Research Article

Impact of Integrating Nano-, Mineral, and Bio-Fertilization on Some Yield Characteristics of Faba Bean (*Vicia faba* L.)

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Abstract | Faba bean (*Vicia faba* L.) is an important leguminous crop, serving as a major staple food and as animal feed. Optimum use of the fertilizer inputs can significantly enhance the production of faba beans in Iraq. This field experiment was carried out to assess the effect of three fertilizer regimes on the growth and yield characteristics of the faba bean (Tornado variety). Treatments included major mineral fertilization (@ 0, 45, and 90% of the fertilizer recommendation), biofertilization with effective microorganism (EM1) technology (@ 0, 40, and 80 L h^{-1}), and foliar application of nano-cobalt powder (@ 0, 10, and 20 mg L^{-1}). Results showed that the application of 45% of the recommended mineral fertilizer exhibited the highest average of number of pods $plant^{-1}$, number of seeds pod^{-1}, weight of 100 fresh seeds, and plant yield of fresh seeds (*i.e.,* 21.5 pods $plant^{-1}$, 4.6 seeds pod^{-1}, 189.8 g, and 193.7 g $plant^{-1}$, respectively). Moreover, the interaction of all three study factors, including mineral fertilization @ 45% of the basic recommendation, EM1 biofertilization @ 20 L ha^{-1}, and spraying nano-cobalt @ 20 mg L^{-1}, exhibited a significant and maximum increase in all plant yield characteristics of faba beans as compared to other treatments. Overall study findings advocate the integrated administration of mineral, bio-, and nano-fertilizers and the foliar application strategy to enhance the faba bean yield characteristics, and this approach of cutting down the use of chemical fertilizers and incorporating EM based biofertilizers would exert long-term and sustainable impacts on soil health, crop productivity, and the environment.

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Introduction

The world population is increasing exponentially, with a simultaneous increase in the demand for food, particularly in developing countries. This situation requires fundamental changes in global food production systems using modern technologies, including nanotechnology, in agriculture to achieve food security (Valdes, 2019). Nanotechnology exhibits a promising potential to promote sustainable agriculture, as nanomaterials can enhance crop productivity through soil amelioration, improving crop nutrition and pest protection (An *et al*., 2022). Therefore, research on nanotechnology implications in agriculture has received considerable attention in recent years (Kah *et al*., 2019; Shukla *et al*., 2024).

Nanotechnology is being employed to fertilize crops more efficiently than traditional strategies (Seleiman *et al*., 2020). Moreover, foliar applications of fertilizers are considered an appropriate and more effective way of nutrient administration to plants than the conventional techniques of broadcasting and soil drenching (Niu *et al*., 2021; Ram *et al*., 2024). Quick nutrification of plants is vital for various physiological and biochemical processes that affect growth and development and increase the crop yield (Al-Kkarawi *et al*., 2024).

Soils of most of the agro-ecological zones of Iraq exhibit considerable deficiency in essential micronutrients (Sheikh-Abdullah, 2019; Madhupriyaa *et al*., 2024). These micronutrients, such as cobalt, are vital elements for the metabolic needs of crop plants. Cobalt plays crucial roles in plants, functioning as a structural component, an enzyme activator, and is essential for optimum plant growth (Hu *et al*., 2021). Some research work has demonstrated that plants treated with cobalt show a 24% increase in crop yield as compared to the untreated plants (Gad *et al*., 2011; Elsonbaty, 2024). Moreover, cobalt supplementation in crops reduces water consumption as it shuts the stomata, lowering the evapotranspiration loss from plants, and this allows the plants to survive under water stress conditions (Gad, 2012; Talukder and Sharma, 2016; Benavides-Mendoza *et al*., 2024).

