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Optimizing iron and zinc nutrition in deep-water culture and nutrient film technique enhances growth performance and nutritional Quality of Tomato

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Abstract

This study evaluated the effect of two hydroponic techniques namely Deep-Water Culture (DWC) and Nutrient Film Technique (NFT) in combination with varying concentrations of Fe and Zn (5, 10, 15, and 20 ppm) on the growth and biochemical composition of the tomato cultivar Reo Grande. Growth parameters including plant height, number of leaves, branches, and fruits were maximized at 10 ppm (59.8 cm, 129.0, 37.0, and 29.0 per plant, respectively), while the number of buds per plant (27.0) was highest at 15 ppm of Fe and Zn in the DWC system compared to NFT. Proximate composition of plant parts (green leaves, diseased leaves, and fruits) showed higher values in DWC, with notable increases in moisture (18.96%), crude protein (9.4%), crude fiber (8.24%), crude fat (4.31%), ash (4.89%), and nitrogen-free extract (84.62%). Similarly, mineral analysis revealed that Na (109 mg/kg), K (668.25 mg/kg), Ca (186 mg/kg), Mg (217.24 mg/kg), P (385.21 mg/kg), Ni (0.49 mg/kg), Fe (5.58 mg/kg), Zn (3.75 mg/kg), Co (21.45 mg/kg), Cu (1.41 mg/kg), and Mn (1.41 mg/kg) were generally higher in fruits, followed by diseased leaves and green leaves, in the DWC system. The effects of nutrient concentration, plant part, and their interaction were significant in most cases ($P<0.05$). Overall, the results demonstrated that the DWC system, particularly at 10 and 15 ppm concentrations of Fe and Zn, had a profound influence on the growth and biochemical composition of Reo Grande tomatoes, highlighting its potential for optimizing hydroponic cultivation practices.

Keywords: Hydroponics; Deep-Water Culture (DWC); Nutrient Film Technique (NFT); Micronutrients (Fe and Zn); *Solanum lycopersicum*

1. Introduction

Tomatoes (*Solanum lycopersicum*) are renowned worldwide for their rich flavor and nutritional value, affirming their place as a staple in global diets (Collins et al., 2022; Ali et al., 2020). As the demand for sustainable agricultural practices increases, hydroponics has emerged as an innovative technique for soil-less crop production (Rajaseger et al., 2023; Ashoka et al., 2024). This technique allows for precise control over the nutrient supply, environmental conditions, and water usage, ultimately leading to enhanced plant growth and fruit quality. However, the nutritional quality of hydroponically grown tomatoes varies considerably with the supplied nutrient composition, particularly in relation to essential micronutrients such as iron (Fe) and zinc (Zn) (Vélez-Terreros et al., 2024; Khalid et al., 2024).

Iron is crucial for chlorophyll synthesis and various enzymatic processes, while zinc plays a vital role in plant growth regulation, enzyme activation, and overall metabolic function for fruit development (Hamzah et al., 2022; Snigdha, et al., 2021). Deficiencies in these micronutrients can impair photosynthesis, reduce fruit size and diminish nutritional

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value impacting both crop yield and consumer health (Nazir et al, 2024; Sharma et al, 2013). Optimizing Fe and Zn uptake in hydroponic systems is thus critical for producing high-quality tomatoes, particularly for cultivars like Reo Grande, which is widely cultivated for its remarkable flavor and adaptability to diverse growing conditions (Anusree et al, 2025; Sasireka et al, 2024).

Research highlights that the nutritional quality of hydroponically grown tomatoes can be significantly impacted by the specific hydroponic system employed, as well as the concentrations of micronutrients provided (Vehar et al, 2025). For instance, studies have shown that Nutrient Film Technique (NFT) systems may yield tomatoes with higher flavonoid and antioxidant content compared to traditional Deep-Water Culture (DWC) systems (Bhattacharya et al, 2025). However, the specific effects of various hydroponic systems on the nutritional profile of Reo Grande tomatoes, particularly about varying levels of Fe and Zn, remain underexplored.

This study aims to investigate the effects of DWC and NFT hydroponic systems on the Fe and Zn content, antioxidant levels, and overall fruit quality of Reo Grande tomatoes grown with varying concentrations of Fe and Zn. By identifying optimal conditions for nutrient uptake and plant health, this research seeks to contribute valuable insights for hydroponic growers aiming to enhance the nutritional value of their produce, supporting sustainable agriculture and improved dietary outcomes.

