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Efficiency of Nano and Mineral Iron in Sustaining Faba Bean (*Vicia Faba* L.) Productivity Within Different Soil Orders

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Abstract: The decline in agricultural production rates necessitates the advancement of this sector by enhancing production efficiency through various modern technologies. Among these technologies in the field of fertilizers and fertilization is nanofertilizer technology. To achieve this goal, a biological experiment was conducted in the greenhouse of the Department of Soil Sciences and Water Resources, College of Agriculture and Forestry, University of Mosul, during the winter season of 2024/2025. The study aimed to evaluate the response of Broad Bean (*Vicia faba* L., Mornash cultivar) to the interaction between nano and mineral iron in two different soil orders within Nineveh Governorate. The experiment was implemented according to a Completely Randomized Design (CRD) as a factorial experiment with three replicates and three factors, first (S) Two types of soil with different textures., Second (M) Mineral fertilization, Tharid (N) Nano-fertilization. The total number of experimental units was 54 (2 soil types $\times$ 3 soil application levels $\times$ 3 foliar application levels $\times$ 3 replicates). Significant differences between treatments were evaluated using the Least Significant Difference (LSD) test at a significance level of 0.05. Key Results, Foliar Application: The foliar application of iron (both nano and mineral) had a clear impact on the growth of the broad bean plant. It resulted in a significant increase in growth indicators compared to the control treatment, including: plant height (cm), number of branches (branch plant⁻¹), leaf area (cm² plant⁻¹), chlorophyll concentration (SPAD), and shoot dry weight (g plant⁻¹). Yield Components, Significant increases were observed in yield components, including seed dry weight, seed fresh weight (g plant⁻¹), and biological yield (g plant⁻¹). Optimal Concentrations, Foliar applications of 100 mg Fe L⁻¹ and 1.5 g L⁻¹ outperformed other treatments, recording the highest values across all growth and yield indicators. Soil Application, Soil application at rates of 15 kg Fe ha⁻¹ and 4 kg Fe ha⁻¹ excelled over other concentrations in all studied growth and yield traits. Interaction Effects, The results of the dual interaction between soil and foliar application methods showed that the fertilizer combination of 100 mg Fe L⁻¹ (foliar) + 4 kg Fe ha⁻¹ (soil) (N2 + M3) significantly outperformed all other interactions in growth indicators and yield components.

Keywords: Faba bean, Nano-fertilizer, Mineral iron, Soil orders, Crop productivity

Introduction

Broad bean (*Vicia faba* L.) is considered one of the most significant pulse crops globally, valued for its high nutritional content of plant proteins, amino acids, minerals, and vitamins. Beyond its direct use as human food and animal feed, it holds strategic importance in sustainable agriculture due to its capacity for atmospheric nitrogen fixation and its role in improving the physical and chemical properties of soil (Abd El-Hady et al., 2023). However, the productivity of broad beans in calcareous soils—which are prevalent in many regions, including Iraq is adversely affected by the low bioavailability of micronutrients, particularly iron (Fe). This occurs due to high pH levels and the presence of calcium carbonates, which lead to the fixation of the element

and the inhibition of its uptake. Consequently, this results in iron-deficiency chlorosis, stunted growth, and degraded yield (Jassim et al., 2023).

Iron (Fe) is a vital micronutrient required by plants in small quantities, yet it performs essential functions in growth and development. It is a structural component of numerous enzymes and proteins responsible for redox reactions, such as cytochromes and ferredoxin. Furthermore, it contributes indirectly to chlorophyll synthesis and the activation of photosynthesis, while playing a crucial role in cellular respiration and energy production. Additionally, iron is a key factor in root nodule formation and the stimulation of *Rhizobium* bacteria activity, which fixes atmospheric nitrogen in legumes, thereby enhancing biological nutrition efficiency and increasing soil fertility (Khan et al., 2022).

Traditionally, mineral fertilization has been employed to address iron deficiency. Soil application of compounds such as ferrous sulfate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) aims to increase available iron concentrations in the soil and improve root uptake. However, the efficacy of this method is often compromised in calcareous soils due to nutrient fixation. Consequently, foliar application has been adopted as a complementary technique, where iron is sprayed directly onto the leaves. This method accelerates absorption, improves chlorophyll content, and exerts a rapid positive effect on vegetative growth (Shirsat et al., 2024).

