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Magnetic Water Irrigation Impact on Sweet Fennel (*Foeniculum vulgare* Mill) Economic Traits Towards Tolerance for Water Salinity Stress

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Abstract: The government's efforts are looking to expand their reclaimed lands however; the major challenges are the sacristy of valid irrigation water availability. Moreover, salinity stress is a major environmental constraint that significantly reduces agricultural productivity worldwide as it forms a harmful effect as a thin layer that interferes with the soil characteristics and prevents seedling growth. While, fennel, is a moderately tolerant plant to salinity exhibits reduced growth and yield under prolonged saline conditions. The current study demonstrates that, salinity stress negatively impacts fennel growth and yield, meanwhile, saline water stress can be mitigated by Magnetic Water Treatment (MWT) at different salinity levels (0.7, 2.5, 4.5, 5.5, 7.5 ds/m). Major effect was noted at salinity levels up to 2.5 and 4.5 ds/m. Morphologically, results reveal that, MWT exerts a significant positive impact on fennel growth and yield throughout the two growing seasons (2020/2021 and 2021/2022) /under saline water irrigation. Nutrients content i.e. chlorophyll a, chlorophyll b, chlorophyll a + b, nitrogen (%), phosphorus (%), potassium (%), and proline (μM) values are all significantly higher after MWT. Finally, the values for bulb dry weight (%) and leaf dry weight (%) are reversed between the two cases. These findings suggest that, MWT is a sustainable approach to enhance fennel growth and yield under saline water stress conditions. MWT practice can be applied to fennel cultivation to improve productivity and reduce the negative effects of salinity. MWT is a promising eco-friendly treatment for saline irrigation water, enabling us to avoid the harmful effects of chemical fertilizers and pesticide pollution.

Key words: Fennel, salinity, irrigation, magnetic water treatment

1. Introduction

Fennel (*Foeniculum vulgare* Mill.) is an annual herbaceous crop that belongs to the *Apiaceae* family. Fennel bulbs contains essential oils that are used for a variety of purposes, including:

providing aroma in several food products **(Zoubiri *et al.*, 2014),** a constituent in cosmetics and medicine products **(Telci *et al.*, 2009 and Kooti *et al.*, 2015),** Therapeutic purposes with high free radical scavenging **(Choudhary *et al.*, 2017 and Lucinewton *et al.*, 2005).** It is also characterized by a high level of mineral and vitamin contents, including calcium, phosphorous, iron, sodium, potassium, thiamine, riboflavin, niacin, and vitamin C **(Anubhuti *et al.*, 2011)**. The vegetative parts of the plant are used as a green salad, while the bulbs have a pleasant, spicy distinct odor and burning sweet taste, as well as pharmaceutical, perfumery, and food flavoring uses. Fennel contains 1-3% volatile oils, which have disinfectant and anti-inflammatory action, primarily on the respiratory and digestive organs, likewise having an antispasmodic effect on smooth muscle **(Mohamed and Abdu, 2004)**. Antioxidant and antimicrobial activity of fennel has also been reported **(Ruberto *et al.*, 2000).**

Fennel as a moderately salt-tolerant plant can afford salinity levels. However, salinity has various negative effects on fennel plants, including reduced growth, yield, quality, and increased susceptibility to pests and diseases **(Cucci and Mazzoleni, 2014).** In order to minimize salinity stress and maximize fennel yield, it is important to manage salinity levels in the soil. Several strategies can be employed to manage salinity and maintain healthy fennel crops such as irrigation with low-salinity water, which is not that available, improving soil drainage, selecting salt-tolerant cultivars, applying organic matter to the soil and monitoring soil salinity levels. By implementing these salinity management practices, growers can effectively cultivate fennel plants in areas with moderate salinity, ensuring optimal growth, yield, and quality **(Semiz and Or, 2012 and Shannon, 2012).** These strategies are labor consuming and expenses to achieve.

