Influence of Foliar-Applied nano-iron oxide on Growth Traits and Yield Components of Four Radish (*Raphanus sativus L.)* Varieties

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Abstract

A field trial was conducted at the Department of Horticultural and Landscape Engineering, Faculty of Agriculture, Tikrit University, during the 2024-2025 growing season to evaluate the effects of foliar application of nano-iron oxide at concentrations of 0, 20, 40, and 60 mg L^{-1} on the vegetative growth and yield of four varieties of radish (Raphanus sativus L.) (Black Local, Cherry Bell, Red Local, and Crimson Giant). The trial was conducted using a fully randomized block design (RCBD) with three replicates.

The results showed that foliar application of nano-iron oxide significantly improved vegetative growth and yield parameters compared to the control group. Most measured growth and yield parameters recorded their highest values at 60 mg L^{-1}. resulting in greater biomass accumulation and the better performance of yield components.

Among the tested varieties, Crimson Giant recorded the highest mean values for most of the studied traits, whereas Cherry Belle generally recorded the lowest values, and the lowest values were for Cherry Bell. Due to the interaction effect, the treatment of nano-iron oxide at 60 mg L-1 induced the highest yield and The lowest yield was recorded by the Cherry Belle variety under the control treatment (0 mg L^{-1}).

Overall, foliar application of nano-iron oxide, particularly at 60 mg L^{-1}, can be useful in enhancing radish growth and yield, and is especially beneficial for high yielding varieties like Crimson Giant.

Keywords: nano-iron oxide, radish, foliar spray, vegetative growth, yield, varieties.

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1- Introduction

Nanotechnology is increasingly recognized as a potential tool for sustainable agricultural commodities due to its ability to deliver high efficiency in the utilization of nutrients in different environments. Nanofertilizers have been gaining interest amongst the applications as they enter plant tissues with smaller particle size and higher surface area, which aids in nutrient absorption, transport and translocation in plant tissues compared to conventional fertilizers (1).

Iron is a micronutrient that is important for plant growth and development, and has been documented to be important for photosynthesis, respiration and enzyme activation. In soils, however, iron may be present in an insoluble form, especially under alkaline conditions, and in this state, may not be readily absorbed by the plant, resulting in deficiency symptoms including chlorophyll deficiency, reduced growth, and decreased yield (2). To resolve this, it was proposed that nanoscale iron oxides ($Fe_2 O_3$ and $Fe_3 O_4$) with their enhanced plant utilization and absorption rates would be more efficient nutrient source.

It has been demonstrated that foliar application of Fe3O4 nanoparticles enhances the plant physiological and biochemical processes such as photosynthetic efficiency, nutrient absorption, and metabolism, thereby enhancing growth, productivity, and nutrient uptake (3).

Raphanus sativus L. (radish) is an economically and nutritionally important crop with a high growth rate and nutritional value, which is a taproot plant. It contains high levels of minerals, dietary fibre, bioactive substances like antioxidants and glucosinolates that have beneficial effects on human health, including the ability to prevent chronic diseases (4). It also has medicinal properties, including antioxidant, anti-inflammatory, digestive and metabolic regulatory properties. (5). Furthermore, due to its richness in bioactive compounds, radishes are used in food and pharmaceuticals, making them an industrially important crop. In addition, it contributes to soil improvement by improving soil structure and aeration, making it suitable as a cover crop (6).

Genetic variation between varieties leads to significant differences in morphological characteristics such as root shape, size, and color, as well as responses to environmental conditions and cultivation methods. Previous studies have shown that differences between varieties are one of the main factors influencing growth and yield, emphasizing the importance of variety selection for optimizing productivity and quality (7).

Therefore, this study aimed to evaluate the effects of foliar application of iron oxide nanoparticles on the growth Therefore, this study aimed to evaluate the effects of foliar application of nano-iron oxide on growth and yield components of different radish varieties and yield of various radish varieties. Furthermore, it aimed to assess the variability of responses between varieties to nano-iron application and identify the most efficient combination for improving productivity and quality under the examined environmental conditions.

