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Effect of biofertilizer application and foliar sprays of nano iron and nano zinc on postharvest soil nutrient availability and growth of tomato (*Solanum lycopersicum* L.)

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Abstract

A field experiment was conducted in the Abi Gharq area, 10 km northwest of Babil Governorate, during 2023–2024, to investigate the effect of biofertilizer application and foliar sprays of nano iron and nano zinc on postharvest soil nutrient availability and the growth of tomato plants (*Solanum lycopersicum* L.). The experiment was arranged as a factorial experiment in a randomized complete block design (RCBD) with three replicates. Three factors were evaluated: biofertilizer with three levels (control, Azotobacter 10 mL, and mycorrhizal fungi 10 g), nano iron foliar spray at three concentrations (0, 10, and 20 mg L^{-1}), and nano zinc foliar spray at three concentrations (0, 10, and 20 mg L^{-1}). The results showed significant effects of biofertilizer, nano iron, nano zinc, and their interactions on postharvest soil nutrient availability and tomato growth traits. Mycorrhizal fungi produced the highest mean values for available nitrogen, phosphorus, potassium, iron, zinc, plant height, and number of fruits per plant. Nano iron and nano zinc applications was associated with higher postharvest soil nutrient availability, plant height, number of fruits per plant, and fruit weight. The three-way interaction between mycorrhizal fungi, nano iron, and nano zinc (H2F2Z2) recorded the highest values for available nitrogen (36.77 mg kg^{-1}), phosphorus (13.56 mg kg^{-1}), potassium (251.23 mg kg^{-1}), iron (6.36 mg kg^{-1}), zinc (2.79 mg kg^{-1}), plant height (139.9 cm), and number of fruits per plant (56.22 fruits $plant^{-1}$). The highest fruit weight (137.82 g) was recorded under the H0F2Z2 treatment. The study aimed to evaluate the individual and combined effects of biofertilizer application and foliar nano-iron and nano-zinc sprays on post-harvest soil nutrient availability, vegetative growth and yield attributes of tomato.

Key words: Biofertilizer, nano-zinc, nano-iron, tomato, foliar spray

Introduction

Biofertilizers promote plant growth by improving nutrient availability, establishing beneficial associations with plant roots, and stimulating rhizosphere activity. Biofertilizers can enhance plant growth and productivity through the use of fertilizers, and biofertilizers may improve nutrient-use efficiency and reduce dependence on synthetic fertilizers (Reddy *et al.,* 2020). They are used to preserve the environment as their effect is directly reflected on the plant and soil, and improves the ability of the plant to absorb nutrients and water from the soil) Hussein and Naser, 2019; Ajeel *et al.*, 2025; Aswad *et al.,* 2026).

Nano fertilizers have been reported to influence the ability of crops to survive and withstand many stresses, improve resistance to disease, preserving the genetic nature, and increasing the number of active substances in crops (Mahdy *et al.*, 2024). Nanomaterials are also used to coat traditional fertilizers to enable their absorption and make their use efficient since they can access cells. They may also facilitate targeted delivery of nutrients to certain areas, *i.e.,* leaves, roots, and fruits, and enhance the metabolic processes, as they increase the photosynthetic activity owing to the excess content of chlorophyll may be associated with improved physiological responses (Hussein *et al.*, 2025; Abd Hamidi and Arak, 2024; Vishwanatha *et al.*, 2025).

Iron is one of the main components of the Earth's crust, as it consists of 7.1 percent, after oxygen, silicon, and aluminum. It is a part of the structure of a majority of enzymes, including cytochromes of the photosynthetic pathway and the electron transport chain, and of Photosystem I, the primary iron-sulfur protein is Ferredoxin. Iron is also required in the production and repair of chlorophyll and the structure of chloroplasts. Zinc is required by plants as it is required in the production of the amino acid tryptophan, which is the precursor of the hormone IAA that promotes water uptake and cell elongation. Another role of zinc is in the formation of the enzyme, protein metabolism, ammonia conversion to amino acid, and chlorophyll (Al-Mamouri *et al.,* 2023).

Tomatoes (*Solanum lycopersicum* L.) is one of the most widely cultivated vegetable crops that is extensively cultivated on a global scale due to its economic importance, nutritional value, and simplicity in processing and storing. They are grown during the entire year with very different conditions in the tropics and in latitudes that are near the poles. Tomato fruits are very nutritious since they contain essential nutrients such as potassium, ascorbic acid (vitamin C), citric acid, malic acid, vitamin E, phenolic compounds, and carotene and lycopene pigments (Gerszberg *et al.*, 2015; Kumar *et al.,* 2021).

