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Effect of Magnetic Iron, *Arthrospira* Sp., and Arbuscular Mycorrhizal on Artichoke Growth and Productivity Under Different Irrigation Water Sources

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Abstract: Field experiments were conducted during the 2022/23 and 2023/24 seasons at two locations in the North Nile Delta, Egypt, to evaluate the effects of foliar *Arthrospira* sp. extract (Ar), arbuscular mycorrhizal fungi (My) and magnetic iron (Mi), compared with an untreated control (C), on the growth, yield, quality and irrigation water productivity (IWP) of globe artichoke (*Cynara cardunculus* var. scolymus) irrigated with three water sources: fresh canal water (FW; ECw 0.635 dS m^{-1}), well water (WW; 2.05 dS m^{-1}) and blended water (BW; 1.78 dS m^{-1}). At Site 1, FW and WW were main plots and the four treatments were subplots in a split-plot randomized complete block design; at Site 2, BW was tested in a separate randomized complete block design. Each design had three replicates. Because the water sources were not replicated across locations, the locations were analyzed separately. Phytochemical analysis of *Arthrospira* sp. showed the existence of phytohormones, minerals, and several secondary metabolites. GC-MS analyses cleared the presence of several bioactive compounds in the *Arthrospira* extract, and phytohormones (gibberellic acid: 4.28 µg g^{-1}; 6-benzyl-adenine: 6.15 µg ml^{-1}; IAA: 2.39 µg g^{-1}). *Arthrospira* achieved the highest total yield over the two seasons (29.30 and 26.90 t ha^{-1} versus 16.88 and 14.42 t ha^{-1} for the untreated control). Under FW, Ar increased IWP to 7.43 and 7.15 kg m^{-3} (44.89 and 65.78% above the FW control, the reference for location 1); under WW, to 6.93 and 7.02 kg m^{-3} (35.14 and 62.87% above the same FW control). My produced the highest plant height in season 1 (91.25 cm versus 65.00 cm), and Mi gave the highest early yield (7.69 t ha^{-1}, significantly above the control) and total head weight (351.30 g) in season 1. Under blended water (Site 2), Ar gave the highest yield and IWP in both seasons, but significantly only in season 1 (16.15 t ha^{-1}; IWP +144.82%). In season 2 the differences

were not significant (10.52 t ha^{-1}; IWP +38.19%). At Site 1, the water source × treatment interaction was significant for total yield, receptacle dry matter and inulin. The findings indicate that the application of *Arthrospira* sp., mycorrhizal, and magnetized iron can improve artichoke growth and productivity under the varying irrigation water sources evaluated in this study

Key words: Artichoke, *Arthrospira*, Arbuscular mycorrhizal fungi, magnetic iron, water sources, irrigation water productivity

1. Introduction

Artichoke (*Cynara scolymus* L.) is an important vegetable crop because of its nutritional and functional properties. Although artichoke is relatively low in protein, it is rich in inulin and dietary fiber, which contribute to its nutritional and functional value. Recent research has highlighted the antioxidant potential of artichoke extracts and their possible contribution to reducing oxidative stress and supporting human health (**Laghezza Masci *et al.* 2025**). Therefore, improving both the productivity and quality of artichoke is important for sustainable horticultural production. However, irrigation with saline or otherwise unsuitable water can adversely affect plant growth through osmotic stress and ion toxicity, which disturb cellular homeostasis and interfere with water and nutrient uptake. Consequently, salinity stress may reduce vegetative growth, productivity, and marketable quality (**Saleh *et al.* 2012**, **Colla et al,2010)**. High concentrations of sodium and chloride in plant tissues can also disrupt ionic balance and restrict the uptake of essential nutrients, particularly potassium, calcium, and magnesium, thereby negatively affecting artichoke growth and quality (**Francois, 1995; Boari *et al.*, 2012**), drainage water in the Nile Deltais is increasingly reused as a supplemental irrigation source, although its salinity and quality differ markedly across spatial scales. **El-Agha *et al.* (2020)** showed that salinity in secondary drains can extend up to four times that of collector drains, because accumulation of salts from deeper soil layers and intrusion of saline groundwater, and that water quality parameters fail to meet irrigation reuse standards. This spatial and temporal heterogeneity in drainage water quality justifies the need to evaluate blended water as a clear irrigation treatment, instead of assuming that drainage water behaves uniformly across the irrigation network. Enhancing plant resistance to salinity and improving water use efficiency (WUE) are vital for sustainable agriculture, particularly in areas with limited freshwater. Recent studies underscore the importance of integrated management techniques and soil amendments, such as magnetic iron, which can enhance nutrient absorption, improve water retention, and boost soil quality. Iron is an essential micronutrient involved in chlorophyll biosynthesis, photosynthetic activity, and several metabolic processes. However, iron availability is frequently limited in alkaline soils because of the low solubility of iron compounds, potentially resulting in iron deficiency and impaired plant growth (**Li *et al.*, 2023**). Iron-based amendments and iron oxide nanoparticles have been investigated for their potential to improve plant nutritional status and alleviate the adverse effects of salinity, including sodium toxicity (**Abou-Baker *et al.* 2019; Alharbi *et al.*, 2022 and Abdulhady, 2023**). In addition to mineral amendments, biological approaches can contribute to improving plant performance under environmental stress.

Arbuscular mycorrhizal fungi (AMF), for example, can enhance nutrient acquisition and support plant tolerance to unfavorable soil conditions through improved plant–fungus interactions. Other beneficial microorganisms, including plant growth-promoting rhizobacteria (PGPR), have also been reported to improve plant responses to environmental stresses (**Bhat *et al.* 2023; Pandino *et al.* 2024; Victoria *et al.* 2025**). Another promising biological resource is *Arthrospira* sp., a filamentous cyanobacterium containing various biologically active compounds, including amino acids, phytohormones, phenolic compounds, antioxidants, macronutrients, and micronutrients. These constituents may contribute to improved plant growth, nutrient status, and physiological performance.

Foliar application of *Arthrospira*-based extracts has been investigated as a potential approach to enhance plant growth and productivity and support defense responses under saline irrigation conditions

(**Gharib and Ahmed, 2023; Abada *et al.*, 2023; Mostafa *et al.*, 2024 and Abdulhassan, 2025**). Nevertheless, the individual and combined contributions of magnetic iron, AMF inoculation, and foliar application of *Arthrospira* sp. to artichoke performance under different irrigation water qualities remain insufficiently understood. In particular, further investigation is needed to clarify how these treatments influence vegetative growth, physiological and nutritional characteristics, yield, inulin content, and water-use efficiency under contrasting irrigation conditions.

Accordingly, the present study aimed to evaluate the effects of magnetic iron application, AMF inoculation, and foliar application of *Arthrospira* sp. on the growth, productivity, and quality of artichoke plants grown under different irrigation water sources. The study also investigated the effects of these treatments on selected physiological and biochemical characteristics, inulin content, and water-use efficiency. The findings are expected to provide information on the potential contribution of these management practices to improving artichoke production under conditions of limited freshwater availability and variable irrigation water quality.

2. Materials and methods

2.1. Experimental sites and design

Two experimental field sites were selected in the North Nile Delta region of Egypt to represent different irrigation water sources. Location A was situated on a farmer's field approximately 15 km west of Kafr El-Sheikh city (31°10′56″N, 30°50′55″E). and was irrigated with fresh from El-Safty canal and well water (farmers' pump). Location B was situated approximately 3 km from location A at 31°11'25.5" N, 30°49' 35.7" E and was irrigated with blended water, consisting of canal water supplied through Om dokhan Mesqa and drainage water from Bahr Nashart Drain. Both experimental sites are located in a region characterized by a semi-arid Mediterranean climate. Globe artichoke (*Cynara scolymus* L.) cv. "Herious" was planted on September 20 and 25 during the 2022/2023 and 2023/2024 growing seasons, respectively. Plants were established at a spacing of 100 cm between rows and 80 cm between plants within rows. The fertilization program commonly used for globe artichoke production in the region was applied, providing of 476 kg N ha^{-1}, 190.4 kg P_2O_5 ha^{-1}, and 238 kg K_2O ha^{-1}. All other recommended agronomic practices, including soil tillage, pest management, and weed control, were carried out as required under local cultivation conditions. The physical and chemical properties of the soils at the experimental sites chemical characteristics of the irrigation water sources found in Table 1 and 2, respectively.

