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Coupled Efficacy of Magneto-Electric Water Irrigation with Foliar Iron Fertilization for Spinach Growth

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Abstract: The lack of trace element iron has become a key factor restricting vegetable yield and quality improvement. To address the low production efficiency of water–fertilizer coupling in agricultural production, we used a combination of experimental research, theoretical analysis, and mathematical modeling to systematically determine the effects of magneto-electric water irrigation with iron application on spinach growth and physiology, its yield and quality, and soil water transport characteristics. Compared with conventional water irrigation, under magneto-electric water irrigation, the water volume and applied iron concentration average increased the total accumulation of nitrogen, carbon, and iron in the aboveground part of spinach by 3.71%, 10.16%, and 14.14%, respectively, and the aboveground part of spinach had the highest total accumulation of nitrogen and carbon when irrigation water was 3300 m^3 ha^{-1} and iron fertilizer application at 0.15%. Additionally, magneto-electric water irrigation increased spinach aboveground fresh weight and soluble sugar and protein content by an average of 13.34, 18.26, and 11.61%, respectively. Based on a comprehensive quantitative evaluation and analysis of aboveground nutrient accumulation in spinach, aboveground fresh weight, water use efficiency, and soluble sugar and protein content, we determined the optimal irrigation water and iron fertilizer application for spinach growth.

Keywords: grey correlation; iron fertilizer; magneto-electric; quality; productivity; yield; WUE

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1. Introduction

China is a large country with extensive vegetable cultivation, but to maintain quality of life and dietary habits, demand for vegetables is increasing daily, and in 2019 China's vegetable planting area reached 20.86 mha, with a total output of 721.02 mt and per capita possession of 515.9 kg, which ranked it first globally [1]. Spinach has a sweet and soft texture, as well as high protein, vitamin, carotene, iron, and other nutrient content. Furthermore, its leaves contain chromium and a kind of insulin substance, which can maintain bodily blood sugar levels and has a therapeutic effect, making it one of the most consumed leafy green vegetables [2]. Covering a large area and rich in light and heat resources, northwest China is an important vegetable production base [3], but yield is relatively low due to low precipitation, lack of water resources, and inefficient utilization of crop water resources. Therefore, the development of a new technology that can both improve water resource productivity and realize efficient and sustainable use of land resources has become an important research focus for the development of efficient water-saving agriculture in arid areas of Xinjiang. Improving the physicochemical properties of irrigation water itself is one of the important ways to improve irrigation water utilization efficiency [4]. Consequently, many scholars have conducted a wide range of in-depth investigations and found a water treatment technology suitable for agricultural irrigation (irrigation water

activation technology). Irrigation water activation technology mainly includes magnetization and de-electronic treatment technologies. Magnetized or de-electrified irrigation water promotes crop seed germination and seedling growth and development, enhancing crop resistance, increasing crop yield, and improving crop quality [5]. However, in the activation technology of irrigation water, which is mostly a single activation treatment, the effect of irrigation water treated with the combination of magnetization and de-electrification technology (hereinafter referred to as magneto-electric water) on soil material transport and crop growth has rarely been reported.

Iron ranks first among trace elements necessary for normal crop growth and is a key element in plant energy conversion, cell structure composition, and metabolism. It is the central substance of signaling and signal transduction [6,7]. Excessive application of large quantities of elements such as nitrogen, phosphorus, and potassium has increased crop yields per unit area, resulting in a decrease in soil micronutrients as they are utilized by the crops [8,9]. Conversely, readily oxidized soil Fe has resulted in a decrease in soil Fe. Fe^{3+} is the main iron element, and in neutral and alkaline soil its solubility is very low, which also limits effective iron absorption [10], resulting in soil iron content insufficient for vegetable growth and restricted development of the vegetable cultivation industry. Notably, crops cannot only absorb iron through the root system but also through the leaves. Recently [11–13], experimental research on soybean, rice, wheat, and other crops has found that foliar spraying of iron fertilizer efficiently promotes its absorption and utilization. Iron deficiency will lead to a decrease in crop yield and quality, while excessive accumulation in the crop will also inhibit crop growth and development [14]. Therefore, to maximize iron production efficiency, it is crucial to determine a reasonable concentration for application under magneto-electric water irrigation.

Therefore, using spinach, we selected different types of irrigation water, irrigation volume, and iron fertilizer concentration treatments to investigate the synergistic effect of magneto-electric water and iron fertilizer foliar spraying on spinach growth. Our aim was to provide a theoretical basis and guidance for the development and scientific application of the coupling technology of magneto-electric water irrigation and iron elements.

2. Materials and Methods

2.1. Experimental Area Overview

The experiment was conducted in a field in the 10th regiment of Alar City, the first division of Xinjiang Construction Corps (latitude 40°39′14″ N, longitude 81°16′21″ E), which is located in the upper reaches of the Tarim River, northern Taklamakan Desert, southern foothills of the Tianshan Mountains. This area belongs to the inland extreme arid climate zone of the warm belt, with an average annual rainfall of c. 50 mm. Average annual evaporation is about 2200 mm, surface evaporation is strong, the annual sunshine hours are c. 2900 h, the frost-free period is more than 200 d, and the depth to groundwater is 5.0 m. The soil texture of the experimental plots at 0–50 cm was sandy (International Triangular System of Soil Texture Classification).

2.2. Experimental Design

Before sowing, 150 kg ha^{-1} of organic fertilizer was evenly spread, followed by ploughing at a rotary tillage depth of 0–30 cm. The spinach seed variety used was "Hybrid Pig's Ear", which has a 45-day fertility period. Spinach planting pattern: a mulch film covers 2 rows of spinach, and a drip irrigation tape is laid in the middle of the 2 rows of spinach, with a row spacing of 10 cm and a plant spacing of 10 cm. The plot size was 150 × 50 cm, and 30 plants were planted in each plot. A patch-type drip irrigation system was used, with a drip head flow rate of 3.8 L h^{-1} and a drip head spacing of 20 cm. With the first irrigation, 300 kg ha^{-1} of urea with 75 kg ha^{-1} of potassium phosphate was applied.

We set up three factors: irrigation water type, irrigation water volume, and iron fertilizer concentration. The irrigation water type contained normal water and magnetized de-electrified water irrigation, the irrigation water volume contained five gradients, and

the iron fertilizer contained five application gradients; the amount of irrigation water and iron fertilizer application in this experiment refer to previous research results [15,16]. The magnetized de-electrified water was prepared by the magneto-electric equipment after 3000 Gs magnetization intensity. The voltage of the electric field was 5–8 mV, and the flow rate of irrigation water in the magneto-electric equipment was 0.35–0.53 m s^{-1}. The iron fertilizer was prepared by $FeSO_4$ solution. A total of 27 experimental treatments were designed, and the specific experimental design is shown in Table 1. Physical and chemical properties of magneto-electric and conventional water are listed in Table 2 [17].

Table 1. Treatment of experimental design.

Irrigation Water Type	Treatments	Irrigation Volume (m^3 ha^{-1})	Iron Fertilizer Concentration (%)
Conventional water	CK III Fe1	2400	0
	CK III Fe3		0.1
Magneto-electric water	MD I Fe1	1500	0
	MD I Fe2		0.05
	MD I Fe3		0.1
	MD I Fe4		0.15
	MD I Fe5		0.2
	MD II Fe1	1950	0
	MD II Fe2		0.05
	MD II Fe3		0.1
	MD II Fe4		0.15
	MD II Fe5		0.2
	MD III Fe1	2400	0
	MD III Fe2		0.05
	MD III Fe3		0.1
	MD III Fe4		0.15
	MD III Fe5		0.2
	MD IV Fe1	2850	0
	MD IV Fe2		0.05
	MD IV Fe3		0.1
	MD IV Fe4		0.15
	MD IV Fe5		0.2
	MD V Fe1	3300	0
	MD V Fe2		0.05
	MD V Fe3		0.1
	MD V Fe4		0.15
	MD V Fe5		0.2

Note: CK is normal water without magneto-electric equipment, MD is magnetized water with magneto-electric equipment.

Table 2. Physical and chemical properties of magneto-electric water and conventional water.

Irrigation Water Type	Dissolved Oxygen in Water (mg L^{-1})	Surface Tension (mN m^{-1})	pH	Mineralization (g L^{-1})
Conventional water	8.77 ± 0.02	73.95 ± 0.52	7.5 ± 0.1	1.21 ± 0.12
Magneto-electric water	10.01 ± 0.16	70.11 ± 0.07	7.6 ± 0.2	1.21 ± 0.09

Foliar spraying of iron fertilizer was used, the experimental treatments irrigated with normal water used non-magneto-electric water to dispense the iron fertilizer, and the experimental treatments irrigated with magnetized de-electrified water used magneto-electric water to dispense the iron fertilizer; each time, the iron fertilizer solution was uniformly applied to spinach leaves with a sprayer until droplets were formed on the foliage to stop the spraying, all the experimental treatments were sprayed three times

throughout the whole plantation period, and all the experimental treatments were sprayed on 8, 18, and 28 June. In order to prevent the rapid oxidation of Fe^{2+} to Fe^{3+} from losing its fertilizer effect and to enhance the viscosity of the iron fertilizer solution on spinach leaves, we added 0.02% ascorbic acid and 0.01% organosilicon surfactant to the iron fertilizer solution.

2.3. Measurement of Indicators

1. Soil moisture content

Samples were taken at 13, 19, 29, and 43 d after sowing (1 d after irrigation), and sampling depths were 0, 10, 20, 30, and 40 cm, respectively. Soil mass water content was determined by the drying method (105 ± 2 °C), and soil volumetric water content was obtained by multiplying soil dry bulk weight with soil mass water content.

2. Plant height, aboveground fresh weight, and yield

Five spinach plants were randomly selected from each treatment on the 10th, 20th, 30th, and 40th d after sowing, and their height (vertical distance from the highest point of the plant to the soil surface) was measured with a steel ruler. Simultaneously, the aboveground part of each spinach plant was harvested and weighed to determine fresh weight. In addition, the yield of the experimental treatments was calculated based on the average aboveground fresh weight of spinach per plant at 40th d with sowing density.