Nowadays, new innovations are urgently needed to reduce the harmful outcome of salt accumulation on soil surface and improve its leeching with low effort and decreased expenses **(Cuevas *et al.*, 2019).** Definitely accumulation of soluble salts in high concentrations can negatively affect the value and productivity of agricultural lands significantly; it might even lead to plant toxicity **(Zein El-Din *et al*., 2021 and Khondoker *et al.*, 2023).** Magnetic water treatment (MWT) or as named Magnetized water (MW) has shown a promising agricultural potential, on both research level and industrial level as well, offering a wide range of benefits for plant production as well as soil enhancement. One of these benefits is “soil desalinization” **(Hassan, 2015). Yadollahpour *et al.* (2014)** stated that MWT has reduced the water consumption unit and improve crop yield and plant growth. MWT has the ability to change salt distribution between soil layers reducing their harmful accumulation effect in the upper soil layers which is the most important layer in the agriculture process **(Zlotopolski, 2020). Maheshwari and Grewal (2009)** stated that MWT has enhanced the productivity of irrigation water. Moreover, flowing saline water within a magnetic field serves as an eco-friendly method both way, for water as well as for crop irrigation, as this process aids in washing salts from the soil, leading to increase the nutrient availability by breaking down salt crystals. Consequently, this will encourage root penetration into the soil, and speed up plant growth **(Fayed *et al.*, 2021 and Suhail and Mahdi, 2013).**

Magnetic Water Treatment (MWT) is an eco-friendly potential treatment to enhance plant growth and to overcome salinity. This treatment involves passing saline water through a magnetic field to alter its physical properties. Numerous studies have reported various benefits of MWT on plant growth, including: reduced soil alkalinity making nutrient uptake more efficient for plants **(Deng *et al.*, 2022),** enhancing nutrient mobility by increasing fertilizer availability for plant absorption **(Kaur and Rajput, 2020),** accelerated germination and growth by promote seed germination and early plant development **(Shukla *et al.*, 2022),** enhanced crop yields as proven in various crops, such as lettuce, tomatoes and peppers **(Ali *et al.*, 2021), i**mproved root development by strengthen plant root systems, leading to better nutrient and water uptake and enhanced protein synthesis **(Ghanem *et al.*, 2022) and** promoted chlorophyll development by contributing healthier plant leaves and improved photosynthesis **(Deng *et al.*, 2022).**

Fennel, is an economically important aromatic and medicinal herb and moderately tolerant to salinity. Since, salinity stress is a major environmental constraint that significantly reduces agricultural productivity worldwide, MTW has emerged as a promising non-chemical approach to mitigate salinity stress and enhance plant performance. This study aims to provide valuable insights into the efficacy of MTW in promoting fennel growth and productivity under salinity stress. The findings of this research will contribute to the development of sustainable agricultural practices for fennel cultivation under salinity stress environments for ensuring food security and economic benefits.

2. Materials and Methods

This experiment was conducted within the framework of cooperation between El-Sabaheya Horticultural Research Station (SHRS), Horticulture Research Institute (HRI), and the Saline and Alkaline Soils Research Dept., Soil, Water and Environment Research Institute (SWERI), Agricultural Research Center (ARC), Alexandria, Egypt. It was carried out at two successive growing seasons (2020-2021 and 2021-2022) at separated basins to achieve the salinity required under study.

Plant material: fennel cultivar used in this study was provided by The Vegetables, Aromatic and Medicinal Plant Breeding Research Dept., Horticulture Research Institute (HRI). This cultivar was characterized by obvious large bulb production.

Experimental layout: two main plots (15 separated $2m^2$ basin each) - inside the Saline and Alkaline Soils Research Department- were prepared carefully and appointed for two types of irrigation water (normal and magnetic) having the same five levels of salinity (0.7 ds/m, 2.5 ds/m, 4.5 ds/m, 5.5 ds/m and 7.5 ds/m) as recommended by **Zaki *et al.* (2009)**, and the ten treatments were replicated three times. Chemical and physical properties of the studied soil are shown in Table (1) according to **Page *et al.* (1982).** Soil EC values were determined during the growing seasons treated with and without magnetic water treatment.