2. Materials and methods

Two hydroponic systems viz. DWC and NFT were constructed locally using glass and PVC pipes to evaluate their effect on the growth and biochemical composition of the tomato cultivar Reo Grande under different concentration of Fe and Zn. In the DWC system, plant roots were submerged in a nutrient-rich solution, whereas in the NFT system, a thin film of nutrient solution was continuously circulated over the roots. Seeds of the cultivar were obtained from the Horticulture Section of the Agricultural Research Institute Tarnab, Peshawar. A nursery was first raised in sand culture following standard agronomic practices, and seedlings were transferred to the hydroponic systems once they reached approximately 10 cm in height. The systems were provided with Hoagland and Arnon et al, (1938) nutrient solution with varying concentrations of Zn and Fe (5, 10, 15, 20 ppm). At maturity, the plants were evaluated for plant height, growth parameters and biochemical composition.

2.1. Hydroponic systems

Figure 1 Hydroponic systems A) Deep Water Culture (DWC) system and B) Nutrient Film Technology (NFT)

The DWC system was constructed from glass in the form of a tub, measuring 2 ft (length) × 1ft (width) × 1 ft (height) (Figure 1A). The tub was filled with water supplemented with the required nutrient solution and covered with a two-inch thick styrene foam sheet perforated with holes for planting. Seedlings were inserted into these holes and supported with PVC pipes filled with 0.3 cm pebbles. Separate units were prepared for each treatment, and nutrient solutions were replenished weekly while data were recorded.

The NFT system consisted of 6-inch diameter PVC pipes through which a thin film of water and nutrient solution continuously flowed from buckets positioned 2 ft above the pipes (Figure 1B). Excess solution drained into collection buckets placed 1 ft below and was recirculated to the upper buckets using pumps, ensuring a continuous flow. Seedlings were similarly supported in small PVC pipes filled with 0.3 cm pebbles. In Both systems the seedlings were allowed to grow until maturity where growth parameters were recorded on weekly basis up to maturity and the biochemical constituents were analyzed at full maturity using standard procedures.

2.2. Nutrient solution

The nutrient solution was prepared following Hoagland and Arnon (1938) with slight modifications using commercial-grade chemicals and supplied to the plants on a weekly basis. It contained N (210), P (31), K (234), Ca (150), Mg (34), S (64), Fe (2.5), Cu (0.02), Zn (0.05), Mn (0.5), B (0.5), and Mo (0.01) mg/L. Unless otherwise indicated, all the chemicals were obtained from Fisher Scientific, Pittsburgh, PA, USA.

Stock solutions of Zn and Fe were made up to 200 ppm in distilled water using their chloride salts, which were diluted to four different concentrations i.e. 5, 10, 15, and 20 ppm for the experiment.

2.3. Plant Growth Parameters

- **Plant height:** The plant height was measured with a tape from the base of the plant to the tip of the plant. Height of 3 plants per treatment were measured and average value was recorded.
- **Number of branches per plant*:*** Branches of three randomly selected plants in each treatment were counted and the average value was calculated.
- **Number of leaves/leaflets:** The leaflets of three randomly selected plants in each treatment were counted and the average values were calculated.
- **Number of flowering buds per plant:** The numbers of buds were counted when the buds emerged.
- **Number of fruits per plant**: The numbers of fruits in each plant in all treatments were counted when the plants started fruiting.

2.4. Proximate composition

2.4.1. Moisture content

Moisture content in the tomato samples was determined using the oven-drying method. One gram of ground tomato was placed in a pre-weighed petri dish, and the weight was recorded. The dish was partially covered and placed in an oven at 105°C until the weight stabilized, indicating complete moisture evaporation. The moisture content was calculated as:

$$\text{Moisture (\%)} = ((W_1 - W_2) / W_1) \times 100$$

Where W_1 = Weight of sample before drying (g) and W_2 = Weight of sample after drying (g).