Similarly, the use of biofertilizers such as Effective Microorganisms (EM) technology in agriculture also encourages beneficial microorganisms to establish a symbiotic relationship with the plants and to enhance the plant growth by increasing nutrients supply, as they increase growth and yield and help to reduce the use of mineral fertilizers by up to 50% (Javaid and Bajwa, 2011; de Araujo-Avila *et al*., 2021). Moreover, biofertilizers also help to preserve the environment and increase the plant's ability to absorb nutrients and water from the soil profile (Reddy *et al*., 2020). Biofertilizers are indeed preparations that contain one or several types of different microorganisms that are added to the soil to increase the readiness of nutrients for the plants and improve growth and development, and regulate the plant physiology, as well as lead to soil fertilization. These biofertilizers are compatible with long-term sustainable agriculture, are usually environment-friendly, and can replace or mitigate chemical fertilizers (Singh *et al*., 2016; Bhunia *et al*., 2021; Gündüz, 2023).

Faba bean (*Vicia faba* L.) is a vital leguminous crop that belongs to the family Fabaceae, and is a vital staple food for millions of people in developing countries because it contains a high protein content of 23 to 42%, and is also being used as animal feed (Dhull *et al*., 2022). It is also used as a cover crop. It also increases the soil fertility by fixing atmospheric nitrogen and, hence, mitigating soil erosion (Sathya *et al*., 2018; Mínguez and Rubiales, 2021). This research work was aimed at evaluating the effect of integrating various combinations of routine mineral fertilizers, biofertilizer (EM1) formulation, and foliar application of nano-cobalt formulation on some yield characteristics of faba bean (*V. faba* L.). The objective was to see if the integration of bio- and nano-fertilization can lessen the need for mineral fertilizers in faba bean cultivation, focusing on optimal fertilizer combinations and their impact on growth and yield.

Materials and Methods

Experimental site and seedbed preparation

This field trial was carried out in a field (32°47′58.77 N; 44°24′5.94 E) during the spring 2023-2024 season in one of the farmers' fields in the Babylon Governorate, Musayyib Project, Iraq. Fava bean (*Vicia faba* L.) (Tornado variety of Cyprus origin) was used in this field trial. The soil was prepared by clearing it from previous crop remnants and was plowed with a flip-flop plow perpendicular plow and smoothed with disc harrows. Then, after leveling the soil, the field was divided into different experimental units. A buffer zone of 1.0 m was maintained between the experimental units. The seeds of faba beans were sown in the field, and after three weeks of planting, the seedlings were thinned to a single plant.

Determination of soil physico-chemical properties

For the determination of some chemical and physical characteristics of soil (as detailed in Table 1), random samples of soil were taken from different locations of the field to a depth of 30 cm, air-dried, ground, and crushed well using a hammer, and then this crushed soil samples were sieved using a 2 mm mesh-size sieve. Then, these soil samples were pooled together and homogenized to get a composite sample. Using previously described protocols (Black *et al*., 1965; Chapman, 1965; Page *et al*., 1982), the soil chemical analyses were carried out in the Soil and Water Department of the Technical College Al-Mussaib, located in the Babylon Government of Iraq.

Table 1: *Physico-chemical properties of the soil under trial determined at the time of seedbed preparation.*

Soil parameters	Values	Units
EC (1:1)	2.1	DS m^{-1}
pH (1:1)	7.5	
CEC	18.36	cmol/kg
Organic matter	7.3	g kg^{-1} soil
Carbonate	237.5	g kg^{-1} soil
Gypsum	3.1	g kg^{-1} soil
Available N (NH_4^++NO_3^-)	32.0	mg kg^{-1} soil
Available P	9.0	
Available K	122.0	
Cobalt (Co)	0.51	
Sand	32	g kg^{-1} soil
Silt	32	
Clay	36	
Soil texture	Sandy loamy	

Experimental protocol

The experimental design was Randomized Complete Block (RCBD), and each treatment was replicated thrice. There were three main factors with three replications, and each replicate consisted of 27 randomly tagged treatments. There were a total of 81 experimental units in the study.