Table (1). Chemical and physical properties of the studied soil:

Soil pH	7.53		
EC (ds/m)	1.38		
Soluble content (meq/L)			
Ca^{++} = 5.50	Mg^{++} =3.50	Na^{+} =4.53	K^{+} = 0.11
Soluble anions			
Cl^{-} = 5.25	HCO^{-}_{3} = 3.00	SO^{-}_{4} =0.39	
Total carbonate (%)	2.35		
Total organic matter (%)	2.01		
Particle size distribution			
Clay (%) = 38.4	Silt (%) = 21.1	Sand (%) = 40.5	
Texture	Clay loam		

The above mentioned concentrations were passed through a Magnetic Water Treatment (MWT) device kindly provided by Delta Water Company® (Figure 1), specified as 1-inch diameter, water flow rate up to 25 m^3/h, magnetic capacity of 14500 Gauss (1.45 Tesla) and ability to treat saline water up to 10 ds/m.

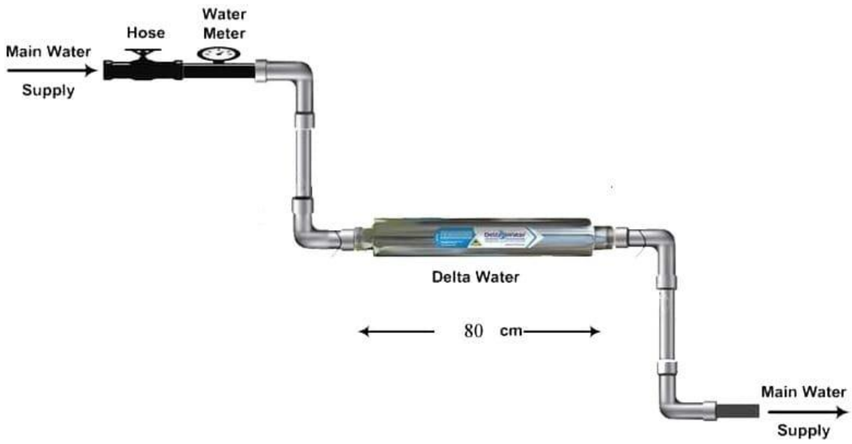

Fig (1). Schematic diagram of the magnetic water device

Measurements and data recorded: morphological measurements were recorded at the end of the season. They included; plant height (cm), number of branches/plant weight (g), root weight (g), number of umbels/plant, no. of umbellate /umbel, no. of seeds/umbel, as well as bulb weight (g) and bulb thickness (cm) as recommended by **Gomaa *et al.* (2023).**

Chemical assay was also recorded as; Total soluble solids were directly measured using a hand refractometer (Model: ATAGO. Tokyo, Japan). Chlorophyll contents a + b (mg/g) were measured according to **Barros *et al.* (2011)** with some modifications. Plant leaves content of actual nitrogen **N** (%) was calculated using the following equation. $\boldsymbol{Ntotal}= (\boldsymbol{\nu s}-\boldsymbol{\nu b}/\ \boldsymbol{md})$ x $\boldsymbol{NH_2\ S}O_4$ x 0.014 $\boldsymbol{meq\ N}$ x 100 Where νs the sample consumed volume, νb is the control treatment consumed volume, NH_2SO_4 is the normality of sulphuric acid at 0.014, meq is the dry weight sample. Mineral composition and determination were done using the atomic absorption spectrophotometer with the dry burning method **(Kacar and Inal, 2008).** Proline content was determined following **Bates *et al.* (1973)** procedure and finally bulb and leaves dry weight percentage were calculated.

Agriculture operations: fennel seeds were directly planted in the field at 1st of December 2020. Proper spacing was maintained between plants to allow adequate room for bulb development and air circulation during growth. Fennel requires consistent moisture, especially during its early growth stages to reduce water wastage and avoiding bulb rot. Irrigation was done every two weeks along the experiment. Standard agricultural practices were then applied as per regional norms. Harvesting of fennel bulbs occurred once they reached the desired size and had a firm texture. Ten plants from each replicate were harvested to take measurement of bulbs, while the rest of the plants were left until the seeds maturity. Bulbs were cut at the base, leaving some foliage attached to maintain post-harvest quality. At October 2021, the same experiment was repeated again for the second time with the same treatments.