2.5. Crude protein

To determine the protein content of tomato fruits and leaves, the nitrogen content of the samples was analyzed through Kjeldahl apparatus. One gram of the sample was digested with CuSO4 (1g) and K2SO4 (7g) with the addition of H2SO4 (15mL) at 350°C until clear. The digest was diluted to 100 mL, and a 10 mL aliquot was mixed with NaOH in a Kjeldahl apparatus to release ammonia, captured in boric acid 4%. Titration with HCl calculated nitrogen content, yielding protein content through the formulas:

Crude Protein (%) = Nitrogen (%) × F

$$\text{Nitrogen (\%)} = [(V_1 - V_2) \times N \times 1.4007] / W$$

Where V_1 = Volume of acid used in titration (sample), V_2 = Volume of acid used in titration (blank) N = Normality of acid, W = Weight of sample (g), F = Conversion factor (6.25 for plant material)

2.6. Crude fats

Crude fat extraction used a Soxhlet apparatus with petroleum ether (40-60°C). A gram of the sample in filter paper was placed in a thimble connected to a pre-weighed flask of ether. The ether evaporated and condensed, siphoning back into the flask until extraction ceased. The flask was dried, cooled, and weighed, with fat content calculated as

$$\text{Crude Fat (\%)} = (Wf / W) \times 100$$

Where Wf = Weight of extracted fat (g), W = Weight of sample (g)

2.7. Crude fiber

Crude fiber was measured by digesting samples with acid and alkali, followed by washing with Ether and ashing. A two-gram sample was digested in 2.5% H2SO2 at 100°C for three hours, filtered, and subsequently treated with 2.5% NaOH. After drying and ashing at 550°C, the fiber content was calculated as:

$$\text{Crude Fiber (\%)} = ((W1 - W2) / W) \times 100$$

Where W1 represents the weight of residues after acid and alkali digestion (g), W2 the weight of ash after incineration of the residue (g) and W the weight of sample (g).

2.8. Ash content

Ash content was assessed by heating a cleaned crucible at 550°C, then weighing it. Two grams of the sample were added, and the crucible was heated until only ash remained. The ash percentage was calculated as:

$$\text{Ash (\%)} = (W_3 / W) \times 100$$

Where: W_3 = Weight of ash after incineration (g) W = Original weight of the dry sample used (g)

2.9. Nitrogen-Free extract (NFE)

Nitrogen-free extract, representing digestible carbohydrates, was calculated by summing the percentages of proximate components and subtracting from 100:

$$\text{NFE (\%)} = 100 - (\text{\%Moisture} + \text{\%Ash} + \text{\%Crude Protein} + \text{\%Crude Fat} + \text{\%Crude Fiber})$$

2.10. Minerals determination

A gram of dried and ground sample was accurately weighed, and it was digested with a mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) and heated gently until a clear solution was obtained. The digest was cool and filtered. The digest was diluted with deionized water to 50 mL and was used for mineral analysis. The FAAS instrument was turned on and allowed to warm up. The wavelength and lamp current specific to the element being analyzed were set up, and the air acetylene flame was adjusted for each element. The blank was first aspirated, then the standard solution (Merck Co.), and after that, the sample solution was aspirated for each mineral determination. The values were calculated by the following formula

$$\text{Concentration (mg/kg)} = (C \times V) / W$$

Where

- C = Concentration of the element from the calibration curve (mg/L)
- V = Final volume of the digest (L)
- W = Weight of the sample (kg)

3. Results and discussion

Two hydroponic systems, i.e. DWC and NFT were evaluated under varying concentration of Fe and Zn (5, 10, 15, and 20 ppm) for their effects on the growth and biochemical composition of the tomato cultivar Reo Grande.

3.1. Growth Parameters

Table 1 summarizes the growth parameters obtained. The tallest plants (59.8 cm) were observed at 10 ppm in the DWC system, followed by 54.0 cm in NFT. Leaf production was also maximized in DWC, with 129 leaves per plant at 10 ppm and 122 at 15 ppm, compared to a maximum of 119 leaves in NFT at 10 ppm. The highest number of branches was recorded at 10 ppm in both systems (37 in DWC and 34 in NFT). Bud formation peaked in DWC at 15 ppm (27 buds per plant), slightly higher than 24 buds at 10 ppm; NFT showed a maximum of 21 buds at 10 ppm. Fruit production followed a similar trend, with the greatest yield at 10 ppm in both systems (29 fruits in DWC and 24 in NFT).