3. Total accumulation of carbon, nitrogen, and iron in the aboveground part of spinach

Five spinach samples were randomly selected from each treatment at 13, 19, 29, and 43 d after sowing, and a dry sample of spinach dried from the fresh weight of the ground part of the spinach was taken and ground into powder and sieved through a 0.15 mm sieve. The sieved spinach powder samples were wrapped in specific tinfoil, and the total carbon and nitrogen contents accumulated by spinach in each treatment were determined with an Elemental Analyzer. The total accumulation of carbon and nitrogen in the aboveground part of spinach was calculated according to dry weight. Another dried sample was taken and decomposed by dry ash, and then digested with dilute hydrochloric acid, and the total iron in the spinach leaves was determined by an atomic absorption spectrophotometer at 248.3 nm. Then, the total accumulation of iron in the aboveground part of spinach was calculated according to the dry weight.

4. Soluble protein and soluble sugar content

After the spinach matured, 5 spinach samples were randomly selected from each treatment. One g of fresh spinach and 2 mL of distilled water were added to fully grind the spinach, then the grinding solution was transferred into a 25 mL volumetric flask. The volume was adjusted to scale, and then shaken well. Two mL was placed in a centrifuge tube and centrifuged at 5000 r min^{-1} for 10 min, and 0.1 mL of supernatant was transferred into a test tube, then 0.9 mL of distilled water was added. Five mL of staining solution was added, shaken, and mixed well, and then the absorbance value of the solution was measured under the wavelength of 595 nm. After 2 min of reaction, the content of soluble proteins and soluble sugars in each sample were calculated according to the standard regression equation.

5. Water use efficiency

Spinach water use efficiency was equal to the ratio of the harvested yield of spinach to the amount of water consumed, calculated by the following formula:

$$WUE = \frac{Y}{ET_c} \quad (1)$$

where WUE is water productivity efficiency (kg m^{-3}); Y is harvested spinach yield (kg ha^{-1}); ET_c is spinach water consumption (m^3 ha^{-1}).

6. Spinach water consumption

The water consumption of different treatments was calculated by the water balance method. Since the irrigation method in this experiment was drip irrigation, after digging the wetted body profile, irrigation water would not seep deeply, and the sandy soil did not produce surface runoff, so they were ignored. The depth of the water table in the test field was about 3 m, and the spinach root system was mainly concentrated between 0–40 cm, so the groundwater supply to spinach growth can be disregarded. In summary, the water balance equation can be simplified as follows:

$$ET_c = I + P + \Delta W \quad (2)$$

where ET_c is spinach water consumption (m^3 ha^{-1}); P is effective rainfall during the reproductive period (m^3 ha^{-1}); I is the amount of irrigation water (m^3 ha^{-1}); ΔW is the change in soil water storage in the calculated soil layer (m^3 ha^{-1}).

2.4. Data Analysis

Experimental data were processed and plotted using Office 2016. Origin 2021 and SPSS25 were used for model parameter fitting and statistical analysis, and the LSD method was used for significance testing.

3. Results

3.1. Magneto-Electric Irrigation with Iron Fertilizer Concentration Effects on Various Spinach Indexes

The irrigation water amount and iron application concentration showed highly significant effects ($p < 0.01$) on F, PH, TCC, TNC, TIC, SS, and SP, respectively (Table 3). The irrigation water type showed highly significant effects ($p < 0.01$) on F, PH, TIC, SS, and SP, but significant effects ($p < 0.05$) on TCC and TNC. There was no interaction between irrigation water type and iron application concentration on all indicators ($p > 0.05$). The irrigation water type and iron application concentration showed no significant effect ($p > 0.05$) on all indicators except for a highly significant effect on TIC ($p < 0.01$).

Table 3. Analysis of main effects of spinach indicators under different irrigation water types, irrigation water volumes, and iron fertilizer concentrations.

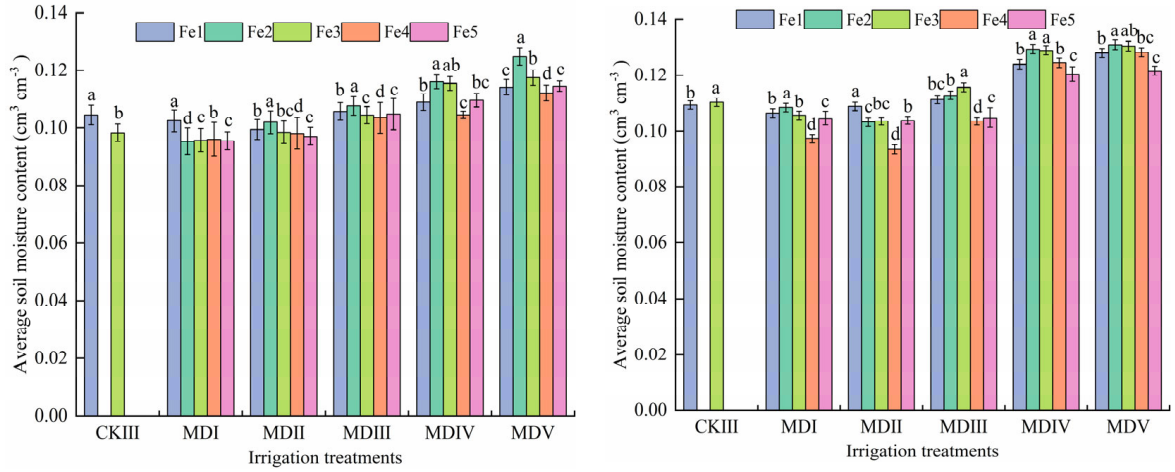
Norm	Treatments				
	Irrigation Water Type × Iron Fertilizer Concentration	**Irrigation Volume × Iron Fertilizer Concentration**	**Irrigation Volume**	**Irrigation Water Type**	**Iron Fertilizer Concentration**
F	ns	ns	**	**	**
PH	ns	ns	**	**	**
TCC	ns	ns	**	*	**
TNC	ns	ns	**	*	**
TIC	ns	**	**	**	**
SS	ns	ns	**	**	**
SP	ns	ns	**	**	**

Note: * indicates a significant effect ($p < 0.05$), ** indicates a highly significant effect ($p < 0.01$), and ns indicates a nonsignificant effect ($p > 0.05$). *F*, *PH*, *TCC*, *TNC*, *TIC*, *SS*, and *SP* represent aboveground fresh weight, plant height, total carbon accumulation, total nitrogen accumulation, total iron accumulation, soluble sugar content, and soluble protein content, respectively.

3.2. Effect of Magneto-Electric Irrigation with Iron Fertilizer Concentration on Soil Moisture Content

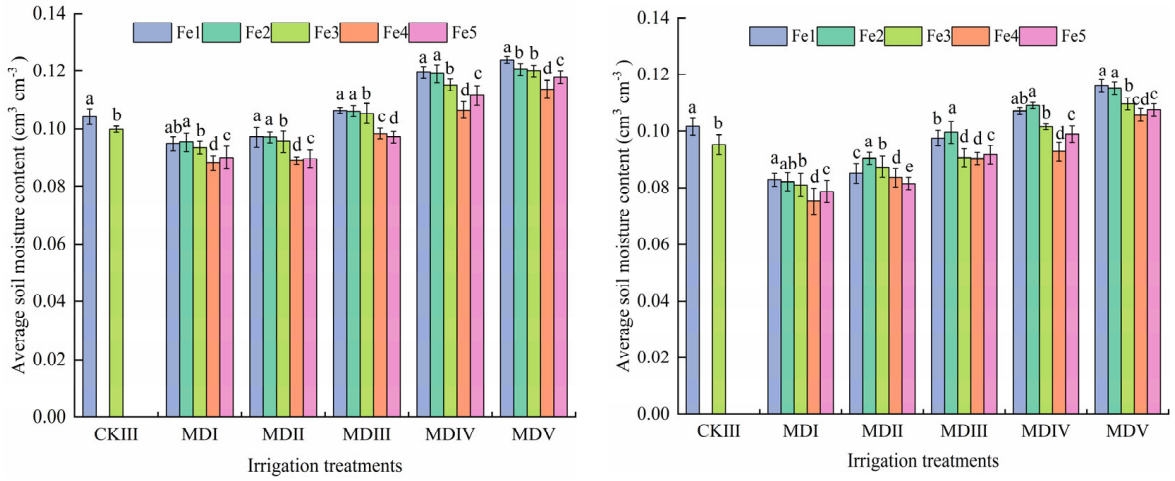
Under CK III, MD I, MD II, MD III, and MD IV treatments, the average soil moisture content 0–20 cm under spinach at 13 d, 19 d, 29 d, and 43 d (1 d after irrigation) after sowing was 0.68–0.78, 0.57–0.74, 0.60–0.73, 0.67–0.78, 0.72–0.89, and 0.79–0.91 times the amount of water holding capacity of the field, respectively (Figures 1 and 2). Fel, Fe2, Fe3, Fe4, and Fe5 showed a gradual increase with increasing irrigation volume. Fel, Fe2,

Fe3, Fe4, and Fe5 treatment of the average soil moisture content 0–20 cm under spinach elicited values of 0.60–0.84, 0.58–0.82, 0.57–0.83, 0.55–0.78, and 0.56–0.79 times the field holding capacity, respectively, indicating that the average soil moisture content of 0–20 cm soil showed an overall trend of decreasing and then increasing with the increase in iron application concentration. The average soil moisture content under magneto-electric water treatment increased by 1.2–6.2% compared with conventional water, indicating that the former water treatment could increase soil water content at soil depths of 0–20 cm.



(**a**) 13 d of sowing (**b**) 19 d of sowing

Figure 1. Soil moisture content under each treatment at 13 d and 19 d (1 d after irrigation) of sowing. Note: Different lowercase letters indicate significant differences ($p < 0.05$).