2- Materials and Methods

A field trial was carried out at the Department of Horticultural and Landscape Engineering, Faculty of Agriculture, Tikrit University during the 2024-2025 growing season to investigate the effect of different rates of foliar application of nano-iron oxide suspension (0, 20, 40 and 60 mg L-1) on growth and yield of four varieties of radish (Raphanus

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sativus L.). Black Local, Cherry Bell, Red Local and Crimson Giant.

Before sowing, soil samples were collected from five locations at a depth of 0–30 cm. The samples were thoroughly mixed, air-dried, and sieved through a 2 mm mesh sieve. Physicochemical analysis of the soil was performed, and the soil characteristics shown in Table 1 were revealed.

The experiment was conducted using a randomized complete block design (RCBD) arranged as a split-plot experiment with three replicates. Nano-iron oxide concentrations were assigned to the main plots, while radish varieties were assigned to the subplots, and radish varieties to the secondary plots. Each replicate consisted of 16 experimental plots (3 m × 3 m).

Organic fertilizer (sheep manure compost) was mixed into the soil at a rate of 25 t ha^{-1} one month before sowing. Nitrogen fertilizer (urea, nitrogen content 46%) was applied in two installments at a rate of 150 kg N ha^{-1}. Phosphate fertilizer (superphosphate, phosphorus content 21%) was applied at 100 kg ha^{-1} at sowing, and potassium fertilizer (potassium sulfate, potassium oxide content 43%) was applied in two installments at a rate of 120 kg ha^{-1}.

Seeds were sown on October 20, 2024, at a rate of 9 kg ha^{-1} at a depth of 1.5 cm. Thinning was performed 20 days after germination, leaving one plant per plot. Standard agricultural practices such as irrigation, weeding, hilling, and pest and disease control were carried out as needed. Irrigation was performed using surface irrigation with well water.

The nano-iron oxide suspension was prepared by dispersing the required amount in a small amount of water with continuous stirring, and then diluting it to the desired concentration. To increase the leaf-to-limb adhesion, a few drops of surfactant were applied. A 16 liter manual sprayer was used to carry out foliar application once a season 25 days after sowing.

Harvest was done 50-60 days after sowing, depending on variety – Cherry Bell at 50 days, Red Local at 55 days and Black Local and Crimson Giant at 60 days.

Trained measurements were leaf number per plant, leaf area (cm2 plant-1), fresh weight of vegetative parts (g $plant^{-1}$), dry weight of vegetative parts (g $plant^{-1}$), root weight (g), root length (cm), root diameter (cm) and yield (kg ha^{-1}). Data analysis was conducted with the computer program SAS. Mean values were compared by the least significant difference (LSD) test at 5% significance level, and analyzed based on a split-plot ANOVA model.

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

Proty	**Value**	**Unit**
Soil pH	7.62	–
Electrical conductivity (EC)	2.66	dS m^{-1}
Cation exchange capacity (CEC)	19.56	cmol kg^{-1} soil
Organic matter (OM)	0.79	%

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Calcium carbonate ($CaCO_3$)	200.14	g kg^{-1}
Gypsum ($CaSO_4$)	80.17	
Available nitrogen (N)	17.54	mg kg^{-1}
Available phosphorus (P)	6.38	
Available potassium (K)	110.74	
Sand	500	g kg^{-1}
Silt	281	
Clay	219	
Soil texture	Sandy loam	–
Available iron	1.101	ppm

The analyses were conducted in the Soil Science Laboratory at the College of Agriculture - Tikrit University

3- Results and Discussion

1-3 Plant Height (cm)

As can be seen in Table (2), the use of the FeNPs had a considerable effect on the height of the radish plants The application of nano-iron oxide had a stimulatory effect on plant vegetative growth with an increase in average plant height from 18.8 cm to 22.8 cm when the spray level increased from 0 to 60 mg L^{-1}. This response may be associated with the known role of iron in chlorophyll formation and several enzymatic processes

Significant differences between varieties were also obtained. Crimson Giant was the tallest variety with a mean height of 22.6 cm followed by Red Local with a mean height of 21.1 cm and then Black Local with a mean height of 20.6 cm. Cherry Belle variety had the shortest height of 19.1 cm. This difference is due to the different nutrient uptake efficiency and response to foliar spraying of the varieties, which in turn has an impact on their physiological activity and vegetative growth rate.