These findings highlight that the 10 ppm Fe and Zn treatment in DWC consistently supported superior vegetative growth and fruiting compared to NFT. Comparable outcomes have been reported by Chowdhury et al. (2024), who observed that hydroponic systems significantly enhanced plant growth and biochemical composition. Likewise, Haripriya et al. (2024) and Chowdhury et al. (2024) demonstrated that hydroponics outperformed soil cultivation, particularly in contexts where soil-based farming is limited or costly. This reinforces the potential of hydroponic systems, especially DWC, as an efficient and sustainable option for tomato production.

Table 1 Growth parameters of tomato Cv. Reo Grande as affected by different concentrations of Fe and Zn in DWC and NFT hydroponic systems

Concentration (Ppm)	**5**		**10**		**15**		**20**	
Hydroponic Systems*	DWC	NFT	DWC	NFT	DWC	NFT	DWC	NFT
Height (Cm)	46.2	37.1	59.8	54.0	52.0	49.0	29.5	28.0
Leave (No/P)	96.0	88.0	129.0	119.0	122.0	116.0	78.0	73.0
Branch (No/P)	28.0	26.0	37.0	34.0	31.0	27.0	20.0	17.0
Bud (No/P)	18.0	15.0	24.0	21.0	27.0	24.0	12.0	10.0
Fruit (No/P)	16.0	13.0	29.0	24.0	23.0	18.0	9.00	7.00

*DWC, Deep Water Culture; NFT, Nutrient Film Technique

Table 2 Analysis of variance (sum of squares) for plant growth parameters of tomato Cv. Reo Grande as affected by different concentrations of Fe and Zn in DWC and NFT hydroponic systems

Source of Variation	**D.F.**	**Sum of Squares/Significance**				
		Height	Leaves (No/P)	Branches (No/P)	Buds (No./P)	Fruits (No./P)
Concentration (C)	3	2551.5**	10434.1**	930.2**	496.8**	237.2**
System (S)	1	223.4**	361.0**	112.9**	22.6**	23.8**
Time (T)	7	9894.3**	65920.8**	4893.4**	2426.9**	3124.1**
C × S	3	33.9**	27.6*	2.05NS	11.8**	4.92NS
C × T	21	664.5**	3248.1**	266.9**	276.2**	463.9**
S × T	7	14.1NS	142.3**	22.0**	11.4*	40.6**
Error	21	19.0	45.1	16.6	13.2	13.20
Total	63	13600.8	80179.0	6243.9	3258.9	3907.7

NS non-significant; * significant at p≤0.05; ** significant at p≤0.01; d.f. = degree of freedom

Analysis of variance results (Table 2) indicated that concentration, hydroponic system and their interactions significantly ($P < 0.05$) influenced tomato growth parameters, with only a few exceptions where no significant effects were observed. Consistent with the descriptive results, Fe and Zn concentrations of 10–15 ppm promoted the highest growth values, suggesting that moderate levels of these micronutrients are optimal for tomato performance in hydroponic systems (Gurmani et al., 2012; Rabbi et al., 2024).

In contrast, higher concentrations (20 ppm) were associated with reduced growth, likely due to nutrient stress or toxicity, as reported in earlier studies where excessive Zn or Fe impaired plant metabolic processes and ionic balance (Meng et al., 2023; Katai et al., 2013).

3.2. Proximate Composition

Table 3 presents the proximate composition of different plant parts (green leaves, diseased leaves, and fruits) as influenced by hydroponic systems and varying concentrations of Fe and Zn.

Table 3 Proximate composition (%) of tomato Cv. Reo Grande as affected by different concentrations of Fe and Zn in DWC and NFT hydroponic systems