Study factors

The first study factor was the foliar spray of bean plants with cobalt oxide as nano-powder in the form of Co_3O_4 (<50 nm, 99.5% purity on a trace metals basis) procured from Sigma Chemical Co. Ltd (St Louis, MO, USA). The fertilizer was applied in three concentrations, *i.e.*, 0 (spray with distilled water only), 10, and 20 mg L^{-1}, and was administered three times every 30 days. The second factor consisted of the application of a biofertilizer formulation (EM1™ Effective Microorganisms®) in three levels (0 (water only), 40, and 80 L ha^{-1}). The addition was carried out by injecting 5 ml of EM1 solution $plant^{-1}$ into the soil near the root zone. The injection was administered 20 days after seedling emergence. The third factor was the mineral fertilization that was applied at three levels (0, 45, and 90%) of the fertilizer recommendation. Nitrogen fertilizer was added in the form of urea (46% (N) @ 125 kg ha^{-1}) in two batches, *i.e.,* one week after planting, and the second batch was applied at the flowering stage. Phosphorus was added as TSP (48% P) (@ 220 kg ha^{-1}) while preparing the land for cultivation. Potassium was added @ 125 kg ha^{-1} as Sulphate of Potash (SOP) K_2SO_4 fertilizer in two batches.

Statistical analysis

Data were subjected to statistical analysis using the R program (version 4.1.2, R, Vienna, Austria). The statistical manipulation of data was conducted according to a randomized complete block design (RCBD). Multifactor factorial ANOVA was run to determine the effect of treatments (fertilizer types) and their interactions on the yield characters of faba bean (*i.e.*, average number of seeds per pod, number of pods per plant, weight of 100 fresh seeds, and fresh seed yield per plant). Moreover, the treatment means were compared using the least significant difference (LSD) post-hoc test using the standard level of significance ($P \geq 0.05$).

Results and Discussion

Effect of fertilizer treatments number of pods per plant

Analysis of data regarding the per plant number of pods presented in Table 2 shows significant differences among the three fertilizer types studied and their interaction in influencing the number of fresh pods per plant. The mineral fertilization treatment (45 % of the recommended fertilization) was superior and exhibited the highest average of pods (21.5 per $plant^{-1}$), while the control treatment (without any mineral fertilization) gave the lowest average (18.4 pods per $plant^{-1}$). As for the EM1 biofertilizer, the addition of 20 L h^{-1} was superior and gave the highest average of 22.2 pods per $plant^{-1}$, whereas the treatment without EM1 biofertilizer (control) exhibited the lowest average of 19.0 pods per $plant^{-1}$. Regarding foliar spraying with nano-cobalt, the treatment 20 mg L^{-1} showed the highest average pods (22.0 pods per $plant^{-1}$), while the control treatment (without spraying any nano-cobalt) gave the lowest average (19.0 pods per $plant^{-1}$). As for the two-way interaction between mineral fertilization and EM1 biofertilization, the treatment 45% of recommended mineral fertilization + 20 L ha^{-1} EM1 biofertilization gave significantly highest average number of pods per plant (24.1 pods per $plant^{-1}$), while the control treatment (without mineral and EM1 fertilization) exhibited the lowest average (17.7 pods per $plant^{-1}$).

Table 2: *The effect of mineral fertilization, biofertilizer, and nano-cobalt foliar spray on the number of pods per plant of faba bean.*

Mineral fertilizer (%)	Biofertilizer EM1 (L ha^{-1})	0	10	20	Mean
0	0	17.4	17.7	18.1	17.7
	10	17.6	18.2	19.7	18.5
	20	18.0	18.5	20.5	19.0
45	0	18.7	19.6	20.6	19.6
	10	19.3	21.1	22.2	20.9
	20	21.0	23.7	27.5	24.1
90	0	18.6	19.4	20.4	19.5
	10	19.2	21.0	22.0	20.7
	20	20.8	23.4	26.6	23.6
LSD 0.05		0.413			0.238
Mineral fertilizer * Nano fertilizer					**Mean**
0	17.6	18.2	19.4		18.4
45	19.7	21.5	23.4		21.5
90	19.5	21.3	23.0		21.3
LSD 0.05	0.238				0.138
Mineral fertilizer * Nano fertilizer					**Mean**
0	18.2	18.9	19.7		18.9
45	18.7	20.1	21.3		20.0
90	19.9	21.9	24.9		22.2
LSD 0.05	0.238				
Mean Nano fertilizer	**19.0**	**20.3**	**22.0**		**0.138**
LSD 0.05	0.138				