With recent advancements in nanotechnology, nano-fertilization has emerged as an innovative strategy to enhance fertilizer use efficiency (FUE). Iron nanoparticles (Fe-NPs) are characterized by their small particle size and large surface area, which increase their solubility and bioavailability to the plant. Soil application of nano-iron contributes to improving the availability of the element and its subsequent uptake by roots. Meanwhile, foliar application has demonstrated exceptional effectiveness in boosting vegetative growth, increasing chlorophyll concentrations, and improving photosynthetic efficiency in leguminous plants, including broad beans (Mohamed et al., 2023; Al-Khafaji et al., 2024).

Accordingly, studying the impact of mineral and nano-iron fertilization—via both soil and foliar applications—on broad bean crops under calcareous soil conditions is a fundamental scientific step toward developing advanced fertilization programs. Such programs aim to enhance production efficiency and achieve agricultural sustainability. The primary objectives of this study are:

1. To evaluate the impact of mineral and nano-iron, along with their application methods, on certain growth parameters and yield components of the broad bean plant.
2. To determine the optimal levels of nano and mineral iron fertilizers, as well as the best interaction between application methods, to achieve the maximum yield for the broad bean crop.

Method

Soil Sampling Sites and Preparation

Two distinct locations with varying chemical and physical properties were selected within Nineveh Governorate to collect soil samples for cultivating the faba bean (*Vicia faba* L.) plant.

Site 1: Al-Rashidiya

Located in the Al-Rashidiya fields on the left bank of the Tigris River. It is situated at Longitude 43.1167° E and Latitude 36.4333° N in the northern suburbs of Mosul, approximately 10 km from the city center. According to the soil taxonomy, the soil at this site belongs to the Inceptisols order (specifically the suborder Uceptisols).

Site 2: Filfil

Located in the Filfil sub-district fields, approximately 60 to 70 km from Mosul city center on the left bank of the Tigris River. It is situated at Longitude 43.0343° E and Latitude 36.5467° N. The soil at this site belongs to the Aridisols order.

The selection of these two sites was based on the clear variation in their soil orders and properties, as illustrated in the figure below.

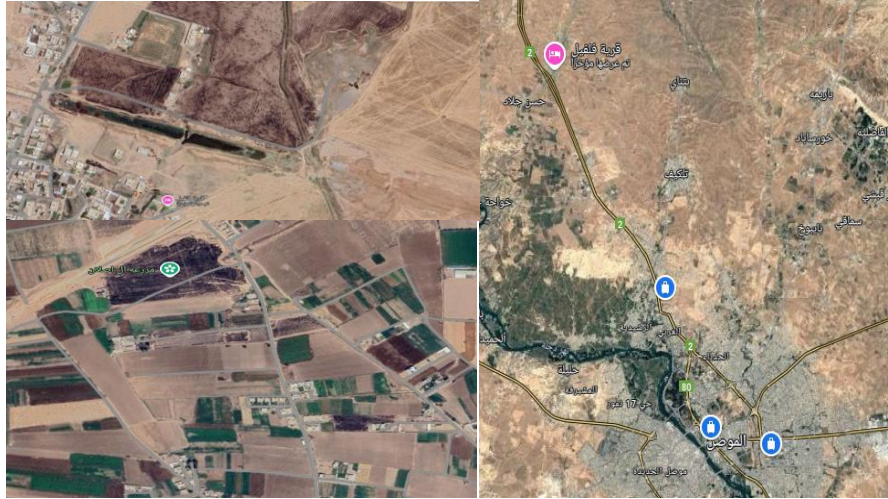


Figure 1. Geographical locations of the two study sites (Source: Google Maps).

Soil Sampling and Preparation

Materials and Methods

Surface soil samples were collected from a depth of 0–30 cm on November 10, 2025. Samples from each site were thoroughly mixed separately to obtain a composite representative sample for the field soil. The samples were then air-dried, crushed, and passed through a 4 mm sieve for use in pot experiments. Each pot (experimental unit) was filled with 8 kg of air-dried soil. For physical and chemical characterization, a sub-sample from each site was ground and passed through a 2 mm sieve, then stored in airtight plastic containers.

Soil Physical Analysis

Particle Size Distribution (Soil Texture): Soil texture was determined using the hydrometer method. A known weight of soil was treated with calgon (sodium hexametaphosphate). Readings were taken at 40 seconds and 2 hours, adjusted for temperature as described by Gee and Bauder (1986). The texture class was identified using the USDA Soil Texture Triangle.