Table (1). Some Soil physical and chemical properties of locations A and B

Experiment location		Location A	Location B
Texture		Clayey	Clayey
pH		7	8.2
Cations (meq /L)	Ca^{++}	4.99	2.28
	K^{+}	0.02	0.09
	Mg^{++}	7.9	2.71
	Na^{+}	2.4	6.06
Anions (meq/L)	Cl^{-}	3.7	3.5
	So_4^{---}	2.45	7.08
	Co_3^{--}	0	0
	HCo_3^{-}	9.03	0.57
EC dS/m		3.22	2.23
SAR (sodium adsorption ratio)		0.96	3.84
ESP% (exchangeable sodium percentage)		0.15	4.21

Table (2). Chemical properties of different Irrigation water sources

Irrigation water		Fresh water	Blended water	Well water
pH		7.38	7.8	7.71
Cations (meq/L)	Ca^{++}	2.9	3.1	2.1
	K^{+}	0.26	1.07	0.3
	Mg^{++}	0.68	2.81	1.45
	Na^{+}	2.17	9.8	16.2
Anions (meq/L)	Cl^{-}	1.71	5.97	4.5
	So_4^{---}	0.96	6.68	8.52
	Co_3^{--}	0	0	1
	HCo_3^{-}	3.75	3.52	6.48
EC dS/m		0.635	1.78	2.05
SAR (sodium adsorption ratio)		1.62	5.7	12.1
RSC (Residual Sodium Carbonate) mg/L		0.17	2.38	3.93

2.2. Site One experiment

A Site One, a split-plot design based on randomized complete blocks design (RCBD) with three replicates was employed. Irrigation water sources Irrigation water sources were assigned to the main plots, while fertilizer treatments and biological treatments were assigned to the subplots, as follows:

A. Main plot treatments (Irrigation water Sources)

- Fresh water (FW): Canal water obtained from El-Safty Canal, used as the reference irrigation treatment, with an electrical conductivity (ECw) of 0.635 dS m^{-1}.
- Well water (WW): Groundwater pumped from an agricultural well, with an ECw of 2.05 dS m^{-1}.

B. Subplot treatments (fertilization treatments)

- Untreated control (C): No application of the tested fertilizer or biological treatments
- Mycorrhizal treatment (My): plants were inoculated with arbuscular mycorrhizal fungi (AMF) at a total application rate 9.52 L ha^{-1}. The inoculum was applied in two equal doses: 4.76 L ha^{-1} during soil preparation at planting and 4.76 L ha^{-1} one month after planting. The inoculum was obtained from the Central Laboratory, Faculty of Agriculture, Ain Shams University.
- *Arthrospira* sp. extract (Ar): The extract was applied as a foliar spray at a rate 2.38 L ha^{-1} on three occasions, at 15, 30, and 60 days after transplanting (DAT), resulting in a total seasonal application rate of 7.14 L ha^{-1}. The cultivation and extraction procedures for *Arthrospira* sp. were performed according to **Yanni *et al.* (2020)**.
- Magnetic iron (Mi): Mi was applied at a total rate of 476 kg ha^{-1}, divided into two equal doses of 238 kg ha^{-1} each. The first dose was applied before planting, whereas the second was applied 45 days after planting. The material was obtained from Al-Ahram for Minerals Company.

2.3. Site Two experiment

At Site Two, a randomized complete block Design (RCBD) with three replicates was employed. The experimental plots were assigned to the same fertilizer treatments described for Site One.

The plots at Site Two were irrigated with blended water (BW), which had an electric conductivity (EC_w) of 1.78 dS m^{-1}.

Irrigation water analysis (Table 3) showed that fresh canal water had EC of 0.635 dSm^{-1}, SAR of 1.62, while blended water had EC 1.78 dSm^{-1} and SAR of 5.7. Well water showed the highest values, with EC 2.05 dSm^{-1} and SAR of 12.1.

2.4. Plant measurements

2.4.1. Plant height

Plant height (cm) was measured after 120 days from planting in five randomly selected plants from each experimental plot. The mean plant height was calculated for each plot during both growing seasons.

2.4.2. Early yield weight (t ha^{-1})

Early yield (t ha^{-1}) was calculated as the cumulative weight of all flower heads harvested from the beginning of the harvest period until the end of February and expressed as tones per hectare.

2.4.3. Total yield weight (t ha^{-1})

Total yield (t ha^{-1}) was calculated as the cumulative weight of all flower heads harvested from the first harvest until the end of May. Thus, end, as total yield included the early yield (harvested up to the end of February) and all subsequent harvests through the end of May.

2.4.4. Flower head weight (g)

Five flower heads were randomly selected from each plot, and their average weight (g) was measured during both the early and total harvest periods in the both seasons.

2.4.5. Receptacle weight (g) in early yield

Five flower heads were randomly collected from each plot during the early harvested period, and average receptacle weight (g) was calculated for both growing seasons.

2.4.6. Dry mater of leaves% and receptacle

Dry matter percentages of leaves and receptacles (in total yield) were determined using 100 g of fresh samples of each plant part. The samples were oven-dried at 70 °C until constant weight was achieved. Dry weight to fresh weight, multiplied by 100, according to **AOAC (2012).**

2.4.7. Inulin%

Inulin content was determined in the dry matter of heads in total yield according to the method described by Winton and Winton (1958).

2.5. *Arthrospira* sp analyses

2.5.1. Determination of total hormones by HPLC

Phytohormones were measured according to **Jones *et al.* (1980)**.

2.5.2. Determination of profile compounds by GC-MS.

The bioactive compounds were determined by GC-MS according to **Huwaimel *et al.* (2023)**.

2.6. Irrigation water measurements

2.6.1. Irrigation water productivity (IWP)

Irrigation water productivity (IWP, kg m^{-3}) was calculated as total yield (kg ha^{-1}) divided by seasonal irrigation water applied (m^3 ha^{-1}) (Kijne et al., 2003). The volume applied at each irrigation was measured and divided by plot area to give water applied per hectare, and the seasonal total was the sum over all irrigation events. Water productivity improvement (WPI, %) followed **Ahmed et al. (2014)**:

$$WPI = ((IWPt - IWPc) / IWPc) \times 100$$

Where

IWPt is the IWP of a treatment and IWPc is the IWP of the reference control in the same season. At Site 1, FW and WW were in the same experiment, so the untreated FW control is the common reference for both sources. At Site 2, the reference is the untreated BW control.

2.7. Statistical analysis

Data were analyzed with CoStat version 6.303 (CoHort Software, Monterey, CA, USA) by analysis of variance, separately for each site and season. At Site 1 the analysis used the split-plot design with separate error terms for main plots and subplots; at Site 2 the randomized complete block design was used. Means were separated by Duncan's test at $P \leq 0.05$. Because FW and WW were tested only at Site 1 and BW only at Site 2, the effect of water source cannot be separated from the effect of site, so no statistical comparison was made among the three sources and Site 2 is reported separately.

3. Results

3.1. Determination of phytohormones by HPLC

The information in **Table 3** demonstrates that *Arthrospira* sp. contains plant hormones. The highest concentration was found in 6-benzyl adenine (6.15 µg g^{-1}), followed by gibberellic acid (4.28 µg g^{-1}) and indole-3-acetic acid (IAA) (2.39 µg g^{-1}).

