhance fertilizer efficiency, yield, and quality (Seleiman et al., 2020). Additionally, nano-Zn fertilizers enhance plant drought tolerance by increasing chlorophyll b content, lipids, amino acids, and proteins (Sedghi et al., 2013). Numerous reports suggest that applying nanoparticles boosts plant tolerance to water deficit by promoting growth, facilitating nutrient uptake, and activating antioxidant enzymes (Zhang et al., 2018). The objectives of this study are to evaluate the efficacy of foliar application (FA) of iron (Fe), zinc (Zn), and manganese (Mn) in two forms (nano and chelated) on the growth parameters, seed yield, chlorophyll content, straw and seed nutrient content, and water use efficiency of faba bean plants under different soil moisture contents.

2. Materials and Methods

2.1. Experimental Site and Soil Properties

A pot experiment was conducted at the Soils and Water Department, Faculty of Agriculture, Al-Azhar University in Cairo, Egypt, during the winter of 2021/2022. The study aimed to investigate the impact of foliar application (FA) of iron (Fe), zinc (Zn), and manganese (Mn) in both nano and chelated forms on the yield and water use efficiency of faba beans under varying soil moisture levels. The experiment used plastic pots with a capacity of 10 kg, a depth of 35 cm, and a diameter of 30 cm. Soil samples were accumulated from the layer 0.0–30.0cm in the EL-Nubaria region, El Beheira Governorate, Egypt. The physicochemical characteristics of the soil were analyzed, and the results are given in Table 1, following the methods of Dane & Topp (2020) and Sparks et al. (2020).

Table 1. Some physicochemical characteristics of the studied soil.

Soil property	Unit	Value	
Particle size distribution:			
Coarse sand	(%)	6.33	
Fine sand		76.17	
Silt		13.87	
Clay		3.63	
Texture class		Loamy sand	
Permanent wilting point	(%)	5.89	
Field capacity		13.67	
Available water		7.78	
ECe (dS m^{-1}, soil paste extract)	(dS m^{-1})	3.87	
pH (1:2.5 soil water suspension)		8.52	
Organic matter (OM)	(g kg^{-1})	2.63	
$CaCO_3$	(%)	2.29	
Soluble cations (mmolc L^{-1})		Soluble anions (mmolc L^{-1})	
Ca^{2+}	8.55	CO_3^{2-}	0.00
Mg^{2+}	11.45	HCO_3^{-}	2.64
Na^{+}	17.85	Cl^{-}	19.86
K^{+}	0.85	SO_4^{2-}	16.20

2.2. Experimental Design and Treatments

The experimental treatments were organized in a randomized complete block design with six replications. The experiment included three irrigation levels of field capacity (FC): 100% FC (full irrigation at 100% of field capacity, control), 80% FC (irrigation at 80% of field capacity), and 60% FC (irrigation at 60% of field capacity). Additionally, foliar application (FA) was performed using each nutrient individually, as well as their combinations, in both chelated (EDTA) and nano (NFs) forms. The treatments were as follows: iron-nano (Fe-NFs), iron-chelated (Fe-EDTA), zinc-nano (Zn-NFs), zinc-chelated (Zn-EDTA), manganese-nano (Mn-NFs), manganese-chelated (Mn-EDTA), iron+zinc+manganese-nano (FeZnMn-NFs), and iron+zinc+manganese-chelated (FeZnMn-EDTA), along with a control treatment (plants treated with redistilled water). The experimental flowchart is illustrated in Fig. 1. These FA treatments were applied at a concentration of 25 mg L^{-1}. The experimental pots were placed under a rain shelter to avoid natural precipitation. Fe, Zn, and Mn oxides were utilized as nano-fertilizers (NFs), while their EDTA forms were used as chelated fertilizers. Each foliar application (FA) treatment was administered three times at three-week intervals, beginning forty days after sowing the faba bean seeds. A hand-held sprayer was used to apply the FA treatments to the upper surface of the *V. faba* leaves. The moisture content of the soil was determined using the gravimetric method. For the first 21 days after planting, all pots were watered uniformly. After this period, the irrigation treatments were implemented. Every two days, just before each irrigation, the pots were weighed to measure water loss and add the necessary amount to maintain a consistent field capacity (FC) at 100%, 80%, and 60% FC. The amount of IWA during the growing season was calculated for each FC level.

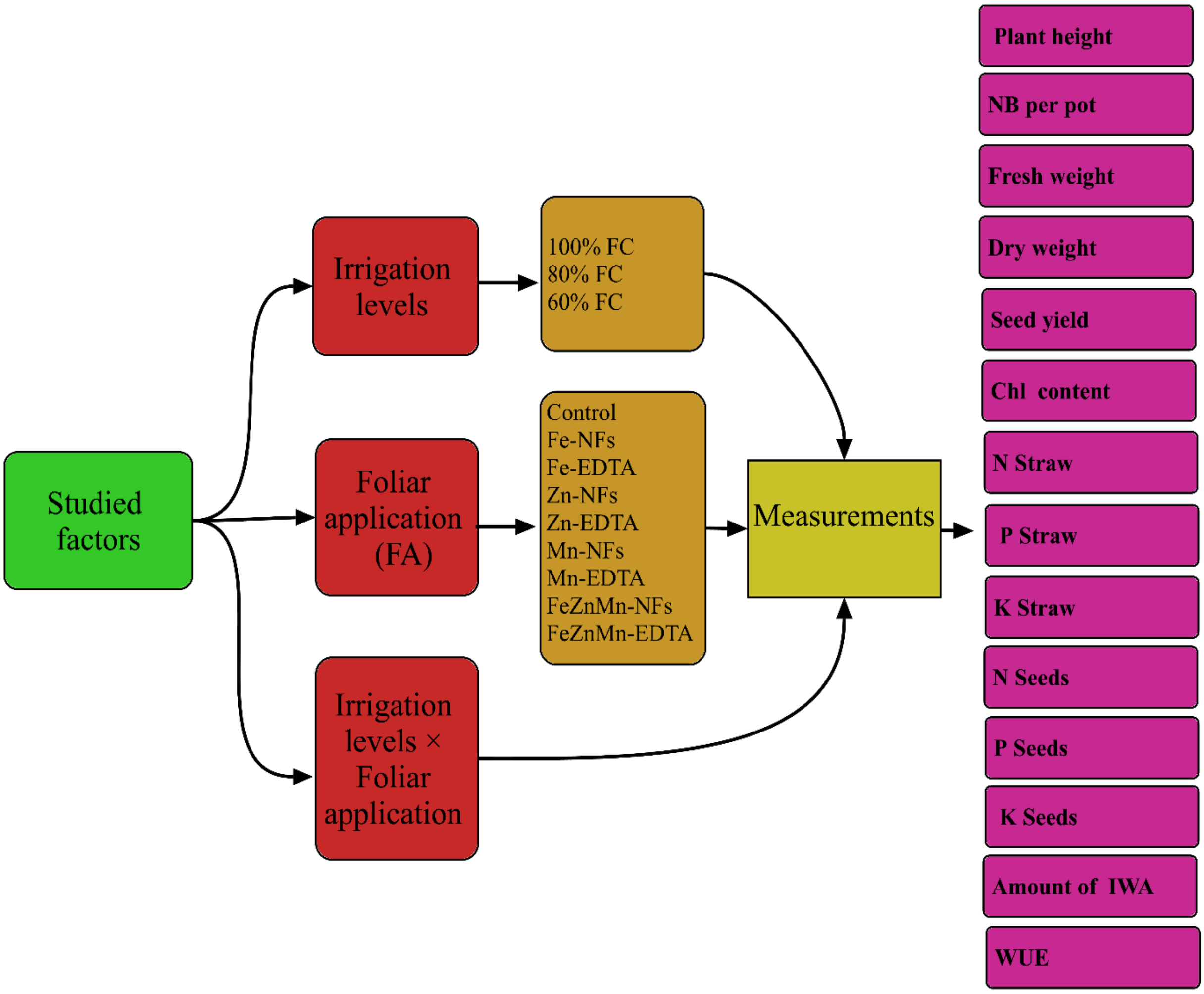

Fig. 1. Experimental flowchart. 100% FC: irrigation at 100% of field capacity, 80% FC: irrigation at 80% of field capacity, 60% FC: irrigation at 60% of field capacity, CT: control, Fe-NFs: iron-nano, Fe-EDTA: iron-chelated, Zn-NFs: zinc-nano, Zn-EDTA: zinc-chelated, Mn-NFs: manganese-nano, Mn-EDTA: manganese-chelated, FeZnMn-NFs: iron+zinc+manganese-nano, FeZnMn-EDTA: iron+zinc+manganese-chelated, NB: number of branches, Chl: chlorophyll, N straw: nitrogen content in straw, P straw: phosphorous content in straw, K straw: potassium content in straw, N seeds: nitrogen content in seeds, P seeds: phosphorous content in seeds, K seeds: potassium content in seeds, IWA: irrigation water applied, and WUE: water use efficiency.

2.3. Characterization of Nano-fertilizers

The Fe-NFs and Zn-NFs were supplied by the Nanotechnology and Advanced Materials Central Lab (NAMCL), Agricultural Research Center (ARC) in Giza, Egypt. At the same time, the Mn-NFs were sourced from the NanoFab Technology company in New Maadi, Cairo, Egypt. For transmission electron microscope (TEM) analysis, a drop of the solution was placed on carbon-coated copper grids (CCG) and dried at room temperature, allowing the water to evaporate. A JEOL GEM-1010 TEM captured electron micrographs at 80 kV at the Regional Center for Mycology and Biotechnology of Al-Azhar University, Cairo, Egypt. The TEM analysis was conducted, and the results are shown in Fig. 2. A zeta voltage test was performed using a zeta sizer (Malvern, Nano ZS, UK) at the NAMCL, ARC in Giza, Egypt, to determine the electrical charge and confirm the stability of the Fe-NFs, Zn-NFs, and Mn-NFs solutions. The zeta potential values for Fe-NFs, Zn-NFs, and Mn-NFs were negative, measuring −10.7, −12.3, and −11.2, respectively, as shown in Fig. 3.