As for the interaction between plant height and varieties at different Fe levels, the highest plant height (24.5 cm) was obtained in 60 mg L^{-1} Fe level and the lowest plant height (17.0 cm) was obtained in the control treatment (0 mg L^{-1} Fe level) for the variety of Crimson Giant. This interaction is a sign of genetic variation among varieties in response to the nano-iron level. For some varieties, they exhibited greater efficiency in the use of iron to improve growth-related physiological processes at optimal Fe concentration (60 mg L^{-1}), No reduction in plant height was observed at the tested concentration

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Table 2. Effect of spraying with nano-iron oxide on plant height of four radish varieties (cm)

Radish varieties	Foliar application level of nano iron oxide (mg L^{-1})				Average of varieties
	0	20	40	60	
Black Local	18.5	20.3	21.0	22.5	20.6
Cherry Belle	17.0	18.8	19.5	21.0	19.1
Red Local	19.0	20.8	21.5	23.0	21.1
Crimson Giant	20.5	22.3	23.0	24.5	22.6
Average iron	18.8	20.5	21.3	22.8	————
L.S.D 0.05	Varieties		**Iron**		**Iron** × Varieties
	1.01		0.80		1.21

3-2 Number of Leaves (leaf plant^{-1})

Table (3) indicated that the number of leaves in radish plant was clearly improved by spraying with nano-iron exudate in comparison to control plants. The leaves were more abundant over time, reaching 12.84, 11.54, 10.03, and 8.46 leaf plant-1 for the 60, 40, 20, and 0 mg L^{-1} spray rates, respectively, clearly showing the response of the plants with leaf production to the increase in iron concentration. This is explained by iron's essential function in the production of chlorophyll and its involvement in the synthesis of proteins and cytochromes participating in electron transport chains. This increases the efficiency of photosynthesis and energy production (ATP and NADPH), thereby stimulating cell division in apical meristems and increasing leaf formation. Iron also contributes to the activation of several enzymes responsible for metabolic processes, leading to an overall increase in vegetative growth (11). Significant differences were also observed among the tested varieties. Crimson Giant recorded the highest mean number of leaves (11.40 leaves plant^{-1}), followed by Red Local (10.89), Black Local (10.50), and Cherry Belle (10.08). These differences may be attributed to genetic variation among varieties in growth vigor and nutrient-use efficiency The results also show significant differences between Regarding the variability, the Crimson Giant variety exhibited the highest average number of leaves (11.40) leaf plant^{-1}, followed by Red Local (10.89) leaf plant^{-1} and Black Local (10.50) leaf plant^{-1}. The Cherry Belle variety had the lowest average (10.08) plant. Genetic changes in productivity are the cause of this variable. of iron absorption and utilization within the plant, as well as differences in physiological activity and the ability to produce a larger vegetative mass, as confirmed by (7). As for the interaction, the Crimson Giant variety recorded the highest number of leaves (13.60) leaf plant^{-1} of 60 mg L^{-1}, while the Cherry

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Belle variety recorded the lowest (7.90) leaf plant^{-1} of 0 mg L^{-1}.