Statistical analysis: the experiment consisted of ten treatments (two different irrigation treatments with 5 levels of salt concentrations) was designed as Split plot in randomized complete blocks design with three replicates for each treatment and were analyzed by Costat version (version 6.400). The treatment means were compared using least significant difference (L.S.D.) test procedure at $p \leq 0.05$ level of probability.

3. Results and Discussion

This investigation was conducted at El-Sabaheya Horticultural Research Station (SHRS), Alexandria governorate, Horticulture Research Institute (HRI), and the Saline and Alkaline Soils Research Dept., Soil, Water and Environment Research Institute (SWERI), Agricultural Research Center (ARC), Egypt, to study the efficacy of magnetic water treatment in promoting fennel growth and productivity under different concentrations of saline water irrigation at two successive growing years.

The presented data for soil electric conductivity (EC) irrigated with different saline water concentrations with and without magnetic treatment reveals interesting trends and potential applications as shown in Table (2). Magnetic treatment significantly decreased soil EC at all saline concentrations compared to the control which explains the significant impact of the magnetic field on dissolved ion behavior, leading to enhanced conductivity. Decreased soil EC with magnetic treatment is proportional to the concentration of dissolved solids. This indicates a stronger influence of the magnetic effect on solutions with higher ion density.

Table (2). EC values for soils during the growing seasons treated with and without magnetic water treatment

Treatments / Soil EC values	0.7 ds/m	2.5 ds/m	4.5 ds/m	5.5 ds/m	7.5 ds/m
Without magnetic treatment (M_0)	3.78	9.43	10.98	12.06	14.67
With magnetic treatment (M)	1.04	7.41	9.68	11.24	14.4

Values were recorded for the interaction M_0S_4 for all traits.

Magnetic treatment mode of action can be explained as suggested by **Mghaiouini *et al.*, (2020),** the magnetic field may align the dipoles of water molecules and dissolved ions, leading to a more ordered and conductive state. **Surendran *et al.* (2016)** proposed that, the magnetic field influences the hydration shells of ions, reducing their drag and facilitating movement, thereby increasing conductivity. **Fanous *et al.* (2017)** and **Ashwini *et al.* (2018)** also suggested that, the magnetic field might induce the formation of small, charged aggregates of dissolved particles, increasing the effective surface area and promoting ion exchange, leading to higher conductivity in water and lower concentration in soil as it is easily leached by the irrigation water as ions. The effect of magnetic treatment on soil salts (EC values) has diverse potential applications across various fields, including: improve nutrient mobility and enhance plant growth, as demonstrated in researches by **Hamza *et al.* (2021)** and **Samarah *et al.* (2021).** They also suggested that, the magnetic effect on ion mobility could potentially be used to improve the efficiency of desalination processes as well as enhancing the removal of pollutants from wastewater by facilitating the precipitation or adsorption of contaminants. This highlights the potential of water magnetic treatment in changing soil electrical conductivity, opening up exciting possibilities in various fields.

Data in Tables (3) and (4) demonstrate the primary effects of the two main factors: magnetic water treatment (MWT) and saline water irrigation, on the vegetative growth and yield characteristics of fennel cultivars, along with their interaction across two growing years under. The findings reveal that, MWT exerts a significant positive impact on fennel growth and yield throughout the two growing seasons. With respect to the main effect of saline water irrigation without MWT, fennel plant length, root weight, number of umbels per plant, number of umbellate per umbel, number of seeds per umbel, bulb weight, and bulb thickness all exhibited significant reductions as salinity increased from 0.7 ds/m to 7.5 ds/m. The most significant reductions in fennel growth and yield were observed at water salinity levels of 4.5 ds/m and above.

Results showed that, MWT had a good influence on fennel traits as, they increased by 56.32%, 48.41%, 38.12%, 24.05%, 23.74%, 23.48% 16.24%, 11.58% and 10.65% for primary branch /plant, plant weight (g), root weight (g), number of umbels/plant, bulb thickness (cm), bulb weight (g), plant length (cm), no. of seeds/umbel and no. of umbellate /umbel respectively compared to plant traits without magnetic water in the first year. Also, second year took the same trend as; there were a significant increase in traits values irrigated with MWT device. Traits were increased less than 50% except for plant weight, it increased by 77% as compared to plants irrigated with normal water.