Field Capacity (Moisture Content): Moisture content was determined gravimetrically. Samples were saturated with water and placed in funnels with filter paper for 24 hours. The remaining moisture content was measured after oven-drying the samples at 105°C for 24 hours, following Klute (1986) and USDA (2006).

Bulk Density: Bulk density was measured in situ using the core sampler method as outlined by Black (1965).

Soil Chemical Analysis

1. *Soil pH:* Determined in a 1:1 (soil:water) extract using a digital pH meter according to Rowell (1996).
2. *Electrical Conductivity (EC):* Measured in a 1:1 soil extract at 25°C using an EC-meter as described by Rowell (1996).
3. *Calcium Carbonate (CaCO_3):* Determined chemically by adding excess 1.0 N HCl to the soil and back-titrating the unreacted acid with 1.0 N NaOH in the presence of phenolphthalein indicator (FAO, 1973).
4. *Organic Matter (O.M.):* Determined by the Walkley-Black wet oxidation method. Organic carbon was oxidized using concentrated H_2SO_4 (95%) and 1.0 M potassium dichromate $\text{K}_2\text{Cr}_2\text{O}_7$ then titrated against 0.5 N ferrous ammonium sulfate using diphenylamine as an indicator.
5. *Cation Exchange Capacity (CEC):* Determined by saturating the soil with 1.0 N sodium acetate (1N) pH=8.2 to replace exchangeable cations with sodium. Sodium was then extracted using 1.0 N ammonium acetate and measured using a flame photometer.
6. *Available Nitrogen (N):* Extracted using 2.0 N KCl (1:20 ratio). Nitrogen in the filtrate was determined via the Micro-Kjeldahl distillation method, with ammonia captured in boric acid containing a mixed indicator (Black, 1965).

7. *Available Phosphorus (P)*: Determined using the Modified Olsen Method (1982). Phosphorus was extracted with 0.5 M NaHCO₃ (pH 8.5) at a 1:20 ratio and measured colorimetrically using a spectrophotometer at a wavelength of 882 nm.
8. *Available Potassium (K)*: Extracted with 1.0 N neutral ammonium acetate (pH 7.0) at a 1:10 ratio and measured using a flame photometer.
9. *Available Iron (Fe, mg/kg)*: Extracted using a DTPA solution (1:2 ratio). 10 g of soil was shaken with 20 ml of DTPA (pH = 7.3) for two hours. The iron concentration was measured using an Atomic Absorption Spectrophotometer.

Seeds Used in the Experiment

Broad bean (*Vicia faba* L.) seeds of the Mornache cultivar were used. This variety is produced by the Moroccan company Agrossem. The germination rate was tested and confirmed at 90%.

Biological Experiment

Experimental Design

To accurately determine plant response to applied fertilizers, a factorial experiment was conducted following a Completely Randomized Design (C.R.D.). The study took place in the greenhouse of the Department of Soil Sciences and Water Resources, College of Agriculture and Forestry, University of Mosul, during the 2024–2025 growing season. The experiment investigated three factors with three replicates:

Factor 1: Two Soil Locations (Varying in Texture, Calcium Carbonate, and Iron Content)

- S1: Filfil region, Nineveh Governorate.
- S2: Al-Rashidiya region, Nineveh Governorate.

Factor 2: Mineral Iron Fertilizer

Using ferrous sulfate (FeSO₄·7H₂O) containing 19% Fe, applied based on fertilizer recommendations:

- M1: Control (No application).
- M2: Soil application (15 kg Fe ha⁻¹).
- M3: Foliar application (100 mlg Fe L⁻¹).

Factor 3: Nano-Iron Fertilizer

An Iranian-origin nano-fertilizer (manufactured by Al-Khadra Company) containing 6% Fe, applied as follows:

- N1: Control (No application).
- N2: Soil application (4 kg Fe ha⁻¹).
- N3: Foliar application (1.5 mlg L⁻¹).

Total Experimental Units

The experiment comprised 54 units (2 Soil Locations × 3 Mineral Levels × 3 Nano Levels × 3 Replicates). Each location included 27 experimental units.

Studied Traits

I. Vegetative Growth Traits

1. *Plant Height (cm)*: Measured from the soil surface to the plant apex using a metallic measuring tape.
2. *Number of Branches (branch plant⁻¹)*: Total count of primary branches per plant.
3. *Chlorophyll Content (SPAD)*: Measured using a portable hand-held Chlorophyll Meter (Model SPAD-502, Minolta, Japan) following the methods of Sotiropoulos and Mouhtaridou (2005) and Cerovic et al. (2012).
4. *Leaf Area (cm²)*: Calculated for a single leaf by measuring the length and maximum width using a ruler, then applying the equation by Wali (2018):

$$LA = 0.04 + 0.45(L \times W)$$

Where:

- *LA*: Leaf Area.
- *L*: Leaf Length.
- *W*: Leaf Width.