The study aimed to evaluate the individual and combined effects of biofertilizer application and foliar nano-iron and nano-zinc sprays on post-harvest soil nutrient availability, vegetative growth and yield attributes of tomato.

Materials and methods

A field experiment was conducted during 2023–2024 in a farmer's field at Abi Gharq, 10 km northwest of Babil Governorate to evaluate the effect of biofertilizer application and foliar spray of nano iron and nano zinc on soil nutrient availability and growth of tomato (*Solanum lycopersicum* L.). The physical and chemical properties of the experimental soil are given in Table 1. The experiment was conducted in a 3 × 3 × 3 factorial randomised complete block design with three replications. The experiment consisted of 81 experimental plots (27 treatments × 3 replications).Treatments included of three levels of biofertilizer (control, Azotobacter chroococcum 10 mL plant^{-1} and Glomus mosseae mycorrhizal fungi 10 g plant^{-1}), three levels of nano iron (0, 10 and 20 mg L^{-1}) and three levels of nano zinc (0, 10 and 20 mg L^{-1}).

The Azotobacter inoculant was prepared in a liquid nutrient broth carrier and contained 1 × 10 8 CFU mL ^{1} viable cells and was applied as a soil drench to the root zone immediately after transplanting. The mycorrhizal inoculum, mainly Glomus mosseae on a sterilised sand, vermiculite and infected-root carrier, contained about 1000 viable spores g^{-1} and was placed directly in the hole before transplanting the seedlings. The viability of both inoculants was tested before application.

The experimental plots were 3 × 2 m in size and comprised four ridges of 50 cm apart. Uniform tomato seedlings (cv. Newton F1, 35 days old) were transplanted at the rate of one plant per hole and 40 cm apart giving 30 plants per plot. Plants were irrigated uniformly using furrow irrigation at a frequency of every 4–5 days, adjusted according to weather conditions and crop requirements. Routine pest and disease management was carried out using standard crop protection protocols as needed to prevent any confounding effects on growth and yield traits. Data collection excluded the two outer ridges and end plants of the inner ridges to reduce border effects. Five central plants from the inner ridges were randomly selected and tagged for recording vegetative and yield traits and post-harvest rhizosphere soil samples were collected as composite samples from these same plants. All observations were reported as plot means.

Phosphate fertiliser was applied at 100 kg ha^{-1} at planting and urea at 200 kg ha^{-1} was applied in two equal splits, at planting and flowering (Steduto *et al.*, 2012). Nano iron and nano zinc fertilisers were supplied as Fe_2O_3 and ZnO nanoparticles, respectively, purchased from SkySpring Nanomaterials, Inc. (Houston, TX, USA). The particle size was reported to be 20–50 nm with spherical morphology and purity above 99%, according to the analytical data of the manufacturer. The required quantities were suspended in distilled water and stirred mechanically for 30 min and agitated before and during application to maintain uniform dispersion.

Table 1. Some physical and chemical properties of the experimental soil

Property	Value
Electrical conductivity degree EC dS/m	2.7
Soil reaction degree pH	7.3
Organic matter g/kg	9.6
Available nitrogen (mg kg^{-1} soil)	29
Available phosphorus (mg kg^{-1} soil)	9.7
Available potassium (mg kg^{-1} soil)	190
Available iron (mg kg^{-1} soil)	3.35
Available zinc (mg kg^{-1} soil)	0.87
Soil fractions	
Clay (g kg^{-1})	281
Sand (g kg^{-1})	130
Silt (g kg^{-1})	589
Soil texture	Clay loam soil

Nano iron and nano zinc were applied as foliar sprays at 30 and 45 DAT using a hand sprayer. Spraying was done in the early morning to reduce evaporation and improve absorption. Approximately 50 mL solution was sprayed per plant to ensure uniform coverage on the foliage.

Available soil nitrogen was determined by the alkaline permanganate method of Bremner as quoted by Black (1965). Available phosphorus was extracted with 0.5 M sodium bicarbonate, pH 8.5, and determined colorimetrically by the Olsen method (Page *et al.*, 1982). Available potassium was extracted with 1 N ammonium acetate and measured with a flame photometer. Available iron and zinc were extracted with DTPA solution and determined by atomic absorption spectrophotometry as described by Lindsay and Norvell (1978). Plant height from soil surface to the top of the main stem was recorded at full growth, number of fruits plant-1 was counted at harvest and average weight of fruit was calculated from the total weight of fruits per plant.