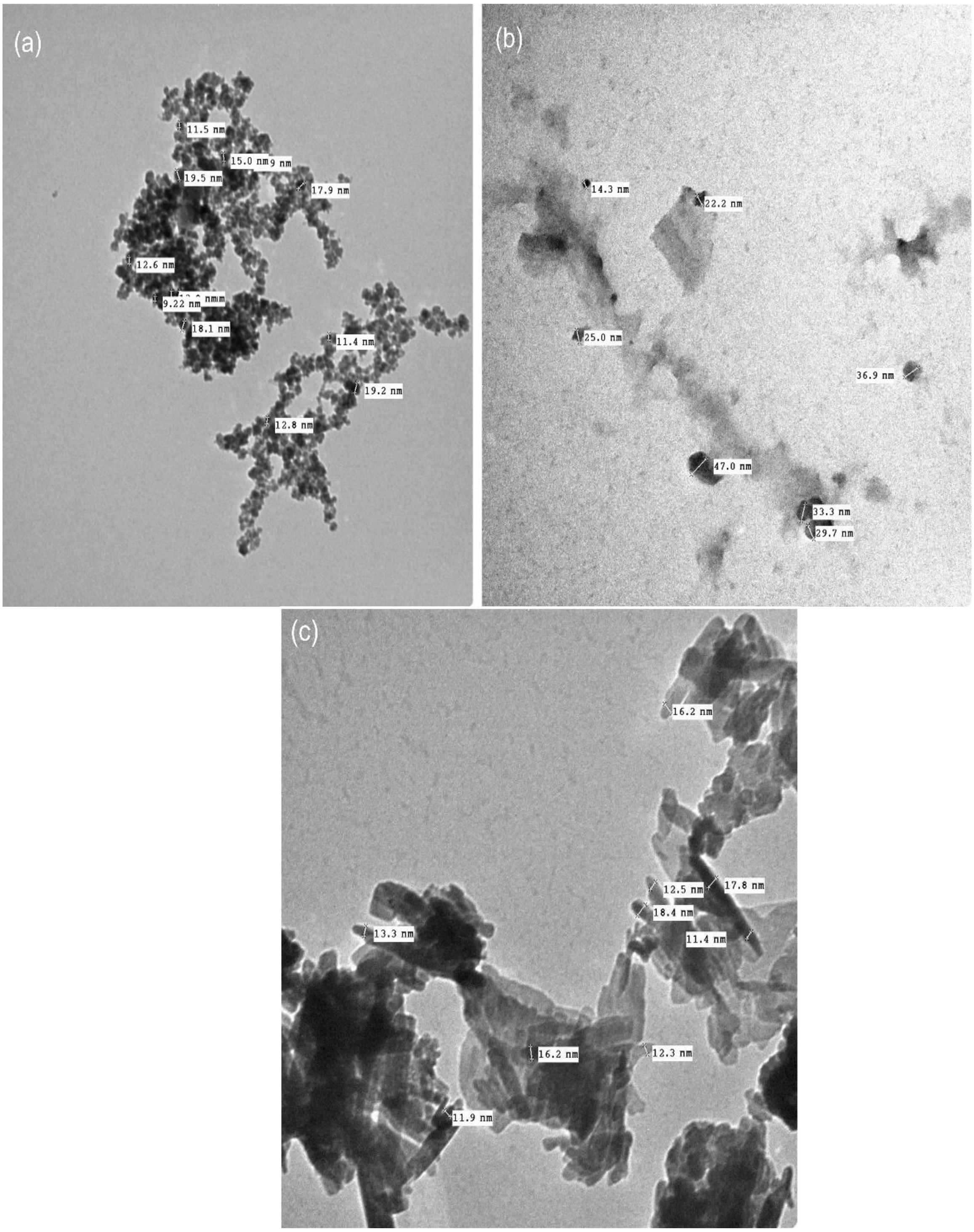

Fig. 2. TEM analysis of Fe (a), Zn (b), and Mn (c) oxide nano-fertilizers.

2.4. Agricultural Practices

Faba bean (*Vicia faba* L.) seeds of the Nubaria 1 variety were provided by the Field Crops Research Institute, ARC in Giza, Egypt. The faba beans were sown on November 17th and harvested on April 16th. Before sowing, the seeds were inoculated with the *Rhizobium leguminosarum* strain. Five seeds were planted in each pot, and after 21 days, the best three plants were selected per pot. All plants received the recommended organic and mineral fertilizers.

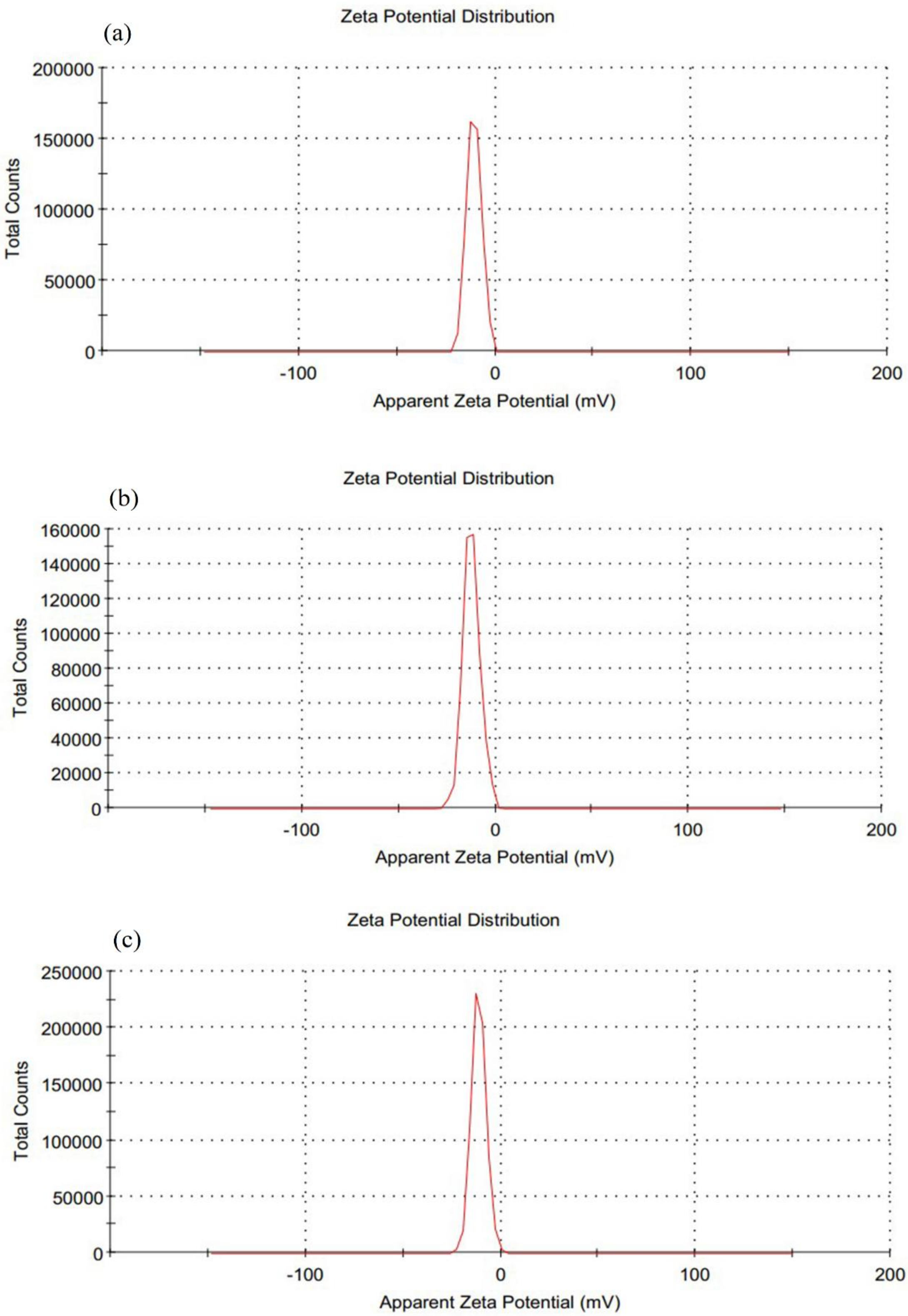

Fig. 3. Zeta potential analysis of Fe (a), Zn (b), and Mn (c) oxide nano-fertilizers.

2.5. Measurements

After 90 days of the sowing, the traits measured for faba bean plants included plant height (PH, cm) and number of branches per pot (NB pot^{-1}). A SPAD chlorophyll meter assessed the relative chlorophyll content (Chl, SPAD). Harvesting was done 150 days after sowing to determine the fresh weight (FW, g pot^{-1}), dry weight

(DW, g pot^{-1}), and seed yield (SY, g pot^{-1}). The macronutrient content (NPK) in both the straw and seeds of the faba bean plants was measured according to Walinga et al. (2013). The amount of IWA during the *V. faba* growing season was calculated in liters per pot. Water use efficiency (kg m^{-3}) was estimated according to Payero et al. (2008); Abd El-Kader et al. (2023); Sheta et al. (2024b) as follows:

$$\mathbf{WUE}=\frac{\textbf{Seed yield (kg pot}^{-1}\textbf{)}}{\textbf{Irrigation water applied } (\textbf{m}^3 \textbf{ pot}^{-1})}$$

2.6. Statistical Analysis

The collected dataset of traits was analyzed using univariate statistical methods. Analysis of variance (ANOVA) was conducted for three irrigation levels, nine foliar application treatments, and their interactions to test for significant differences, following the methodology of Gomez & Gomez (1984), using the XLSTAT (Addinsoft, NY, USA) statistical package. Duncan's Multiple Range Test was employed for mean comparisons of mutations. Analysis of the correlation between the studied traits was conveyed using R software.

3. Results

3.1. Growth Parameters, Seed Yield, and Chlorophyll Content

As indicated in Table 2, plant parameters such as plant height (PH), number of branches per pot (NB pot^{-1}), fresh weight (FW, g pot^{-1}), dry weight (DW, g pot^{-1}), seed yield (SY, g pot^{-1}), and chlorophyll content (Chl, SPAD) significantly increased with full irrigation (100% FC) and the foliar application (FA) of nano-fertilizers (NFs) and/or EDTA, or their combination (Figures 4 and 5). The highest values for PH (32.07 cm), NB (9.70 pot^{-1}), FW (101.46 g pot^{-1}), DW (58.70 g pot^{-1}), SY (21.25 g pot^{-1}), and Chl content (49.33 SPAD) were observed in plants irrigated at 100% FC (Table 2). Conversely, the lowest values for PH (22.26 cm), NB (4.00 pot^{-1}), FW (58.11 g pot^{-1}), DW (35.76 g pot^{-1}), SY (14.25 g pot^{-1}), and Chl content (37.11 SPAD) were recorded under the 60% FC treatment (Table 2).

Table 2. Effect of irrigation levels and different forms of Fe, Zn, and Mn as a foliar spray on the growth parameters, seed yield, and chlorophyll content of *V. faba* plants.