II. Maturity and Yield Traits

5. *Shoot Dry Weight (g plant⁻¹)*: Plants were placed in perforated paper bags and dried in an electric oven at 60–65°C for 48–72 hours until a constant weight was achieved (Al-Sahaf, 1989).
6. *Biological Yield (g plant⁻¹)*: Calculated as the total weight of pods plus the total weight of the vegetative shoot system.
7. *Seed Fresh Weight (g plant⁻¹)*: Measured immediately after harvesting seeds from the pods.
8. *Seed Dry Weight (g plant⁻¹)*: Seeds were extracted from pods and dried in an oven at 60–65°C for 48–72 hours until weight stabilization (Al-Sahaf, 1989).

Results and Discussion

Plant Height (cm)

Table (1) illustrates the impact of nano and mineral iron fertilization, soil texture, and application methods on plant height (cm). The data indicates that both nano and mineral iron fertilization—applied via soil and foliar methodshad a statistically significant effect on plant height.Nano-Fertilization EffectsRegarding nano-iron treatments, the highest plant height was recorded under the N3 treatment (foliar application), reaching 100.17 cm. This treatment significantly outperformed the control, achieving a growth increase of 7.58%. In contrast, the soil application of nano-fertilizer (N2) resulted in a more modest increase of 2.80% compared to the non-fertilized control.Mineral Fertilization Effects For mineral iron fertilization, the foliar application (M₃) yielded the most substantial results, with a significant increase of 19.31%. Soil application of mineral iron (M₂) followed with an increase of 9.09%. Environmental and Interaction Factors A significant difference was observed between the two study locations: Al-Rashidiya (S₂) and Filfil (S₁). Site S₂ exhibited superior growth, surpassing S₁ by 1.08%. The triple interaction—encompassing application method, fertilizer type (nano vs. mineral), and soil texture—showed that the highest overall plant height was recorded at site S₂ under the M₃N₃S₂ treatment, reaching 113 cm (a 34.52% increase over the control).

Table 1. Effect of nano-iron and mineral iron fertilization and soil texture on plant height (cm).

Effect S	Effect M	N3	N2	N1		
95.82	88.00	92.33	89.67	87.00	M1	S1
		97.67	96.00	94.00	M2	
		109.00	98.67	98.00	M3	
96.85	105.00	89.00	86.00	84.00	M1	S2
		100.00	96.67	91.67	M2	
		113.00	107.33	104.00	M3	
LSD N= 0.6629	M= 0.6629	100.17	95.72	93.11	Effect N	
S= 0.5412	MNS= 1.6237					

At site S₁, the peak height was 109 cm under the M₃N₃S₁ treatment, representing a significant increase of 25.28% compared to the control.Scientific DiscussionThe positive response of the plants to both soil and foliar fertilization, as evidenced by increased plant height, can likely be attributed to the enhanced bioavailability of iron (Fe) in the soil and its efficient uptake by the root system. This availability stimulates vital biological processes and metabolic activities, which are directly reflected in improved growth parameters, specifically plant height (Al-Ansi & Al-Maghrabi, 2025).

Number of Branches (branch plant⁻¹)

Table (2) illustrates the impact of nano and mineral iron fertilization, along with soil texture, on the number of branches (branch plant⁻¹). The data reveals that both nano and mineral iron fertilization, via soil and foliar applications, significantly influenced plant growth parameters. Effects of Nano-Iron Fertilization Regarding nano-fertilization, foliar application (N₃) resulted in the highest number of branches, reaching 9 branches plant⁻¹. This represents a statistically significant increase of 40% over control. Meanwhile, soil application (N₂) achieved a 20% increase compared to the non-fertilized treatment. Effects of Mineral Iron Fertilization Mineral iron fertilization showed even more pronounced effects. The foliar application (M₃) recorded a substantial significant increase of 166%, while the soil application (M₂) resulted in a 100% increase. Site Variations and Interactions Statistical analysis showed a significant difference between the two study sites, with the first site (S1) outperforming the second by 6.66%. Regarding the triple interaction (application method × fertilizer type × soil texture): In the first site (S1), the M3N3S1 treatment yielded the highest number of tillers, with a 200% increase compared to the control. In the second site (S2), the M3N3S2 treatment achieved the maximum response, with a significant increase of 350% over the non-fertilized treatment. Scientific Discussion The increase in the number of branches and tillers can be attributed to the development of a dense root system resulting from soil fertilization. This robust root architecture enables the plant to absorb higher quantities of water and essential nutrients, thereby enhancing overall vegetative growth. Furthermore, the effectiveness of foliar nano-fertilization is due to the unique properties of nanoparticles, specifically their small particle size. This allows for efficient penetration of the leaf surface and rapid integration into the plant's internal tissues, where they participate in vital biological processes that stimulate branching. These findings are consistent with the results reported by Rabih et al. (2023).