Table (3). Phytohormones of *Arthrospira* sp

Compound	Concentration µg g^{-1}
GBA	4.28
6-Benzyle adenine	6.15
IAA	2.39

3.2. Bioactive compounds by Arthrospira sp. identified by GC-MS

GC–MS analysis was performed to identify the chemical constituents of the *Arthrospira* sp. extract. The identified compounds, their proposed chemical classes, and their reported biological activities are presented in **Table 4**.

3.3. Site One Experiment

3.3.1. Plant measurements

3.3.1.1. Effect of mycorrhizal inoculation, foliar application of *Arthrospira* sp., and magnetic iron application under different sources of irrigation water on plant height (cm), early yield and total yield (t ha^{-1}) of artichoke plants

As shown in **Table 5A**, irrigation water source significantly affected total yield only during the first growing season, whereas its effects on plant height and early yield were not significant in either season. In contrast, the amendment treatments significantly affected plant height in seasons, early yield in the first season only, and total yield in both growing seasons. Plant height and early yield did not differ significantly between fresh-water and well-water irrigation in either growing season. However, well-water irrigation resulted in a significantly higher total yield than fresh-water irrigation during the first season (23.34 versus 22.27 t ha^{-1}), whereas no significant difference was observed during the second season.

Among the amendment treatments, mycorrhizal inoculation produced the highest plant height during the first season (91.25 cm), whereas magnetic iron application recorded the highest early yield in both seasons (7.69 and 8.80 t ha^{-1}, respectively). Foliar application of *Arthrospira* sp. extract resulted in the highest total yield during both seasons (29.30 and 26.90 t ha^{-1}, respectively).

The interaction between irrigation water source and amendment treatment was not significant for plant height or early yield in either growing season. However, a significant interaction was observed for total yield during the first season, but not during the second season (**Table 5B**).

3.3.1.2. Effects of irrigation water sources and different agricultural treatments on flower head and receptacle weights, and total yield flower head weight of artichoke plants

The results presented in **Table 6** indicated that irrigation water sources had variable effects on artichoke yield components across the two growing seasons. Fresh water irrigation generally resulted in

higher flower head weights than well water irrigation, particularly during the second season, although the differences were not significant for all measured traits. Regarding the agricultural treatments, mycorrhizal inoculation recorded the highest flower head weight in early yield during both seasons (554.71 and 549.13 g, respectively). Magnetic iron application produced the highest receptacle weight during the first season (202.91 g), whereas mycorrhizal inoculation achieved the highest value during the second season (202.01 g). Concerning total flower head weight, magnetic iron application recorded the highest value in the first season (351.30 g), while mycorrhizal inoculation recorded the highest value in the second season (383.19 g).

Table (4). The bioactive compounds of *Arthrospira* sp

Compound	Class	Biological activity
Uvidin A	Indole alkaloid	Enhances plant defense against pathogens, reduces stress damage, and may improve growth, quality, and storability of artichoke heads
Vanillin lactoside	Phenolic glycoside	Enhances plant defense against microbial pathogens, improves stress tolerance, and contributes to overall quality by reducing oxidative damage
D-Fructose, diethyl mercaptal, pentaacetate	Sugar derivative (modified fructose, acetylated mercaptal)	**stabilized sugar derivative** improving osmoprotection, supporting energy metabolism under stress, and potentially enhancing plant resilience and storability
Propanoic acid	Short-chain fatty acid (carboxylic acid)	Improves plant health by inhibiting fungal pathogens, may reduce postharvest spoilage, and can act as a carbon source in microbial metabolism supporting biofertilization
Cyclopropaneoctanoic acid, 2-octyl-, methyl ester	Fatty acid ester (cyclopropane derivative)	May help stabilize cell membranes under stress, enhance plant defense against microbial pathogens, and improve storability and quality of crops such as onion and artichoke
cis-13-Octadecenoic acid	Monounsaturated fatty acid	Helps maintain membrane fluidity, improves stress tolerance (heat, drought, salinity
Hexadecanoic acid, methyl ester	Fatty acid methyl ester (derivative of palmitic acid)	Enhances plant defense, reduces microbial spoilage, improves storability
Dasycarpidan-1-meth anol, acetate (ester)	Indole alkaloid derivative	Supports defense against pathogens, may regulate plant growth via signaling
Methyl linolenate	Fatty acid methyl ester (PUFA derivative)	Protects against oxidative stress, enhances tolerance to cold and drought
9-cis,11-trans-octade Cadienoate	Conjugated linoleic acid isomer (PUFA)	Improves resistance to oxidative stress, may contribute to growth regulation
Phytol	cyclic diterpene alcohol (chlorophyll derivative)	Chlorophyll degradation product; precursor of Vitamin E & K. Improves plant stress resistance, enhances quality and nutritional value, contributes to photosynthetic pigment recycling
Isopropyl linoleate	Fatty acid ester (linoleic acid derivative)	Energy storage; membrane fluidity; antimicrobial; reflects presence of linoleic acid
Ethyl iso-allocholate	teroidal ester (bile acid derivative / triterpenoid-like	Can act as a growth regulator mimic, may enhance stress signaling and pathogen defense
Glycidyl palmitate	Fatty acid ester (palmitic acid derivative)	Energy storage; membrane component; antimicrobial potential; reflects presence of palmitic acid
Trilinolein	Triacylglycerol (storage lipid)	Major energy storage. Provides energy reserve, enhances stress tolerance, and improves seedling vigor
3,5,9-Trioxa-5-phosph aheptacos-18-en-1-aminium	Phospholipid-like / phosphonium derivative	Membrane stability; cell signaling; possible antimicrobial role. Could enhance nutrient transport, improve stress adaptation, and contribute to plant-microbe interactions
Oleyl oleate	Fatty acid ester (oleic acid derivative)	Protects cell membranes, improves drought tolerance, may reduce postharvest spoilage

Table (5A). Effect of mycorrhizal inoculation, foliar application of *Arthrospira* sp., and magnetic iron application under different sources of irrigation water on plant height (cm), early yield and total yield (t ha^{-1}) of artichoke plants

Treatment		Plant height (cm)		Early flower yield (t ha^{-1})		Total flower yield (t ha^{-1})	
		Season$_1$	Season$_2$	Season$_1$	Season$_2$	Season$_1$	Season$_2$
main	FW	79.45	76.33	6.679	7.479	22.27b	20.89
	WW	74.37	71.83	6.267	6.802	23.34a	20.74
	F test	N.S	N.S	N.S	N.S	*	N.S
Sub main	C	65.00b	63.33b	4.769b	4.938	16.88d	14.42c
	My	91.25a	83.33a	6.842ab	7.068	24.57b	21.59b
	Ar	76.41b	72.66ab	6.601ab	7.757	29.30a	26.90a
	Mi	75.00b	76.99a	7.691a	8.799	20.47c	22.36b
	F test	**	*	**	N.S.	***	***

N.S.: Not-significant ($P > 0.05$); *: Significant ($P < 0.05$). Means followed by the same letter are not significantly different (≤ 0.05).

Table (5B). Effect of the interaction between mycorrhizal inoculation, foliar application of *Arthrospira* sp., and magnetic iron application under different sources of irrigation water on plant height (cm), early yield and total yield (t.ha^{-1}) of artichoke plants

Main plot	Sub plot	Plant height (cm)		Early flower yield (t ha^{-1})		Total flower yield (t ha^{-1})	
		Season$_1$	Season$_2$	Season$_1$	Season$_2$	Season$_1$	Season$_2$
FW	C	67.50	66.66	4.416	5.150	19.43c	15.07
	My	95.00	88.33	7.740	7.818	22,87bc	20.51
	Ar	80.33	73.66	6.086	7.783	28.10a	24.97
	Mi	75.00	76.66	8.475	9.185	18.50c	22.39
WW	C	62.50	60.00	5.104	4.726	14,28d	13.78
	My	87.50	78.33	5.943	6.319	26.28ab	22.67
	Ar	72.50	71.66	7.115	7.731	30,43a	28.81
	Mi	75.50	77.33	6.907	8.431	22.36bc	22,32
F test		N.S.	N.S.	N.S.	N.S.	*	N.S.