Saline water concentrations used for irrigation without MWT in the experiment generally showed a great decline in the plant traits along the two seasons, as salinity concentration increase, values of the plant traits go down. Values decline exceeded 50 % at 7.5 ds/m saline water concentration compared to the control for all traits under study except for no. of seeds/umbel, plant length and no. of umbellate /umbel. Again the decline in plant traits was significant at salinity level of 2.5 ds/m for all traits except two traits, plant height (227.75) and no. of umbellate /umbel (36.33) compared to the control (224.75) - (38.14), respectively at the first year. Whereas for the second year, plant traits were declined the most at 7.5 ds/m saline water irrigation concentration. Number of umbels/plant was declined by 77.74% compared to control. The rest of the traits declined by more than 50% at salinity level of 7.5 ds/m except for no. of seeds/umbel and plant length.

Concerning the interaction between the two main factors under study on fennel yield, MWT generally increased fennel vegetative growth and yield significantly at MS_1 and MS_2. Interaction between irrigation by different salinity levels used in irrigation and magnetized water treatment was significant for most of the growth and yield parameters, as it was most pronounced at water salinity levels of 4.5 and 5.5 ds/m. Overall, the data suggests that magnetized water treatment can be an effective way to mitigate the negative effects of saline water irrigation on fennel growth and yield at these concentrations (Table 3 and 4). Specific results showed that saline irrigation water of $MS_{0\ \text{and}}$ MS_1 treatments generally had the highest fennel plant length, root weight, number of umbels per plant, number of umbellate per umbel, number of seeds per umbel, and bulb weight. Irrigation with magnetized saline water MS_1 and MS_2 treatments generally had the highest bulb thickness and finally saline irrigation water without magnetic treatment M_0S_4 had the lowest values for all growth and yield parameters (Table 3 and 4).

Regarding the interaction between magnetized water and salinity at the two years of cultivation, it was found that, there were significant differences between most of the treatments under study. In general, it was found that the used of magnetized water with salt concentrations led to bad effect reduction resulting from salinity on the vegetative characteristics under study. The highest value for the traits was recorded for the interaction treatment MS_0 and MS_1, without significant differences between them except for plant height and number of seeds, while the lowest.

MWT has shown promising results in numerous studies, proposed explanations for MWT mode of action include; changes in water structure as it alter the arrangement of water molecules, making them more readily available to plants **(Ghanem *et al.*, 2022)**. The magnetic field may influence the movement of ions in water, potentially affecting nutrient uptake **(Kaur and Rajput, 2020),** also can trigger cellular processes that enhance plant growth **(Shukla *et al.*, 2022).**

Data in table (5) shows the plant nutrients content after being irrigated with saline water with / without MTW. Chlorophyll a, chlorophyll b, cholorophyll a+b, nitrogen (%), phosphorus (%), potassium (%), and proline values are all significantly lower in the absence of magnetized water. Finally, the values for bulb dry weight (%) and leaf dry weight (%) are reversed between the two cases. Overall data suggests that, the presence of MWT has a significant impact on the levels of chlorophyll and other compounds in the sample.