Treatments	PH	NB pot^{-1}	FW (g pot^{-1})	DW (g pot^{-1})	SY (g pot^{-1})	Chl (SPAD)
Irrigation levels						
100% FC	32.07±2.2a	9.70±0.95a	101.46±6.84a	58.70±3.54a	21.25±2.38a	49.33±2.34a
80% FC	27.30±3.9b	8.19±1.14b	80.54±12.03b	48.65±5.98b	18.92±2.98b	44.61±3.06b
60% FC	22.26±3.0c	4.00±0.88c	58.11±4.74c	35.76±3.00c	14.25±1.71c	37.11±5.49c
Foliar application (FA)						
CT	24.33±3.9e	6.44±2.19d	72.38±14.46e	40.47±9.87f	15.47±5.24e	39.96±6.18d
Fe-NFs	29.67±3.0ab	8.00±2.60a	82.27±17.53b	50.95±9.40bc	20.65±5.82a	47.92±3.14a
Fe-EDTA	25.56±5.1cd	7.22±1.99bc	74.98±20.80d	45.46±9.58e	16.54±4.07cde	40.79±6.66cd
Zn-NFs	28.78±3.1b	7.78±2.49ab	83.62±17.41b	51.69±10.01ab	19.18±5.53b	46.64±3.75ab
Zn-EDTA	24.89±5.0de	6.67±2.74cd	75.38±20.34d	45.31±9.20e	15.98±4.39de	41.75±6.28c
Mn-NFs	30.11±5.7a	7.78±3.15ab	84.15±20.02b	50.13±13.54c	20.26±5.62a	46.34±3.99b
Mn-EDTA	24.22±5.0e	6.56±2.88cd	74.14±19.22de	45.81±10.17de	16.63±4.69cd	40.96±6.27cd
FeZnMn-NFs	30.78±3.7a	8.22±2.99a	94.89±24.51a	52.71±10.34a	21.24±5.89a	47.98±5.18a
FeZnMn-EDTA	26.56±6.1c	7.00±2.87cd	78.51±19.55c	46.78±9.05d	17.30±4.86c	40.83±8.30cd

PH: plant height, NB pot^{-1}: number of branches per pot, FW: fresh weight, DW: dry weight, SY: seed yield, Chl: chlorophyll content, 100% FC: irrigation at 100% of field capacity, 80% FC: irrigation at 80% of field capacity, 60% FC: irrigation at 60% of field capacity, CT: control, Fe-NFs: iron-nano, Fe-EDTA: iron-chelated, Zn-NFs: zinc-nano, Zn-EDTA: zinc-chelated, Mn-NFs: manganese-nano, Mn-EDTA: manganese-chelated, FeZnMn-NFs: iron+zinc+manganese-nano, and FeZnMn-EDTA: iron+zinc+manganese-chelated. Values represent means ±SD. Means within the same column that share the same letter do not differ significantly (p<0.05 level).

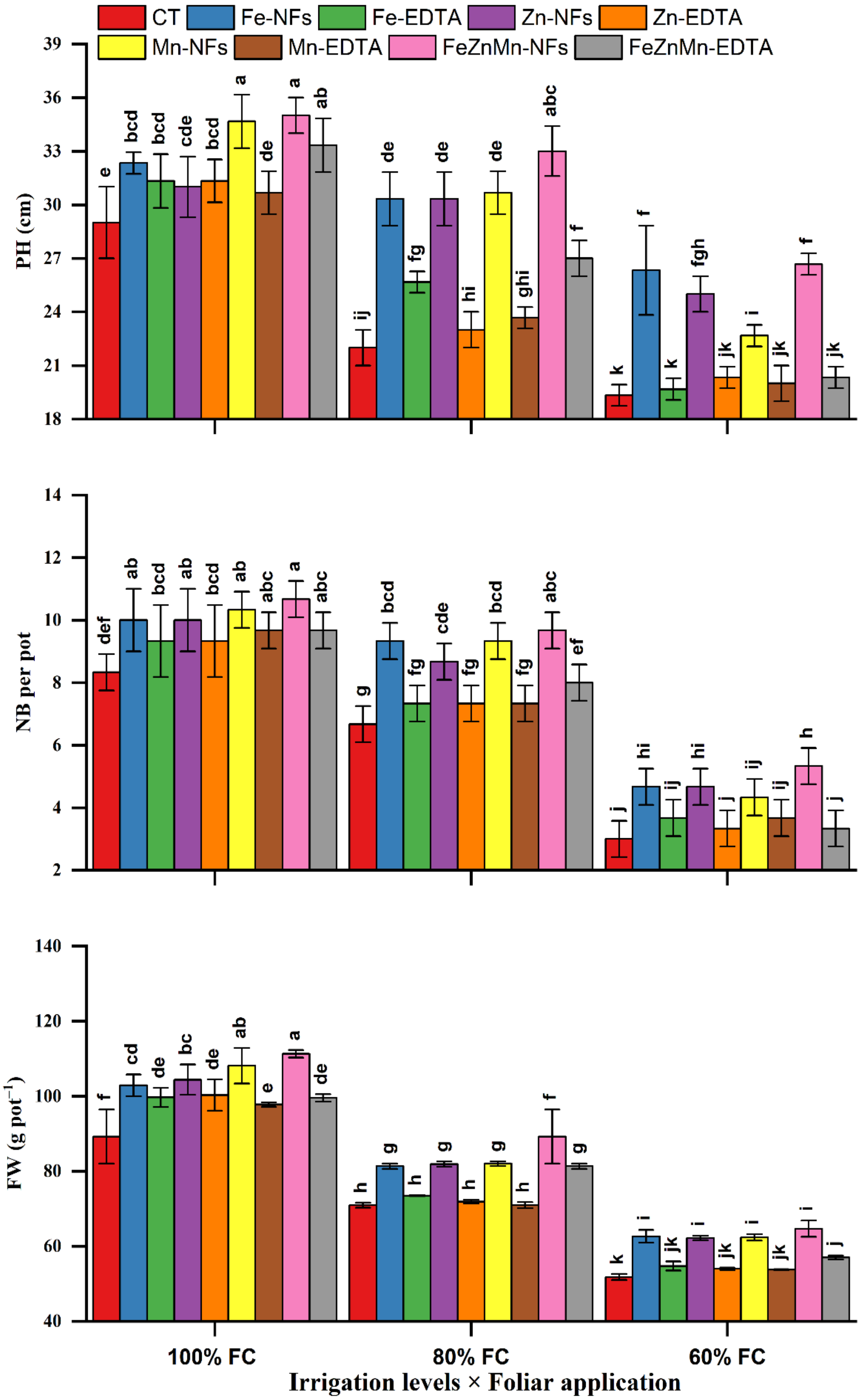

Fig. 4. Effect of the interaction between irrigation levels and different forms of Fe, Zn, and Mn as a foliar spray on the plant height (PH), number of branches (NB), and fresh weight (FW) of *V. faba* plants. 100% FC: irrigation at 100% of field capacity, 80% FC: irrigation at 80% of field capacity, and 60% FC: irrigation at 60% of field capacity. Different bars indicate the values of means ±SD. Bars with different letters above them indicate a statistically significant difference (*P*<0.05 level), whereas bars with the same letters show no significant difference.

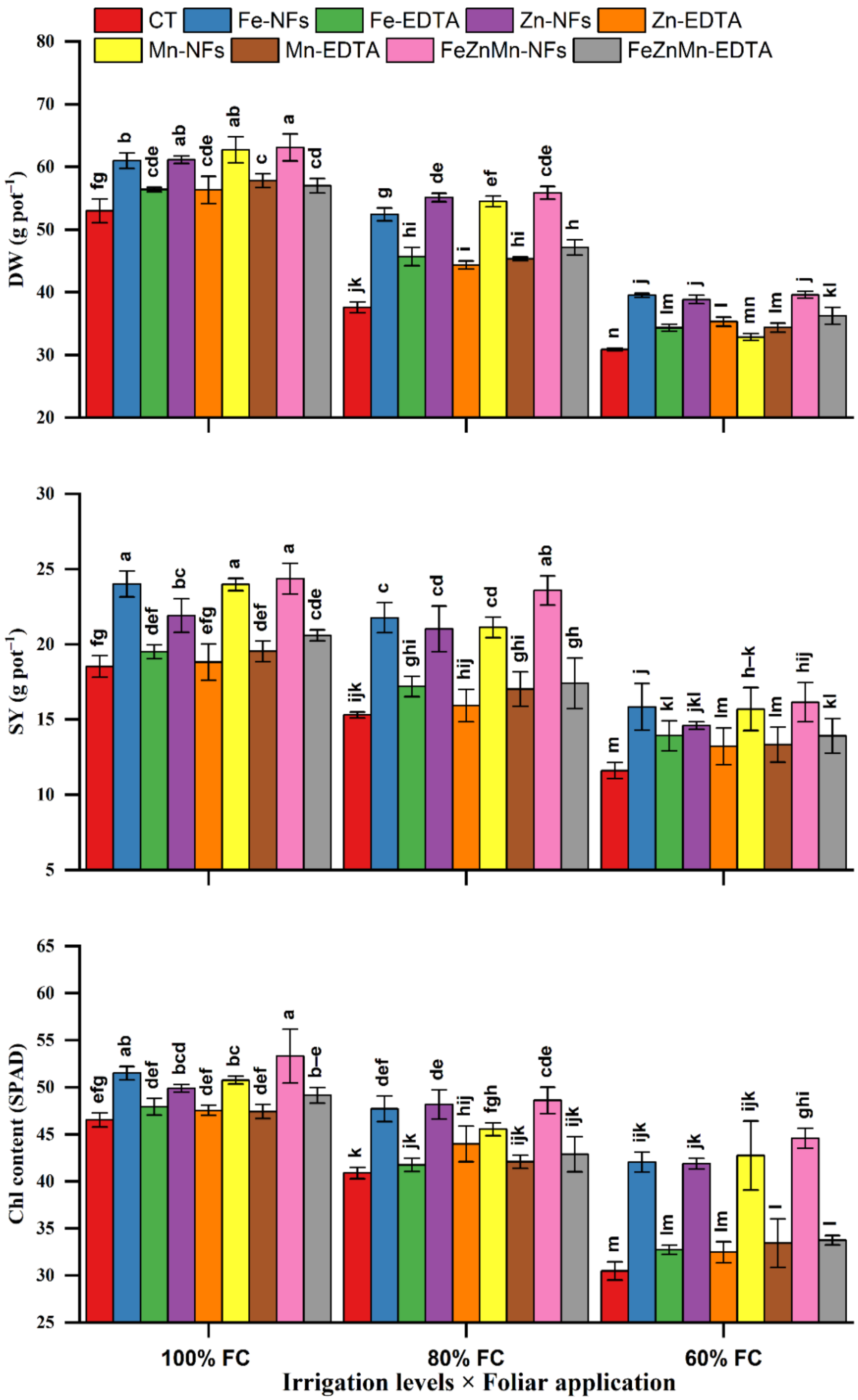

Fig. 5. Effect of the interaction between irrigation levels and different forms of Fe, Zn, and Mn as a foliar spray on the dry weight (DW), seed yield (SY), and chlorophyll (Chl) content of *V. faba* plants. 100% FC: irrigation at 100% of field capacity, 80% FC: irrigation at 80% of field capacity, and 60% FC: irrigation at 60% of field capacity. Different bars indicate the values of means ±SD. Bars with different letters above them indicate a statistically significant difference (*P*<0.05 level), whereas bars with the same letters show no significant difference.