Table 3. Effect of spraying with nano-iron oxide on the number of leaves of four radish varieties (leaf plant^{-1})

Radish varieties	Foliar application level of nano iron oxide (mg L^{-1})				Average of varieties
	0	20	40	60	
Black Local	8.25	9.80	11.35	12.60	10.50
Cherry Belle	7.90	9.45	10.85	12.10	10.08
Red Local	8.60	10.15	11.75	13.05	10.89
Crimson Giant	9.10	10.70	12.20	13.60	11.40
Average iron	8.46	10.03	11.54	12.84	————
	Varieties		**Iron**		**Iron** × Varieties
L.S.D 0.05	0.74		0.58		0.95

3-3 Leaf Area (cm^2 plant^{-1})

The results in Table (4) show that spraying with nano-iron oxide led to a significant increase in the leaf area of the radish plant. Increasing the spray level from (0) to (60) mg L^{-1} led to a significant increase in leaf area, reaching (179, 211, 228, 247) cm² plant^{-1} for spray levels (0, 20, 40, 60) mg L^{-1} respectively, with an increase of (17.88%, 27.37%, 37.99%) This result is consistent with previous studies reporting the role of iron in enhancing photosynthetic efficiency, chlorophyll formation, and vegetative growth. (12). The table also shows notable variations amongst radish cultivars. The greatest average was seen in the Crimson Giant variety. leaf area at 229 cm² plant^{-1}, followed by the Black Local variety at 220 cm² plant^{-1}, then Cherry Belle at 212 cm² plant^{-1}. The Red Local variety had the lowest average leaf area at 204 cm² plant^{-1}. Genetic differences among varieties may influence nutrient uptake and utilization efficiency Genetic changes in nutrients are the cause of this variety.

absorption and utilization efficiency among the varieties, as well as differences in their ability to develop a large shoot mass and increase the rate of cell division and elongation, which is reflected in the leaf area (13). The interaction between iron and varieties indicates that at a level of 60 mg L^{-1}, the highest leaf area was 259 cm² plant^{-1} belonging to the Crimson Giant variety, and the lowest, 0mg L^{-1}, to the Red Local variety. Leafy, reaching (168) cm² plant^{-1}.

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Table 4. Effect of spraying with nano-iron oxide on the leaf area of four radish varieties (cm^2 $plant^{-1}$)

Radish varieties	Foliar application level of nano iron oxide (mg L^{-1})				Average of varieties
	0	20	40	60	
Black Local	182	218	231	249	220
Cherry Belle	175	203	228	241	212
Red Local	168	197	212	238	204
Radish varieties	192	224	241	259	229
Average iron	179	211	228	247	————
L.S.D 0.05	Varieties		**Iron**		**Iron** × Varieties
	9.65		7.42		14.38

4-3 Dry weight of the vegetative parts (g $plant^{-1}$)

The results shown in Table (5) demonstrate that foliar application of nano-iron oxide significantly improved the dry weight of vegetative organs in all tested radish varieties compared to the control treatment. Regardless of the application concentration (20, 40, and 60 mg L^{-1}), all showed higher dry matter accumulation than untreated plants. The average value was highest at 60 mg L^{-1} (8.34 g $plant^{-1}$), followed by 40 mg L^{-1} (7.98 g $plant^{-1}$), and 20 mg L^{-1} (7.07 g $plant^{-1}$), with the control treatment showing the lowest value (6.20 g $plant^{-1}$).

This was a progressive rise in the dry biomass, which is an overall improvement in growth characteristics of vegetative organs. Better nutrient supply and physiological activity was believed to have resulted in greater elongation of leaves and assimilation surface area, thereby increasing dry matter production. The improvements in the early growth elements resulted in higher biomass production, in other words.

The promoting effect of nanoiron is thought to be related to its high absorption and translocation efficiency. This stimulates metabolism and helps with the synthesis of important biochemical reactions for plant growth and the synthesis of plant assimilation products. The effect was not linearly increased at all concentrations, however, 60 mg L^{-} 1 showed optimum nutrient availability and balanced utilization capacity of the plants, indicating the efficiency of the effect is starting to stabilize at higher concentrations.