(**a**) 29 d of sowing (**b**) 43 d of sowing

Figure 2. Soil moisture content under each treatment at 29 d and 43 d (1 d after irrigation) of sowing. Note: CK III indicates conventional water irrigation and the irrigation volume is 2400 m^3 ha^{-1}; MD I, MD II, MD III, MD IV, and MD V indicate magneto-electric water irrigation where the irrigation volume is 1500, 1950, 2400, 2850, and 3300 m^3 ha^{-1}, respectively. Fe1, Fe2, Fe3, Fe4, and Fe5 indicate concentrations of iron applied of 0, 0.05, 0.1, 0.15, and 0.2%, respectively. Different lowercase letters indicate significant differences ($p < 0.05$).

3.3. Effect of Magneto-Electric Irrigation with Iron Fertilizer Concentration on Total Accumulation of Carbon, Nitrogen, and Iron in the Aboveground Part of Spinach

The irrigation water type, irrigation volume, and iron fertilizer concentration significantly affected the total accumulation of carbon, nitrogen, and iron in the aboveground part of spinach ($p < 0.05$) (Figures 3–5). Under the same irrigation volume condition, the total

accumulation of carbon, nitrogen, and iron in the aboveground part of spinach increased and then decreased with increasing iron fertilizer concentration. The total accumulation of carbon, nitrogen, and iron in the aboveground part of spinach gradually increased with increasing irrigation water under the same iron fertilizer concentration. Under the same irrigation volume conditions, the total accumulation of carbon, nitrogen, and iron in the aboveground part of spinach was significantly higher ($p < 0.05$) in the Fe4 treatment than in the unfertilized treatment, and iron fertilizer concentration significantly increased the total accumulation of carbon, nitrogen, and iron in the aboveground part of spinach by 4.72, 13.12, 26.14, and 21.76%; 1.79, 3.79, 6.49, and 5.04%; and 22.95, 42.97, 65.68, and 55.47%, respectively, compared with the unfertilized treatment. Under the same iron fertilizer concentration, the total accumulation of carbon, nitrogen, and iron in the aboveground part of spinach under MD V treatment reached a maximum, and total nitrogen and carbon accumulations were not significantly higher than under MD IV ($p > 0.05$). Moreover, iron in the aboveground part of spinach accumulation under Fe2 and Fe5 treatment was not significantly higher than under MD IV treatment. The total accumulation of carbon, nitrogen, and iron in the aboveground part of spinach under MD III treatment was significantly higher than under CK III treatment ($p < 0.05$).

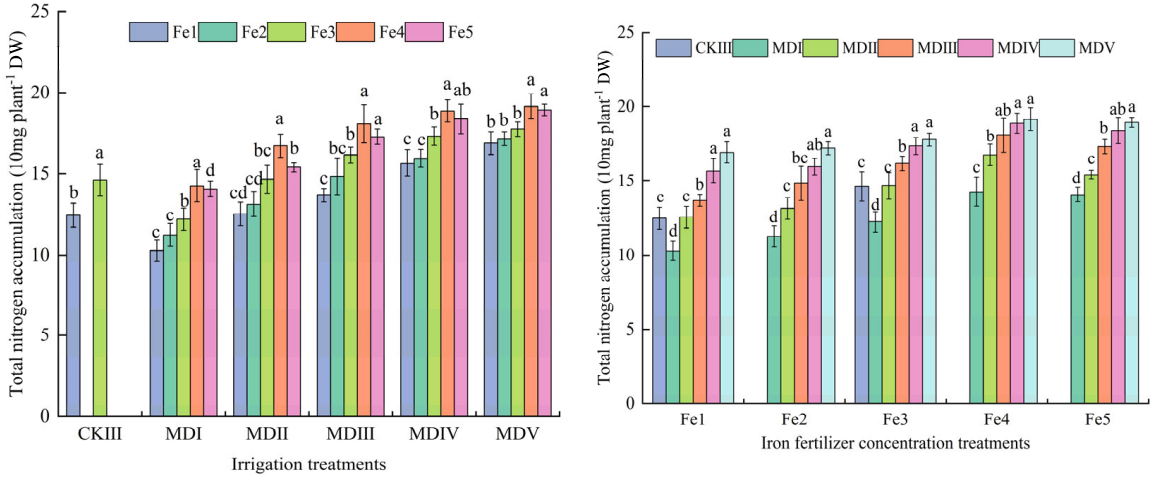


Figure 3. Effect of different treatments on total accumulation of nitrogen in the aboveground part of spinach. Note: Different lowercase letters indicate significant differences ($p < 0.05$).

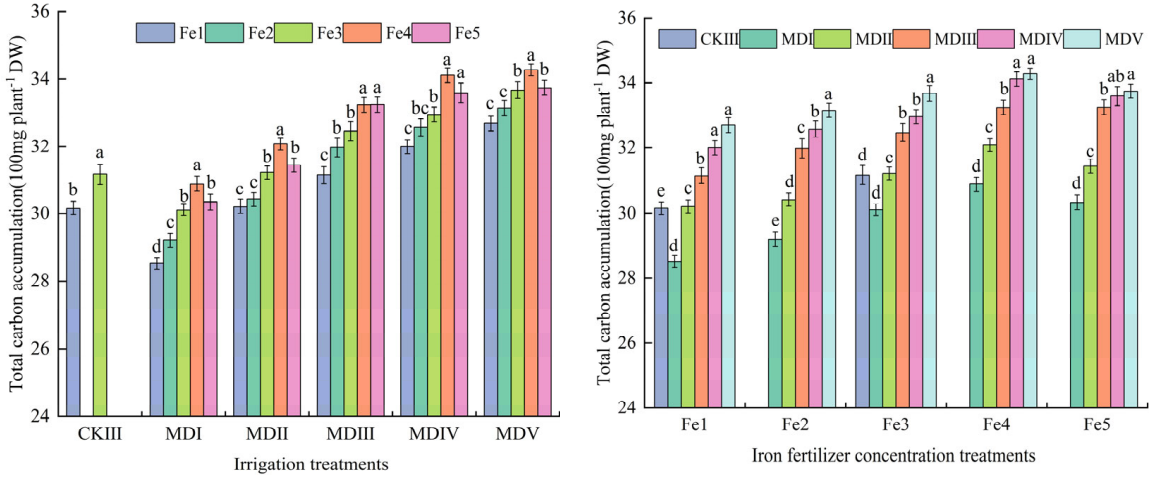


Figure 4. Effect of different treatments on total accumulation of carbon in the aboveground part of spinach. Note: Different lowercase letters indicate significant differences ($p < 0.05$).

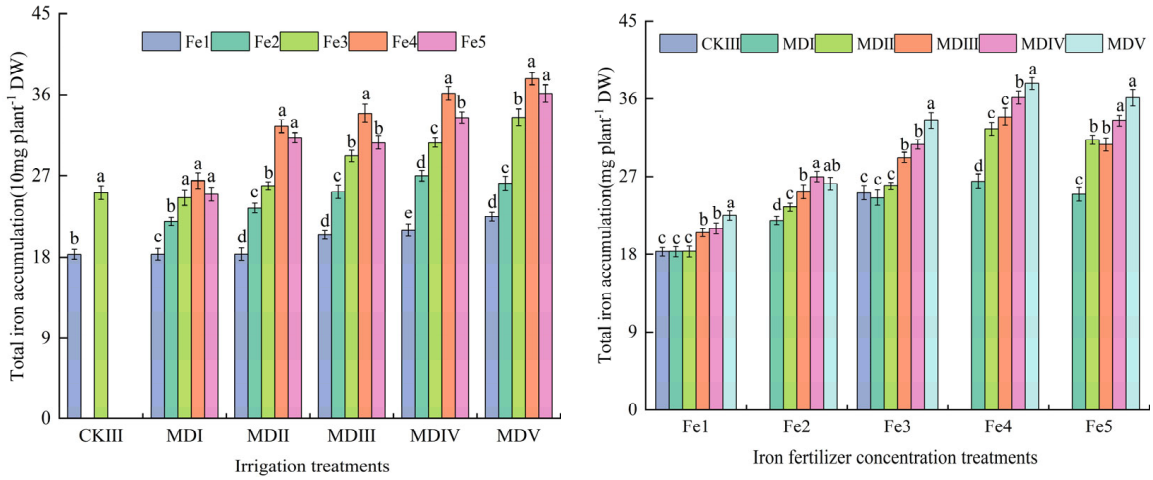


Figure 5. Effect of different treatments on total accumulation of iron in the aboveground part of spinach. Note: CK III indicates conventional water irrigation and the irrigation volume is 2400 m^3 ha^{-1}; MD I, MD II, MD III, MD IV, and MD V indicate magneto-electric water irrigation where the irrigation volume is 1500, 1950, 2400, 2850, and 3300 m^3 ha^{-1}, respectively. Fe1, Fe2, Fe3, Fe4, and Fe5 indicate concentrations of iron applied of 0, 0.05, 0.1, 0.15, and 0.2%, respectively. Different lowercase letters indicate significant differences ($p < 0.05$).

3.4. Effect of Magneto-Electric Irrigation with Iron Fertilizer Concentration on Spinach Growth Characteristics

The irrigation water type, irrigation volume, and iron fertilizer concentration had significant ($p < 0.05$) effects on spinach plant height and aboveground fresh weight (Figures 6–9). Under the same irrigation volume conditions, spinach plant height and aboveground fresh weight increased and then decreased with increased iron concentration. Under the same iron fertilizer concentration, spinach plant height and aboveground fresh weight gradually increased with increasing irrigation water. Under the same irrigation volume conditions, plant height and aboveground fresh weight were significantly higher in the Fe4 treatment than in the unfertilized treatment ($p < 0.05$). Fe application significantly increased 9.04, 19.92, 29.21, and 24.89%; 13.45, 26.73, and 41.68%; and 34.10%, respectively, compared with the unfertilized treatment. Under the same iron fertilizer concentration, plant height and aboveground fresh weight reached a maximum under MD V treatment but were not significantly higher than MD IV ($p > 0.05$). Spinach plant height and aboveground fresh weight were significantly higher under MD III than under CK III treatment ($p < 0.05$).