Proximate Composition	**Conc. (ppm)**	**5**		**10**		**15**		**20**	
	Systems	DWC	NFT	DWC	NFT	DWC	NFT	DWC	NFT
Crude Protein	Green leaves	4.3	3.91	4.81	4.1	9.4	8.5	3.7	2.7
	Dry leaves	5.46	4.21	8.53	5.28	2.18	3.51	8.2	5.87
	Fruits	7.43	4.51	1.31	2.32	4.15	5.21	4.37	2.51
Moisture	Green leaves	10.67	11.2	10.61	11.7	18.90	7.50	17.5	5.2
	Dry leaves	9.79	10.25	10.53	9.45	16.64	9.25	18.05	12.36
	Fruits	10.63	9.21	9.74	8.47	18.96	11.25	16.2	12.42
Ash	Green leaves	3.77	3.8	3.56	4.2	3.36	4.82	1.515	3.8
	Dry leaves	0.925	1.23	0.36	1.89	1.665	1.72	4.89	1.33
	Fruits	0.11	2.14	3.06	3.26	3.2	3.01	0.38	2.21
Crude Fiber	Green leaves	8.24	4.25	7.23	5.24	4.62	3.25	4.25	2.5
	Dry leaves	7.84	4.35	7.04	5.23	4.61	3.24	4.23	2.57
	Fruits	7.60	5.31	4.64	3.50	4.58	4.10	3.86	2.68
Crude Fat	Green leaves	2.12	1.98	3.08	2.5	1.24	2.15	2.87	1.18
	Dry leaves	1.99	0.95	2.17	1.72	1.17	0.22	1.24	0.77
	Fruits	1.17	1.12	1.87	1.88	4.31	2.74	3.17	2.55
NFE	Green leaves	74.74	74.86	70.68	72.2	72.46	73.78	70.15	84.62
	Dry leaves	73.96	79.01	71.35	76.4	73.7	82.05	63.37	77.1
	Fruits	73.03	77.71	79.36	80.5	64.78	73.69	71.99	77.63

The results indicated that crude protein was highest (9.4%) in green leaves, whereas moisture content reached its maximum (18.96%) in fruits at 15 ppm under the DWC system. Ash content was highest (4.89%) in diseased leaves at 20 ppm, while crude fiber showed a maximum value (8.24%) in green leaves at 5 ppm. Crude fat was highest (3.08%) in green leaves at 10 ppm in the same system. Nitrogen-free extract (NFE) recorded its maximum value in the NFT system at 15 ppm. The data was in line with Sapkota et al, 2019 who worked on nutrient composition of plants grown in hydroponic systems. The work done was also supported by Okonwu et al (2018) and Yang et al. 2020) who worked on plant composition grown in hydroponic and other media.

ANOVA results (Table 4) revealed that plant part, mineral concentration, hydroponic system, and their interactions generally had no significant effect, except in the case of crude fiber, where all factors and their interactions significantly influenced the outcome ($p < 0.05$). This differential response suggests that proximate parameters vary in their sensitivity to Fe and Zn supplementation, possibly due to the roles of these micronutrients in enzymatic processes and nutrient assimilation, including nitrogen and phosphorus metabolism (Akca et al., 2023; Kihara et al., 2024). Interestingly, at higher concentrations of Fe and Zn (20 ppm), most proximate components declined, except for ash, indicating potential stress effects. However, the increased ash content may reflect enhanced accumulation of structural elements such as carbon and nitrogen, which are integral to protein, crude fiber, and other biochemical constituents (Yu et al., 2022).

Table 4 Analysis of variance (sum of squares) for proximate composition (%) of tomato Cv. Reo Grande as affected by different concentrations of Fe and Zn in DWC and NFT hydroponic systems

Source of Variation	**D.F.**	**Sum of Squares/Significance**					
		Moisture	Crude Protein	Lipids	Ash	Crude Fibers	NFE
Plant Parts (P)	2	14.80^{NS}	9.43^{NS}	5.16*	15.08^{NS}	0.80**	1.75^{NS}
Concentrations (C)	3	49.84^{NS}	4.33^{NS}	1.31^{NS}	3.23^{NS}	31.52**	16.68^{NS}
Systems (S)	1	66.53*	5.24*	1.84^{NS}	1.82^{NS}	21.13**	204.98**
P × C	6	56.86^{NS}	77.73^{NS}	8.40^{NS}	12.07^{NS}	5.55**	205.16*
P × S	2	0.303^{NS}	0.59^{NS}	0.12^{NS}	2.83^{NS}	1.13**	15.16^{NS}
C × S	3	58.13^{NS}	4.54	0.31^{NS}	0.39^{NS}	4.08**	69.90^{NS}
Error	6	35.62	7.60	2.38	10.16	0.19	38.82
Total	23	281.73	109.45	19.53	45.59	64.41	552.46

NS non-significant; * significant at p≤0.05; ** significant at p≤0.01; d.f. = degree of freedom

3.3. Mineral Profile of Tomato Crop

Table 5 summarizes the effects of Fe and Zn concentrations and hydroponic systems on the mineral contents of different plant parts of tomato cultivar Reo Grande.