Chlorophyll levels vary across different saline irrigation levels, with MWT, the highest values of chlorophyll a were observed in MS_0, MS_1 and MS_2. Chlorophyll b followed the similar trend, with higher values in the MWT group compared to the untreated group. The total chlorophyll (a+b) content shows a similar pattern, with higher values in the MWT group and varying levels across saline water irrigation levels. As salinity level increased from 2.5 to 7.5 ds/m, there is a general decrease in the levels of chlorophyll a, chlorophyll b, and cholorophyll a+b. This suggests that, salinity may have a negative impact on the growth and production of chlorophyll in these plants. Nitrogen (%), phosphorous (%), and potassium (%) levels also show some variation with salinity. Nitrogen (%) and phosphrous (%) tend to decrease inversely with salt concentration, while potassium (%) shows a more irregular pattern. These changes may reflect the changing availability of nutrients in the water as salinity increases. Nitrogen (%) levels were generally higher in MWT group, especially at high salinity water levels. Phosphorus (%) and potassium (%) showed varied patterns but didn't consistently follow the trend of nitrogen levels, differences in nitrogen, phosphorus, and potassium levels indicate that these nutrients may play a role in chlorophyll synthesis. Proline content varies according to the saline level of irrigation water, with the highest values observed at MS_4. Bulb dry weight values are higher at the saline water irrigation without MWT, especially at higher irrigation salinity levels. Leaves dry weight values show variations across conditions but generally followed the same trend at higher levels of salinity without magnetization. The differences in dry weight between across different salinity levels in with and without magnetic treatment groups suggest that the presence or absence of a certain factor has an impact on plant growth. Proline level, bulb dry weight (%), and leaf dry weight (%), also show some variation with different salinity level. Proline showed an increase with increasing salinity concentration; while bulb dry weight (%) and leaf dry weight (%) tend to decrease. These changes may reflect the physiological adaptations of these plants to changes in salinity. Overall, the data suggests that salinity has a significant impact on the physiology and biochemistry of these plants.

Table (3). Mean performances of fennel characteristics as affected by magnetic water treatment, salinity concentrations and the interaction through 2020-2021

	Plant length (cm)	Primary branch /plant	Plant weight (g)	Root weight (g)	Number of umbels/plant	No. of umbellate /umbel	No. of seeds/umbel	Bulb weight (g)	Bulb thickness (cm)
Magnetic factor									
M	218.09	17.93	1505.82	274.51	19.86	32.61	18.88	750.50	8.60
M_0	187.62	11.47	1014.62	198.74	16.01	29.47	16.92	607.76	6.95
L.S.D.	6.51	1.40	234.30	5.47	1.70	1.72	0.35	35.22	0.30
Saline water irrigation factor									
S_0	224.75	18.18	1690.05	307.59	22.72	38.14	21.21	794.04	9.18
S_1	227.75	16.91	1467.83	283.55	21.33	36.33	19.42	750.44	8.67
S_2	208.83	13.63	1282.17	246.35	17.18	30.95	17.78	723.56	8.23
S_3	192.43	13.28	1016.44	187.91	15.37	26.56	16.14	637.47	7.23
S_4	160.46	11.52	844.64	157.712	13.26	23.17	14.91	490.11	5.58
L.S.D.	7.99	0.72	79.60	12.17	0.95	3.11	1.15	25.01	0.32
Interaction between magnetic water treatment and saline irrigation									
M-S_0	225.17	18.87	1620.03	305.71	22.43	38.35	21.15	788.38	9.14
M-S_1	246.33	17.97	1546.68	296.75	21.13	35.23	19.41	786.96	9.12
M-S_2	224.67	17.25	1523.04	285.46	19.93	32.61	18.37	752.83	8.52
M-S_3	207.87	18.73	1437.86	257.37	18.37	30.32	17.84	726.06	8.28
M-S_4	186.42d	16.85	1401.58	227.31	17.53	26.35	17.62	698.28	7.96
M_0-S_0	224.33	17.50	1760.10	309.47	23.03	38.25	21.31	799.70	9.22
M_0-S_1	209.17	15.83	1389.12	270.36	21.53	37.34	19.41	713.96	8.23
M_0-S_2	193.24	10.06	1041.33	207.38	14.33	29.23	17.20	694.33	7.92
M_0-S_3	177.36	7.83	595.14	118.43	12.27	22.81	14.43	548.85	6.18
M_0-S_4	134.58	6.19	287.68	88.13	8.93	20.11	12.23	281.91	3.19
L.S.D.	11.30	1.02	112.57	17.21	1.34	4.39	1.63	35.38	0.45

As M = irrigation water with magnetic treatment, M_0= irrigation water without magnetic treatment, S_0 = saline irrigation water with 0.7 ds/m, S_1 = saline irrigation water with 2.5 ds/m, S_2= saline irrigation water with 4.5 ds/m, S_3= saline irrigation water with 5.5 ds/m, S_4= saline irrigation water with 7.5 ds/m.
L.S.D. test procedure is the least significant difference at $p \leq 0.05$ level of probability.