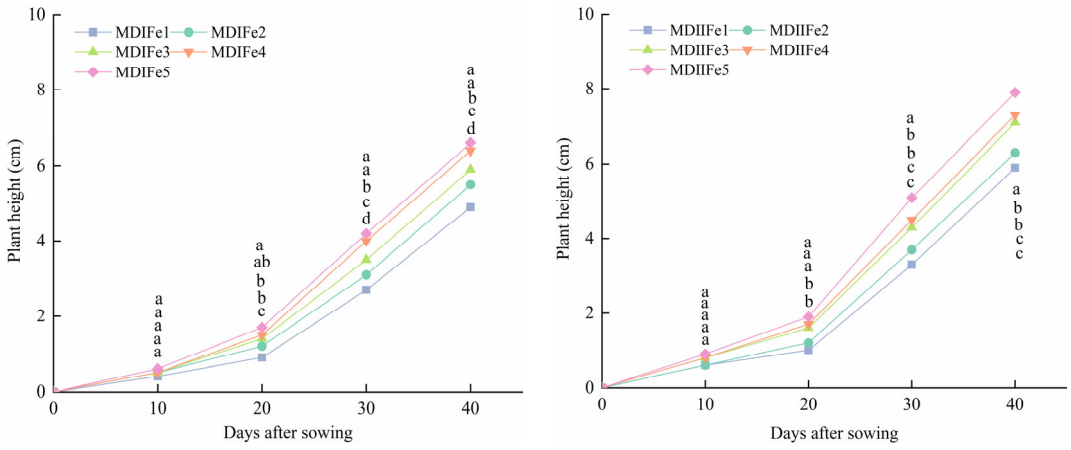


Figure 6. *Cont.*

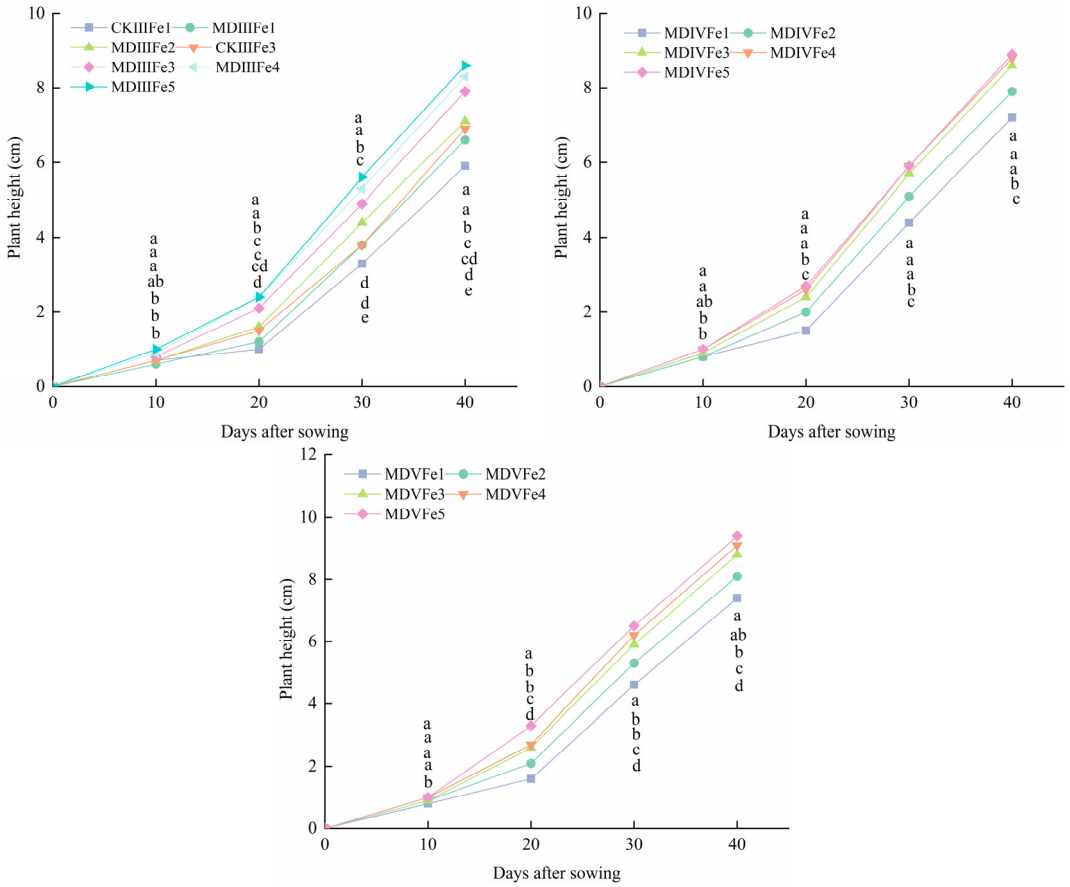


Figure 6. Effect of iron fertilizer concentration on spinach plant height at various irrigation rates. Note: Different lowercase letters indicate significant differences ($p < 0.05$).

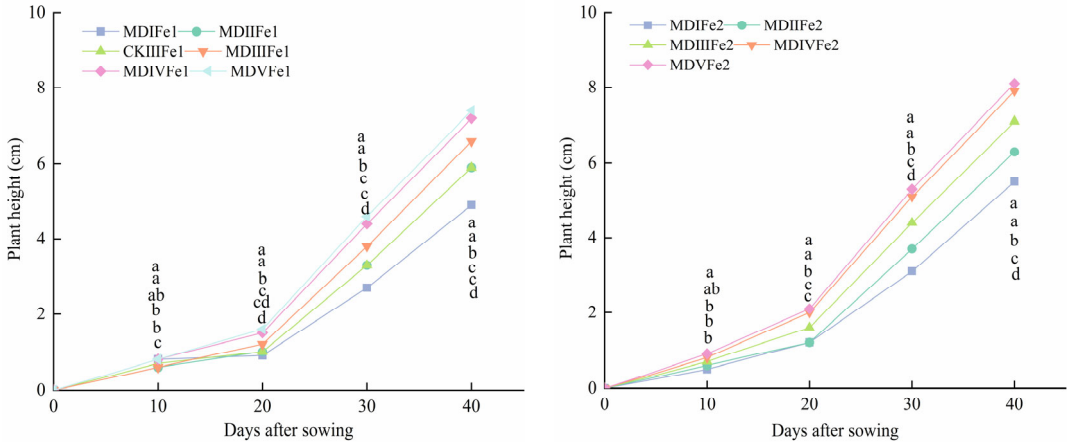


Figure 7. *Cont.*

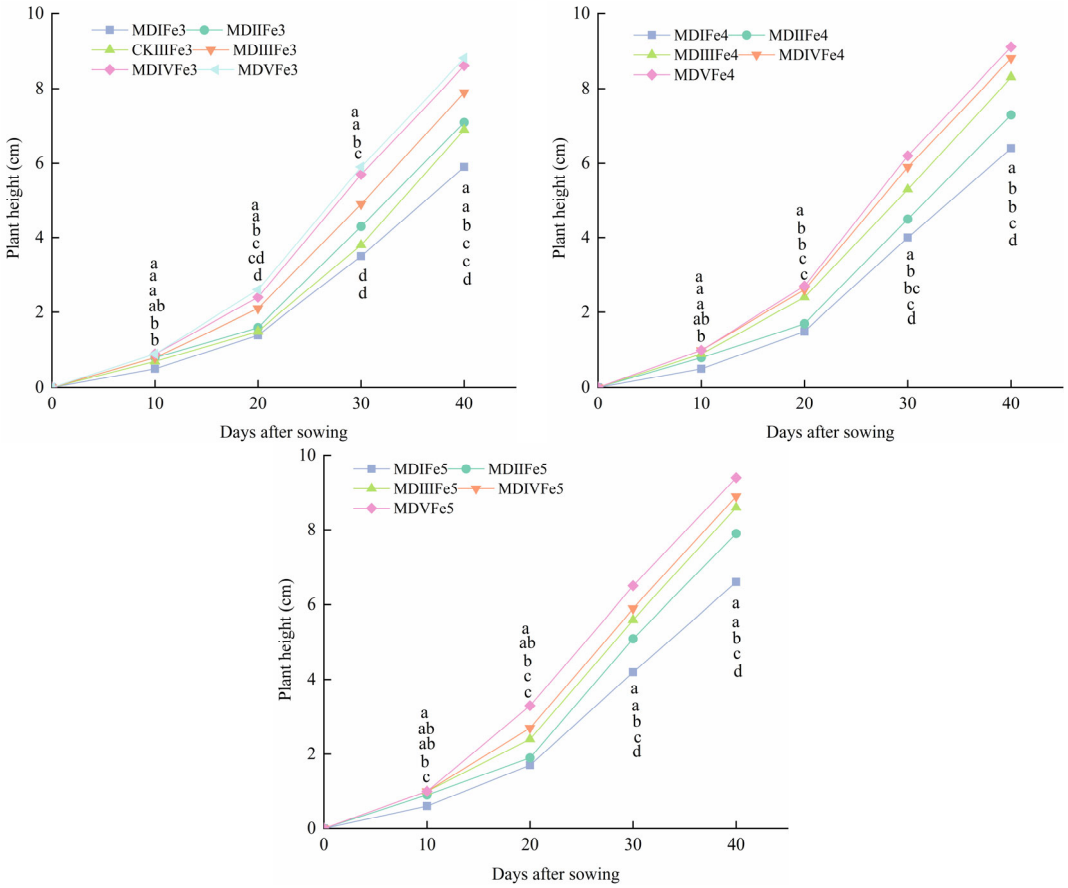


Figure 7. Effect of irrigation volume on spinach plant height at different iron fertilizer concentrations. Note: Different lowercase letters indicate significant differences ($p < 0.05$).