N.S.: Not-significant (P > 0.05); *: Significant ($P < 0.05$). Means followed by the same letter are not significantly different ($P \leq 0.05$)

Table (6). Effect of mycorrhizal inoculation, foliar application of *Arthrospira* sp., and magnetic iron application under different sources of irrigation water on flower head weight, receptacle weight (g) in early yield and total yield flower head weight of artichoke plants

Treatment		Early yield				Total yield flower head weight (g)	
		Flower head weight(g)		Receptacle weight(g)			
		Season$_1$	Season$_2$	Season$_1$	Season$_2$	Season$_1$	Season$_2$
main	FW	484.30	532.24a	180.55	175.31	311.95	364.15a
	WW	436.28	444.94b	170.14	175.37	322.89	298.13b
	F test	N.S	*	N.S	N.S	N.S	**
Sub main	C	404.06b	363.52c	126.97b	129.47b	323.11ab	283.58b
	My	554.71a	549.13a	185.97a	202.01a	298.63b	383.19a
	Ar	467.53ab	503.03ab	185.54a	175.07a	296.64b	373.70a
	Mi	528.08a	425.47bc	202.91a	194.84a	351.30a	284.58b
	F test	**	*	*	*	*	**

N.S: Not-significant (P > 0.05); *: Significant (P < 0.05). **, high significant (P < 0.01). Means followed by the same letter are not significantly different (P ≤ 0.05)

3.3.1.3 Interaction between irrigation water sources and agricultural treatments on flower head weight of artichoke plants during early yield

As shown in Fig. 1A and B, the interaction between irrigation water source and agricultural treatments significantly affected flower head weight of artichoke plants during early yield in both growing seasons. In the 2022/2023 season, the highest flower head weight was recorded with mycorrhizal inoculation (My) under fresh water irrigation (FW), whereas the lowest value was obtained with magnetic iron application (Mi) under well water irrigation (WW). Interestingly, *Arthrospira* sp. extract application (Ar) under WW irrigation resulted in a higher flower head weight than under FW irrigation. In the 2023/2024 season, me under FW irrigation again produced the highest flower head weight, followed by Ar under FW irrigation. In contrast, the response to Mi was relatively similar under both irrigation water sources. These results demonstrate that the effects of agricultural treatments on flower head weight depended on the irrigation water source and growing season.

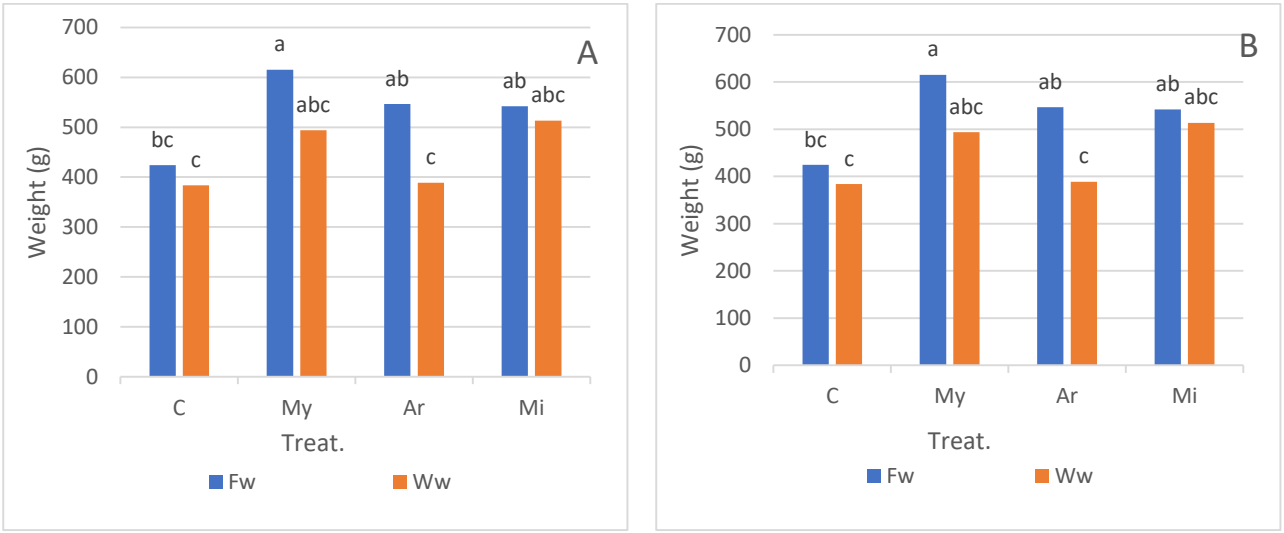


Fig (1). Effects of the interactions among irrigation water sources, mycorrhizal inoculation, foliar application of *Arthrospira* sp., and magnetic iron application on flower head weight (g) of artichoke plants during early yield in the 2022/2023 (A) and 2023/2024 (B) growing seasons

3.3.1.4. Interaction between irrigation water sources and agricultural treatments on receptacle weight (g) of early yield

As shown in Fig. 2 A and B, receptacle weight of artichoke plants during early yield was influenced by the interaction between irrigation water sources and agricultural treatments during both growing seasons. During the 2022/2023 season, the highest receptacle weights were recorded with *Arthrospira* sp. extract (Ar) and magnetic iron (Mi) applications under fresh water irrigation (FW), with no significant differences between these treatments. Mycorrhizal inoculation (My) also produced relatively high receptacle weights under both irrigation water sources. In the 2023/2024 season, the highest values were obtained with magnetic iron application under FW irrigation and mycorrhizal inoculation under well water irrigation (WW), with both treatments belonging to the same statistical group. In contrast, the untreated control under FW irrigation recorded the lowest receptacle weight in both seasons. These findings indicate that the effects of agricultural treatments on receptacle weight varied depending on the irrigation water source and growing season.

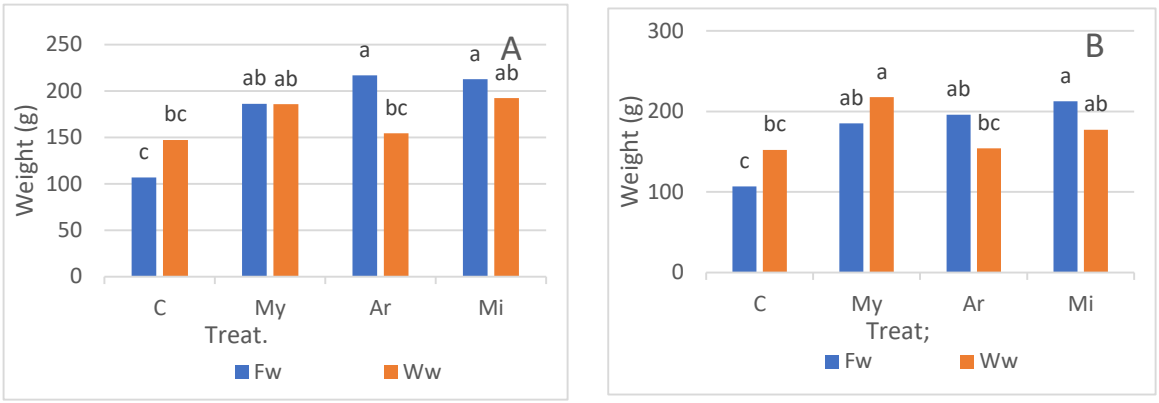


Fig. (2). Effect of interactions of mycorrhizal inoculation, foliar spraying of *Arthrospira* sp., and magnetic iron application under different sources of irrigation water on receptacle weight (g) of early yield artichoke during two seasons of 2022/23 (A), and 2023/24 (B)