The interaction between mineral fertilization and nano-cobalt spray, the treatment 45% of recommended mineral fertilization + 20 mg L^{-1} nano-cobalt, was significant and produced the highest average number of pods (23.4 pods per $plant^{-1}$). In contrast, the control group yielded the least (17.6) pods per plant. The EM1 biofertilizer (@ 20 liters ha^{-1}) and nano-cobalt (@ 20 mg L^{-1}) treatment showed a significantly higher yield, averaging 24.9 pods $plant^{-1}$ compared to 18.2 pods/plant in the control treatment (Table 2). As for the triple interaction coefficients between the studied factors, the treatment (mineral fertilization at 45% of the recommendation + EM1 biofertilization @ 20 L ha^{-1} + spraying nano-cobalt @ 20 mg L^{-1}) was significantly superior and gave the highest average regarding the average number of pods per plant, reaching 27.5 pods per $plant^{-1}$. Control treatment without any type of fertilization exhibited the lowest average of pods (17.4 pods $plant^{-1}$).

Effect of fertilization treatments on the average number of fresh seeds per pod

Significant differences were found between the levels of the studied factors and their interaction regarding their impact on the trait of the number of fresh seeds per bean pod (Table 3). The mineral fertilization treatment (@ 45 fertilizer recommendation) was superior and gave the highest average of 4.6 seeds pod^{-1}, while the control treatment exhibited the lowest average for this trait (4.1 seeds pod^{-1}). The EM1 treatment (@ 20 L h^{-1}) gave the highest average of 4.8 seeds pod^{-1}, whereas the treatment without EM1 biofertilizer (control) gave the lowest average of 4.1 seeds pod^{-1}. As for the nano-cobalt spray factor, the treatment (@ 20 mg L^{-1}) was superior and gave the highest average value (4.8 seeds pod^{-1}), whereas the treatment without any nano-fertilizer (control) produced the lowest seeds per pot (4.1 seeds pod^{-1}).

Table 3: *The effect of mineral fertilization, biofertilizer, and nano-cobalt foliar spray on the number of seeds per pod of faba bean.*

Mineral fertiliz-er(%)	Biofertilizer EM1 (L ha^{-1})	Nano Co fertilizer (mg L^{-1}) 0	10	20	Mean
0	0	3.57	3.83	4.17	3.86
	10	3.80	4.17	4.43	4.13
	20	4.07	4.27	4.53	4.29
45	0	3.87	4.27	4.53	4.22
	10	4.17	4.63	4.83	4.54
	20	4.53	4.97	5.70	5.07
90	0	3.80	4.20	4.43	4.14
	10	4.20	4.57	4.77	4.51
	20	4.43	4.90	5.63	4.99
LSD 0.05	0.166				0.096
Mineral fertilizer * Nano fertilizer					**Mean**
0		3.81	4.09	4.38	4.09
45		4.19	4.62	5.02	4.6
90		4.14	4.56	4.94	4.55
LSD 0.05		0.096			0.055
Bio fertilizer * Nano fertilizer					**Mean**
0		3.74	4.10	4.38	4.07
45		4.06	4.46	4.68	4.40
90		4.34	4.71	5.29	4.78
LSD 0.05		0.096			0.055
Mean Nano fertilizer		**4.05**	**4.42**	**4.78**	
LSD 0.05		0.055			

The two-way interaction between mineral fertilization and EM1 biofertilization exhibited the highest average number of seeds per pod (5.1 seeds pod^{-1}). Whereas the treatment without any mineral or biofertilizer (control) exhibited the lowest per pod seeds (3.9 seeds pod^{-1}). As for the interaction between mineral fertilization and nano-cobalt supplementation, the treatment (@ 45% recommended mineral fertilization + spraying nano-cobalt @ 20 mg L^{-1}) was significantly superior and gave the highest average pods (5.0 seeds pod^{-1}), while the control treatment EM1 biofertilizer (@ 20 L h^{-1}) and nano-cobalt spraying (@ 20 mg L^{-1}), showed the highest and significant average of pods per plant (5.3 seeds pod^{-1}). Moreover, the treatments combining 45% mineral fertilizer, 20 L h^{-1} EM1 biofertilizer, and 20 mg/L nano-cobalt spray yielded the highest average seed number per pod (5.7), outperforming other triple-factor interactions. However, the control treatment had the lowest average seed yield (3.6 seeds per pod).