The data in Table 2 also revealed that these parameters were significantly enhanced by the FA of Fe, Zn, and Mn in either nanofertilizer (NFs) or EDTA forms. The highest values for PH (30.78 cm), NB per pot (8.22 pot^{-1}), FW (94.89 g pot^{-1}), DW (52.71 g pot^{-1}), SY (21.24 g pot^{-1}), and Chl content (47.98 SPAD) were observed in faba bean plants treated with the FA of FeZnMn-NFs. In contrast, the lowest values for PH (24.33 cm), NB (6.44 pot^{-1}), FW (72.38 g pot^{-1}), DW (40.47 g pot^{-1}), SY (15.47g pot^{-1}), and Chl content (39.96 SPAD) were recorded in untreated plants (control).

The results in Figures 4 and 5 indicated the interaction effects of all treatments studied on faba bean. The highest values for PH (35.00 cm), NB per pot (10.67 pot^{-1}), FW (111.28 g pot^{-1}), DW (63.07 g pot^{-1}), SY (24.36 g pot^{-1}), and Chl content (53.30 SPAD) were achieved with the interaction between IWA at 100% FC and FA of FeZnMn-NFs. Conversely, the lowest values for PH (19.33 cm), NB (3.00 pot^{-1}), FW (51.80 g pot^{-1}), DW (30.87 g pot^{-1}), SY (11.60 g pot^{-1}), and Chl content (30.47 SPAD) were observed with the interaction between IWA at 60% FC and untreated plants (control).

3.2. Straw and Seed Nutrient Content

The data in Table 3 indicate that the NPK concentration (%) in straw and seeds of faba bean plants significantly decreased as the irrigation water was reduced from 100% FC to 60% FC. The highest NPK content in straw (1.73%, 0.14%, and 1.76%, respectively) and seeds (2.14%, 0.157%, and 2.14%, respectively) was observed in plants irrigated at 100% FC. Conversely, the lowest NPK content in straw (1.30%, 0.11%, and 1.13%, respectively) and seeds (1.34%, 0.117%, and 1.70%, respectively) were found in plants irrigated at 60% FC.

The findings (Table 3) indicated that FA with nano-fertilizers (NFs) positively influenced the nutrient content in both straw and seeds regarding the impact of FA of Fe, Zn, and Mn in nano and chelated forms. The highest NPK content in straw (1.82%, 0.149%, and 1.75%, respectively) and seeds (2.24%, 0.160%, and 2.39%, respectively) were achieved with the FA of FeZnMn-NFs treatment. In contrast, the lowest NPK content in straw (1.26%, 0.116%, and 1.30%, respectively) and seeds (1.51%, 0.128%, and 1.70%, respectively) were observed in the control treatment (without FA).

Table 3. Effect of irrigation levels and different forms of Fe, Zn, and Mn as a foliar spray on straw and seed nutrients content of *V. faba* plants.

Treatments	Nutrient content in straw (%)			Nutrient content in seeds (%)		
	N	P	K	N	P	K
Irrigation levels						
100% FC	1.73±0.258a	0.141±0.015a	1.76±0.151a	2.14±0.228a	0.157±0.012a	2.14±0.221a
80% FC	1.55±0.292b	0.128±0.019b	1.45±0.315b	1.78±0.418b	0.142±0.015b	1.96±0.290b
60% FC	1.30±0.234c	0.111±0.006c	1.13±0.089c	1.34±0.180c	0.117±0.008c	1.70±0.228c
Foliar application (FA)						
CT	1.26±0.184d	0.116±0.006d	1.30±0.196e	1.51±0.535d	0.128±0.021f	1.70±0.395e
Fe-NFs	1.81±0.184a	0.128±0.013bcd	1.45±0.284c	1.88±0.475b	0.149±0.020b	2.02±0.159b
Fe-EDTA	1.75±0.197a	0.130±0.012bc	1.40±0.324cd	1.81±0.298b	0.146±0.21c	1.86±0.179c
Zn-NFs	1.35±0.188bc	0.118±0.016cd	1.34±0.310de	1.64±0.275cd	0.131±0.016e	1.81±0.185cd
Zn-EDTA	1.29±0.181cd	0.118±0.014cd	1.31±0.307e	1.52±0.373d	0.129±0.014f	1.79±0.181d
Mn-NFs	1.37±0.147b	0.131±0.015b	1.55±0.289b	1.74±0.330bc	0.131±0.016e	2.04±0.074b
Mn-EDTA	1.28±0.236cd	0.122±0.011bcd	1.30±0.304e	1.57±0.332d	0.130±0.015ef	1.76±0.189de
FeZnMn-NFs	1.82±0.160a	0.149±0.035a	1.75±0.418a	2.24±0.529a	0.160±0.022a	2.39±0.430a
FeZnMn-EDTA	1.81±0.296a	0.125±0.014bcd	1.61±0.327b	1.87±0.336b	0.143±0.015d	2.02±0.083b

N: Nitrogen, P: phosphorous, K: potassium, 100% FC: irrigation at 100% of field capacity, 80% FC: irrigation at 80% of field capacity, 60% FC: irrigation at 60% of field capacity, CT: control, Fe-NFs: iron-nano, Fe-EDTA: iron-chelated, Zn-NFs: zinc-nano, Zn-EDTA: zinc-chelated, Mn-NFs: manganese-nano, Mn-EDTA: manganese-chelated, FeZnMn-NFs: iron+zinc+manganese-nano and FeZnMn-EDTA: iron+zinc+manganese-chelated. Values represent means ±SD. Means within the same column that share the same letter do not differ significantly (p<0.05 level).

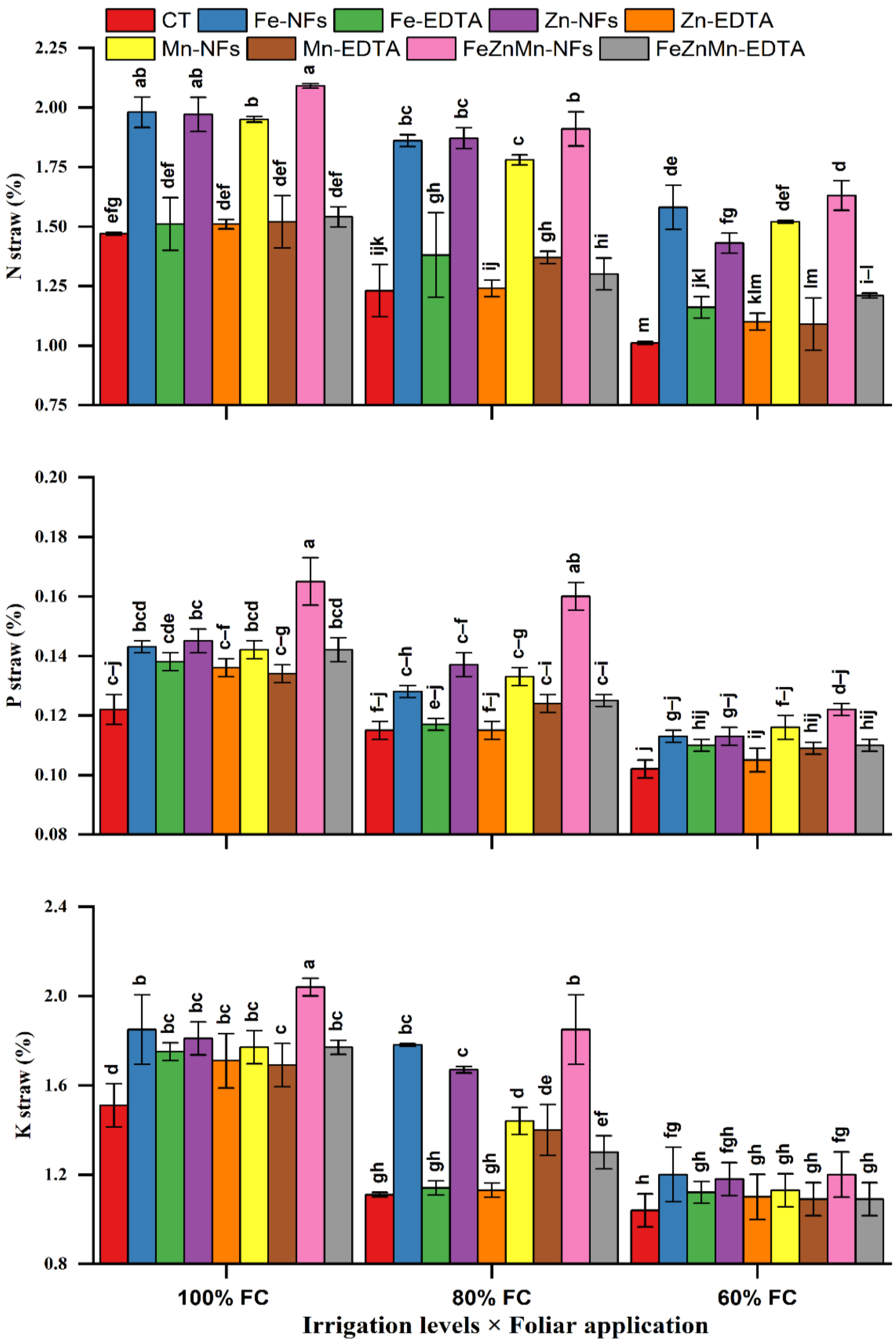

Fig. 6. Effect of the interaction between irrigation levels and different forms of Fe, Zn, and Mn as a foliar spray on nutrient content in the straw of *V. faba* plants. N: Nitrogen, P: phosphorous, K: potassium, 100% FC: irrigation at 100% of field capacity, 80% FC: irrigation at 80% of field capacity, and 60% FC: irrigation at 60% of field capacity. Different bars indicate the values of means ±SD. Bars with different letters above them indicate a statistically significant difference (*P*<0.05 level), whereas bars with the same letters show no significant difference.