Table (4). Mean performances of fennel characteristics as affected by magnetic water treatment, salinity concentrations and the interaction through 2021-2022

	Plant length (cm)	primary branch /plant	Plant weight (g)	Root weight (g)	Number of umbels/plant	No. of umbellate /umbel	No. of seeds/umbel	Bulb weight (g)	Bulb thickness (cm)
Magnetic factor									
M	157.82	13.68	980.63	259.91	21.49	21.95	18.47	736.78	8.05
M_0	141.38	10.67	552.35	179.92	16.42	16.99	15.27	509.07	5.63
L.S.D.	15.24	1.03	108.15	23.30	2.01	0.86	1.33	20.04	0.10
Saline water irrigation factor									
S_0	160.36	16.16	982.67	274.84	24.19	23.82	20.36	763.23	8.48
S_1	157.97	13.81	916.167	247.41	21.71	21.62	18.41	740.25	7.94
S_2	147.04	11.56	745.61	235.22	18.88	19.98	16.38	630.312	6.73
S_3	147.84	9.69	607.69	170.33	16.40	16.58	15.31	543.89	6.32
S_4	135.47	9.73	580.33	171.76	13.61	15.35	13.93	436.96	4.73
L.S.D.	7.31	1.32	118.49	17.68	1.95	1.13	0.85	15.85	0.33
Interaction between magnetic water treatment and saline irrigation									
M-S_0	162.65	16.63	956.32	274.43	24.33	23.86	20.25	769.71	8.83
M-S_1	166.68	14.62	1037.06	275.70	23.21	22.77	18.73	752.63	8.08
M-S_2	159.93	12.03	1018.35	272.28	21.47	22.46	18.06	747.06	8.1
M-S_3	149.49	12.71	959.38	241.92	20.50	20.17	17.87	717.36	8.23
M-S_4	150.33	12.45	932.12	235.22	18.07	20.52	17.47	697.16	6.97
M_0-S_0	158.04	15.71	1009.02	275.26	24.05	23.80	20.47	756.76	8.16
M_0-S_1	148.85	13.36	795.31	219.11	20.2 6	20.47	18.13	727.86	7.81
M_0-S_2	134.15	11.06	472.88	198.16	16.36	17.55	14.71	513.56	5.26
M_0-S_3	146.21	6.67	256.03	108.30	12.32	12.97	12.73	370.44	4.43
M_0-S_4	119.68	7.36	228.55	98.74	9.22	10.21	10.33	176.75	2.53
L.S.D.	10.34	1.87	167.58	25.01	2.76	1.611	1.21	22.42	0.46

As M = irrigation water with magnetic treatment, M_0= irrigation water without magnetic treatment, S_0 = saline irrigation water with 0.7 ds/m, S_1 = saline irrigation water with 2.5 ds/m, S_2= saline irrigation water with 4.5 ds/m, S_3= saline irrigation water with 5.5 ds/m, S_4= saline irrigation water with 7.5 ds/m.
L.S.D. test procedure is the least significant difference at $p \leq 0.05$ level of probability.

Finally, it is noticed that, MTW significantly improve fennel vegetative growth parameters under salinity level stress compared to non-magnetized water treatment. These improvements include; increased umbel number, umbel weight, and seed weight. MTW will mitigate salinity-induced oxidative stress in fennel plants by increasing antioxidant enzyme activity and maintaining photosynthetic pigments. MTW promoted nutrient uptake in fennel plants under salinity stress, contributing to improved growth and yield. MTW will be an effective and sustainable strategy for enhancing fennel plant growth, yield, and stress tolerance under salinity stress conditions.

Results clearly demonstrate that MWT significantly enhances fennel growth and yield, while saline water stress adversely affects these parameters. MWT has emerged as a promising agricultural practice due to its potential to mitigate the negative effects of abiotic stresses and promote plant growth and productivity. This could involve increased enzyme activity, photosynthesis, and nutrient uptake. Again salt mitigation as shown to alleviate salinity stress in various plants, including fennel **(Deng *et al.*, 2022).** This protective effect could be attributed to improved antioxidant activity and nutrient uptake under salinity conditions.