Statistical analysis: The collected data were subjected to analysis of variance (ANOVA) for a factorial RCBD using GenStat (12th Edition) software. When the F-test indicated significant treatment effects, the differences among treatment means were compared using Fisher's Least Significant Difference (LSD) test at a probability level of $P \leq 0.05$ (Al-Rawi and Khalaf Allah, 1980).

Results

ANOVA revealed that biofertilizer, nano iron, and nano zinc significantly affected available N, P, K, Fe, and Zn in soil, indicating strong individual effects on soil nutrient availability (Table 2). Most interaction effects, including the three-way interaction (H × F × Z), were also significant. Significant H × F, H × Z, and F × Z interactions indicated that the response of soil nutrient availability depended on the combined application of biofertilizer, nano iron, and nano zinc treatments.

Table 2. Analysis of variance (ANOVA) mean squares for available nitrogen (N), phosphorus (P), potassium (K), iron (Fe), and zinc (Zn) in soil as affected by biofertilizer, nano iron, and nano zinc applications

Source of variation	df	N	P	K	Fe	Zn
Replications	2	0.92	0.19	42.38	0.04	0.0064
Biofertilizer (H)	2	586.95**	59.82**	34543.44**	9.52**	7.74**
Nano iron (F)	2	93.55**	8.16**	2764.74**	8.79**	10.58**
Nano zinc (Z)	2	3.29**	14.18**	295.99**	2.83**	1.04**
H × F	4	12.62**	1.58**	168.03**	2.49**	0.27**
H × Z	4	1.26*	2.63**	57.66*	0.98**	0.02**
F × Z	4	1.25*	0.26*	57.65*	0.19**	0.07**
H × F × Z	8	1.04*	0.22*	47.93*	0.20**	0.04**
Error	52	0.36	0.08	16.74	0.02	0.0025
Total	80	1457.19	188.25	77680.60	59.41	40.64

N = available nitrogen, P = available phosphorus, K = available potassium, Fe = available iron, and Zn = available zinc. H = biofertilizer, F = nano iron fertilizer, and Z = nano zinc fertilizer. Values represent ANOVA mean squares. * Significant at $P < 0.05$; ** Significant at $P < 0.01$; ns = non-significant.

Available nitrogen in soil (mg N kg^{-1} soil): Table 3 shows the impact of biofertilizer and foliar spray of nano iron and nano zinc on the level of nitrogen in soil. The three-way combination H 2 F 2 Z 2 (36.77 mg kg^{-1}) showed the highest available nitrogen content, whereas the lowest level was found in combination H0F0Z0

Table 3. Effect of biofertilization and foliar application of nano iron and nano zinc fertilizers on available nitrogen in soil (mg N kg⁻¹ soil)

Biofertilizer	Nano iron fertilizer	Nano zinc fertilizer mg L⁻¹ Z0	Z1	Z2	Mean (H x F)
H0	F0	24.11 c	24.15 c	24.21 c	24.16 c
	F1	24.33 c	24.43 c	24.67 c	24.48 c
	F2	25.12 c	25.32 c	25.44 c	25.30 c
H1	F0	25.55 c	25.62 c	25.72 c	25.63 c
	F1	27.11 c	27.23 c	27.44 bc	27.26 c
	F2	29.33 b	30.24 b	31.25 b	30.27 b
H2	F0	30.45 b	31.13 b	31.27 b	30.95 b
	F1	33.45 a	34.42 a	34.55 a	34.14 a
	F2	35.66 a	36.54 a	36.77 a	36.32 a
LSD 0.05			0.90		0.52
			H x Z		Mean H
H0		24.52 c	24.63 c	24.77 c	24.64 c
H1		27.33 b	27.69 b	28.13 b	27.71 b
H2		33.19 a	34.03 a	34.19 a	33.80 a
LSD 0.05			0.52		0.30
			F x Z		Mean F
F0		26.70 c	26.96 c	27.06 c	26.90 c
F1		28.29 b	28.69 b	28.88 b	28.62 b
F2		30.03 a	30.70 a	31.15 a	30.62 a
LSD 0.05			0.45		0.30
Mean Z		28.34 b	28.78 ab	29.03 a	
LSD 0.05			0.30		

H0 = no biofertilizer; H1 = *Azotobacter chroococcum* 10 mL plant⁻¹; H2 = *Glomus mosseae* 10 g plant⁻¹; F0, F1 and F2 = nano iron at 0, 10 and 20 mg L⁻¹; Z0, Z1 and Z2 = nano zinc at 0, 10 and 20 mg L⁻¹.