Influence of fertilizer types and their interactions on the weight of 100 fresh seeds

Table 4 indicates the significant differences among different levels of studied fertilizer regimes and their interaction in influencing the average weight (g) of 100 fresh seeds. The mineral fertilization @ 45% of the fertilizer recommendation showed the highest average of 100 g seeds (189.8 g), while the control treatment (without any mineral fertilization) gave the lowest average weight (179.2 g). The application of EM1 biofertilizer @ 20 L h^{-1} was superior and exhibited the highest average (195.8 g) of 100 fresh seeds, while its control treatment had the lowest average 180.4 g). Moreover, the nano-cobalt treatment (@ 20 mg L^{-1}) exhibited the highest average weight of 100 fresh seeds (192.8 g), while the average of the control treatment (with any nano-cobalt) was 180.5 g.

The two-way interaction between mineral fertilization and EM1 biofertilization, and between mineral fertilization and spraying nano-cobalt showed that the treatment (@ 45%recommended mineral fertilization + 20 L ha^{-1} EM1 biofertilizer, and 45% recommended mineral fertilization + spraying nano-cobalt @ 20 mg L^{-1} were significantly superior and gave the highest average for the weight of 100 fresh seeds *i.e.*, 202.9 and 198.3 g, respectively. Moreover, the interaction between the EM1 biofertilizer (@ 20 L ha^{-1}) and spraying nano-cobalt (@ 20 mg L^{-1} produced the highest average weight of 100 fresh seeds (211.5 g). Similarly, the triple interaction coefficients between the studied factors, the treatment (mineral fertilization @ 45% + the EM1 biofertilizer @ 20 L ha^{-1} + spraying nano-cobalt (@ 20 mg L^{-1}) were significantly superior and gave the highest average weight of 100 fresh seeds (224.2 g). The lowest average (175.4 g) was recorded for the control treatment without any type of fertilization (Table 4).

Table 4: *The effect of mineral fertilization, biofertilizer, and nano-cobalt foliar spray on the average weight (g) of 100 fresh seeds of faba bean.*

Mineral fertilizer (%)	Biofertilizer EM1 (L ha^{-1})	Nano Co fertilizer (mg L^{-1})			Mean
		0	10	**20**	
0	0	175.4	177.0	179.4	177.3
	10	176.6	178.8	180.0	178.5
	20	177.8	181.3	186.7	181.9
45	0	179.3	181.9	184.9	182.1
	10	181.7	185.8	185.7	184.4
	20	186.7	197.8	224.2	202.9
90	0	179.0	181.7	184.7	181.8
	10	181.5	185.7	185.5	184.2
	20	186.6	197.5	223.8	202.6
LSD 0.05	2.936				1.675
Mineral fertilizer * Nano fertilizer					**Mean**
0		176.6	179.0	182.0	179.2
45		182.6	188.5	198.3	189.8
90		182.3	188.3	198.0	189.5
LSD 0.05		1.675			0.979
Bio fertilizer * Nano fertilizer					**Mean**
0		177.9	180.2	183.0	180.4
45		179.9	183.5	183.7	182.4
90		183.7	192.2	211.5	195.8
LSD 0.05		1.675			0.979
Mean Nano fertilizer		180.5	185.3	192.8	
LSD 0.05		0.979			

Effect of fertilizer treatments on plant seed yield

A similar trend of significant influence of all fertilizer treatments and their interactions was recorded for the average yield of fresh seeds per plant (Table 5). The mineral fertilization @ 45% of the recommended fertilizer produced a significantly higher average of seed yield (193.7 g), whereas the treatment without EM1 biofertilizer (control) produced the lowest average for this trait (135.8 g). As for the EM1 biofertilization, the treatment (20 L ha^{-1}) exhibited the highest average seed yield (216.9 g), while its control treatment gave the lowest average (140.1 g). The treatment of nano-cobalt application (@ 20 mg L^{-1}) showed the highest average seed yield (209.6 g), while its control treatment exhibited the lowest average of 140.5 g.