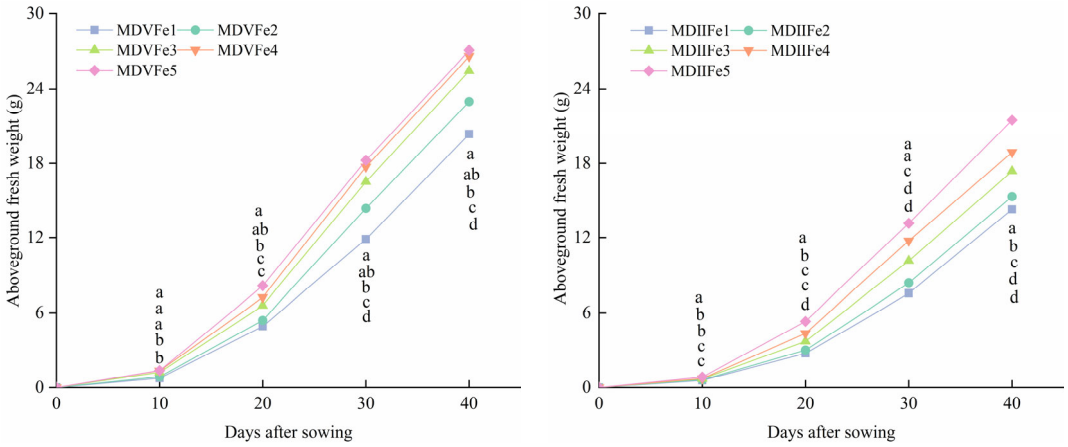


Figure 8. *Cont.*

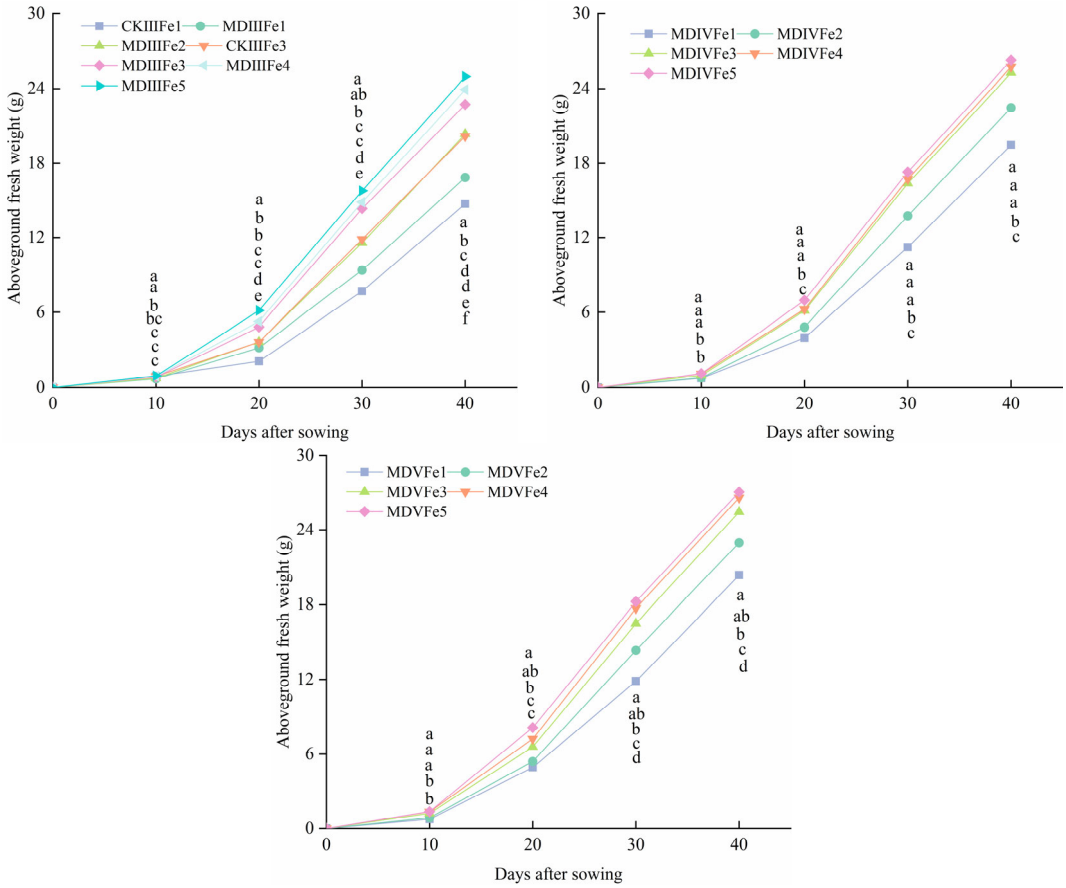


Figure 8. Effect of applied iron fertilizer concentration on aboveground fresh weight of spinach under different irrigation volumes. Note: Different lowercase letters indicate significant differences ($p < 0.05$).

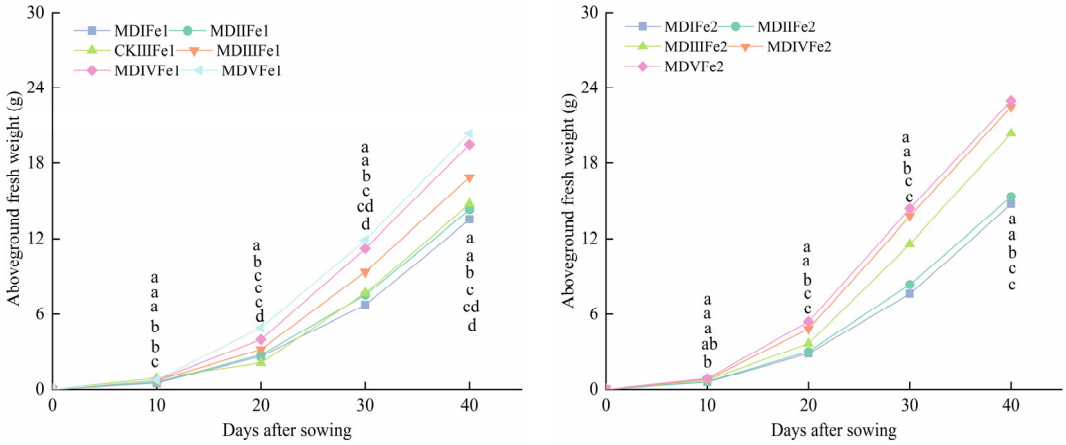


Figure 9. *Cont.*

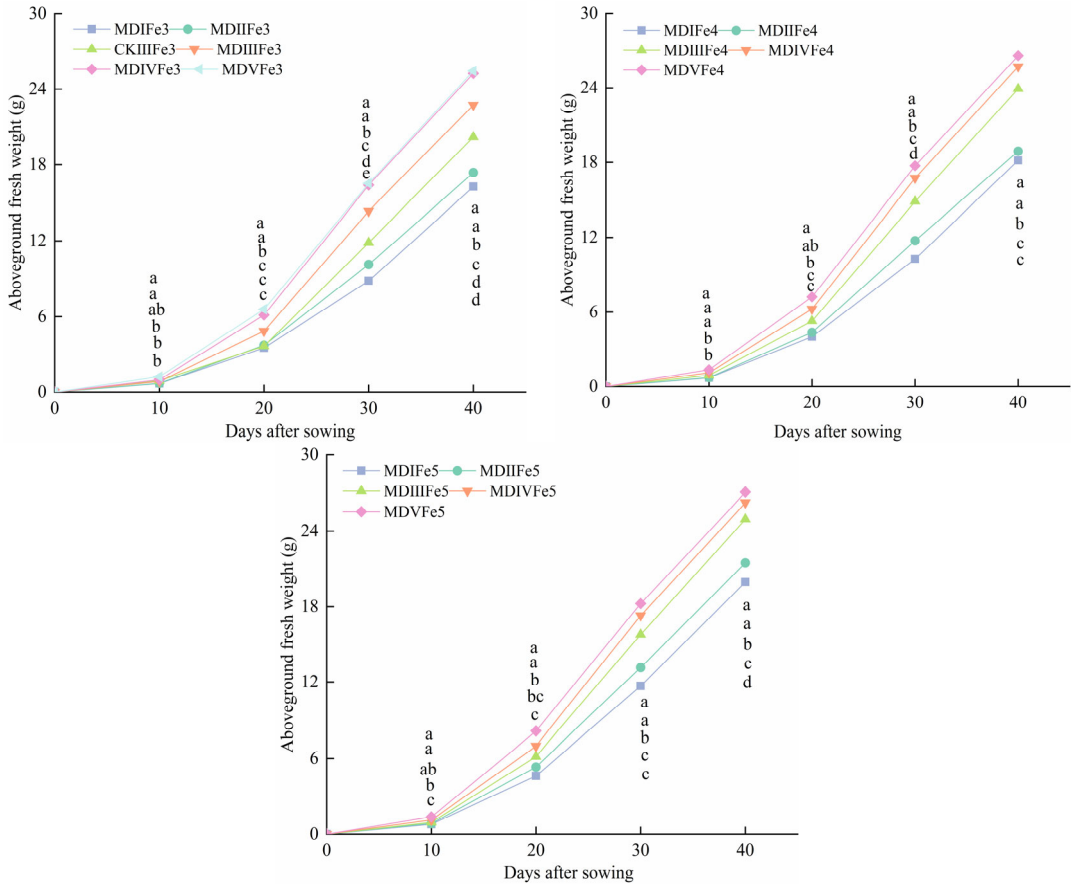


Figure 9. Effect of irrigation volume on aboveground fresh weight of spinach at different concentrations of iron fertilizer application. Note: CK III indicates conventional water irrigation and the irrigation volume is 2400 m^3 ha^{-1}; MD I, MD II, MD III, MD IV, and MD V indicate magneto-electric water irrigation where the irrigation volume is 1500, 1950, 2400, 2850, and 3300 m^3 ha^{-1}, respectively; Fe1, Fe2, Fe3, Fe4, and Fe5 indicate concentrations of iron applied of 0, 0.05, 0.1, 0.15, and 0.2%, respectively. Different lowercase letters indicate significant differences ($p < 0.05$).