Table 2. Effect of nano and mineral iron fertilization and soil texture on the number of branches (branch plant⁻¹).

Effect S		Effect M		N3	N2	N1		
6.4	3			6	4	3	M1	S1
				8	7	5	M2	
				9	8	8	M3	
6	8			5	3	2	M1	S2
				7	6	6	M2	
				9	8.	8	M3	
LSD	M= 0.6707	N= 0.6707	S=	7	6	5	Effect	
0.5477	MNS=1.643						N	

Chlorophyll Concentration (SPAD)

Table (3) illustrates the impact of nano and mineral iron fertilization, alongside soil texture, on chlorophyll concentration (SPAD). The results indicated that both fertilization types, applied via soil and foliar methods, significantly influenced chlorophyll levels. Nano-Iron Fertilization Effects Regarding nano-fertilization, the foliar application (N₃) yielded the highest chlorophyll concentration, reaching 52.221 SPAD, which represents a significant increase of 17.48% over the control. In comparison, the soil application (N₂) showed an increase of 8.11% relative to non-fertilized treatment. Mineral Iron Fertilization Effects Mineral iron fertilization also showed substantial improvements. The foliar application (M₃) achieved a significant increase of 61.75%, while the soil application resulted in a 33.33% increase. A significant geographical variation was observed, as the second site (S2) outperformed the first by 1.08%. Interaction Effects. The triple interaction (application method × fertilizer type × soil texture) revealed that: At the second site (S2), the M3N3S2 treatment achieved the peak chlorophyll concentration of 64 SPAD, a 95.89% increase over the control. At the first site (S1), the M3N3S1 treatment reached 63.33 SPAD, representing a significant increase of 82.66% compared to the control.

Table 3. Effect of nano and mineral iron fertilization and soil texture on chlorophyll concentration (SPAD).

Effect S	Effect M	N3	N2	N1			
47.1852	36.6	39	37	34.67	M1	S1	
		50	47.67	43	M2		
		63.33	57	53	M3		
49.2963	59.2	40.67	35.67	32.67	M1	S2	
		56.33	50.67	45.67	M2		
		64	60.33	57.67	M3		
LSD	M= 0.8996	N= 0.8996	S=	52.221	48.056	44.45	Effect
	0.7345	MNS=2.2036					N

Scientific Discussion The increase in chlorophyll concentration across fertilized treatments (both nano and mineral, soil and foliar) can be attributed to the enhanced activity of enzymes responsible for chlorophyll biosynthesis as a result of increased internal iron (Fe) concentrations. Iron plays a critical role in the photoperiod of the photosynthetic process, acting as a structural component of various enzymes and co-enzymes. These findings are consistent with the results reported by Abdul-Jabbar (2017).

Leaf Area (cm²)

Table (4) presents the impact of nano and mineral iron fertilization, along with soil texture, on leaf area (cm²). The results indicate that both nano and mineral iron treatments, applied through soil and foliar methods, significantly influenced the leaf area. Effects of Nano-Iron Fertilization Regarding nano-fertilization, the foliar application (N3) recorded the highest leaf area at 10.5488 cm², representing a significant increase of 21.46% over the control. Meanwhile, the soil application (N2) achieved a 9.53% increase compared to the non-fertilized treatment. Effects of Mineral Iron Fertilization Mineral iron fertilization also showed substantial improvements. The foliar application (M3) achieved a significant increase of 79.02%, while the soil application resulted in a 38.12% increase. Additionally, a significant difference was observed between the two sites, with the second site (S2) outperforming the first site (S1) by a margin of 9.57%. Interaction Effects The triple interaction (application method × fertilizer type × soil texture) revealed that: In the second site (S2), the highest leaf area reached 14.2045 cm² under the M3N3S2 treatment, with a remarkable increase of 147.9% compared to the control. In the first site (S1), the maximum value was 12.0700 cm² under the M3N3S1 treatment, showing a significant increase of 84.65% over the non-fertilized treatment. Scientific Discussion The enhancement in leaf area following the application of nano and mineral fertilizers (via both soil and foliar routes) can be attributed to the high efficiency and rapid penetration of nanoparticles into plant tissues. This rapid integration into vital biological processes subsequently improves overall plant growth and expands the photosynthetic surface area. These findings are in alignment with the results reported by Rafiq and Al-Jubour (2020).