The two-way interaction between mineral fertilization and EM1 biofertilization, mineral fertilization and spraying nano-cobalt and between the EM1 biofertilizer and spraying nano-cobalt showed that the treatments (@ 45%recommended mineral fertilization, EM1 biofertilizer @ 20 L ha^{-1} and nano-cobalt spray @ 20 mg L^{-1}) remained superior and produced the highest average plant seed yields *i.e.*, 254.1, 241.0 and 286.9 g, respectively, while their respective control treatments showed the lowest average values of 121.5, 118.9, 121.7 g, respectively. As for the triple interaction coefficients between the studied factors, the treatment (mineral fertilization @ 45% of the recommendation + EM1 biofertilization @ 20 L ha^{-1} + spraying nano-cobalt @ 20 mg L^{-1}) exhibited the highest value for the plant yield of fresh seeds, reaching 351.9 g, as compared to control treatment without any type of fertilization (108.6 g) (Table 5).

Table 5: *The effect of mineral fertilization, biofertilizer, and nano-cobalt foliar spray on the average seed yield (g) per plant of faba bean.*

Mineral fertilizer (%)	Biofertilizer EM1 (L ha^{-1})	Nano Co fertilizer (mg L^{-1})			Mean
		0	10	20	
0	0	108.6	120.4	135.6	121.5
	10	118.1	135.9	157.2	137.1
	20	129.9	143.3	173.5	148.9
45	0	129.7	152.4	172.4	151.5
	10	146.3	181.4	198.9	175.5
	20	178.0	232.5	351.9	254.1
90	0	126.7	148.3	167.1	147.4
	10	146.1	177.8	194.8	172.9
	20	180.5	226.7	335.3	247.5
LSD 0.05	7.526				4.345
Mineral fertilizer * Nano fertilizer					**Mean**
0		118.9	133.2	155.4	135.8
45		151.4	188.8	241.1	193.7
90		151.1	184.3	232.4	189.3
LSD 0.05		4.345			2.509
Bio fertilizer * Nano fertilizer					**Mean**
0		121.7	140.4	158.4	140.1
45		136.9	165.0	183.6	161.8
90		162.8	200.9	286.9	216.9
LSD 0.05		4.345			2.509
Mean Nano fertilizer		140.5	168.7	209.6	
LSD 0.05		2.509			

Faba bean (*V. faba*) is a major staple crop in Iraq, holding substantial nutritional and economic importance for the indigenous population. However, its production per unit area is far less than the crop's real potential and from other bean-growing countries (Alshummary *et al*., 2021; Jasim *et al*., 2023). One of the reasons behind this yield gap of faba beans in Iraq is that the country's soils are deficient in micronutrients such as cobalt. Appropriate administration of basic mineral fertilizers and essential micronutrients is very crucial towards achieving sustainable faba bean yield (Jensen *et al*., 2010). To this end, this study was designed to understand the effect of different types of fertilizers (*i.e.*, mineral, bio-, and nano-formulations) and their interactions on some important yield characteristics of faba bean plants (*i.e.*, average number of seeds per pod, number of pods per plant, weight of 100 fresh seeds, and fresh seed yield per plant).

The study showed a significant influence of all three fertilizer types and their interactions on all yield characteristics of the faba beans studied. Number of seeds per pod, number of pods per plant, weight of 100 fresh seeds and yield of fresh seeds per plant all increased with the application of mineral fertilizer, EM1 biofertilizer and foliar application of nano-cobalt powder particularly for the treatments included mineral fertilization @ 45% of the basic recommendation, EM1 biofertilization @ 20 L ha^{-1} and spraying nano-cobalt @ 20 mg L^{-1}.