Table 4. Effect of biofertilization and foliar application of nano iron and nano zinc fertilizers on available phosphorus in soil (mg P kg⁻¹ soil)

Biofertilizer	Nano iron fertilizer	Nano zinc fertilizer (mg L⁻¹) Z0	Z1	Z2	Mean (H x F)
H0	F0	8.21 c	8.31 c	8.54 c	8.35 c
	F1	8.38 c	8.41 c	8.59 c	8.46 c
	F2	8.45 c	8.55 c	8.72 c	8.57 c
H1	F0	8.51 c	9.15 b	9.66 b	9.10 b
	F1	8.62 c	9.69 b	10.14 b	9.48 b
	F2	8.94 bc	10.58 b	11.42 a	10.31 b
H2	F0	9.58 b	10.72 b	11.83 a	10.71 b
	F1	9.69 b	11.36 a	12.19 a	11.08 a
	F2	11.29 a	12.57 a	13.56 a	12.47 a
LSD 0.05			0.41		0.24
			H x Z		Mean H
H0		8.35 c	8.42 c	8.62 c	8.46 c
H1		8.69 b	9.81 b	10.41 b	9.63 b
H2		10.19 a	11.21 a	12.11 a	11.17 a
LSD 0.05			0.24		0.14
			F x Z		Mean F
F0		8.77 c	9.39 b	10.01 a	9.39 c
F1		8.90 c	9.82 b	10.31 a	9.67 b
F2		9.56 c	10.22 b	10.82 a	10.20 a
LSD 0.05			0.24		0.14
Mean Z		9.07 c	9.81 b	10.38 a	
LSD 0.05			0.14		

(24.11mg kg⁻¹). The two-way interactions also showed significant increase, *e.g.*, H2F2 (36.32 mg kg⁻¹) and H2Z2 (34.19 mg kg⁻¹), which serves to illustrate the interaction effect of biofertilizer and nano micronutrients.

Available phosphorus in soil (mg P kg⁻¹ soil): Significantly affected by the interaction among biofertilizer, nano iron, and nano zinc treatments. The highest phosphorus content was recorded under the H2F2Z2 treatment combination (13.56 mg P kg⁻¹ soil), whereas the lowest value was observed in the control treatment H0F0Z0 (8.21 mg P kg⁻¹ soil). The H2F2 interaction produced the highest mean value among H × F combinations (12.47 mg P kg⁻¹ soil), while the H2Z2 interaction recorded the highest mean value among H × Z combinations (12.11 mg P kg⁻¹ soil), indicating the positive effect of biofertilization and foliar application of nano micronutrients on phosphorus availability in soil.

Table 5. Effect of biofertilization and foliar application of nano iron and nano zinc fertilizers on available potassium in soil (mg K kg⁻¹ soil)

Biofertilizer	Nano iron fertilizer (mg L⁻¹)	Nano zinc fertilizer (mg L⁻¹) Z0	Z1	Z2	Mean (H x F)
H0	F0	160.84 i	164.25 h	168.65 g	164.58 i
	F1	165.20 h	167.72 g	170.16 g	167.69 h
	F2	175.87 f	178.76 f	180.07 f	178.23 g
H1	F0	185.12 e	188.07 e	191.73 d	188.30 f
	F1	196.67 d	200.56 c	206.13 c	201.12 e
	F2	212.85 c	216.53 c	220.81 b	216.73 d
H2	F0	225.18 b	231.76 b	236.35 b	231.09 c
	F1	241.59 a	243.83 a	246.31 a	243.91 b
	F2	248.54 a	249.34 a	251.23 a	249.70 a
LSD 0.05			6.13		3.54
			H x Z		Mean H
H0		167.30 c	170.24 c	172.96 c	170.16 c
H1		198.21 b	201.72 b	206.22 b	202.05 b
H2		238.43 a	241.64 a	244.63 a	241.57 a
LSD 0.05			3.54		2.04
			F x Z		Mean F
F0		190.38 c	194.69 b	198.91 a	194.66 c
F1		201.15 c	204.03 b	207.53 a	204.23 b
F2		212.42 c	214.87 b	217.37 a	214.88 a
LSD 0.05			3.54		2.04
Mean Z		201.31 c	204.53 b	207.93 a	
LSD 0.05			2.04		