The results showed that several minerals, including Na (119.2 mg/kg), Ca (186.02 mg/kg), Mg (217.24 mg/kg), P (385.21 mg/kg), Ni (0.491 mg/kg), Fe (5.58 mg/kg), Zn (3.75 mg/kg), Cu (1.15 mg/kg), and Mn (1.41 mg/kg), reached their maximum values in fruits or diseased leaves at 10 ppm under the DWC system. In contrast, K (668.25 mg/kg) and Co (21.45 mg/kg) attained peak levels at 15 ppm, also under DWC. Compared with NFT, DWC consistently promoted higher mineral accumulation.

Table 5 Mineral (mg/Kg) of tomato Cv. Reo Grande as affected by different concentrations of Fe and Zn in DWC and NFT hydroponic systems

Mineral	**Conc.(ppm)**	**5**		**10**		**15**		**20**	
	Systems	DWC	NFT	DWC	NFT	DWC	NFT	DWC	NFT
Na	Green leaves	59.5	52.3	92.2	84.24	88.2	79.1	69	61
	Dry leaves	71.32	64.1	109.21	99.5	95.5	87.3	75.4	66.1
	Fruits	84.15	76.8	119.2	102.4	116.5	105.7	86.5	71.2
K	Green leaves	488.34	474.7	538.24	523.8	518.21	506.11	497.2	471.7
	Dry leaves	495.36	474.5	585.25	561.4	542.45	529.2	515.25	504.5
	Fruits	623.2	612.8	652.21	635.98	668.25	653.5	628.21	602.2
Ca	Green leaves	125.3	102.1	167.5	149.9	146.2	135.8	130.02	120.7

	Dry leaves	155.45	145.1	186.02	166.5	151.21	139.9	145.22	133.9
	Fruits	99.45	91.01	145.02	131.1	123.21	115.4	109.22	102
Mg	Green leaves	165.24	146.9	195.23	178.2	167.2	156.3	149.25	139
	Dry leaves	174.21	162.8	208.21	199	184.25	172	155.2	148
	Fruits	168.23	142	217.24	197.2	187.26	175.8	169.11	151.6
P	Green leaves	338.15	309.9	376.21	363.9	349.21	338.5	321.21	303.0
	Dry leaves	355.21	337.1	385.21	371.9	261.35	248.08	232.15	220.5
	Fruits	351.21	342.8	371.2	364.3	363.21	351.6	338.21	317.0
Ni	Green leaves	0.329	0.318	0.381	0.369	0.358	0.345	0.327	0.315
	Dry leaves	0.420	0.412	0.491	0.471	0.441	0.433	0.427	0.416
	Fruits	0.329	0.318	0.378	0.365	0.350	0.341	0.330	0.319
Fe	Green leaves	4.79	4.68	5.23	5.11	4.98	4.89	4.72	4.61
	Dry leaves	5.23	5.11	5.58	5.46	5.42	5.30	5.26	5.12
	Fruits	5.15	5.03	5.56	5.38	5.44	5.33	5.28	5.09
Zn	Green leaves	1.95	1.83	2.37	2.21	2.12	2.01	1.87	1.76
	Dry leaves	2.25	2.13	2.65	2.51	2.48	2.35	2.30	2.19
	Fruits	3.39	3.21	3.75	3.66	3.35	3.39	3.28	3.21
Co	Green leaves	10.11	10.02	10.54	10.45	10.33	10.22	10.11	10.01
	Dry leaves	10.39	10.28	10.63	10.55	10.48	10.37	10.26	10.15
	Fruits	21.02	20.96	21.21	21.11	21.45	21.33	21.12	21.04
Cu	Green leaves	0.74	0.61	1.07	0.95	0.84	0.77	0.72	0.66
	Dry leaves	0.91	0.83	1.15	1.02	0.99	0.91	0.87	0.81
	Fruits	0.114	0.101	0.135	0.122	0.128	0.100	0.106	0.101
Mn	Green leaves	0.42	0.29	0.81	0.75	0.62	0.51	0.45	0.34
	Dry leaves	0.62	0.51	0.95	0.88	0.74	0.61	0.58	0.52
	Fruits	1.12	1.01	1.41	1.29	1.25	1.24	1.11	1.00

Overall, these findings suggest that moderate Fe and Zn supplementation (10–15 ppm) enhances the uptake and translocation of multiple minerals, likely by improving enzymatic activity and ionic balance within the plant (Wang et al., 2018). The stronger performance of DWC may be attributed to its more stable nutrient environment, which minimizes fluctuations and supports synergistic or antagonistic interactions among nutrients.