3.3.1.5. Interaction between irrigation water sources and agricultural treatments on flower head weight (g) of total yield

Fig. 3 (A and B) illustrates the interaction effects of irrigation water sources and different bio-treatments, including mycorrhizal inoculation (My), foliar application of *Arthrospira* sp. (Ar), and magnetic iron application (Mi), on the total flower head weight of artichoke plants during the 2022/23 and 2023/24 growing seasons. During the first season (Fig. 3A), under fresh water irrigation (FW), mycorrhizal inoculation (My) recorded the highest flower head weight, followed by *Arthrospira* sp. application (Ar), whereas the control treatment (C) recorded the lowest value. Under well water irrigation (WW), *Arthrospira* sp. application produced the highest numerical value, followed by mycorrhizal inoculation (My), while the control treatment recorded the lowest value. In the second season (Fig. 3B), magnetic iron application (Mi) recorded the highest flower head weight under both fresh water and well water irrigation. Under fresh water irrigation, the control treatment ranked second, whereas mycorrhizal inoculation recorded the lowest numerical value. Under well water irrigation, the control treatment also showed a relatively high value, while mycorrhizal inoculation and *Arthrospira* sp. application exhibited comparable values. Overall, the results revealed seasonal variation in the responses of artichoke plants to the applied treatments, with the relative performance of the bio-treatments and magnetic iron varying according to the irrigation water source and growing season.

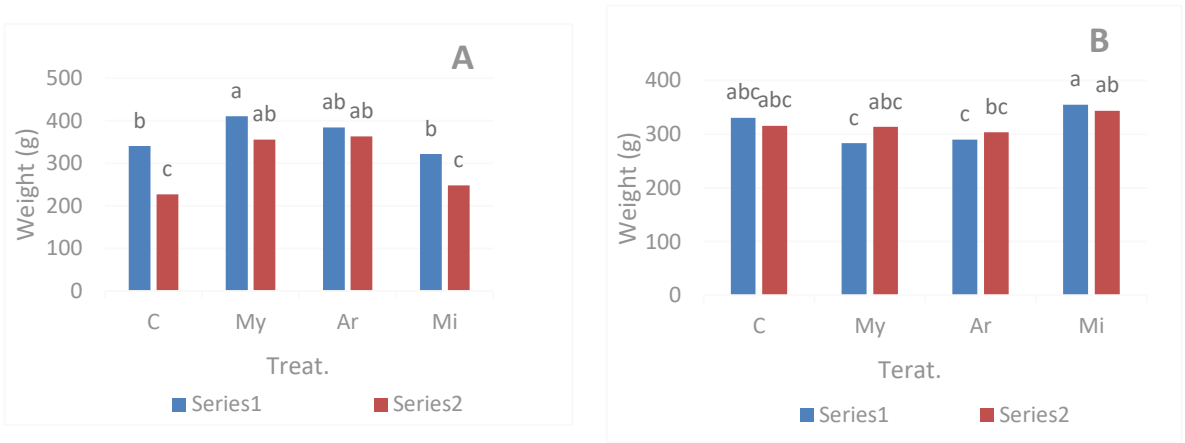


Fig (3). Effect of interactions of mycorrhizal inoculation, foliar spraying of *Arthrospira* sp., and magnetic iron application under different sources of irrigation water on flower head weight (g) of total yield artichoke during the two seasons of 2022/23 (A), and 2023/24 (B)

3.3.1.6. Effects of treatments under studied on dry matter of leaves and receptacle (%), and inulin content (%) in total yield of artichoke plants

Data presented in Table 7A show that irrigation water sources had no significant effects on leaf dry matter content during either growing season. Similarly, no significant differences were observed in receptacle dry matter content during the first season. However, in the second season, fresh water irrigation resulted in a significantly higher receptacle dry matter content (17.06%) than well water irrigation (16.19%). Inulin content was not significantly affected by irrigation water sources in either growing season. The sub-main treatments, significant differences in leaf dry matter content were observed during both growing seasons. Foliar application of *Arthrospira* sp. (Ar) recorded the highest values, reaching 27.96% and 26.57% in the first and second seasons, respectively. Mycorrhizal inoculation (My) ranked second, with corresponding values of 25.97% and 24.39%, whereas the control treatment recorded the lowest values of 23.09% and 20.41%, respectively.

Concerning receptacle dry matter content, significant differences among treatments were detected only during the first season. Magnetic iron application (Mi) recorded the highest value (17.88%), followed by mycorrhizal inoculation and *Arthrospira* sp. application (both 17.50%), while the control treatment recorded the lowest value (15.83%). In the second season, no significant differences were detected among the applied treatments, despite the numerical variation in their values. Inulin content, the effects of the applied treatments were not significant during the first season. However, significant treatment differences were reported in the second season, with *Arthrospira* sp. application recording the highest numerical value (1.77%), followed by mycorrhizal inoculation (1.35%), magnetic iron application (1.15%), and the control treatment (1.10%).

Table (7A). Effects of the mycorrhizal inoculation, *Arthrospira* sp. extract, and magnetic iron application under different sources of irrigation water on dry matter of leaves and receptacle (%), and inulin content (%) in total yield of artichoke plants

Treatments		Dry mater of leaves %		Dry mater of receptacle %		Inulin %	
		$Season_1$	$Season_2$	$Season_1$	$Season_2$	$Season_1$	$Season_2$
Main	FW	25.64	23.65	17.80	17.06a	1.50	1.19
	WW	24.44	23.48	17.30	16.19b	1.27	1.50
F test		N.S	N.S	N.S	**	N.S	N.S
Sub main	C	23.09b	20.41c	15.83a	15.23	1.21	1.10a
	My	25.97a	24.39b	17.50ab	16.73	1.41	1.35b
	Ar	27.96a	26.57a	17.50ab	17.19	1.45	1.77a
	Mi	23.57b	22.41c	17.88a	17.37	1.47	1.15b
F test		**	**	*	N.S.	N.S.	**

N.S.: Not-significant ($P > 0.05$); *: Significant ($P < 0.05$). **, high significant ($P < 0.01$). Means followed by the same letter are not significantly different ($P \leq 0.05$)

3.3.1.7. Interactions between mycorrhizal inoculation, *Arthrospira* sp. extract, and magnetic iron application under different sources of irrigation water on dry matter of leaves and receptacle (%), and inulin content (%) in total yield of artichoke plants

Data presented in Table 7B indicate that the interaction between irrigation water sources and the applied treatments had variable effects on leaf dry matter, receptacle dry matter, and inulin content of globe artichoke plants during the two growing seasons. Regarding leaf dry matter content, no significant interaction effects were detected in either season, despite the numerical variations among treatments. Under fresh water irrigation (FW), foliar application of *Arthrospira* sp. (Ar) recorded the highest values, reaching 27.47% and 26.71% in the first and second seasons, respectively. Under well water irrigation (WW), *Arthrospira* sp. application also recorded the highest leaf dry matter content, with values of 28.45% and 26.43%, respectively. Concerning receptacle dry matter content, the interaction effects were significant in both seasons. Under fresh water irrigation, *Arthrospira* sp. application recorded the highest value (20.41%) in the first season, whereas mycorrhizal inoculation and *Arthrospira* sp. application showed relatively high values in the second season (17.47% and 17.74%, respectively). Under well water irrigation, magnetic iron application (Mi) produced the highest receptacle dry matter content in

both seasons, reaching 19.77% and 19.26%, respectively. These results indicate that the response of receptacle dry matter to the applied treatments varied according to the irrigation water source. Regarding inulin content, significant interaction effects were observed in the first season, whereas no significant interaction effect was detected in the second season. Under fresh water irrigation, *Arthrospira* sp. application recorded the highest inulin content (1.85%) in the first season, followed by mycorrhizal inoculation (1.47%). Under well water irrigation, magnetic iron application recorded the highest value (1.87%), followed by the control treatment (0.833%). In the second season, although *Arthrospira* sp. application under well water irrigation recorded the highest numerical inulin content (1.78%), the differences among treatment combinations were not statistically significant. *Arthrospira* sp. application consistently produced the highest numerical leaf dry matter content under both irrigation water sources and contributed to higher inulin content under fresh water irrigation in the first season. Meanwhile, magnetic iron application was particularly effective in increasing receptacle dry matter under well water irrigation across both seasons.