Available potassium in soil (mg K kg⁻¹ soil): Table 5 shows the impact of biofertilizer and foliar sprays of nano iron and nano zinc on the potassium concentration of the soil. The highest concentration of potassium was found in the three-way H2F2Z2 (251.23 mg kg⁻¹) and the lowest in the H0F0Z0 control

Table 6. Effect of biofertilization and foliar application of nano iron and nano zinc fertilizers on available iron in soil (mg Fe kg⁻¹ soil)

Biofertilizer	Nano iron fertilizer (mg L⁻¹)	Nano zinc fertilizer (mg L⁻¹) Z0	Z1	Z2	Mean (H x F)
H0	F0	3.24 h	3.34 h	3.44 h	3.34 f
	F1	3.49 gh	3.58 gh	3.64 gh	3.57 ef
	F2	3.75 fg	3.84 f	3.94 ef	3.84 de
H1	F0	3.78 fg	3.96 ef	4.35 d	4.03 d
	F1	4.57 cd	4.59 cd	4.64 cd	4.60 c
	F2	4.20 de	4.28 d	5.25 b	4.58 c
H2	F0	3.14 h	3.80 fg	3.51 gh	3.48 f
	F1	4.03 ef	5.27 b	5.53 b	4.94 b
	F2	4.77 c	6.24 a	6.36 a	5.79 a
LSD 0.05			0.35		0.20
			H x Z		Mean H
H0		3.49 c	3.59 c	3.67 c	3.58 c
H1		4.18 b	4.28 b	4.75 b	4.40 b
H2		3.98 b	5.10 a	5.13 a	4.74 a
LSD 0.05			0.20		0.12
			F x Z		Mean F
F0		3.39 c	3.70 b	3.77 b	3.62 c
F1		4.03 b	4.48 a	4.60 a	4.37 b
F2		4.24 b	4.79 a	5.18 a	4.74 a
LSD 0.05			0.20		0.12
Mean Z		3.89 c	4.32 b	4.52 a	
LSD 0.05			0.12		

combination (160.84 mg kg^{-1}). Two-way interactions also played an important role, *e.g.*, H2F2 (249.70 mg kg^{-1}) and H2Z2 (244.63 mg kg^{-1}), where the effect of biofertilizer with the combined one of nano micronutrients on improving the potassium status of soil was observed

Available iron in soil (mg Fe kg^{-1} soil): Table 6 shows the effect of biofertilizer and foliar application of nano iron and nano zinc fertilizers on available iron in soil. The three-way interaction H2F2Z2 recorded the highest value (6.36 mg Fe kg^{-1} soil), whereas the control H0F0Z0 recorded the lowest value (3.24 mg Fe kg^{-1} soil). The two-way interactions H2F2 (5.79 mg Fe kg^{-1} soil) and H2Z2 (5.13 mg Fe kg^{-1} soil) also showed higher values, indicating the combined effect of biofertilizer and nano micronutrients on iron availability in soil.

Available zinc in soil (mg Zn kg^{-1} soil): Table 7 summarizes the influence of biofertilizer and foliar sprays of nano iron and nano zinc on the zinc content in the soil. The three-way interaction between H2F2Z2 (2.79 mg kg^{-1}) and the control combination H0F0Z0 (0.21mg kg^{-1}) had the highest and lowest zinc concentration, respectively. Two-way interactions also played an important role, *e.g.*, H2 F2 (2.63 mg kg^{-1}) and H 2 Z 2 (2.03 mg kg^{-1}), which indicated the combined effect of biofertilizer and micronutrients on improving zinc availability in soils.

Table 7. Effect of biofertilization and foliar application of nano iron and nano zinc fertilizers on available zinc in soil (mg Zn kg^{-1} soil)