3.5. Effect of Magneto-Electric Irrigation with Iron Fertilizer Concentration on Spinach Quality

The irrigation water type, irrigation volume, and iron fertilizer concentration had a significant effect on spinach soluble sugar and soluble protein content ($p < 0.05$) (Figures 10 and 11). Under the same irrigation volume conditions, with increasing iron concentration, protein content increased and then decreased. In the MD I and MD II treatments, soluble sugar contents initially increased and then decreased with increasing Fe concentration, while in the other treatments, soluble sugar contents gradually decreased with increasing Fe concentration. Simultaneously, iron fertilizer concentration and spinach soluble sugar and protein content all increased and then decreased with increased irrigation water. Under the same irrigation conditions, soluble sugar and protein contents were significantly higher ($p < 0.05$) in the Fe4 treatment than in the no-Fe fertilization treatment. Furthermore, Fe application significantly increased 5.49, 12.33, 19.68, and 16.2%; and 3.71, 9.84, 17.2, and 13.99%, respectively, compared with the unapplied Fe. Spinach soluble sugar and soluble protein contents reached a maximum in the MD IV treatment at the same Fe application concentration.

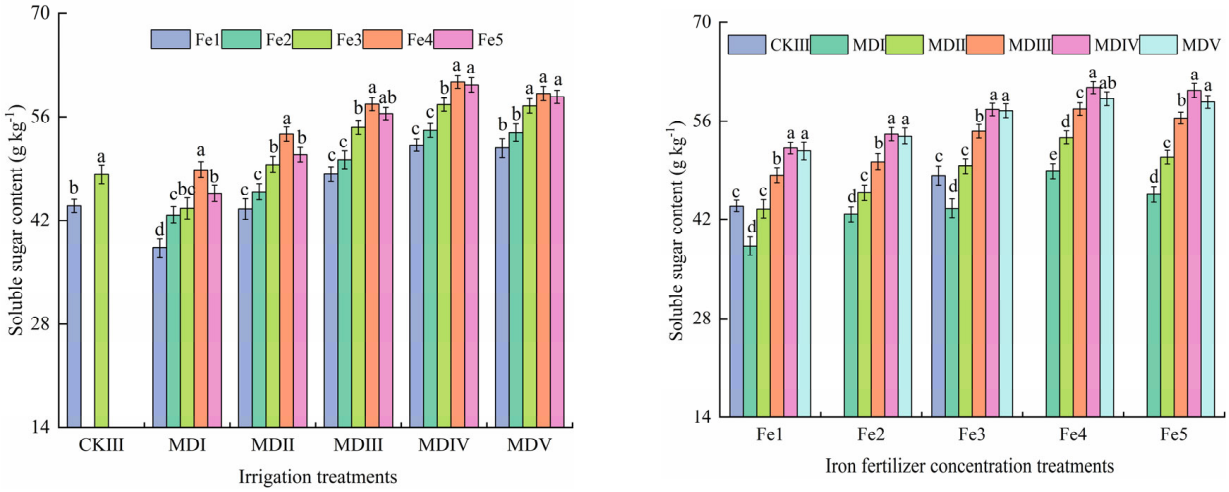


Figure 10. Soluble sugar content of spinach in different treatments. Note: Different lowercase letters indicate significant differences ($p < 0.05$).

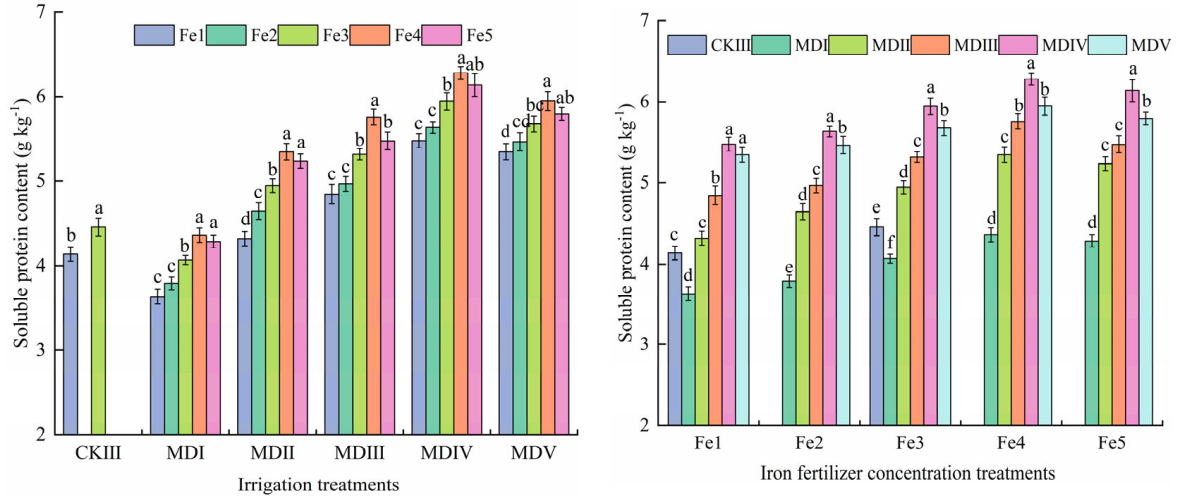


Figure 11. Soluble protein content of different treatments. Note: CK III indicates conventional water irrigation and the irrigation volume is 2400 m^3 ha^{-1}; MD I, MD II, MD III, MD IV, and MD V indicate magneto-electric water irrigation where the irrigation volume is 1500, 1950, 2400, 2850, and 3300 m^3 ha^{-1}, respectively; Fe1, Fe2, Fe3, Fe4, and Fe5 indicate concentrations of iron applied of 0, 0.05, 0.1, 0.15, and 0.2%, respectively. Different lowercase letters indicate significant differences ($p < 0.05$).

3.6. Spinach Water Consumption and Water Use Efficiency under Magneto-Electric Irrigation with Foliar Iron Fertilizer Application

Spinach total water consumption under magneto-electric water irrigation was higher than conventional water irrigation treatment (Table 4). Among them, spinach total water consumption under MD III treatment was higher than CK III Fe treatment by 13.6 to 16.84%. At the same irrigation level, spinach total water consumption increased and then decreased with increased Fe concentration application. The average total water consumption under Fe2, Fe3, Fe4, and Fe5 treatments was higher than Fe1 treatment by 3.33, 5.74, 13.15, and 8.28%, respectively. At the same iron fertilizer concentration, spinach total water consumption gradually increased with increased irrigation water. Spinach average total water consumption under MD II, MD III, MD IV, and MD V treatments was higher than MD I treatment by 13.88, 49.59, 67.57, and 85.9%, respectively. At different spinach growth stages, water consumption was at a maximum at 14–19 d and minimum at 0–13 d. Among all treatments, spinach total water consumption under MDVFe4 treatment was highest at 356.7 mm.

Table 4. Water consumption and water use efficiency of spinach in different treatments.

Iron Fertilizer Concentration	Irrigation Volume	Water Consumption of Spinach at Different Sowing Days (mm)				Total Water Consumption (mm)	Water Use Efficiency (kg m^{-3})
		0–13 d	14–19 d	20–29 d	30–43 d		
Fe1	MD I	40.1	32.4	36.8	49	158.3	0.93
	MD II	32.4	52.8	55.2	53.5	193.9	0.96
	CK III	50.3	57.1	62.8	61.4	231.6	1.05
	MD III	46.2	61.7	78.1	77.1	263.1	1.28
	MD IV	51.7	67.9	83	94.8	297.4	1.10
	MD V	65	72.7	89.3	102.4	329.4	0.95
Fe2	MD I	30.9	40.4	46.8	49	167.1	1.01
	MD II	33.8	51.5	56	65.7	207	1.11
	MD III	53.4	60.4	76.7	77.2	267.7	1.14
	MD IV	57.6	67.2	82	95.4	302.2	1.32
	MD V	62.1	83.1	90.1	104.2	339.5	1.11
Fe3	MD I	33.9	46.4	53.2	60.2	193.7	1.23
	MD II	35.5	37.7	55.1	65.9	194.2	1.18
	CK III	55.1	62.2	65.5	64.2	247	1.16
	MD III	51.6	75.7	81.4	79.9	288.6	1.34
	MD IV	60.4	73.4	88.5	83.2	305.5	1.24
	MD V	65.7	88.2	88.7	88.8	331.4	1.29
Fe4	MD I	33.6	59.2	55.2	55.2	203.2	1.14
	MD II	36.2	70.3	68.5	61.2	236.2	1.36
	MD III	54.7	73.6	78.1	82.8	289.2	1.47
	MD IV	60.9	80.4	87	91.8	320.1	1.23
	MD V	72.3	88.8	92.2	103.4	356.7	1.15
Fe5	MD I	31.2	55.4	52	58.2	196.8	1.13
	MD II	36.4	64.9	56.1	58	215.4	1.35
	MD III	48.9	64.7	75.3	77.4	266.3	1.38
	MD IV	63.4	71.9	87.6	92	314.9	1.22
	MD V	66.1	95.7	89.6	100.2	351.6	1.15

Note: CK III indicates conventional water irrigation and the irrigation volume is 2400 m^3 ha^{-1}; MD I, MD II, MD III, MD IV, and MD V indicate magneto-electric water irrigation where the irrigation volume is 1500, 1950, 2400, 2850, and 3300 m^3 ha^{-1}, respectively; Fe1, Fe2, Fe3, Fe4, and Fe5 indicate concentrations of iron applied of 0, 0.05, 0.1, 0.15, and 0.2%, respectively.

Spinach water use efficiency increased and then decreased with increased irrigation volume and iron fertilizer concentration, with MD III Fe4 treatment being the highest at 1.47 kg m^{-3} (Table 4). Spinach water use efficiency under magneto-electric water irrigation was higher than conventional water irrigation treatment. Spinach water use efficiency under the MD III Fe treatment was higher than the CK III Fe treatment by 15.68–21.63%. At the same irrigation level, spinach water use efficiency increased and then decreased with increasing Fe application concentration. The average water use efficiency under Fe2, Fe3, Fe4, and Fe5 treatments was higher than Fe1 treatment by 9, 20.2, 21.61, and 19.37%, respectively. Under the same iron fertilizer concentration, spinach water use efficiency gradually increased with increased irrigation volume. The average spinach water use efficiency under MD II, MD III, MD IV, and MD V treatments was higher than MD I treatment by 9.63, 21.67, 12.52, and 4.03%, respectively.