Table (7B). Effect the interactions between mycorrhizal inoculation, *Arthrospira* sp. extract, and magnetic iron application under different sources of irrigation water on dry matter of leaves and receptacle (%), and inulin content (%) in total yield of artichoke plants

Main plot	Sub plot	Dry mater of leaves %		Dry mater of receptacle %		Inulin %	
		$Season_1$	$Season_2$	$Season_1$	$Season_2$	$Season_1$	$Season_2$
FW	C	20.99	20.69	16.56bc	17.74ab	19.26a	0.80
	My	25,40	23.27	18.23ab	17.47ab	1.47abc	1.32
	Ar	27.47	26.71	20.41a	17.74ab	1.85A	1.67
	Mi	23.92	23.49	15.bc	15.48b	1.07bc	0.87
WW	C	25.19	20.13	15.09c	12.91c	0.833c	1.40
	My	26.52	25.05	16.78bc	15.97b	1.35abc	1.39
	Ar	28.45	26.43	17.89abc	16.64b	1.06bc	1.78
	Mi	23.22	22.30	19.77a	19.26a	1.87a	1.43
F test		N.S.	N.S.	*	**	**	N.S.

N.S.: Not-($P > 0.05$); *: Significant ($P < 0.05$). **, high significant ($P < 0.01$). *** high significant ($P < 0.001$). Means followed by the same letter are not significantly different ($P \leq 0.05$)

3.3. Site Two Experiment

3.3.1. Effects of mycorrhizal inoculation, foliar application of *Arthrospira* sp., and magnetic iron application under irrigation blended water on plant height (cm), early and total yield (t ha^{-1}) and dry matter% (leaves and receptacle) of artichoke plants.

Data presented in Table 8 show that the applied treatments under blended water irrigation significantly influenced several growth and yield parameters of globe artichoke plants, although their effects varied between the two growing seasons. Regarding plant height, *Arthrospira* sp. (Ar) application recorded the highest numerical values in both seasons, reaching 71.00 and 78.33 cm in the first and second seasons, respectively. However, differences among treatments were not statistically significant in either season. Concerning early yield, significant treatment differences were detected only during the first season. Foliar application of *Arthrospira* sp. produced the highest early yield (2.61 t ha^{-1}), followed by the control treatment (1.77 t ha^{-1}), whereas mycorrhizal inoculation and magnetic iron application recorded 1.58 and 1.55 t ha^{-1}, respectively. In the second season, no significant differences were observed among treatments, despite the highest numerical value being recorded with *Arthrospira* sp. application (2.239 t ha^{-1}). The total yield, highly significant treatment differences were observed in the first season, with *Arthrospira* sp. application producing the highest yield (16.150 t ha^{-1}), followed by mycorrhizal inoculation (12.892 t ha^{-1}). The control and magnetic iron treatments recorded considerably lower yields (6.640 and 7.130 t ha^{-1}, respectively). However, no significant differences among treatments were detected during the second season, although *Arthrospira* sp. application recorded the highest numerical yield (10.517 t ha^{-1}).

With respect to leaf dry matter content, significant treatment differences were detected only in the first season. *Arthrospira* sp. application recorded the highest value (23.50%), followed by

mycorrhizal inoculation (23.10%), while magnetic iron application recorded the lowest value (21.12%). In the second season, no significant differences were observed among treatments.

Concerning Table 8, receptacle dry matter content was not significantly affected by the applied treatments in both seasons, but *Arthrospira* sp. application recording non-significant increase (27.11%), followed by mycorrhizal inoculation (25.11%). Overall, *Arthrospira* sp. The application showed the most consistent numerical superiority across the measured parameters, particularly in total yield and dry matter accumulation, although the statistical significance of these responses varied between growing seasons.

Table (8). Effect of the mycorrhizal inoculation, foliar application of *Arthrospira* sp., and magnetic iron application under irrigation blended water on plant height (cm), early and total yield (t/ha) and dry matter% (leaves and receptacle) of artichoke plants

Treatments	Plant height (cm)		Early yield (t $ha^{-1)}$		Total yield (t ha^{-1})		Dry matter leaves %		Dry matter Receptacle%	
	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
C	50.33	53.33	1.77b	1.409	6,640b	7.646	21.56b	21.56	20.93	20.00
My	56.50	60.00	1.58b	2.000	12.892a	7.665	23.10ab	23.18	25.11	25.35
Ar	71.00	78.33	2.61a	2.239	16.150a	10.517	23.50a	24.50	27.11	27.54
Mi	64.00	50.00	1.55b	1.232	7.13b	8.632	21.12b	21.12	20.93	22.54
F test	N.S.	N.S.	*	N.S.	**	N.S.	**	N.S	N.S	N.S.

N.S. : Not-(P > 0.05); *: Significant (P < 0.05). **, high significant (P < 0.01). Means followed by the same letter are not significantly different ($P \leq 0.05$)

3.3.2. Effect of mycorrhizal inoculation, *Arthrospira* sp. extract, and magnetic iron application under irrigation blended water on flower head weight (A), and Inulin (B) over the two growing seasons of 2022/23 and 2023/24

Figure 4 (A, B) illustrates the effects of magnetic iron application (Mi), foliar application of *Arthrospira* sp. (Ar), and mycorrhizal inoculation (My) on flower head weight (Figure 4A) and inulin content (Figure 4B) of artichoke plants under blended-water irrigation during the two growing seasons. Flower head weight (Fig. 4A), the control treatment (C) recorded the highest numerical values in both seasons. However, no significant differences were observed between the control, magnetic iron, and *Arthrospira* sp. treatments. In contrast, mycorrhizal inoculation (My) resulted in significantly lower flower head weights during both seasons. Inulin content (Fig. 4B), no significant differences were observed among the treatments during the first season. In the second season, both magnetic iron application and mycorrhizal inoculation significantly increased inulin content compared with the control treatment, whereas *Arthrospira* sp. application exhibited an intermediate response.