Table 4. Effect of nano and mineral iron fertilization and soil texture on leaf area (cm²).

Effect S	Effect M	N3	N2	N1		
9.14417	6.8910	7.7185	7.0540	6.5365	M1	S1
		10.1845	8.8420	7.9915	M2	
		12.0700	11.2615	10.6390	M3	
10.01967	12.3368	7.8025	6.5065	5.7280	M1	S2
		11.3125	9.9775	8.8000	M2	
		14.2045	13.4335	12.4120	M3	
LSD N= 0.2327	M= 0.2327	S= 0.19			Effect	
	MNS= 0.5701	10.5488	9.5125	8.6845	N	

Shoot Dry Weight (g plant⁻¹)

Table (5) presents the impact of nano and mineral iron fertilization, along with soil texture, on the shoot dry weight (g plant⁻¹). The data indicates that both fertilization types, applied via soil and foliar methods, significantly influenced the dry matter accumulation of the shoots. Effects of Nano-Iron Fertilization For the nano-iron treatments, the foliar application (N3) yielded the highest value of 22.83 g plant⁻¹, representing a statistically significant increase of 17.49% over the control. Meanwhile, the soil application (N2) resulted in a 9.41% increase compared to the non-fertilized treatment. Effects of Mineral Iron Fertilization Mineral iron fertilization also showed substantial improvements. The foliar application (M3) achieved a significant increase of 48.53%, while the soil application resulted in a 25.5% increase. A significant difference was observed between the study locations, with the first site (S1) outperforming the second site (S2) by 9.12%. Interaction Effects Regarding the triple interaction (application method × fertilizer type × soil texture): In the first site (S1), the highest shoot dry weight was recorded under the M3N3S1 treatment, with an increase of 86.30% compared to the control. In the second site (S2), the M3N3S2 treatment showed a significant increase of 71.02% over the non-fertilized treatment. Scientific Discussion The increase in shoot dry weight in the fertilized treatments can be attributed to the enhanced uptake of iron (Fe) following soil application, as well as the high efficiency of both nano and mineral fertilizers in translocating across plant cell membranes. This leads to stimulated vegetative growth due to the vital role of these elements in cell division, photosynthesis, and the enhancement of enzymatic activity and biochemical reactions. Furthermore, nanoparticles play a protective role by reducing the formation and activity of reactive oxygen species (ROS) and preventing oxidative stress, which delays senescence and

promotes sustained vegetative growth. These findings are in agreement with (Mohammed, 2022), who highlighted the role of nano and mineral fertilizers in increasing the dry matter of plant shoots.

Table 5. Effect of nano and mineral iron fertilization and soil texture on shoot dry weight (g plant⁻¹).

Effect S	Effect M	N3	N2	N1		
		19.30	16.80	14.60	M1	S1
22.073		24.10	23.23	22.30	M2	
	16.983	27.20	26.23	24.90	M3	
	21.316	18.83	16.70	15.67	M1	S2
20.277	25.226	20.77	19.67	17.83	M2	
		26.80	24.93	21.30	M3	
LSD	N= 0.289 M= 0.289 S= 0.2359	22.83	21.26	19.43	Effect	
	MNS= 0.7078				N	

Seed Fresh Weight (g plant⁻¹)