Biofertilizer	Nano iron fertilizer (mg L^{-1})	Nano zinc fertilizer (mg L^{-1}) Z0	Z1	Z2	Mean (H x F)
H0	F0	0.21 l	0.30 k	0.39 j	0.30 f
	F1	0.60 i	0.76 h	1.12 g	0.83 e
	F2	1.22 f	1.30 e	1.46 d	1.33 c
H1	F0	0.36 j	0.40 j	0.52 i	0.43 f
	F1	0.78 h	0.89 h	1.40 d	1.02 d
	F2	1.43 d	1.99 c	2.12 bc	1.85 b
H2	F0	1.16 g	1.45 d	1.53 d	1.38 c
	F1	1.29 e	1.57 d	1.78 c	1.55 c
	F2	2.53 b	2.58 b	2.79 a	2.63 a
LSD 0.05			0.12		0.07
			H x Z		Mean H
H0		0.68 c	0.79 c	0.99 c	0.82 c
H1		0.86 c	1.09 b	1.34 b	1.09 b
H2		1.66 b	1.87 a	2.03 a	1.85 a
LSD 0.05			0.07		0.04
			F x Z		Mean F
F0		0.57 c	0.72 b	0.81 a	0.70 c
F1		0.89 c	1.07 b	1.43 a	1.13 b
F2		1.72 c	1.96 b	2.12 a	1.93 a
LSD 0.05			0.07		0.04
Mean Z		1.06 c	1.25 b	1.46 a	
LSD 0.05			0.04		

Analysis of variance (Table 8) indicated that biofertilizer, nano-iron and nano-zinc had highly significant effect on plant height, number of fruits $plant^{-1}$ and fruit weight. It indicates that these treatments had strong individual effect on tomato growth and yield traits. All two and three factor interactions were highly significant. It denotes that combined application of biofertilizer with nano-iron and nano-zinc had more impact on plant growth and yield than individual application.

Plant height (cm): Table 9 illustrates the impact of biofertilizer, and foliar spray of nano iron and nano zinc on tomato plant height. The greatest plant height was observed in the triple interaction H2F2Z2(139.9 cm), and the lowest in the control combination H 0 F0Z0 (117.3 cm). Two-way interactions were also notable *e.g.* H2F2 (137.8 cm) and H2Z2 (136.0 cm), which reflects the significant interaction effect of biofertilizer and nano micronutrients on promoting plant growth.

Table 8. Analysis of variance (mean squares) for plant height, number of fruits per plant, and fruit weight of tomato as affected by biofertilizer, nano iron, nano zinc, and their interactions

Source of variation	df	Plant height	No. of fruits $plant^{-1}$	Fruit weight
Replications	2	13.495	2.760	12.635
Biofertilizer (H)	2	769.703**	1165.717**	2705.297**
Nano iron (F)	2	293.180**	95.285**	174.685**
Nano zinc (Z)	2	109.340**	7.130**	21.405**
H × F	4	18.385**	5.618**	22.878**
H × Z	4	18.378**	3.745**	17.195**
F × Z	4	18.313**	3.768**	17.220**
H × F × Z	8	15.269**	3.124**	14.300**
Error	52	5.332	1.090	4.993
Total	80	2991.144	2675.972	6431.237

** indicates significance at $P \leq 0.01$, whereas NS indicates non-significant differences. SE represents the standard error of the mean, and CV (%) represents the coefficient of variation. H = biofertilizer, F

Table 9. Effect of biofertilization and foliar application of nano iron and nano zinc fertilizers on plant height (cm)

Biofertilizer	Nano iron fertilizer (mg L^{-1})	Nano zinc fertilizer (mg L^{-1}) Z0	Z1	Z2	Mean (H x F)
H0	F0	117.3 i	119.7 h	120.4 h	119.1 g
	F1	120.5 h	123.7 g	124.9 fg	123.0 f
	F2	124.7 fg	126.7 ef	128.9 de	126.8 e
H1	F0	122.9 g	125.7 f	128.8 de	125.8 e
	F1	126.9 ef	127.5 ef	129.9 cd	128.1 d
	F2	129.7 cd	130.6 cd	131.9 c	130.7 c
H2	F0	128.2 de	130.3 cd	133.8 b	130.8 c
	F1	130.9 c	131.7 c	134.5 b	132.4 b
	F2	135.7 b	137.9 a	139.9 a	137.8 a
LSD 0.05			3.45		1.99
			H x Z		Mean H
H0		120.8 c	123.3 c	124.7 c	122.9 c
H1		126.5 b	127.9 b	130.2 b	128.2 b
H2		131.6 a	133.3 a	136.0 a	133.6 a
LSD 0.05			1.99		1.15
			F x Z		Mean F
F0		122.8 c	125.3 b	127.6 a	125.2 c
F1		126.1 c	127.6 b	129.8 a	127.8 b
F2		130.0 c	131.7 b	133.6 a	131.8 a
LSD 0.05			1.99		1.15
Mean Z		126.3 c	128.2 b	130.3 a	
LSD 0.05			1.15		