The analysis of variance results further confirmed that Fe and Zn concentration, plant parts, and hydroponic system individually had significant effects ($p < 0.05$) on most minerals (Table 6). However, interactions such as plant parts × system and concentration × system were not significant, indicating that the trends of mineral response were consistent across different systems and plant organs. This highlights that mineral accumulation patterns are primarily shaped by individual factors, particularly nutrient concentration and hydroponic system, rather than their combined effects.

The overall results emphasize the importance of maintaining Fe and Zn at moderate levels to optimize mineral nutrition in tomatoes, with DWC offering a more favorable platform for nutrient uptake compared to NFT.

Table 6A Analysis of variance (sum of squares) for macro-mineral contents of tomato Cv. Reo Grande as affected by different concentrations of Fe and Zn in DWC and NFT hydroponic systems

Source of Variation	D.F.	Sum of Squares/Significance				
		Na	K	Ca	Mg	P
Plant Parts (P)	2	1958.6**	79579.9**	5891.2**	987.2**	10154.6**
Concentrations (C)	3	5000.1**	12285.3**	5253.6**	7708.3**	22142.4**
Systems (S)	1	569.8**	1695.1**	942.6**	1229.5**	1259.3**
P × C	6	181.5**	414.5**	660.2**	427.4**	15006.0**
P × S	2	24.1 NS	0.6NS	34.5NS	77.2*	28.9NS
C × S	3	15.7 NS	48.7NS	60.0NS	52.5NS	61.0NS
Error	6	14.7	129.5	45.6	37.3	107.1
Total	23	7764.9	96226.1	12887.8	10519.3	48759.4

NS non-significant; * significant at p≤0.05; ** significant at p≤0.01; d.f. = degree of freedom

Table 6B Analysis of variance (sum of squares) for micro-mineral contents of tomato Cv. Reo Grande as affected by different concentrations of Fe and Zn in DWC and NFT hydroponic systems

Source of Variation	D.F.	Sum of Squares/Significance					
		Ni	Fe	Zn	Co	Cu	Mn
Plant Parts (P)	2	0.050**	0.943**	8.391**	627.81**	3.09**	0.742**
Concentrations (C)	3	0.012**	0.620**	0.681**	0.435**	0.15**	0.431**
Systems (S)	1	8.1E-4**	0.097**	0.070**	0.056**	0.03**	0.077**
P × C	6	3.3E-4**	0.034**	0.028NS	0.154**	0.06**	0.014**
P × S	2	1.1E-6NS	0.002NS	0.003NS	1.58E-4NS	0.008**	0.002NS
C × S	3	2.5E-5NS	0.002NS	0.005NS	6.33E-4NS	0.002NS	0.002NS
Error	6	2.8E-5	0.001	0.008	8.42E-4	0.002	0.001
Total	23	0.06	1.700	9.188	628.5	3.351	1.500

NS non-significant; * significant at p≤0.05; ** significant at p≤0.01; d.f. = degree of freedom

4. Conclusion

The present study demonstrates that hydroponic systems significantly influence the growth and mineral composition of tomato plants, even under identical nutrient treatments. Deep Water Culture (DWC) consistently outperformed the Nutrient Film Technique (NFT), resulting in better growth and nutrient accumulation. Variations in Fe and Zn concentrations had a pronounced effect on plant growth and biochemical constituents, with moderate levels (10–15 ppm) producing the most favorable responses. In contrast, higher concentrations (20 ppm) adversely affected growth and composition, indicating potential toxicity. Additionally, certain minerals accumulated more at elevated Fe and Zn levels, suggesting possible synergistic interactions between micronutrients. Based on these findings, the use of DWC is recommended for maximizing plant growth and nutrient uptake in hydroponic systems. Furthermore, careful management of micronutrient application is crucial; maintaining Fe and Zn concentrations within the moderate range (10–15 ppm) is advised to achieve optimal growth, yield, and biochemical composition while avoiding the detrimental effects of excessive micronutrient levels.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interests.

Authorship contribution statement

Sara Aslam: Investigation. Methodology, Formal analysis, Writing-original draft, Project administration. Saleem Ullah: Conceptualization, Methodology, Project supervision. Aimal Khan: Methodology, Data visualization, Writing-review and editing, Project supervision

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