At the variety level, significant differences were observed among cultivars. Crimson Giant had the highest average dry weight (7.75 g $plant^{-1}$ ± 0.57), followed by Black Local (7.46 g $plant^{-1}$) and Red Local (7.29 g $plant^{-1}$), while Cherry Bell had the lowest average (7.09 g $plant^{-1}$ ± 0.82). These differences are thought to be due to genetic differences that affect growth vigor, nutrient absorption efficiency, and

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physiological responsiveness to foliar-applied nutrients.

The Further, there was interaction between the nanoiron concentration and variety that explained these differences. Crimson Giant showed the greatest dry weight (8.68 g plant^{-1}) at 60 mg L^{-1} indicating better responsiveness and utilization efficiency at higher nutrient supply. The control treatment exhibited the lowest value (5.87 g plant^{-1}) as Cherry Bell had relatively low growth potential under the limited nutrient supply conditions.

In general, it can be concluded that these interactions are determining factors in the genetic regulation of the effect of nano iron application and the optimal concentration and highly responsive genotype is the most important factor for the yield of dry matter.

Table 5. Effect of nano-iron oxide foliar application on dry weight of vegetative parts of four radish varieties (g plant^{-1})

Radish varieties	Foliar application level of nano iron oxide (mg L^{-1})				Average of varieties
	0	20	40	60	
Black Local	6.23	7.14	8.06	8.39	7.46
Cherry Belle	5.87	6.76	7.63	8.08	7.09
Red Local	6.11	6.95	7.88	8.21	7.29
Crimson Giant	6.57	7.42	8.34	8.68	7.75
Average iron	6.20	7.07	7.98	8.34	————
L.S.D 0.05	Varieties		Iron		Iron × Varieties
	0.34		0.29		0.47

5-3Fresh Weight of Vegetative Parts (g plant^{-1})

As can be seen in the results in Table 6, all the radish varieties presented an increase in fresh weight of the vegetative biomass due to the use of iron nanoparticles as foliar spraying. The control treatment (0 mg L^{-1}) was outperformed by all spray treatments (20 mg L^{-1}, 40 mg L^{-1} and 60 mg L^{-1}). The average fresh weight was highest at the 60 mg L^{-1} level (35.09 g plant^{-1}), followed by the 40 mg L^{-1} level (32.92 g plant^{-1}), and then the 20 mg L^{-1} level (29.86 g plant^{-1}). The plants in the control treatment had the lowest fresh weight (26.05 g plant^{-1}). The ability to this is attributed to the ability of the iron nanoparticles to increase the efficiency of photosynthesis by incorporating them into iron containing proteins, such as cytochromes. In addition, iron fertilization results in an increase in chlorophyll content and light utilization efficiency, which in turn results in higher accumulation of organic matter, better vegetative growth and ultimately higher

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leaf fresh weight. Nano- and foliar-iron have been suggested by several researchers to improve essential physiological functions in plant growth, including growth, photosynthesis, and enzymatic activity, and to boost biomass.

Within cultivars, results were clear and statistically significant for all varieties of radishes. The 'Crimson Giant' variety had the greatest fresh weight (32.64 g plant-1) followed by 'Black Local' (31.51 g plant-1) and 'Red Local' (30.29 g plant^{-1}). The lowest average fresh weight (29.47 g plant-1) was obtained from 'Cherry Bell'. The differences observed may be due to genetic variations in the varieties, which influence growth efficiency, vegetative development and nutrient uptake and utilization, including iron. They account for variation in metabolic performance and nutrient utilization efficiency and thus in growth characteristics and biomass production.

Variety x level of spray, too, showed a significant interaction. The highest fresh weight (36.85 g plant^{-1}) was obtained at the same concentration for the variety 'Crimson Giant' and the lowest fresh weight (33.44 g plant^{-1}) was obtained at the same concentration for the variety 'Cherry Bell'. The 'Crimson Giant' variety had the highest fresh weight (27.64 g plant^{-1}) and the 'Cherry Bell' variety had the lowest (24.76 g plant^{-1}) in the control condition (0mg L^{-1}).