Interaction between MWT and salinity was significant for most growth and yield parameters. This suggests that MWT's ability to mitigate salinity stress is not constant across different salinity levels. The most pronounced beneficial effects of MWT were observed at salinity levels of 2.5 ds/m and 4.5 ds/m. The findings of this study provide valuable insights into the potential of MWT as a sustainable approach to enhance fennel growth and yield under salinity stress conditions. MWT can be integrated into fennel cultivation practices to improve productivity and reduce the negative effects of salinity stress till 4.5ds/m keeping in mind that, the relationship between magnetic water treatment and plant traits can be complex, and findings may vary based on factors such as soil type, climate, and specific crop varieties.

Table (5). Mean performances of fennel compound contents as affected by magnetic water treatment, salinity concentrations and the interaction through 2020-2021

	TSS	Chlor. a (m/gm)	Chlor. b (m/gm)	Chlor. a+b (m/gm)	N (%)	P (%)	K (%)	Proline (μM)	Bulb DW %	Leaves DW %
Magnetic factor										
M	11.05	10.447	3.64	14.254	2.09	0.282	1.49	11.749	28.45	46.314
M_0	9.35	6.83b	2.97	10.189	1.93	0.231	1.41	14.529	24.852	42.18
L.S.D.	0.62	0.77	0.094	1.66	0.019	0.009	0.066	1.051	0.590	0.8103
Saline water irrigation factor										
S_0	10.025	10.731	3.874	14.585	2.27	0.2855	1.573	11.435	29.26	46.57
S_1	9.875	9.651	3.727	13.767	2.06	0.312	1.29	12.380	29.59	47.819
S_2	10.320	8.533	3.401	12.222	1.95	0.26	1.50	12.928	26.89	44.73
S_3	10.475	7.456	2.84	10.952	1.89	0.231	1.43	13.647	24.22	42.35
S_4	10.325	6.835	2.711	9.583	1.883	0.191	1.47	15.306	23.29	39.77
L.S.D.	0.62	0.662	0.32	1.09	0.092	0.02	0.066	0.75	0.791	1.341
Interaction between magnetic water treatment and saline irrigation										
M-S_0	11.35	11.156	3.902	15.221	2.35	0.28	1.69	11.162	28.87	46.264
M-S_1	10.6	11.118	3.872	15.177	2.218	0.315	1.19	11.315	29.86	47.58
M-S_2	11.25	11.073	3.88	14.781	2.08	0.28	1.55	11.432	28.72	46.25
M-S_3	11.12	9.745	3.341	13.776	1.93	0.27	1.54	12.129	27.69	45.87
M-S_4	11.31	9.14	3.234	12.318	1.92	0.25	1.49	12.704	27.136	45.60
M_0-S_0	8.71	10.306	3.846	13.949	2.18	0.281	1.45	11.689	29.66	46.87
M_0-S_1	9.15	8.18	3.58	12.358	1.91	0.309	1.39	13.444	29.32	48.05
M_0-S_2	9.61	5.995	2.92	9.663	1.83	0.243	1.458	14.424	25.07	43.22
M_0-S_3	9.95	5.167	2.34	8.127	1.85	0.189	1.3149	15.167	20.75	38.84
M_0-S_4	9.35	4.528	2.19	6.847	1.849	0.132	1.461	17.912	19.45	33.93
L.S.D.	0.88	0.93	0.46	1.55	0.131	0.0329	0.094	1.062	1.11	1.897

As M = irrigation water with magnetic treatment, M_0= irrigation water without magnetic treatment, S_0 = saline irrigation water with 0.7 ds/m, S_1 = saline irrigation water with 2.5 ds/m, S_2= saline irrigation water with 4.5 ds/m, S_3= saline irrigation water with 5.5 ds/m, S_4= saline irrigation water with 7.5 ds/m
L.S.D. test procedure is the least significant difference at $p \leq 0.05$ level of probability.

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