3.7. Water–Fertilizer Production Function and Comprehensive Evaluation of Appropriate Water–Fertilizer Dosage for Spinach Based on Grey Correlation Method

To understand spinach yield dynamics and continuous changes, water use efficiency, and quality in the water and fertilizer dosage setting interval under magneto-electric irrigation, we constructed regression equations with irrigation volume and iron concentration as independent variables, and yield, water use efficiency, and quality indexes as dependent variables (e.g., soluble sugar content and soluble protein content in response to irrigation water quantity and iron fertilizer concentration), and the fitting accuracy was >0.8 (Figure 12; Table 5).

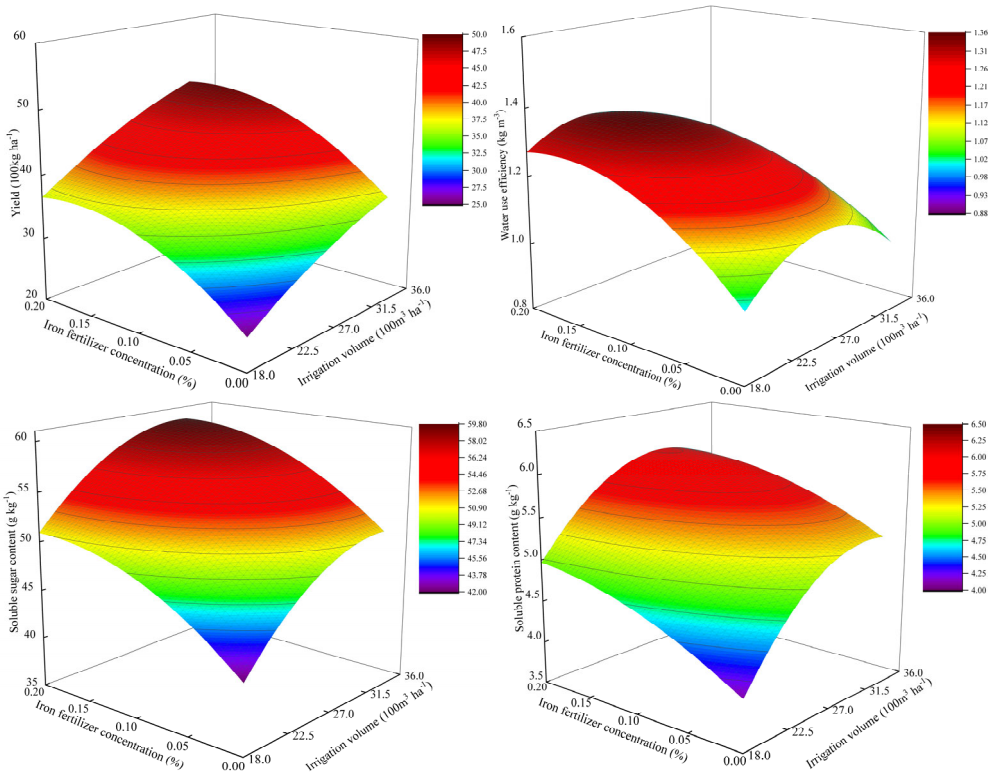


Figure 12. Relationship between irrigation volume, iron fertilizer concentration and spinach yield, water use efficiency and quality indexes.

Table 5. Relationship between water and fertilizer dosage and spinach yield, water use efficiency, and quality indexes.

Implicit Variable	Regression Equation	R^2
Spinach yield	$Y = -413.496F^2 - 0.022W^2 + 132.294F + 1.881W + 0.403FW - 1.671$	0.944
Water use efficiency	$WUE = -9.714F^2 - 0.002W^2 + 4.146F + 0.113W - 0.047FW - 0.314$	0.807
Soluble sugar	$SS = -232.991F^2 - 0.044W^2 + 93.598F + 2.872W - 0.141FW + 4.66$	0.959
Soluble protein content	$SP = -17.023F^2 - 0.007W^2 + 8.985F + 0.438W - 0.069FW - 1.518$	0.955

Note: Y, WUE, SS, SP, F, and W denote spinach yield, water use efficiency, soluble sugar content, soluble protein content, iron fertilizer concentration, and irrigation volume, respectively.

Fitted values of spinach yield, water use efficiency, soluble sugar content, and soluble protein content were calculated using the fitted water–fertilizer production function and compared with the measured values (Figure 13). After error analysis, coefficients of determination between the fitted and measured values of spinach yield, water use efficiency, soluble sugar content, and soluble protein content were >0.8, and the root mean square errors (RMSE) were 175.335 kg ha^{-1}, 1.212 g kg^{-1}, and 0.154 g kg^{-1}, respectively. So, the fit between simulated and measured values was good, and the fitted production function simulated well the regulation of irrigation volume and iron application concentration on spinach yield, water use efficiency, soluble sugar content, and soluble protein content under magneto-electric water irrigation.

We used grey correlation analysis to comprehensively evaluate the appropriate amount of water and fertilizer for spinach, the response index data of different spinach treatments collected in the experiment were used as the comparison series, and the maximum values of the response indexes under different treatments formed the reference series. Then, we calculated the correlation coefficients between the evaluation and the reference indexes (Table 6).

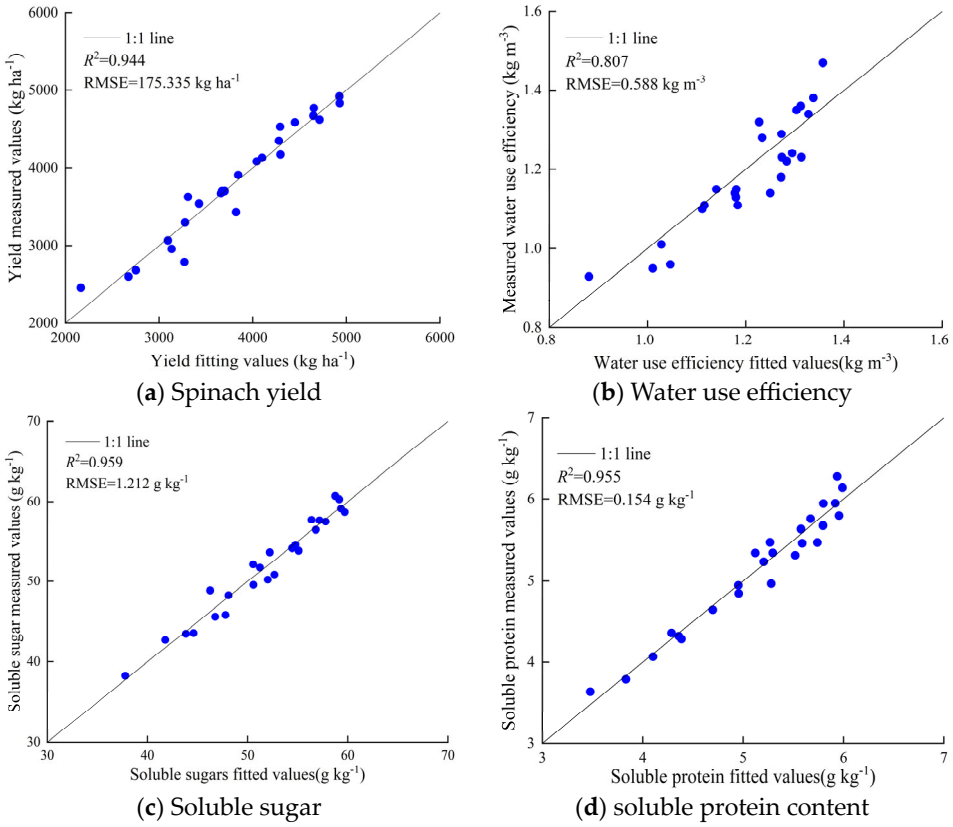


Figure 13. Measured and fitted values of spinach yield, water use efficiency, and quality indicators.

Table 6. Coefficients of correlation between evaluation indicators and reference indicators.

Treatments	*TNC*	*TCC*	*TIC*	*F*	*WUE*	*SS*	*SP*
CK III Fe1	0.626	0.731	0.366	0.477	0.964	0.401	0.84
CK III Fe3	0.713	0.782	0.47	0.621	0.973	0.473	0.86
MD I Fe1	0.558	0.661	0.366	0.453	0.954	0.333	0.809
MD I Fe2	0.586	0.689	0.414	0.476	0.961	0.385	0.818
MD I Fe3	0.618	0.729	0.46	0.51	0.979	0.397	0.835
MD I Fe4	0.697	0.767	0.498	0.612	0.971	0.487	0.854
MD I Fe5	0.689	0.74	0.467	0.558	0.971	0.427	0.849
MD II Fe1	0.629	0.734	0.366	0.468	0.956	0.395	0.851
MD II Fe2	0.651	0.744	0.439	0.489	0.969	0.43	0.873
MD II Fe3	0.715	0.785	0.486	0.537	0.975	0.501	0.894
MD II Fe4	0.823	0.836	0.68	0.668	0.99	0.615	0.923
MD II Fe5	0.75	0.798	0.632	0.579	0.989	0.533	0.915
MD III Fe1	0.673	0.781	0.394	0.524	0.983	0.474	0.887
MD III Fe2	0.722	0.83	0.472	0.626	0.971	0.516	0.895
MD III Fe3	0.79	0.861	0.567	0.722	0.988	0.648	0.921
MD III Fe4	0.913	0.915	0.745	0.842	1	0.788	0.956
MD III Fe5	0.857	0.916	0.614	0.782	0.992	0.725	0.933
MD IV Fe1	0.763	0.831	0.401	0.597	0.968	0.568	0.933
MD IV Fe2	0.778	0.868	0.51	0.71	0.987	0.632	0.946
MD IV Fe3	0.86	0.895	0.614	0.862	0.98	0.785	0.971
MD IV Fe4	0.976	0.986	0.873	0.933	0.979	1	1
MD IV Fe5	0.936	0.943	0.722	0.893	0.978	0.965	0.988
MD V Fe1	0.832	0.876	0.423	0.626	0.956	0.556	0.923
MD V Fe2	0.85	0.909	0.492	0.733	0.969	0.621	0.932
MD V Fe3	0.889	0.949	0.723	0.874	0.984	0.776	0.949
MD V Fe4	1	1	1	1	0.972	0.877	0.971
MD V Fe5	0.982	0.955	0.872	0.961	0.972	0.847	0.959

Note: *F*, *TNC*, *TCC*, *TIC*, *WUE*, *SS*, and *SP* denote aboveground fresh weight, total nitrogen accumulation, total carbon accumulation, total iron accumulation, water use efficiency, soluble sugar content, and soluble protein content, respectively.