Table (6) presents the impact of nano and mineral iron fertilization, along with soil texture, on the seed fresh weight (g plant⁻¹). The results demonstrate that both nano and mineral iron fertilization—via soil and foliar applications—significantly influenced the seed fresh weight. Effects of Nano-Iron Fertilization Regarding nano-fertilization, the foliar application (N3) yielded the highest value of 81.92 g plant⁻¹, representing a statistically significant increase of 52.63% over the control. Meanwhile, the soil application (N2) achieved a 36.63% increase compared to the non-fertilized treatment. Effects of Mineral Iron Fertilization Mineral iron fertilization also showed substantial improvements. The foliar application (M3) recorded a significant increase of 50.34%, while the soil application resulted in a 23.26% increase. A significant difference was observed between locations, with the second site (S2) outperforming the first site (S1) by 3.39%. Interaction Effects The triple interaction (application method × fertilizer type × soil texture) revealed that: At the second site (S2), the maximum total seed fresh weight was recorded under the M3N3S2 treatment, with an increase of 104.3% compared to the control. At the first site (S1), the M3N3S1 treatment showed a significant increase of 76.63% over the non-fertilized treatment. Scientific Discussion The enhancement in seed fresh weight is attributed to the fact that nano and mineral fertilizers improve the utilization of Photosynthetically Active Radiation (PAR). This enhances the availability of photosynthetates required for the initiation and development of tiller primordia. This, in turn, positively reflects on the total seed fresh weight per cultivated area due to the increased bioavailability of iron (Fe) concentrations. These results align with the findings of Al-Saidan (2019). Furthermore, the absorption of nutrients through the stomata during foliar application led to accelerated plant growth and development, as noted by Sajadinia et al. (2021).

Table 6. Effect of nano and mineral iron fertilization and soil texture on seed fresh weight (g plant⁻¹).

Effect S	Effect M	N3	N2	N1		
		65.96	61.66	55.67	M1	S1
72.55		76.96	70.70	66.33	M2	
	59.45	98.33	84.53	72.83	M3	
	72.51	61.66	58.10	53.67	M1	S2
75.01	89.38	78.97	74.46	67.67	M2	
		109.67	90.53	80.40	M3	
LSD	N= 0.6119 M= 0.6119 S= 0.4996	81.92	73.33	66.10	Effect	
	MNS= 1.4988				N	

Seed Dry Weight (g plant⁻¹)

Table (7) illustrates the impact of nano and mineral iron fertilization, along with soil texture, on seed dry weight (g plant⁻¹). The data indicates that both fertilization types, applied via soil and foliar methods, significantly influenced the dry matter accumulation in seeds. Effects of Nano-Iron Fertilization Regarding nano-fertilization, the foliar application (N3) recorded the highest value of 23.32 g plant⁻¹, representing a statistically significant increase of 21.9% over the control. In contrast, the soil application (N2) achieved an increase of 8.89% compared to the non-fertilized treatment. Effects of Mineral Iron Fertilization Mineral iron fertilization also showed substantial improvements. The foliar application (M3) achieved a significant increase of 61.92%, while the soil application resulted in a 16.89% increase. A significant difference was observed between the study locations, with Site S2 outperforming Site S1 by a margin of 3.91%. Interaction Effects The triple interaction

(application method $\times$ fertilizer type $\times$ soil texture) revealed that: At Site S2, the highest seed dry weight was recorded under the M3N3S2 treatment, with a 97.89% increase over the control. At Site S1, the M3N3S1 treatment reached its peak with a significant increase of 90.39% compared to the non-fertilized treatment. Scientific Discussion The enhancement in seed dry weight is attributed to the role of nano and mineral fertilizers in improving the utilization of Photosynthetically Active Radiation (PAR). This facilitates the availability of essential compounds that support the initiation of tiller primordia, which positively reflects on the total seed dry weight per unit area due to the increased bioavailability of iron (Fe). These findings are consistent with the results reported by Al-Jubouri et al. (2017, 2019). Furthermore, the efficient nutrient uptake through the stomata during foliar application led to enhanced plant growth and developmental stages, as noted by Sajadinia et al. (2021).

Table 7. Effect of nano and mineral iron fertilization and soil texture on seed dry weight (g plant⁻¹).

Effect S	Effect M	N3	N2	N1		
20.69	16.81	18.53	15.73	14.67	M1	S1
		22.43	20.33	17.53	M2	
		27.93	25.30	23.80	M3	
21.50	26.83	19.66	16.60	15.67	M1	S2
		20.33	19.50	17.80	M2	
		31.01	27.60	25.33	M3	
LSD	N= 0.2114 M= 0.2114 S= 0.1726	23.32	20.83	19.13	Effect	
	MNS= 0.5178				N	

Biological Yield (g plant⁻¹)