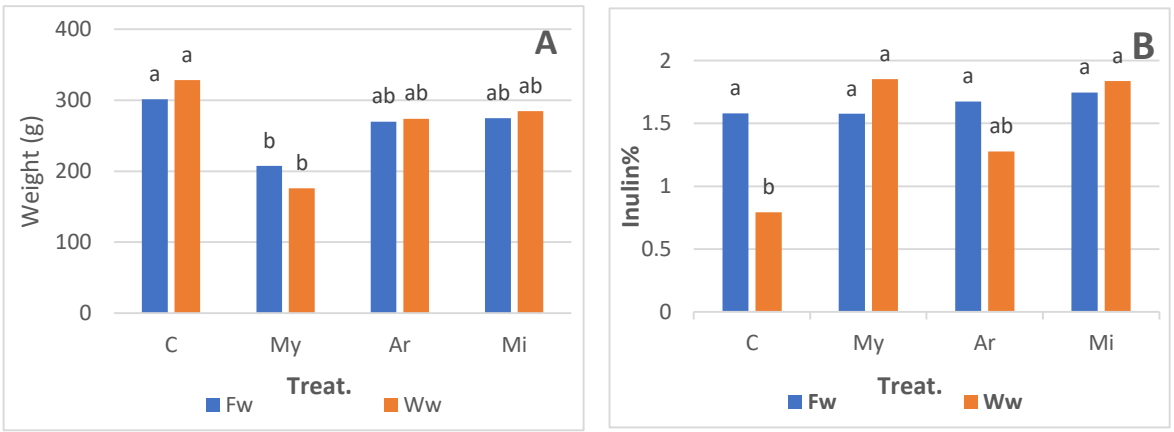


Fig. (4). Effect of mycorrhizal inoculation, foliar spraying of *Arthrospira* sp., and magnetic iron application under irrigation blended water on Flower head weight (A), and Inulin (B) over the two growing seasons of 2022/23 and 2023/24

3.3.3. Amounts of seasonal irrigation water applied (IWA), irrigation water productivity (IWP), and improved water productivity (WPI %) under different treatments

Table 9 indicates that irrigation water productivity (IWP) at location 1 affected by both the irrigation water source and the fertilization treatments. Seasonal irrigation water applied ranged from 3482.58 to 3786.92 m^3 ha^{-1} under irrigation with fresh water (FW) and from 4103.72 to 4399.45 m^3 ha^{-1} under irrigation with well water (WW). The untreated FW control gave an IWP of 5.13 and 4.31 kg m^{-3} in the two growing seasons, respectively, while the untreated WW control gave 3.25 and 3.35 kg m^{-3}. in comparison to the FW untreated control, the WW control had an WPI of −36.65% and −22.19% in seasons 1, and 2, respectively. the highest Irrigation water productivity was under spraying of the (Ar) extract under both irrigation water sources in both growing seasons. The Irrigation water productivity under Fresh water was 7.43 and 7.15 kg m^{-3} (with improvements of 44.89 and 65.78%), and it was 6.93 and 7.02 kg m^{-3} (with improvements of 35.14 and 62.87%) under well water. inoculation by Mycorrhiza (My) enhanced IWP by 18.31 and 36.63% under Fresh water and by 16.42 and 27.63% under Well Water. Magnetic iron (Mi) application slightly decreased IWP during season 1 under both Fresh and well water (−4.55%, and −0.86%), and then increased it during season 2 (48.73 and 25.96%). using WW, Ar and My outperformed the FW control in both growing seasons, which suggests that these treatments balance the lower productivity of untreated control of well irrigation water.

Table (9). Amounts of seasonal irrigation water applied (IWA), irrigation water productivity (IWP), and improved water productivity (WPI %) under different treatments

Irrigation water	Treatment	Total yield (t ha^{-1})		IWA (m^3 ha^{-1})		IWP (kg m^{-3})		WPI %	
		22/2023	23/2024	22/2023	23/2024	22/2023	23/2024	22/2023	23/2024
FW	C	19.43	15.07	3786.92	3496.12	5.13	4.31	-	-
	My	22.87	20.51	3767.43	3482.58	6.07	5.89	18.31	36.63
	Ar	28.10	24.97	3780.01	3494.31	7.43	7.15	44.89	65.78
	Mi	18.50	22.39	3777.39	3492.34	4.90	6.41	-4.55	48.73
WW	C	14.28	13.78	4393.34	4108.49	3.25	3.35	-36.65	-22.19
	My	26.28	22.67	4399.45	4120.60	5.97	5.50	16.42	27.63
	Ar	30.43	28.81	4388.57	4103.72	6.93	7.02	35.14	62.87
	Mi	22.36	22.32	4395.65	4110.75	5.09	5.43	-0.86	25.96

Ty: Total yield
IWA: Irrigation water applied
IWP: Irrigation water productivity
IWP%: Irrigation water improvement (%)
C: Control
My: Mycorrhizal inoculation
Ar: *Arthrospira* sp extract
MI: Magnetic iron
FW: Fresh water
WW: Well Water
BW: Blended water

Table 10 illustrates the effect of differentvtreatments on irrigation water productivity (IWP) at location 2 under blended irrigation water (BW). Seasonal irrigation water applied ranged from 4668.97 to 4712.15 m^3 ha^{-1} , and from 4384.12 to 4425.25 m^3 ha^{-1} in season1 & 2, respectively. The IWP of untreated control was 1.41 kg m^{-3} in season 1 and 1.73 kg m^{-3} in season 2. The highest IWP value was achieved with Arthrospira extract (Ar) in both seasons (3.45 and 2.39 kg m^{-3}), representing improvements of 144.82% and 38.19% above the control. There is a significant yield increase under blended water in first season only. Mycorrhizal inoculation (My) enhanced IWP by 95.74% during the first season (2.76 kg m^{-3}), while its effect nearly disappeared in the second season (from 1.75 kg m^{-3}; 0.90%) where yield dropped from 12.89 to 7.66 t ha^{-1}. Magnetic iron (Mi) gave slight and stable increases (8.52% and 13.72%; 1.53 and 1.97 kg m^{-3}).

Table (10). Total yield (TY), amounts of seasonal irrigation water applied (Wa), irrigation water productivity (IWP), and improved water productivity (WPI %) as affected by blended irrigation water

Treatment	TY (t ha^{-1})		Wa (m^{3}ha^{-1})		IWP (kg m^{-3})		WPI (%)	
	2022/2023	2023/2024	2022/2023	2023/2024	2022/2023	2023/2024	2022/2023	2023/2024
C	6.64	7.65	4712.15	4425.25	1.41	1.73	-	-
My	12.89	7.66	4673.39	4388.54	2.76	1.75	95.74	0.90
Ar	16.15	10.52	4681.31	4396.46	3.45	2.39	144.82	38.19
Mi	7.14	8.63	4668.97	4384.12	1.53	1.97	8.52	13.72

TY: Total yield (t ha^{-1})
Wa: Seasonal irrigation water applied (m^{3}ha^{-1})
IWP: Irrigation water productivity (kg m^{-3})
IWP improvement (%): Improved water productivity

4. Discussion

The results of the present study demonstrated that irrigation water quality was an important factor influencing artichoke growth, yield, and irrigation water productivity. The three irrigation water sources differed considerably in their electrical conductivity (ECw) and sodium adsorption ratio (SAR). Freshwater exhibited the lowest ECw (0.635 dS m^{-1}) and SAR (1.62), whereas well water showed higher values (2.05 dS m^{-1} and 12.1, respectively). Blended water had intermediate values, with an ECw of 1.78 dS m^{-1} and an SAR of 5.7. According to the general irrigation water quality guidelines proposed by **Ayers and Westcot (1985)**, the ECw values of well and blended water fall within the slight-to-moderate restriction category regarding salinity. Consequently, the relatively high SAR of well water indicates a potential concern regarding soil structural stability and infiltration, depending on soil texture, mineralogy, and drainage conditions. These considerations emphasize the importance of evaluating irrigation water quality in relation to the physicochemical properties of the receiving soil rather than relying on water salinity alone.

Artichoke is generally classified as a moderately salt-tolerant crop. **Francois (1995)** reported a soil salinity threshold of 6.1 dS m^{-1}, expressed as the electrical conductivity of the saturated soil extract (ECe), above which bud yield decreased by approximately 11.5% for each additional unit increase in ECe. Importantly, this threshold refers to soil salinity and should not be directly compared with the ECw values of irrigation water used in the present study. The findings of **Francois (1995)** provide a useful physiological reference for understanding the potential effects of salt accumulation in the root zone. Nevertheless, the actual salinity stress experienced by artichoke plants depends on several factors, including irrigation frequency, leaching, drainage, soil texture, and the accumulation of soluble salts during the growing season.