The coefficient of variation method was used to calculate the weight of each indicator. The fresh weight of the aboveground part was the highest at 21.109%, and the total carbon accumulation was the lowest at 4.836% (Table 7).

Table 7. Indicator weights.

Indicators	Average Value	Standard Deviation	Coefficient of Variation	Weights (%)
F	20.561	4.236	0.206	21.109
TNC	15.474	2.326	0.150	15.403
TCC	31.873	1.504	0.047	4.836
TIC	27.228	4.201	0.154	15.809
WUE	1.185	0.134	0.113	11.562
SS	51.4	7.909	0.154	15.766
SP	5.085	0.770	0.151	15.515

According to the correlation coefficient and weights to calculate the average correlation of each evaluation index and rank them (Table 8), the highest correlation was found in the MD V Fe4 treatment, indicating that it had the best comprehensive response indexes for spinach. Additionally, the overall low correlation of treatments under MD I irrigation indicated that they were less effective.

Table 8. Comprehensive evaluation of different treatments based on different response indicators in spinach.

Evaluation Item	Relatedness	Rankings
CK III Fe1	0.0850	24
CK III Fe3	0.0962	17
MD I Fe1	0.0800	27
MD I Fe2	0.0840	26
MD I Fe3	0.0880	23
MD I Fe4	0.0963	19
MD I Fe5	0.0921	21
MD II Fe1	0.0848	25
MD II Fe2	0.0892	22
MD II Fe3	0.0955	18
MD II Fe4	0.1100	9
MD II Fe5	0.1024	13
MD III Fe1	0.0915	20
MD III Fe2	0.0987	16
MD III Fe3	0.1092	11
MD III Fe4	0.1241	5
MD III Fe5	0.1160	8
MD IV Fe1	0.0991	15
MD IV Fe2	0.1075	12
MD IV Fe3	0.1204	7
MD IV Fe4	0.1370	2
MD IV Fe5	0.1301	4
MD V Fe1	0.1016	14
MD V Fe2	0.1088	10
MD V Fe3	0.1236	6
MD V Fe4	0.1390	1
MD V Fe5	0.1333	3

4. Discussion

1. Effect of magneto-electric irrigation with foliar iron fertilizer on spinach nutrient accumulation

At the same applied iron concentration, the total accumulation of nitrogen, carbon, and iron in spinach under magneto-electric water irrigation + iron was higher than in con-

ventional water irrigation. This may be because after magneto-electric irrigation, surface water tension was reduced and dissolved oxygen increased [18,19], weakening hydrogen bonds between water molecules and forming more active and permeable monomer water molecules [20]. This led to a subsequent increase in the solubility of various mineral salts and the effectiveness of soil nutrients [21], which facilitates the uptake and utilization of nutrients by the spinach root system [22]. Some scholars have found [23] that crop photosynthesis strength increases with increased nitrogen supply. Magneto-electric water irrigation promotes efficient use of spinach nitrogen; on the one hand, it increases leaf nitrogen content and nitrogen metabolism activity and prompts more nitrogen allocation to chloroplasts [24], while on the other hand, it enhances the stimulatory activity of ribulose-1,5-bisphosphate carboxylase/oxygenase and the carboxylation and regeneration of ribulose-1,5-bisphosphate [25]. This enhances spinach photosynthesis [26] and increases spinach's total carbon accumulation. Additionally, under the same irrigation volume, the total iron accumulation under magneto-electric water irrigation was significantly higher than the total iron accumulation under conventional water irrigation because the leaf iron fertilizer sprayed in the former irrigation treatment was also configured using magneto-electric water, which has a reduced surface tension relative to conventional water, and which assists increased wetting and adhesion of the spray liquid on the foliage surface, thus improving the spraying effect.

The irrigation volume affected spinach's total nitrogen, carbon, and iron accumulations. In this experiment, with increased irrigation water, spinach total nitrogen, carbon, and iron accumulations gradually increased, but the growth trend gradually decreased. This is because crop water absorption is accompanied by nutrient uptake, and increased irrigation volume can increase soil water content, so that the crop can absorb more soil nutrients. Conversely, the appropriate irrigation volume can promote crop growth, which can enhance photosynthesis and the uptake and utilization of foliar iron fertilizer. Excessive irrigation can lead to the filling of soil pores with water, making it difficult for outside air to enter, and resulting in soil hypoxia, which increases soil acidity and hinders crop nutrient uptake capacity [27].

The iron application concentration similarly affects spinach total nitrogen, carbon, and iron accumulations. In this experiment, spinach total nitrogen, carbon, and iron accumulations initially increased and then decreased with increasing iron application concentration. This may be because iron is an essential nutrient for crop chlorophyll synthesis and participates in crop photosynthesis. Moderate iron supplementation can promote spinach growth and increase photosynthesis as well as nutrient requirements, whereas excessive iron application concentration hinders spinach growth [28], thus limiting spinach nutrient uptake.

2. Effect of magneto-electric irrigation with foliar iron fertilizer on spinach growth characteristics

We found that the irrigation type and water volume are closely related to spinach growth characteristics, and a reasonable irrigation water volume and scientific irrigation type are the key to improving spinach yield [29]. Compared with conventional water, magneto-electric water irrigation can improve spinach growth and water use efficiency, as spinach plant height and aboveground fresh weight were significantly higher than under conventional water irrigation ($p < 0.05$). This may be due to the weakening of hydrogen bonds between water molecules and the formation of more active and permeable monomer water molecules under magneto-electric irrigation, which increased the solubility and transport rate of nutrients such as nitrogen and calcium in the soil [30], and improved spinach uptake and utilization of required nutrients, thus promoting spinach aboveground growth. Spinach growth indicators all gradually increased with increasing irrigation water. An appropriate irrigation water increase enables spinach to absorb more nutrients from the soil and promote growth. However, excess irrigation water will lead to soil hypoxia, hindering spinach nutrient uptake capacity. We showed that the level of iron application had a significant effect on spinach growth characteristics. This may be related to the movement and

conversion of ferritin in the soil and the absorption threshold of the spinach root system for ferritin. While iron deficiency will cause a decrease in leaf chlorophyll content, slowing crop growth and development, iron fertilizer foliar spraying can dramatically increase ferritin absorption, improve photosynthetic efficiency, and promote plant nutrient uptake and material accumulation, which will in turn improve spinach's growth characteristics [31]. However, too much iron not only causes stress on nutrient organs, but also causes nutrient imbalance within plants, which in turn inhibits spinach growth [32].

3. Effect of magnetization to remove electrons through drip irrigation with foliar iron fertilizer on spinach quality

We found that spinach soluble sugar and protein content irrigated with magneto-electric water was higher than irrigated with conventional water under the same applied iron concentration, which indicated that spinach quality was improved by the former. This is because under magneto-electric irrigation, positive and negative ions in the irrigation water move under the action of the magnetic field or the grounded conductor, generating a tiny electric current, which increases the content of dissolved oxygen in the magnetization to remove electrons in water [33]. Numerous scholars have shown that increased oxygen content in the water improves crop quality, which may result from increased dissolved oxygen increasing root vitality [34,35], which promotes soluble sugar and protein accumulation.

A total of 80% of the iron in crops is distributed in the cysts [36], and iron deficiency leads to the destruction of chloroplasts within the leaves and the inability to synthesize chlorophyll. Meanwhile, Fe is involved in respiration, nitrogen fixation, and intracellular detoxification functions in crops [37]. In addition, it has also been shown [38] that Fe is involved in physiological processes such as stomatal opening and closing and transpiration in crop leaves. Therefore, Fe plays a key role in maintaining normal crop growth. Spinach soluble sugar and protein content increased and then decreased with increasing irrigation volume. However, among all the treatments, the one with the high aboveground fresh weight did not have the highest soluble sugar and protein content, which was because too much irrigation volume resulted in a large amount of water being absorbed by the crop [39], whereas too little irrigation volume also reduced the soluble sugar and protein content.

Iron concentration also affected spinach soluble sugar and protein contents. With increasing iron concentration, total nitrogen, carbon, and iron accumulations increased and then decreased. Moderate spraying of foliar iron fertilizer can improve crop quality [40,41], while too little or too much is not conducive to crop quality improvement [42].

5. Conclusions

Compared with conventional water irrigation, magneto-electric water can promote nutrient absorption and utilization by spinach by increasing soil water and nutrient contents. The appropriate amount of magneto-electric water irrigation and applied iron concentration can improve the accumulation of nutrients, water utilization efficiency, as well as vegetable yield and quality. The irrigation water volume and iron application concentration had significant effects on spinach nutrient accumulation and yield ($p < 0.05$), and the irrigation water volume had a greater effect on total nitrogen, total carbon accumulation, and aboveground fresh weight than iron concentration, but iron concentration had a greater effect on total iron accumulation than irrigation water volume. Spinach nutrient accumulation and yield were greatest at an irrigation volume of 3300 m^3 ha^{-1} and an Fe concentration of 0.15%. Additionally, both irrigation water volume and applied iron concentration had significant effects ($p < 0.05$) on spinach quality, and irrigation water volume affected spinach quality to a greater extent than iron concentration. In particular, the best spinach quality was obtained at an irrigation volume of 2850 m^3 ha^{-1} and an iron concentration of 0.15%. Based on a comprehensive quantitative evaluation and analysis of spinach total nitrogen accumulation, total carbon accumulation, total iron accumulation, aboveground fresh weight, water use efficiency, soluble sugar content, and soluble protein content under all treatments,

the optimal treatment for spinach yield and quality improvement was a magneto-electric irrigation volume of 3300 m^3 ha^{-1} and iron fertilizer concentration of 0.15%.

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Data Availability Statement: The original contributions presented in the study are included in the article, and further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

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