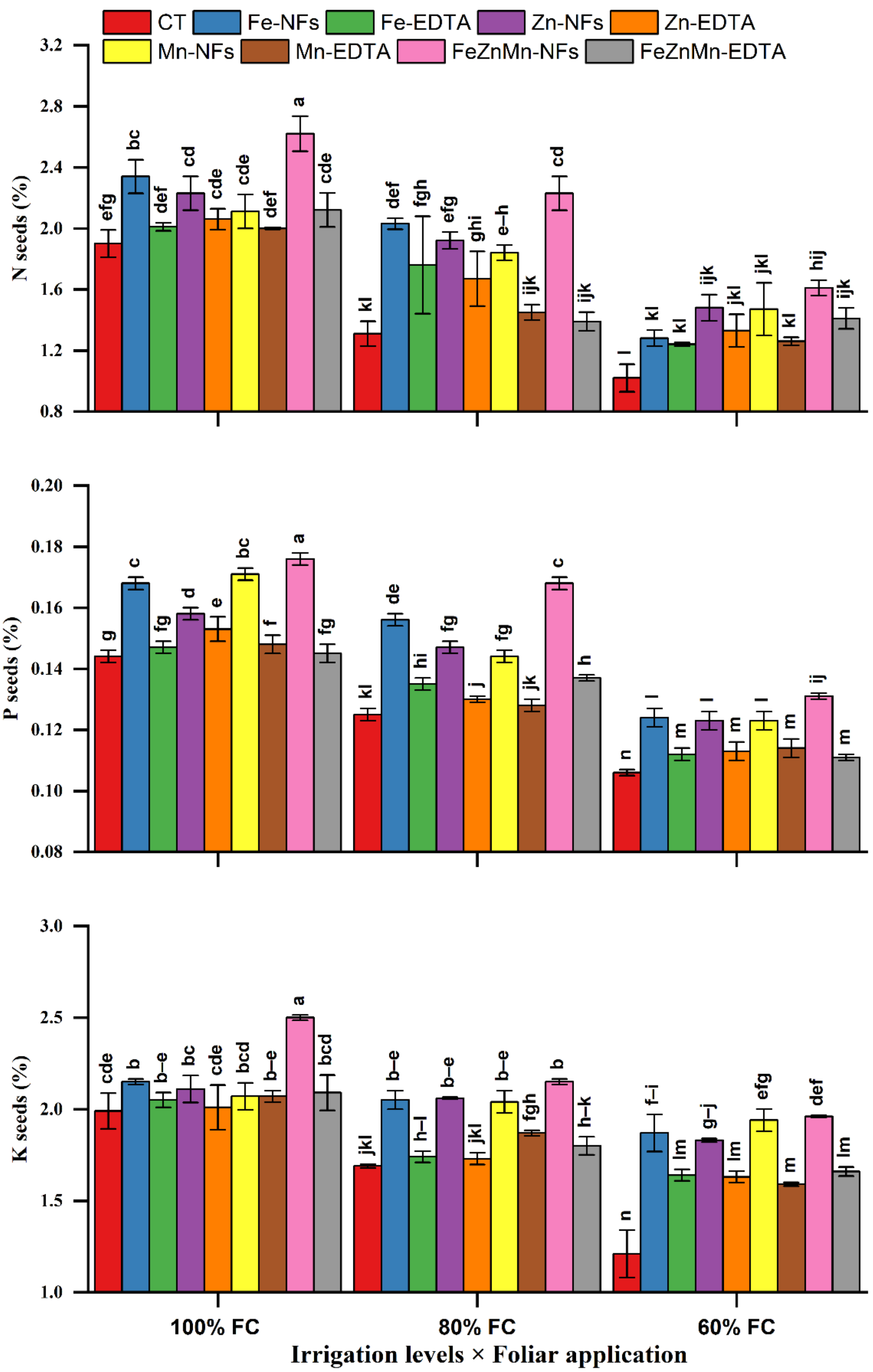

Fig .7. Effect of the interaction between irrigation levels and different forms of Fe, Zn, and Mn as a foliar spray on nutrient content in the seed of *V. faba* plants. N: Nitrogen, P: phosphorous, K: potassium, 100% FC: irrigation at 100% of field capacity, 80% FC: irrigation at 80% of field capacity, and 60% FC: irrigation at 60% of field capacity. Different bars indicate the values of means ±SD. Bars with different letters above them indicate a statistically significant difference (*P*<0.05 level), whereas bars with the same letters show no significant difference.

Regarding the interaction between irrigation treatments and foliar spray treatments of faba bean plants, as shown in Figures 6 and 7, the highest NPK content in straw (2.09%, 0.165%, and 2.04%, respectively) and seeds (2.62%, 0.176%, and 2.50%, respectively) was achieved with the combination of IWA at 100% FC and FA of FeZnMn-NFs. Conversely, the lowest NPK content in straw (1.01%, 0.102%, and 1.04%, respectively) and seeds (1.02%, 0.106%, and 1.21%, respectively) were observed with the combination of IWA at 60% FC and without FA (control).

3.3. Irrigation Water Applied and Water Use Efficiency

The results in Table 4 demonstrated a significant impact of irrigation levels and FA treatments (NFs and EDTA) on the amount of IWA and WUE of broad bean plants, as well as their interaction (Fig. 8). Increasing the irrigation levels significantly raised the amount of IWA and decreased the WUE. The highest IWA value (13.84 L pot^{-1}) was recorded at the 100% FC irrigation treatment, while the lowest IWA value (5.58 L pot^{-1}) was observed under the 60% FC treatment (Table 4). Conversely, the highest WUE value (2.55 kg m^{-3}) was recorded at the 60% FC irrigation level, whereas the lowest WUE value (1.54 kg m^{-3}) was observed at the 100% FC irrigation level.

Table 4. Effect of irrigation levels and different forms of Fe, Zn, and Mn as a foliar spray on the amount of irrigation water applied (IWA) and water use efficiency (WUE) of *V. faba* plants.

Treatments	Amount of IWA (L pot^{-1})	WUE (kg m^{-3})
Irrigation levels		
100% FC	13.84±0.66a	1.54±0.19c
80% FC	8.21±0.64b	2.30±0.45b
60% FC	5.58±0.24c	2.55±0.51a
Foliar application (FA)		
CT	9.64±4.81a	1.60±0.36e
Fe-NFs	9.46±4.51ab	2.18±0.80b
Fe-EDTA	9.08±4.45bc	1.82±0.69de
Zn-NFs	9.31±4.56ab	2.06±0.65bc
Zn-EDTA	9.28±4.58ab	1.72±0.62de
Mn-NFs	9.34±4.53ab	2.17±0.62b
Mn-EDTA	9.04±4.41bc	1.84±0.58de
FeZnMn-NFs	8.72±4.18c	2.44±0.79a
FeZnMn-EDTA	9.02±4.26bc	1.92±0.61cd

100% FC: irrigation at 100% of field capacity, 80% FC: irrigation at 80% of field capacity, 60% FC: irrigation at 60% of field capacity, CT: control, Fe-NFs: iron-nano, Fe-EDTA: iron-chelated, Zn-NFs: zinc-nano, Zn-EDTA: zinc-chelated, Mn-NFs: manganese-nano, Mn-EDTA: manganese-chelated, FeZnMn-NFs: iron+zinc+manganese-nano and FeZnMn-EDTA: iron+zinc+manganese-chelated. Values represent means ±SD. Means within the same column that share the same letter do not differ significantly ($p<0.05$ level).

The data in Table 4 also indicated that the amount of IWA and WUE significantly increased with the FA of NFs and EDTA. The highest IWA value (9.64 L pot^{-1}) was observed in the control (without FA), while the lowest IWA value (8.72 L pot^{-1}) was recorded with the FA of FeZnMn-NFs treatment. Conversely, the highest WUE value (2.44 kg m^{-3}) was achieved with the FeZnMn-NFs treatment, compared to the lowest WUE value (1.60 kg m^{-3}) in the control.

Regarding the interaction of all treatments on the amount of IWA WUE values, the data in Fig. 8 showed that the highest IWA value (14.65 L pot^{-1}) was observed with the combination of 100% FC irrigation and the control treatment (without FA). In contrast, the lowest IWA value (5.44 L pot^{-1}) was recorded using 60% FC irrigation and the FeZnMn-NFs treatment. On the other hand, the highest WUE value (3.17 kg m^{-3}) was achieved with the combination of 60% FC irrigation and the FeZnMn-NFs treatment. The lowest WUE value (1.34 kg m^{-3}) was compared with the combination of 100% FC irrigation and the control treatment (without FA).

3.4. Correlation Analysis

Correlations among measured traits across three irrigation levels and foliar application treatments are presented in Fig. 9. WUE trait showed a negative correlation with all characteristics. In contrast, N straw and K seeds traits showed a non-significant negative correlation (p >0.05) correlation (r = –0.134 and –0.197) for N straw and K seeds, respectively. In addition, significant and high negative (p< 0.05) correlations (r = –0.615**, –0.616**, and –0.829**, respectively) were given between WUE and NBP, DW, and IWA, respectively. Moreover, a high positive and significant (p < 0.05) correlation was obtained between SY and all traits except WUE. However,

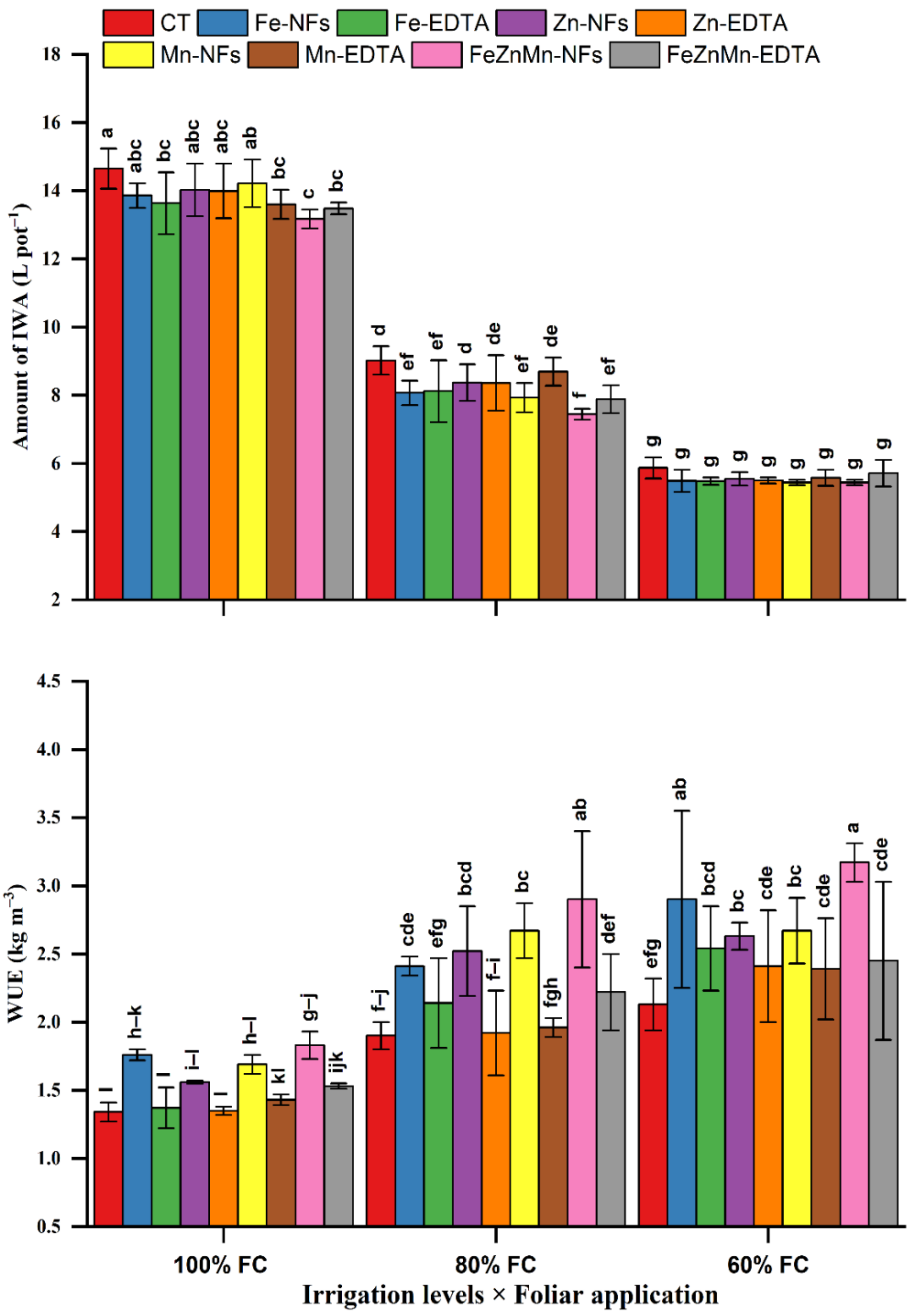

Fig. 8. Effect of the interaction between irrigation levels and different forms of Fe, Zn, and Mn as a foliar spray on the amount of IWA and WUE. of *V. faba* plants. IWA: Irrigation water applied, WUE: water use efficiency, 100% FC: irrigation at 100% of field capacity, 80% FC: irrigation at 80% of field capacity, and 60% FC: irrigation at 60% of field capacity. Different bars indicate the values of means ±SD. Bars with different letters above them indicate a statistically significant difference (*P*<0.05 level), whereas bars with the same letters show no significant difference.

correlation coefficients ranged from r = 0.737**, given by P straw, to r = 0.940**, presented by P seeds. On the other hand, IWA traits showed a highly positive and significant ($p < 0.05$) correlation with all traits except WUE. However, a moderate correlation was given by IWA and N straw (r = 0.542**) and K seeds (r =0.553**). Correlations were positively correlated with the most significant correlation coefficients between studied traits.