The soil characteristics presented in Tables 1 and 2 provide additional information for interpreting the crop responses. Differences in soil electrical conductivity, SAR, and exchangeable sodium percentage (ESP) between the experimental sites may have influenced water movement, nutrient availability, and root-zone conditions. In particular, the relatively higher soil salinity and sodicity indicators recorded at the second site suggest that the plants may have experienced less favorable soil conditions than those at the first site. Increased exchangeable sodium can adversely affect soil aggregation and hydraulic conductivity, particularly in soils containing appreciable amounts of swelling clay minerals. Such changes may restrict root development and water uptake and consequently affect crop growth and productivity (**Ayers and Westcot, 1985**). Irrigation water productivity (IWP) depends on both yield and water applied (Kijne et al., 2003). Because the water applied differed by less than 1.5% among treatments within each source (Tables 9 and 10), the differences in IWP reflect differences in yield and not savings of water. Foliar *Arthrospira* sp. extract (Ar) gave the highest IWP under all three water sources in both seasons. At Site 1 it reached 7.43 and 7.15 kg m^{-3} under fresh water and 6.93 and 7.02 kg m^{-3} under well water, which is 44.89–65.78% and 35.14–62.87% above the untreated fresh-water control. The untreated well-water

control had lower IWP than the fresh-water control (−36.65% and −22.19%), consistent with the poorer quality of the well water (ECw 2.05 dS m^{-1}, SAR 12.1). Ar and mycorrhizal inoculation (My) raised IWP under well water above the fresh-water control in both seasons, so these treatments offset part of the productivity loss. Magnetic iron (Mi) was less consistent, and the effect of My under blended water disappeared in season 2 (0.90%), when its yield fell. These responses may be related to the hormones and fatty acids in the extract, but ion balance and antioxidant activity were not measured, so this remains a hypothesis. At Site 2, Ar also gave the highest IWP under blended water (144.82% in season 1 and 38.19% in season 2), but the yield differences were significant in season 1 only. The sites differ in soil and in the water applied, so water quality and site effects cannot be separated, and the improvements should be judged only against the control at that site.

An increase in water productivity does not necessarily indicate an equivalent increase in total crop yield. The positive response observed in the present study is consistent with the findings of **Deligios *et al.* (2019)**, who reported a 36% improvement in water productivity in globe artichoke through an innovative irrigation management system involving canopy cooling and precision irrigation. Although the approaches differed, both studies highlight the potential of improved crop management practices to enhance water productivity under conditions of limited water resources.

The beneficial response to *Arthrospira* application may be partly associated with its biochemical composition. Chemical characterization of the extract using HPLC and GC–MS (Table 3 and 4) revealed the presence of several biologically active compounds, the presence of phytohormone-related compounds, including auxin-, gibberellin-, and cytokinin-related substances, may contribute to the regulation of plant growth and development. Such compounds are potentially involved in cell division, cell expansion, leaf development, and the regulation of source–sink relationships, which may ultimately influence the development and productivity of artichoke plants. In addition, the mineral constituents of the extract may contribute to plant nutritional status, particularly when nutrient availability is affected by unfavorable soil or irrigation water conditions. Previous studies have demonstrated that *Arthrospira* contains biologically active compounds and can promote plant growth under saline conditions (**Xu *et al.*, 2023**). Nevertheless, the relative contribution of individual compounds to the observed responses cannot be established from chemical characterization alone.

The improvement in artichoke growth and yield following *Arthrospira* application may also be related to its potential role in supporting plant tolerance to salinity-associated stress. Salinity imposes both osmotic and ionic constraints, which can interfere with water uptake, nutrient balance, and normal cellular metabolism. Under severe conditions, these disturbances may increase the accumulation of reactive oxygen species (ROS), resulting in oxidative stress and impairment of cellular membranes and photosynthetic processes. Previous investigations have demonstrated that *Spirulina platensis* extract can improve plant growth and defense responses under saline and other stressful soil conditions. For example, **Rady *et al.* (2023)** reported improvements in common bean production, photosynthetic performance, and antioxidant defense following the application of *Spirulina platensis* extract in saline, heavy-metal-contaminated soil. Similarly, **Xu *et al.* (2023)** demonstrated that *Arthrospira* application improved plant growth and salt tolerance, partly through improved potassium/sodium balance and ROS scavenging. These findings provide a plausible physiological basis for the positive responses observed in the present artichoke study. However, since antioxidant enzyme activities, ROS accumulation, and plant ion balance were not directly measured in the present experiment, their involvement should be considered a possible explanation rather than a demonstrated mechanism.

The positive response of artichoke to *Arthrospira* extract under blended-water irrigation is particularly relevant to agricultural production in regions where freshwater resources are limited. The improvement in yield-related traits compared with the untreated control receiving the same irrigation water suggests that the microalgal extract may help maintain crop performance under relatively less favorable irrigation conditions. This response may be associated with the combined contribution of bioactive compounds and mineral constituents present in the extract. However, the yield obtained under blended-water irrigation should be compared separately with that obtained under freshwater irrigation, because the latter represents a different water quality condition and, in the present experimental

arrangement, may also be associated with different site and soil characteristics. Thus, the beneficial effect of *Arthrospira* under blended water should not be interpreted as evidence that blended water produced higher yields than freshwater.

Regarding the other biological and mineral treatments, the observed responses to mycorrhizal inoculation and magnetic iron should be discussed according to their respective treatment comparisons and statistically significant effects. These treatments may influence plant nutrient acquisition and physiological performance through different pathways. Nevertheless, unless a combined treatment involving *Arthrospira* and mycorrhizal inoculation was included in the experimental design, their effects should not be described as a synergistic or combined response. Similarly, the superiority of a particular treatment should be established using the statistical comparisons presented in the relevant tables and figures rather than numerical differences alone.

Overall, the findings indicate that foliar application of *Arthrospira* sp. extract represents a promising biological approach for improving artichoke productivity and irrigation water productivity under the irrigation and soil conditions evaluated in this study. Its potential value is particularly relevant in areas facing freshwater limitations and increasing dependence on marginal-quality irrigation water. However, the results should be interpreted within the limitations of the experimental design, especially the differences in initial soil properties between sites. Further studies involving the same soil conditions across irrigation water treatments, together with direct measurements of plant mineral composition, photosynthetic characteristics, antioxidant activities, and soil salinity dynamics, would help clarify the physiological mechanisms responsible for the observed responses and establish the broader applicability of *Arthrospira*-based biostimulants in artichoke production.

5. Conclusion

The findings of this study demonstrated that artichoke growth, yield, and irrigation water productivity were influenced by irrigation water quality and the application of biological and mineral treatments under the evaluated experimental conditions. Freshwater generally provided more favorable conditions for artichoke production, whereas well and blended irrigation water presented relatively greater salinity and sodium-related concerns. Nevertheless, the application of biological treatments and magnetized iron improved several growth and yield attributes, although the magnitude of their responses varied according to the irrigation water source and experimental site.

Among the evaluated treatments, foliar application of *Arthrospira* sp. extract showed promising potential for improving artichoke productivity and irrigation water productivity, particularly under blended-water irrigation, compared with the corresponding untreated control. Mycorrhizal inoculation and magnetized iron also improved specific growth and yield characteristics, with their practical value depending on the response variable and experimental conditions. These findings suggest that *Arthrospira* sp. extract could be considered a promising component of sustainable artichoke production strategies in regions facing freshwater limitations and increasing dependence on marginal-quality irriglation water.

However, the differences in initial soil properties between the experimental sites should be considered when interpreting the responses to irrigation water sources. Further investigations under comparable soil conditions, supported by direct measurements of plant physiological responses and soil salinity dynamics, are needed to clarify the mechanisms involved and validate the effectiveness of these treatments across different production environments.

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