Number of fruits ($plant^{-1}$): Table 10 shows that biofertilizer, nano iron, and nano zinc treatments increased the number of fruits per plant. The three-way interaction H2F2Z2 recorded the highest value (56.22 fruits $plant^{-1}$), whereas H0F0Z0 recorded the lowest value (41.11 fruits $plant^{-1}$). Among the two-way interactions, H2F2 (56.10 fruits $plant^{-1}$) and H2Z2 (55.31 fruits $plant^{-1}$) gave the highest values. The mean values also showed that H2 (54.90 fruits $plant^{-1}$), F2 (49.15 fruits $plant^{-1}$), and Z2 (47.96 fruits $plant^{-1}$) recorded the highest means.

Fruit weight (g): Table 11 shows that the highest fruit weight was recorded under H0F2Z2 with 137.82 g, while the lowest value was observed in H2F0Z0 with 112.33 g. The results indicate that increasing fertilizer level (F2) improved fruit weight across treatments. Nano zinc (Z2) recorded the highest overall mean compared with Z1 and Z0. Biofertilizer levels showed a decrease in fruit weight from H0 to H2

Table 10. Effect of biofertilization and foliar application of nano iron and nano zinc fertilizers on number of fruits (plant^{-1})

Biofertilizer	Nano iron fertilizer (mg L^{-1})	Nano zinc fertilizer (mg L^{-1})			Mean (H x F)
		Z0	Z1	Z2	
H0	F0	41.11 i	41.22 i	41.32 i	41.21 g
	F1	42.12 h	42.21 h	42.31 h	42.21 f
	F2	43.22 g	44.24 f	44.45 f	43.97 e
H1	F0	42.23 h	42.33 h	42.45 h	42.33 f
	F1	44.55 f	44.62 f	46.67 e	45.28 d
	F2	45.77 e	47.88 d	48.47 d	47.37 c
H2	F0	51.65 d	52.83 c	53.77 c	52.75 b
	F1	55.74 b	55.88 b	55.94 b	55.85 a
	F2	55.97 b	56.11 ab	56.22 a	56.10 a
LSD 0.05			1.56		0.90
			H x Z		Mean H
H0		42.15 c	42.56 c	42.69 c	42.47 c
H1		44.18 b	44.94 b	45.86 b	44.99 b
H2		54.45 a	54.94 a	55.31 a	54.90 a
LSD 0.05			0.90		0.52
			F x Z		Mean F
F0		44.97 c	45.46 b	45.85 a	45.43 c
F1		47.47 c	47.57 b	48.30 a	47.78 b
F2		48.32 c	49.41 b	49.71 a	49.15 a
LSD 0.05			0.90		0.52
Mean Z		46.93 c	47.48 b	47.96 a	
LSD 0.05			0.52		

Table 11. Effect of biofertilization and foliar application of nano iron and nano zinc fertilizers on fruit weight (g)

Biofertilizer	Nano iron fertilizer (mg L^{-1})	Nano zinc fertilizer (mg L^{-1})			Mean (H x F)
		Z0	Z1	Z2	
H0	F0	128.55 e	129.63 d	130.87 c	129.68 c
	F1	133.66 b	135.98 a	136.89 a	135.51 b
	F2	137.11 a	137.45 a	137.82 a	137.46 a
H1	F0	121.11 h	121.45 h	122.12 h	121.56 f
	F1	122.55 g	123.67 f	124.53 e	123.58 e
	F2	125.78 d	126.66 d	127.92 d	126.79 d
H2	F0	112.33 k	113.32 j	113.39 j	113.01 i
	F1	114.21 i	114.42 i	114.74 h	114.46 h
	F2	114.88 h	115.21 h	115.32 h	115.14 g
LSD 0.05			3.34		1.93
			H x Z		Mean H
H0		133.11 a	134.35 a	135.19 a	134.22 a
H1		123.15 b	123.93 b	124.86 b	123.98 b
H2		113.81 c	114.32 c	114.48 c	114.20 c
LSD 0.05			1.93		1.12
			F x Z		Mean F
F0		120.66 c	121.47 b	122.13 a	121.42 c
F1		123.47 c	124.69 b	125.39 a	124.52 b
F2		125.92 c	126.44 b	127.02 a	126.46 a
LSD 0.05			1.93		1.12
Mean Z		123.36 c	124.20 b	124.84 a	
LSD 0.05			1.12		