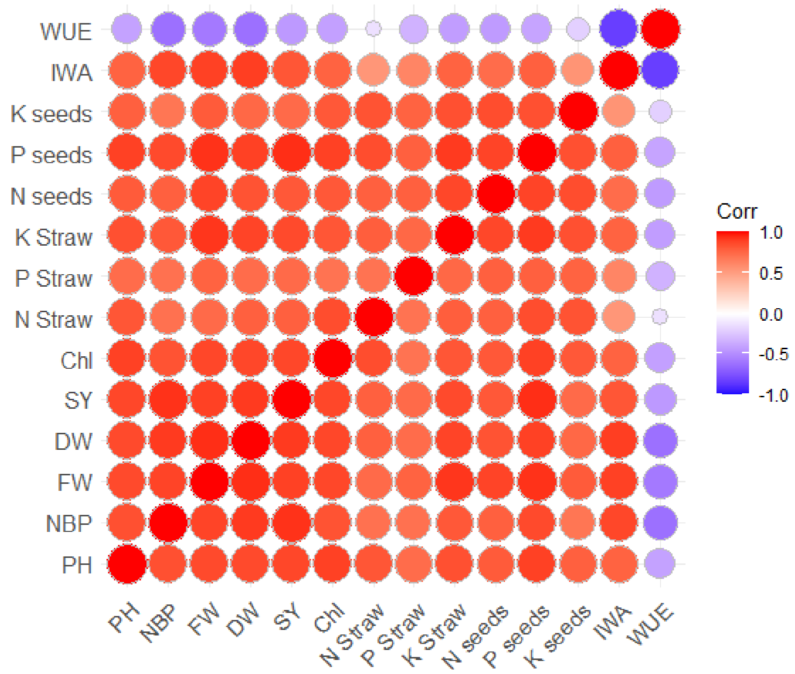

Fig. 9. Correlation heatmap for studied traits. PH: plant height, NBP: number of branches per pot, FW: fresh weight, DW: dry weight, SY: seed yield, Chl: chlorophyll content, N straw: nitrogen content in straw, P straw: phosphorous content in straw, K straw: potassium content in straw, N seeds: nitrogen content in seeds, P seeds: phosphorous content in seeds, K seeds: potassium content in seeds, IWA: irrigation water applied, and WUE: water use efficiency.

4. Discussion

The results of this study showed that parameters such as plant height, number of branches, fresh weight, dry weight, seed yield, and chlorophyll content of faba bean significantly increased compared to the control treatment when Fe, Zn, and Mn fertilizers were applied, regardless of the form used. The FA of combined Fe, Zn, and Mn fertilizers resulted in a higher seed yield than single applications due to the excellent supply of these nutrients. Combining nano-fertilizers (FeZnMn-NFs) proved more effective than the chelated fertilizers (FeZnMn-EDTA). This effectiveness is likely due to the enhanced supply of Fe, Zn, and Mn, which promotes chlorophyll synthesis and the photosynthetic apparatus, leading to higher yields. Similar findings, indicating enhanced vegetative growth parameters, could be attributed to increased chlorophyll content, photosynthesis rate, and nutrient uptake, significantly boosting the accumulation of polysaccharides and organic matter in various plant organs (Elfeky et al., 2013). Faba bean responded positively to the foliar application (FA) of micronutrients. The FA of iron (Fe) improved growth parameters, likely due to enhanced protein synthesis and carbohydrate and increased photosynthesis (Chao & Chao, 2022).

Additionally, Fe is essential for synthesizing growth promoters such as auxins, chlorophyll production, nucleic acid metabolism, and seed maturation (Liu et al., 2014). Zinc is vital for auxin production, which regulates growth and development and promotes the formation of auxin compounds like indole acetic acid (El-Boray et al., 2024). Mn activates enzymes involved in photosynthesis and respiration, which are crucial for nitrogen metabolism and absorption (Andresen et al., 2018). Consequently, improvements in these parameters lead to higher seed yields (Hafeez et al., 2022). These findings are consistent with the results reported by El-Gioushy et al. (2021), who found that spraying nano-Fe significantly enhances plant growth parameters and fruit quality compared to chelated and conventional Fe treatments due to increased photosynthesis pigments and nutrient absorption. Nano-fertilizers demonstrated higher content and translocation efficiency than chelated fertilizers

(Pudhuvai et al., 2024). The current results are consistent with previous studies, where applying nano-fertilizers in faba beans resulted in higher yields than chelated fertilizers (Mahmoud et al., 2022a). Similarly, Nadi et al. (2013) found that applying Fe-NFs positively impacted faba bean yield and yield parameters. Chlorophyll is a crucial pigment in photosynthesis, absorbing and transferring light energy (Simkin et al., 2022). The chlorophyll content in leaves is a key indicator of the physiological performance of plant photosynthetic tissues, significantly affecting plant photosynthesis (Sharma et al., 2020). The present study showed that faba beans treated with nano-fertilizers (NFs) had superior leaf chlorophyll content. This improvement was partly due to Fe-NFs enhancing the activity of Fe oxygen reductase, which indirectly boosted porphyrin metabolism to produce aminolevulinic acid, a chlorophyll precursor (Li et al., 2018). Similarly, Plaksenkova et al. (2019) found that Fe-NFs increased chlorophyll levels in the leaves of *Eruca sativa* compared to the control (CT) treatment.

The foliar application of Fe, Zn, and Mn, individually and in combination, regardless of the form used, resulted in significantly higher NPK content (%) in the straw and seeds of faba bean compared to the control. This increase was attributed to the immediate availability of nutrients, as FA directs nutrients to the leaves. Generally, the higher nutrient content (%) in the straw and seeds of faba bean plants treated with nano-fertilizers (NFs) compared to chelated fertilizers may be due to the properties of NFs, which have a smaller surface area and higher absorption. NFs of nutrients increased the macronutrient content more effectively than chelated forms. The combined application of FeZnMn-NFs positively influenced the NPK content in the straw and faba bean seeds. This enhancement in macronutrient (NPK) content could be attributed to the foliar spraying of different micronutrients, which improved plant nutrient absorption. Nano-fertilizers (NFs) demonstrated more significant potential in increasing NPK content in both straw and seeds than chelated fertilizers, as the single application of NFs was more effective than the single application of chelated fertilizers. Similar findings on the higher effectiveness of NFs compared to chelated fertilizers have been noted by Ponce-García et al. (2019). Mahmoud et al. (2022a) reported that NFs are more effective than chelated fertilizers in enhancing nutrient content in faba bean plants. The increase in N content with Fe fertilization can be attributed to Fe's crucial role in promoting nodule formation and improving symbiotic associations, thereby boosting nitrogen fixation (NF) (Brear et al., 2013). Abou El-Nasr et al. (2015) found that FA with Fe oxide nanoparticles at a concentration of 250 ppm resulted in the highest nitrogen content in pear leaves. Similarly, Askary et al. (2017) reported significant increases in Fe, phosphorus (P), and potassium (K) content in the presence of Fe, especially Fe nanoparticles. Consequently, many researchers have concluded that using NFs at optimal concentrations significantly improves crops' vegetative growth, yield, and nutritional status in arid and semi-arid regions and nutrient-poor sandy soils (Abou Tahoun et al., 2022; El-Gioushy et al., 2021).

The current study demonstrated that foliar application (FA) of nano-fertilizers (NFs) led to improved WUE, followed by chelated fertilizers, compared to unfertilized plants (control). The highest amount of IWA was observed in control treatment, followed by chelated fertilizers and plants treated with NFs. This positive trend can be attributed to the ability of NFs containing Fe, Zn, and Mn to mitigate the inhibitory effects of drought stress on plants. Zinc-based micronutrient fertilizers have been shown to alleviate water stress in plants by detoxifying drought-induced free radicals, maintaining cell integrity, and improving water potential. Dimkpa et al. (2019) support these findings. Various studies suggest that Zn-based fertilizers are crucial in mitigating plant drought stress by enhancing photosynthetic pigments, reducing lipid peroxidation, and reactive oxygen scavenging substances (Rai-Kalal et al., 2021). Mahmoud et al. (2022b) found that an increase in photosynthesis rate will likely improve plants' water use efficiency (WUE). Consequently, this study demonstrated that NFs significantly help reduce drought stress's adverse effects. These conclusions are corroborated by Abou-Sreea et al. (2022), Al-Selwey et al. (2023), Ghiyasi et al. (2023), and Liu et al. (2024), who observed that adding NFs to plants underwater stress conditions enhanced WUE.

Conclusions

The findings of this study indicate that Fe, Zn, and Mn nano-fertilizers, owing to their unique structural properties, can be utilized more effectively than their chelated counterparts. Moreover, the combined use of Fe, Zn, and Mn NFs led to a notable increase in yield and nutrient content (%) in the straw and seeds of faba bean. The study also highlighted the crucial role of Fe, Zn, and Mn in enhancing seed yield, as their availability improved faba bean yield regardless of the form in which they were applied. Conversely, the FeZnMn-NFs treatment achieved the highest WUE under deficit irrigation conditions. Additionally, foliar application of NFs positively impacted the plant's ability to withstand water stress. Therefore, the foliar application of Fe, Zn, and Mn nano-fertilizers is particularly noteworthy for improving the productivity and faba bean nutrient content, addressing malnutrition of micronutrients.

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5. References

Abd El-Kader SH, Mohamed MM, Ahmed HK, Sheta MH (2023). Mulching effect on evaporation from the soil surface and water use efficiency of cowpea crop. Al-Azhar J. Agric. Res., 48(3), 347–358.