Table (8) presents the impact of nano and mineral iron fertilization, along with soil texture, on the biological yield (g plant⁻¹). The results indicate that both types of fertilization—applied via soil and foliar methods—had a significant effect on the total biological yield. Effects of Nano-Iron Fertilization Regarding nano-fertilization, the foliar application (N3) recorded the highest value of 45.60 g plant⁻¹, representing a statistically significant increase of 24.62% over the control. In contrast, the soil application (N2) achieved a 14.18% increase compared to the non-fertilized treatment. Effects of Mineral Iron Fertilization For mineral iron treatments, the foliar application (M3) achieved a significant increase of 45.68%, while the soil application resulted in an 18.51% increase. A significant difference was also observed between the study locations (Filfil & Al-Rashidiya), with Site S2 outperforming Site S1 by 1.19%. Interaction Effects The triple interaction (application method $\times$ fertilizer type $\times$ soil texture) revealed that: At Site S2, the M3N3S2 treatment achieved the highest total seed fresh weight, with an increase of 73.51% compared to the control. At Site S1, the M3N3S1 treatment yielded the most significant response, showing an increase of 85.37% over the non-fertilized treatment. Scientific Discussion The enhancement in biological yield is attributed to the role of nano and mineral fertilizers in optimizing the utilization of Photosynthetically Active Radiation (PAR). This improvement increases the availability of essential compounds that support the development of tiller primordia, leading to a higher total seed dry weight within the cultivated area due to the increased bioavailability of iron (Fe). These findings are consistent with (Al-Jubouri et al., 2019). Furthermore, the absorption of nutrients through the stomata during foliar application led to accelerated plant growth and overall development, as noted by Al-Hayali et al. (2018).

Table 8. Effect of nano and mineral iron fertilization and soil texture on biological yield (g plant⁻¹).

Effect S	Effect M	N3	N2	N1		
41.13	34.04	37.96	31.23	28.23	M1	S1
		44.67	40.86	35.26	M2	
		52.33	50.63	47.96	M3	
41.62	49.59	40.33	36.33	30.16	M1	S2
		46.00	42.00	33.26	M2	
		52.33	49.67	44.67	M3	
LSD	N= 0.3709 M= 0.3709 S= 0.3028	45.60	41.78	36.59	Effect	
	MNS= 0.9084				N	

Conclusion

This study concludes that the application of nanotechnology in iron fertilization, whether via foliar spray or soil addition, led to a significant advancement in all morphological and yield parameters of the wheat plant. The

(M3N3) treatment demonstrated exceptional efficiency in maximizing biological yield and seed weight. This success is attributed to the ability of nanoparticles to rapidly penetrate through stomata and cell membranes, subsequently activating enzymes responsible for chlorophyll biosynthesis and photosynthesis. Furthermore, the results indicated that the interaction between fertilizer type and soil texture at the Al-Rashidiya site (S2) effectively enhanced nutrient uptake efficiency. This synergy promoted the initiation of tiller primordia and mitigated oxidative stress within plant tissues, ultimately The study demonstrates that iron fertilization (both nano and mineral) significantly improved all growth and yield parameters of the wheat plant. The conclusions are summarized as follows:

1. *Superiority of Nanotechnology:* Nano-fertilizers exhibited high efficiency, particularly via foliar application (N3), in enhancing plant height, leaf area, and chlorophyll concentration. This reflects the superior penetration ability of nanoparticles into plant tissues.
2. *Enhanced Photosynthetic Efficiency:* Improved iron uptake increased the utilization of Photosynthetically Active Radiation (PAR), which supported tiller primordia initiation and subsequently increased dry weight, shoot biomass, and biological yield.
3. *Triple Interaction Effects:* The interaction between foliar application, nano/mineral fertilizers, and soil texture at the Al-Rashidiya site (S2) yielded the highest biological yield and seed fresh weight, indicating the role of soil properties in maximizing fertilization efficiency.
4. *Protective Role:* Nano-iron contributed to reducing oxidative stress (ROS) and delaying senescence, thereby maintaining vegetative vigor for a longer duration.

Recommendations

1. *Adopting Foliar Application:* It is recommended to utilize foliar spray techniques for nano and mineral fertilizers as an alternative or supplement to soil application to ensure rapid absorption and avoid iron fixation in the soil.
2. *Integrated Fertilization:* Implementing the (M3N3) combination is advised to achieve maximum biological yield and seed weight, especially in soils with textures similar to the Al-Rashidiya site.
3. *Economic Studies:* Conducting an economic feasibility study to compare the cost of nano-fertilizers against the qualitative increase in yield to encourage farmers to adopt these technologies.
4. *Expanding Research:* Further investigation is suggested regarding the impact of various nano-iron concentrations on grain quality (protein and starch content) across different growing seasons.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Conflict of Interest

* The author declares that there is no conflict of interest

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