The increase in the number of pods because of adding mineral fertilizers is attributed to the fact that absorption of abundant soil nutrients by the roots plays a major role in enhancing crop productivity (Abu El-Fotoh *et al*., 2008; Cucci *et al*., 2019; Esmail and Esmail, 2021; Mossa *et al*., 2024). The results of this study are consistent with Dida and Etisa (2019) and Laftta and Habib (2021), who showed that the number of faba bean pods can be significantly affected by potassium addition in the soil. Moreover, Kadhim (2022) and Thebti *et al*. (2024) demonstrated that optimum fertilization of faba beans enhances soil nitrogen, which helps the plant absorb nutrients easily and thus helps increase the seed yield components. The addition of mineral fertilizer plays a crucial role in the development of a better root system of the plant, and thus increasing the absorption of other nutrients, as well as the need for large bacterial nodules for phosphorus and potassium, which is positively reflected in the weight of 100 seeds (Alrawi *et al*., 2023). Our results corroborate the findings of Aziz and Zrar (2019), Cucci *et al*. (2019), Patra *et al*. (2021) and Liu *et al*. (2022) that increasing nitrogen and phosphorus fertilizers work to develop a better root system and photosynthetic activities in aerial parts, thus encouraging vegetative growth, increasing the number of branches on the plant, seed formation, seed filling, and weight of seeds.

Nevertheless, cobalt (Co) also increases the vegetative growth indicators by encouraging the formation of vitamin B12, which plays an important role in increasing fruit setting, reflected by the increased number of pods in the plant (Gad and El-habbak, 2024). It has a positive effect on the formation of nitrogen-fixing root-nodule bacteria in legumes, improving plant growth and speeding up the plant growth, encouraging blossoms, mitigating abiotic stress, and therefore, leading to bigger and better harvests (Noreen *et al*., 2018; Hu *et al*., 2021). Foliar applications of cobalt and other micronutrients can easily move from leaves to other plant parts and increase the crop yield and other traits of faba beans (Saleem *et al*., 2014; Talukder and Sharma, 2016; Gad *et al*., 2018; Faiyad and Abd-El-Azeiz, 2024).

In addition, faba bean pods and seed weight increased with the administration of EM1 biofertilization. These findings are in line with the results of Abd El-Ati (2017), Alwan and Alkarawi (2024), and Mossa *et al*. (2024) for faba bean with EM biofertilization in comparison to no fertilization. Compared to the full recommended chemical fertilizer treatment, half of the recommended mineral or chemical fertilizers plus EM biofertilization showed a significant increase in the yield traits of faba beans. Effective microorganisms (EM1) are a biofertilizer consisting of bacteria from three major genera of microorganisms, including lactic acid bacteria (*Lactobacillus*), phototrophic bacteria (*Rhodopseudomonas*), and yeast (*Saccharomyces*) (Ristić *et al*., 2021). These beneficial microorganisms produce many bioactive compounds, plant hormones and antioxidants, which all help with the solubilization and bioavailability to plant roots (Murugan *et al*., 2022; Ahmed *et al*., 2023).

Similarly, Kamel (2025) observed significant differences between the nano-fertilization and non-fertilization treatments in the dry weight of faba bean and mung bean, respectively. This increase in some of the above-mentioned plant traits would be because of the unique behavior and properties of nano-fertilizers. Their small size allows them to get absorbed more efficiently through the plant surfaces. Their increased surface area enables faster absorption and direct entry into plant cells rather than root-to-leaf translocation (Mala *et al*., 2017; Channab *et al*., 2024).

Conclusions and Recommendations

Based on the overall study findings, it is concluded that mineral fertilizer application @ 45% of the recommended fertilization exhibited better performance in most of the studied traits when it was supplemented with the administration of EM1 biofertilizer @ 20 L ha^{-1} and with the foliar application of nano-cobalt @ 20 mg L^{-1}. The integrated application of the mineral, bio-, and nano-fertilization led to a significant increase in the number of seeds per pod, the number of pods per plant, the weight of 100 fresh seeds, and the yield of fresh seeds.

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Novelty Statement

This research showed the integrated administration of mineral, bio- and nano-fertilizers and foliar application strategy can enhance the faba bean yield characteristics, and this approach of cutting down the use of chemical fertilizers and incorporating EM based fertilizers would exert long-term and sustainable impacts on soil health, crop productivity, and the environment.

Generative AI or AI-assisted technology statement
The author declares that no Generative AI was used in the creation of this manuscript.

Conflict of interest
The author have declared no conflict of interest.

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