Table 6. Effect of spraying with nano-iron oxide on Fresh Weight of Vegetative Parts the fresh gravity of the flora mass of four radish varieties (g plant^{-1})

Radish varieties	Foliar application level of nano iron oxide (mg L^{-1})				Average of varieties
	0	20	40	60	
Black Local	26.41	30.12	33.58	35.94	31.51
Cherry Belle	24.76	28.63	31.05	33.44	29.47
Red Local	25.38	29.41	32.26	34.12	30.29
Crimson Giant	27.64	31.28	34.77	36.85	32.64
Average iron	26.05	29.86	32.92	35.09	————
	Varieties		Iron		Iron × Varieties
L.S.D 0.05	1.34		1.15		1.82

6-3 Root Length (cm)

From the results presented in Table 7, it is evident that spraying of irritant nanoparticles on radish leaves resulted in a significant increase in the Root length of all the four varieties studied. The length of the Root increased gradually with the Fe concentration, the overall average length of the Root were 5.97, 6.31, 6.71 and 6.98 cm for the treatments (0, 20, 40 and 60 mg L^{-1}). The maximum value (6.98 cm) was obtained at 60 mg L^{-1}, which is 16.9% higher than the control group (0 mg L^{-1}).

The positive response is achieved due to the The increase may be related to the role of iron in physiological processes associated with photosynthesis and plant growth, and better rate of photosynthesis,

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which boost up the metabolic processes that are correlated with root growth and elongation. The findings are in line with earlier investigations which showed that applying nano-iron fertilizer can increase the uptake of plant nutrients and boost plant growth by enhancing the physiological and biochemical parameters associated with plant photosynthesis and enzyme activation.

The differences between the cultivars studied were significant at the cultivar level. The Root length of the cultivars ranged from 6.17 cm in the 'Cherry Bell' cultivar to 6.89 cm in the 'Crimson Giant' cultivar with the lowest and highest mean values respectively. These differences are due to genetic variations in metabolic and nutrient utilization efficiency, which mean that the plant will differ in its response to nutrient applied to the foliage and thus in root growth.

The nano-iron interaction with cultivar indicated a clear positive trend in all cultivars with the increase in iron level. For Crimson Giant variety, the maximum value was obtained at 60 mg L^{-1} (7.32 cm) which showed better response to this variety than other treatments and genotype.

Table 7. Effect of nano-iron oxide spraying on Root length of four radish varieties (cm)

Radish varieties	Foliar application level of nano iron oxide (mg L^{-1})				Average of varieties
	0	20	40	60	
Black Local	5.95	6.21	6.65	6.88	6.42
Cherry Belle	5.59	5.97	6.42	6.71	6.17
Red Local	6.05	6.34	6.72	7.01	6.53
Crimson Giant	6.48	6.72	7.05	7.32	6.89
Average iron	5.97	6.31	6.71	6.98	———
L.S.D 0.05	Varieties		Iron		Iron × Varieties
	0.28		0.18		0.32

3 -7 Root diameter (cm)

Table (8) indicated that foliar application of nano-iron oxide resulted in significant increase in the Root diameter of the radish varieties and their responses were positive and increased as the level of application increased (0–60 mg L^{-1}). The overall average Root diameter was 5.11 cm for the control treatment, while it was 5.48, 5.88 and 6.26 cm for the 20, 40 and 60 mg L^{-1} treatments, respectively, a 22.5% increase in Root diameter from the control treatment at the highest concentration of 60 mg L^{-1}. Treatment at 60 mg L^{-1} was significantly more effective compared to other treatments. This is because enhancing the physiological processes in the plant, particularly its chlorophyll synthesis, its photosynthetic activity and proliferation of plant growth promoting enzymes is how the nano-iron helps the plant. The data also showed significant differences in Root diameter among the

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cultivars, with the highest being from Red Local (5.73 cm) and the lowest being from Black Local (5.59 cm). Cherry Belle variety had the smallest average diameter of 5.30 cm. These differences are thought to be due to the genetic efficiency of growth and/or response to nutrients in the varieties and the different abilities to absorb and utilize Fe. There was a significant interaction between nano-iron oxide concentration and variety for root diameter and interaction between both spray levels and varieties was significant and it was seen that at 60 mg L^{-1} level the Crimson giant variety had highest fruit diameter (6.81 cm).