Aboseif EM, Abdel-Mottaleb MA, Rizk AH, Shawer SS (2022). Effect of organic and inorganic fertilizers on yield of broad bean plant grown on West Delta region. Al-Azhar J. Agric. Res., 47(2), 121–32.

Abou El-Nasr MK, El-Hennawy HM, El-Kereamy AMH, Abou El-Yazied A, Salah Eldin TA (2015). Effect of magnetite nanoparticles (Fe_3O_4) as nutritive supplement on pear saplings. Middle East J. Appl. Sci., 5(3), 777–785.

Abou Khater L, Maalouf F, Balech R, He Y, Zong X, Rubiales D, Kumar S (2024). Improvement of cool-season food legumes for adaptation to intercropping systems: breeding faba bean for intercropping with durum wheat as a case study. Front. Plant Sci., 15, 1368509.

Abou Tahoun, AM, Abou El-Enin MM, Mancy AG, Sheta MH, Shaaban A (2022). Integrative soil application of humic acid and foliar plant growth stimulants improves soil properties and wheat yield and quality in nutrient-poor sandy soil of a semi-arid region. J. Soil Sci. Plant Nutr., 22(3), 2857–2871.

Abou-Sreea A IB, Kamal M, El Sowfy DM, Rady MM, Mohamed GF, Al-Dhumri SA, AL-Harbi MS, Abdou NM (2022). Small-sized nanophosphorus has a positive impact on the performance of fenugreek plants under soil-water deficit stress: A Case Study under Field Conditions. Biology, 11(1), 115.

Abou-Yuoseff AM, Abou El-Khair RA, El-Mohtasem MO, Shawer SS (2022). Impacts of nano-fertilizers and chemical fertilizers on plant growth and nutrient uptake by faba bean (*Vicia faba* L.) plant. Al-Azhar J. Agric. Res., 47(1), 216–229.

Afreen U, Mukhopadhyay K, Kumar M (2024). DNA methylation in wheat: current understanding and future potential for enhancing biotic and abiotic stress tolerance. Physiol. Mol. Biol. Plants, 1–13.

Ahmad A, Javad S, Iqbal S, Shahid T, Naz S, Shah AA, Shaffique S, Gatasheh MK (2024). Efficacy of soil drench and foliar application of iron nanoparticles on the growth and physiology of *Solanum lycopersicum* L. exposed to cadmium stress. Sci Rep, 14(1), 27920.

Ahmad M, Ishaq M, Shah WA, Adnan M, Fahad S, Saleem MH, Khan FU, Mussarat M, Khan S, Ali B, Mostafa YS, Alamri S, Hashem M (2022). Managing phosphorus availability from organic and inorganic sources for optimum wheat production in calcareous soils. Sustainability, 14(13), 7669.

Ali B, Wang X, Saleem MH, Azeem MA, Afridi MS, Nadeem M, Ghazal M, Batool T, Qayyum A, Alatawi A, Ali S (2022). *Bacillus mycoides* PM35 reinforces photosynthetic efficiency, antioxidant defense, expression of stress-responsive genes, and ameliorates the effects of salinity stress in maize. Life, 12 (2), 219.

Almendros P, Obrador A, Alvarez JM, Gonzalez D (2019). Zn-DTPA-HEDTA-EDTA application: a strategy to improve the yield and plant quality of a barley crop while reducing the N application rate. J. Soil Sci. Plant Nutr., 19(4), 920–934.

Al-Selwey WA, Alsadon AA, Ibrahim AA, Labis JP, Seleiman MF (2023). Effects of zinc oxide and Silicon dioxide nanoparticles on physiological, yield, and water use efficiency traits of potato grown under water deficit. Plants, 12(1), 218.

Andresen E, Peiter E, Küpper H (2018). Trace metal metabolism in plants. J. Exp. Bot. 69(5), 909–954.

Arora PK, Tripathi S, Omar RA, Chauhan P, Sinhal VK, Singh A, Srivastava A, Garg SK, Singh VP (2024). Next-generation fertilizers: the impact of bionanofertilizers on sustainable agriculture. Microb. Cell Fact., 23(1), 254.

Askary M, Amirjani MR, Saberi T (2017). Comparison of the effects of nano-iron fertilizer with iron-chelate on growth parameters and some biochemical properties of *Catharanthus roseus*. J. Plant Nutr., 40(7), 974–982.

Avila-Quezada GD, Ingle AP, Golińska P, Rai M (2022). Strategic applications of nano-fertilizers for sustainable agriculture: Benefits and bottlenecks. Nanotechnol. Rev., 11(1), 2123–2140.

Bamber N, Arulnathan V, Puddu L, Smart A, Ferdous J, Pelletier N (2024). Life cycle inventory and assessment of Canadian faba bean and dry bean production. Sustain. Prod. Consump., 46, 442–459.

Brear EM, Day DA, Smith PMC (2013). Iron: an essential micronutrient for the legume-rhizobium symbiosis. Front. Plant. Sci., 4, 359.

Chao Z-F, Chao D-Y (2022). Similarities and differences in iron homeostasis strategies between graminaceous and nongraminaceous plants. New Phytol., 236, 1655–1660.

Dane JH, Topp CG (2020). Methods of soil analysis, Part 4: Physical methods (Vol. 20). John Wiley and Sons.

Dhaliwal SS, Sharma V, Shukla AK, Verma V, Behera SK, Singh P, Alotaibi SS, Gaber A, Hossain A (2021). Comparative efficiency of mineral, chelated and nano forms of zinc and iron for improvement of zinc and iron in Chickpea (*Cicer arietinum* L.) through Biofortification. Agronomy, 11(12), 2436.

Dimkpa CO, Singh U, Bindraban PS, Elmer WH, Gardea-Torresdey JL, White JC (2019). Zinc oxide nanoparticles alleviate drought-induced alterations in sorghum performance, nutrient acquisition, and grain fortification. Sci. Total Environ., 688: 926–934.

Easwaran C, Moorthy G, Christopher SR, Mohan P, Marimuthu R, Koothan V, Nallusamy S (2024). Nano hybrid fertilizers: A review on the state of the art in sustainable agriculture. Sci. Total Environ., 172533.

El-Badry MM, Zeid MS, Mancy AG, Abdeen SA (2023). Integrative application of organic and inorganic fertilizers on some soil properties and growth of faba bean under different levels of irrigation water. Al-Azhar J. Agric. Res., 48(3), 331–346.

El-Boray MS, Shalan AM, Mostafa AS, Allam FM (2024). Effect of different forms of microelements foliar application on vegetative growth of " Sukkari" orange citrus trees. J. Plant Prod., 15(9), 575–578.

Elfeky SA, Mohammed MA, Khater MS, Osman YA, Elsherbini,E (2013). Effect of magnetite nano-fertilizer on growth and yield of *Ocimum basilicum* L. Int. J. Indig. Med. Plants, 46(3), 1286–11293.

El-Gioushy SF, Ding Z, Bahloul AME, Gawish MS, Abou El Ghit HM, Abdelaziz AMRA, El-Desouky HS, Sami R, Khojah E, Hashim TA, Kheir AMS, Zewail RMY (2021). Foliar application of nano, chelated, and conventional iron forms enhanced growth, nutritional status, fruiting aspects, and fruit quality of Washington navel orange trees (*Citrus sinensis* L. *Osbeck*). Plants, 10(12), 2577.

Elsherpiny MA, Kaney MA (2023). Maximizing faba bean tolerance to soil salinity stress using gypsum, compost and selenium. Egypt. J. Soil Sci., 63(2), 243–253.

Faiyad RMN, Abd EL-Azeiz EH (2024). Mitigation the deleterious effect of salinity on faba bean by cobalt and bio-stimulants. Egypt. J. Soil Sci., 64(1), 181–192.

Faridvand S, Amirnia R, Tajbakhsh M, El Enshasy HA, Sayyed RZ (2021). The effect of foliar application of magnetic water and nano-fertilizers on phytochemical and yield characteristics of fennel. Horticulturae, 7(11), 475.

Fathi A, Tari DB (2016). Effect of drought stress and its mechanism in plants. Int. J. Life Sci. 10, 1–6.

Fayed MH, Sheta MH, Mancy AG (2021). Improving the growth and productivity of faba bean (*Vicia faba* L.) under deficit irrigation conditions by spraying of potassium selenate and potassium silicate. Egypt. J. Soil Sci., 61(1), 95–111.

Ghiyasi M, Rezaee Danesh Y, Amirnia R, Najafi S, Mulet JM, Porcel R (2023). Foliar applications of ZnO and its nanoparticles increase safflower (*Carthamus tinctorius* L.) growth and yield under water stress. Agronomy, 13(1), 192.

Ghorbani A, Emamverdian A, Pehlivan N, Zargar M, Razavi SM, Chen M (2024). Nano-enabled agrochemicals: mitigating heavy metal toxicity and enhancing crop adaptability for sustainable crop production. J. Nanobiotechnol., 22(1), 91.

Gomez KA, Gomez AA (1984). Statistical procedures for agricultural research; John Wiley & Sons: Hoboken, NJ, USA.

Gu Y, Xu Q, Zhou W, Han C, Siddique KH (2024). Enhancing faba bean yields in alpine agricultural regions: The impact of plastic film mulching and phosphorus fertilization on soil dynamics. Agronomy, 14(3), 447.

Gupta R, Verma N, Tewari RK (2024). Micronutrient deficiency-induced oxidative stress in plants. Plant Cell Reports, 43(9), 213.

Hacisalihoglu G (2020). Zinc (Zn): The last nutrient in the alphabet and shedding light on Zn efficiency for the future of crop production under suboptimal Zn. Plants, 9(11), 1471.

Hafeez A, Rasheed R, Ashraf MA, Rizwan M, Ali S (2022). Effects of exogenous taurine on growth, photosynthesis, oxidative stress, antioxidant enzymes and nutrient accumulation by *Trifolium alexandrinum* plants under manganese stress. Chemosphere, 308, 136523.

Ishfaq M, Kiran A, ur Rehman H, Farooq M, Ijaz NH, Nadeem F, Azeem I, Li X, Wakeel A (2022). Foliar nutrition: Potential and challenges under multifaceted agriculture. Environ. Exp. Bot., 200, 104909.

Jomova K, Alomar SY, Alwasel SH, Nepovimova E, Kuca K, Valko M (2024). Several lines of antioxidant defense against oxidative stress: antioxidant enzymes, nanomaterials with multiple enzyme-mimicking activities, and low-molecular-weight antioxidants. Arch. Toxicol., 98(5), 1323–1367.

Joudeh N, Linke D (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. J. Nanobiotechnol., 20(1), 262.

Kandhol N, Jain M, Tripathi DK (2022). Nanoparticles as potential hallmarks of drought stress tolerance in plants. Physiol. Plant., 174(2), e13665.

Kashyap PL, Kumar S, Srivastava AK (2017). Nano diagnostics for plant pathogens. Environ. Chem. Lett., 15, 7–13.