Discussion

Foliar application of nano-iron and nano-zinc was associated with improved soil nutrient availability and tomato growth under the conditions of this experiment. The positive effects of nano iron could partly be explained by its potential role in developing better chlorophyll production, photosynthesis, enzyme activity, and root functioning. These effects may be associated with the higher levels of N, P, K, Fe, and Zn in soil. These findings are in agreement with previous reports on nano and chelated iron fertilizers, which demonstrated their positive effects on nutrient uptake and plant growth. Similar improvements in nutrient acquisition and crop performance following nano iron application have also been documented by(Ajeel and Al-Hakeim, 2024; Ajeel, 2026; Merghany *et al.*, 2025).

Nano zinc also seemed to enhance plant performance. Zinc is involved in the synthesis of tryptophan, which is necessary for the synthesis of IAA, a hormone involved in cell division, cell elongation and root growth. It also increases the activity of the enzymes, protein metabolism and photosynthesis. Therefore, the improvement under nano zinc treatment could partly be explained by better movement of nutrients within the plant and increased activity of roots (Abd Hamidi and Arak, 2024).

The significant increase in post-harvest available N, P, and K in the treated soils, despite the uniform application of basal chemical fertilizers (urea and phosphate) across all plots, may be associated with distinctive synergistic mechanisms triggered by the treatments rather than a simple residual effect of the conventional fertilizers. In the control plots (H0F0Z0), which received only the basal chemical fertilizers, the available nutrient levels were the lowest, confirming that conventional fertilizers alone are highly susceptible to pathways of nutrient loss, such as ammonia volatilization, nitrogen leaching, and phosphorus fixation in calcareous soils. In contrast, the application of biofertilizers significantly enhanced microbial activity; Azotobacter actively fixed atmospheric nitrogen and released growth-promoting substances, while the extensive hyphal network of mycorrhizal fungi may be associated with the secretion of organic acids (such as citric and oxalic acids) that chelate calcium and solubilized fixed mineral phosphorus, transforming it into plant-available forms. Furthermore, the foliar sprays of nano iron and nano zinc could partly be explained as physiological stimulants. By potentially optimizing chlorophyll synthesis and photosynthetic efficiency, these nano-micronutrients may have stimulated the plants to translocate more carbon downwards. The observed increase in post-harvest available nutrients may be associated with improved plant–rhizosphere activity under combined biofertilizer and nano-micronutrient treatments. This, in turn, may have indirectly supported a more dynamic root-zone environment that contributed to unlocking both native and basal-applied nutrients, without assuming a direct, unmeasured modification of root exudation rates or altered rhizosphere chemistry (Marschner, 2012).

Biofertilizers also had a clear effect on the measured traits, mycorrhizal fungi outperformed Azotobacter in most parameters, likely because fungal hyphae increase the effective root surface area, allowing plants to explore a larger volume of soil for nutrient uptake. These fungi may also be associated with the release of organic acids that assist in dissolving fixed nutrients. But Azotobacter possibly contributed mainly by nitrogen fixation. Bacilieri *et al.* (2022) reported similar positive effects of biofertilizers in soybean.

The best overall treatment for the majority of the parameters was the combination of mycorrhizal fungi with the highest nano iron and nano zinc (H2F2Z2), which recorded the highest values of soil nutrient availability, plant height, and fruit number. However, a distinct physiological trade-off was observed regarding individual fruit weight, which reached its maximum under H0F2Z2. This phenomenon can be effectively explained by the source–sink relationship and the fruit-load effect. The enhanced nutrient uptake efficiency potentially facilitated by mycorrhizae could partly explain the robust flower setting and a higher fruit load (increased number of sinks). However, since the plant's total photosynthetic capacity and available carbohydrate supply (the source) remained finite, these assimilates had to be partitioned among a much larger number of developing fruits, reducing individual fruit weight under H2.

Although the findings demonstrate clear benefits, certain limitations should be acknowledged; the study did not directly measure microbial colonization, chlorophyll content, root traits, or nutrient uptake in plant tissue. Nevertheless, the study showed that the use of mycorrhizal fungi and foliar nano iron and nano zinc can be a useful tool for improving soil fertility and tomato growth. This approach may also contribute to reducing reliance on traditional chemical fertilizers with better nutrient uptake and plant performance may may improve nutrient availability and crop performance when integrated with conventional fertilization practices.

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