Table 8. Mean fruit in four cultivars of radish in four cultivars of radish through the four replicates after 3 varieties of spraying with nano-iron oxide (cm)

Radish varieties	Foliar application level of nano iron oxide (mg L^{-1})				Average of varieties
	0	20	40	60	
Black Local	5.02	5.41	5.79	6.12	5.59
Cherry Belle	4.78	5.12	5.49	5.83	5.30
Red Local	5.18	5.55	5.92	6.28	5.73
Crimson Giant	5.45	5.83	6.32	6.81	6.10
Average iron	5.11	5.48	5.88	6.26	————
L.S.D 0.05	Varieties		Iron		Iron × Varieties
	0.33		0.24		0.41

8-3 Root Weight (g)

As shown in Table (9), the result of this study showed that the (root) weight of the varieties of radish studied was significantly higher with foliar spraying with nano-iron oxide. From the obtained results, the increase in spray level from (0, 20, 40 and 60 mg L^{-1}) has gradually and clearly reflected in the average rate of the weight of the Root, with an overall average weight for the iron treatments was(89.19, 102.80, 116.48 and 126.99) g, respectively. The maximum weight value belonged to the treatment (60 mg L^{-1}) and the lowest belonged to the control treatment (0 mg L^{-1}). This shows the beneficial contribution of nano-iron in enhancing root development, and dry matter progression in the root level. The stimulated chlorophyll and photosynthesis efficiency have resulted in higher levels of photosynthetic production, which explains this increment. This contributes to higher accumulation of carbohydrates and organic matter that are translocated from the leaves to the sink (roots), and therefore heavier fruit. It is also an important element in several enzymatic reactions involved in oxidation-reduction processes which increases the physiological activity of the plant as a whole. Results also highlight

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contrasts between varieties Maximum average fruit weight (121.35 g) was obtained from the Crimson Giant variety, while the minimum average fruit weight (94.62 g) was obtained from the Cherry Belle variety. This is likely due to growth efficiency differences between varieties and the ability to utilize nutrients and convert those nutrients into material stored in the roots. Interaction between varieties and spray levels significantly affected fruit weight The highest root weight was recorded by Crimson Giant at 60 mg L^{-1} (139.02 g), whereas the lowest value was recorded by Cherry Belle under the control treatment (77.34 g). This is due to the fact that systemically higher amount of iron caused by the interaction of the genetically superior variety with this high level of iron would increase the ability of photosynthesis while also enhancing the bringing of elements-containing nutrients to the roots as well. Consequently increased dry matter accumulation and heavier fruit than control treatment.

Table 9. Effect of spraying with nano-iron oxide on fruit weight of four radish varieties (g)

Radish varieties	Foliar application level of nano iron oxide (mg L^{-1})				Average of varieties
	0	20	40	60	
Black Local	92.48	108.63	121.75	130.42	113.32
Cherry Belle	77.34	89.21	101.58	110.36	94.62
Red Local	85.67	97.88	112.94	124.15	105.16
Crimson Giant	101.26	115.47	129.63	139.02	121.35
Average iron	89.19	102.80	116.48	126.99	
L.S.D 0.05	Varieties		Iron		Iron × Varieties
	5.37		4.12		6.84

9-3 Total Yield (kg ha^{-1})

Table (10)'s findings demonstrate that The foliar application of nano-iron oxide significantly increased total root yield, led to a significant increase in root yield (kg ha^{-1}) for both of the studied radish varieties. The average yields ranged from (4244,4891,5543,6036) kg ha^{-1}, respectively in the iron treatments, where the spray level increase from (0 to 20, 40, and 60 mg L^{-1}) lead to increase steadily and significantly on the average yield. The highest and lowest yields were related to (60 mg L^{-1}) and control treatment (0 mg L^{-1}), respectively, which indicates that nanoiron can increase the productivity of the radish plant. The yield increase is related to the positive effect of nano-iron in enhancing the efficiency of photosynthesis due to enhanced chlorophyll content and activation of some factors involved in oxidation-reduction processes . It then results in elevated carbohydrate and protein synthesis and their downstream transport. Additionally, enhancing nutritional status of the plants links directly to higher vegetative and root growth (15). But the coordination of these results with those referred(6,7,8) clearly