Kopecká R, Kameniarová M, Černý M, Brzobohatý B, Novák J (2023). Abiotic stress in crop production. Int. J. Mol. Sci., 24(7), 6603.

Kumar N, Samota SR, Venkatesh K, Tripathi SC (2023). Global trends in use of nano-fertilizers for crop production: Advantages and constraints–A review. Soil Tillage Res., 228, 105645.

Kumar P, Thakur N, Kumar K, Kumar S, Dutt A, Thakur VK, Gutiérrez-Rodelo C, Thakur P, Navarrete A, Thakur N (2024). Catalyzing innovation: Exploring iron oxide nanoparticles-Origins, advancements, and future application horizons. Coord. Chem. Rev., 507, 215750.

Li J, Hu J, Xiao L, Wang Y, Wang X (2018). Interaction mechanisms between α-Fe_2O_3, γ-Fe_2O_3 and Fe_3O4 nanoparticles and *Citrus maxima* seedlings. Sci. Total Environ., 625, 677–685.

Lilay GH, Thiébaut N, du Mee D, Assunção AG, Schjoerring JK, Husted S, Persson DP (2024). Linking the key physiological functions of essential micronutrients to their deficiency symptoms in plants. New Phytol., 242(3), 881–902.

Liu A, Xiao W, Lai W, Wang J, Li X, Yu H, Zha Y (2024). Potential application of selenium and copper nanoparticles in improving growth, quality, and physiological characteristics of strawberry under drought stress. Agriculture, 14(7), 1172.

Liu J, Chakraborty S, Hosseinzadeh P, Yu Y, Tian S, Petrik I, Bhagi A, Lu, Y (2014). Metalloproteins containing cytochrome, iron–sulfur, or copper redox centers. Chem. Rev., 114(8), 4366–4469.

Madhupriyaa D, Baskar M, Sherene Jenita Rajammal T, Kuppusamy S, Rathika S, Umamaheswari T, Sriramachandrasekran MV, Mohanapragash AG (2024). Efficacy of chelated micronutrients in plant nutrition. commun. Soil Sci. Plant Anal., 55(22), 3609–3637.

Mahanta N, Ashok D, Montrishna R (2019). Nutrient use efficiency through nano-fertilizers. Int. J. Chem. Stud., 7, 2839–2842.

Mahmoud AWM, Ayad AA, Abdel-Aziz HS, Williams LL, El-Shazoly RM, Abdel-Wahab A, Abdeldaym EA (2022a). Foliar application of different iron sources improves morpho-physiological traits and nutritional quality of broad bean grown in sandy soil. Plants, 11(19), 2599.

Mahmoud AWM, Samy MM, Sany H, Eid RR, Rashad HM, Abdeldaym EA (2022b). Nanopotassium, nanosilicon, and biochar applications improve potato salt tolerance by modulating photosynthesis, water status, and biochemical constituents. Sustainability, 14, 723.

Makhasha E, Al-Obeed RS, Abdel-Sattar M (2024). Responses of nutritional status and productivity of Timor mango trees to foliar spray of conventional and/or nano zinc. Sustainability, 16(14), 6060.

Moustafa MM, Abd El-wahed AH, Awad AH, Sheta MH (2024b). Morpho-physiological traits, quality and productivity of garlic under drought stress of different growth stages. Egypt. J. Soil Sci., 64(1), 99–118.

Moustafa MM, Abd El-wahed AH, Hamad SA, Sheta MH (2024a). Improved water use efficiency and yield of drip-irrigated pepper under full and deficit irrigation conditions. Egypt. J. Soil Sci., 64(2), 423–442.

Muñoz-Márquez E, Soto-Parra JM, Noperi-Mosqueda LC, Sánchez E (2022). Application of molybdenum nanofertilizer on the nitrogen use efficiency, growth and yield in green beans. Agronomy, 12(12), 3163.

Nadi E, Aynehband A, Mojaddam M (2013). Effect of nano-iron chelate fertilizer on grain yield, protein percent and chlorophyll content of faba bean (*Vicia faba* L.). Int. J. Bioscis., 3 (9), 267–272.

Naumann G, Alfieri L, Wyser K, Mentaschi L, Betts RA, Carrao H, Spinoni J, Vogt J, Feyen L (2018). Global changes in drought conditions under different levels of warming. Geophys. Res. Lett. 45, 3285–3296.

Niu J, Liu C, Huang M, Liu K, Yan D (2021). Effects of foliar fertilization: a review of current status and future perspectives. J. Soil Sci. Plant Nutr., 21, 104–118.

Obeng SK, Kulhánek M, Balík J, Černý J, Sedlář O (2024). Manganese: From soil to human health—a comprehensive overview of its biological and environmental significance. Nutrients, 16(20), 3455.

Payero JO, Tarkalson DD, Irmak S, Davison D, Petersen JL (2008). Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semi-arid climate. Agric. Water Manag., 95: 895–908.

Plaksenkova I, Jermalonoka M, Bankovska L, Gavarane I, Gerbreders V, Sledevskis E, Sniķeris J, Kokina I (2019). Effects of Fe_3O_4 nanoparticle stress on the growth and development of rocket *Eruca sativa*. J. Nanomater., 1, 2678247.

Ponce-García CO, Soto-Parra JM, Sánchez E, Muñoz-Márquez E, Piña-Ramírez FJ, Flores-Córdova MA, Pérez-Leal R, Yáñez Muñoz RM (2019). Efficiency of nanoparticle, sulfate, and zinc-chelate use on biomass, yield, and nitrogen assimilation in green beans. Agronomy, 9(3), 128.

Pudhuvai B, Koul B, Das R, Shah MP (2024). Nano-Fertilizers (NFs) for resurgence in nutrient use efficiency (NUE): a sustainable agricultural strategy. Curr. Pollut. Rep., 11(1).

Rahman MM, Ghosh PK, Akter M, Al Noor MM, Rahman MA, Keya S S, Roni S, Biswas A, Bulle M (2024). Green vanguards: Harnessing the power of plant antioxidants, signal catalysts, and genetic engineering to combat reactive oxygen species under multiple abiotic stresses. Plant Stress, 100547.

Rai-Kalal P, Tomar RS, Jajoo A (2021). H_2O_2 signaling regulates seed germination in ZnO nanoprimed wheat (*Triticum aestivum* L.) seeds for improving plant performance under drought stress. Environ. Exp. Bot., 189, 104561.

Saleh TA (2020). Nanomaterials: Classification, properties, and environmental toxicities. Environ. Technol. Innov., 20, 101067.

Sedghi M, Hadi M, Toluie S (2013). Effect of nano zinc oxide on the germination parameters of soybean seeds under drought stress. Ann. West Univ. Timis. Ser. Biol (2). 16, 73–78.

Seleiman MF, Almutairi KF, Alotaibi M, Shami A, Alhammad BA, Battaglia ML (2020). Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use? Plants, 10(1), 2.

Sharma A, Kumar V, Shahzad B, Ramakrishnan M, Singh Sidhu GP, Bali AS, Handa N, Kapoor D, Yadav, P Khanna K, Bakshi P, Rehman A, Kohli SK, Khan EA, Parihar RD, Yuan H, Thukral AK, Bhardwaj R, Zheng B (2020). Photosynthetic response of plants under different abiotic stresses: a review. J. Plant Growth Regul., *39*, 509–531.

Sheta MH, Ghanem HG, Elzanaty TM, Mosaad IS, Fayed MH (2024b). Effect of surge flow irrigation on water use efficiency and maize production. Egypt. J. Soil Sci., 64(4), 1601–1616.

Sheta, MH, Abd El-Wahed, AHM, Elshaer, MA, Bayomy HM, Ozaybi NA, Abd-Elraheem MAM, El-Sheshtawy, A-NA, El-Serafy RS, & Moustafa MMI (2024a). Green synthesis of zinc and iron nanoparticles using *Psidium guajava* leaf extract stimulates cowpea growth, yield, and tolerance to saline water irrigation. Horticulturae, 10(9), 915.

Simkin AJ, Kapoor L, Doss CGP, Hofmann TA, Lawson T, Ramamoorthy S (2022). The role of photosynthesis related pigments in light harvesting, photoprotection and enhancement of photosynthetic yield in planta. Photosynth. Res., 152(1), 23-42.

Simon-Miquel G, Reckling M, Plaza-Bonilla D (2024). Faba bean introduction makes protein production less dependent on nitrogen fertilization in Mediterranean no-till systems. Field Crop. Res., 308, 109307.

Singh A, Rajput VD, Varshney A, Sharma R, Ghazaryan K, Minkina T, Alexiou A, El-Ramady H (2024b). Revolutionizing crop production: Nanoscale wonders-current applications, advances, and future frontiers. Egypt. J. Soil Sci., 64(1), 221–258.

Singh A, Rawat S, Rajput VD, Minkina T, Mandzhieva S, Eloyan A, Singh RK, Singh O, El-Ramady H, Ghazaryan K (2024a). Nanotechnology products in agriculture and environmental protection: advances and challenges. Egypt. J. Soil Sci., 64(4), 1355–1378.

Sparks DL, Page AL, Helmke PA, Loeppert RH (Eds.). (2020). Methods of soil analysis, part 3: Chemical methods (Vol. 14). John Wiley and Sons.

Taha AA, Youssef MA, Omar MM (2024). Enhancing spinach performance: Effectiveness of nano-fertilizers in conjunction with conventional NPK fertilizers. Egypt. J. Soil Sci., 64(3), 927–950.

Wahab A, Muhammad M, Ullah S, Abdi G, Shah GM, Zaman W, Ayaz A (2024). Agriculture and environmental management through nanotechnology: Eco-friendly nanomaterial synthesis for soil-plant systems, food safety, and sustainability. Sci. Total Environ., 171862.

Wairich A, Aung MS, Ricachenevsky FK, Masuda H (2024). You can't always get as much iron as you want: how rice plants deal with excess of an essential nutrient. Front. Plant Sci., 15, 1381856.

Walinga I, Van Der Lee JJ, Houba VJ, Van Vark W, Novozamsky I (2013). Plant analysis manual. Springer Science & Business Media.

Wang S, Wang Z, Gao Y, Liu L, Yu R, Jin J, Luo L, Hui X, Li F, Li M (2017). EDTA alone enhanced soil zinc availability and winter wheat grain Zn concentration on calcareous soil. Environ. Exp. Bot., 141, 19–27.

Zhang W, Yu X, Li M, Lang D, Zhang X, Xie Z (2018). Silicon promotes growth and root yield of *Glycyrrhiza uralensis* under salt and drought stresses through enhancing osmotic adjustment and regulating antioxidant metabolism. Crop Prot., 107, 1–11.

Zhou CX, Zhang CC, Zhao QY, Yu BG, Zhang W, Chen XP, Zou CQ (2024). Iron biofortification and yield of wheat grain in response to Fe fertilization and its driving variables: A meta-analysis. Glob. Food Secur., 40, 100737.