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demonstrates that the higher yellow is a direct effect of better growth atributes and yield long standing(10). The nano iron increased the fruit length (Table-7), fruit diameter (Table-8) and fruit weight (Table-9) which are the essential yield contributing factor. Fruit length increases is associated with a broader development of the main storage plant mass, whereas, breadth increases reflects the expansion of parenchyma tissues and improves the capacity of storage. The extra weight reflects the build-up of dry matter, water and sugars. Now, these properties, when combined, can directly result in an increased total yield. Our results are similar to the results of (2). The differences between varieties are also highly significant in these results. Yields were highest for the Crimson Giant variety (5770 kg ha^{-1}) and lowest for Cherry Belle (4503 kg ha^{-1}). This is considered to be due to genetic variation in their efficiency in photosynthesis and in varieties in nutrient uptake, transport, and utilization in storage organ formation.These results are consistent with those of (16), (17), (18), and (19). The interaction results between varieties and spray levels showed that the highest yield was achieved with the treatment (60 mg L^{-1} × Crimson Giant), reaching 6619 kg ha^{-1}, while the treatment (0 mg L^{-1} × Cherry Belle) recorded the lowest value at 3680 kg ha^{-1}.

Table 10. Effect of spraying with nano-iron oxide on the fruit yield of four radish varieties (kg ha^{-1})

Radish varieties	Foliar application level of nano iron oxide (mg L^{-1})				Average of varieties
	0	20	40	60	
Black Local	4398	5168	5790	6200	5394
Cherry Belle	3680	4245	4836	5249	4503
Red Local	4077	4657	5375	5909	5002
Crimson Giant	4819	5494	6171	6619	5770
Average iron	4244	4891	5543	6036	
	Varieties		Iron		Iron × Varieties
L.S.D 0.05	256		196		325

4-Conclusions and Recommendations

1-4 Conclusions

- Foliar spraying with nano-iron oxide showed a significant positive effect on all vegetative growth characteristics, yield components, and radish productivity, the highest observed values were generally recorded at the highest tested concentration of 60 mg L^{-1} This is attributed to improved photosynthetic efficiency and activation of enzymatic processes associated with energy production and growth.
- The improvement in vegetative growth characteristics was associated with a clear increase in root characteristics and yield,

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indicating a direct physiological relationship between vegetative growth efficiency and yield formation efficiency through increased carbohydrate translocation to the root system.

- The varieties showed genetic differences in response, with the Crimson Giant variety outperforming the others in most characteristics. This reflects variations in genetic efficiency in iron uptake and utilization in biological processes.
- The interaction between the 60 mg L^{-1} concentration and the Crimson Giant variety resulted in the highest values for most of the studied characteristics, confirming that optimal production performance is achieved when genetic factors are combined with the optimal nutrient treatment.

2-4 Recommendations

- To date, foliar application of nano-iron oxide at the rate of 60 mg L^{-1} has proven to be effective in enhancing growth and yield of the radish and.
- Under the conditions of this experiment, Crimson Giant showed the highest yield among the tested varieties as its response to nano-fertilization is better and higher yield as compared to other varieties.
- The application of nano-fertilizers should be integrated into the plant nutrition management system to improve the efficiency and avoid the losses in the utilization of the nutrients.
- Future research is needed to establish the best environmental conditions for the response of various varieties and treatments, particularly in relation to environmental stresses like salinity and drought.
- The physiological and economic aspects of using nano-iron should be studied to determine its practical feasibility in large-scale agricultural production.

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