Productivity of Chia crop in the sandy soils of East Delta, Egypt

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Abstract

Chia (*Salvia hispanica* L.) crop is a newly introduced herbaceous plant to the Egyptian cropping system. No information is available on water requirements of chia crop under Egyptian conditions. A field experiment was conducted to determine the effect of irrigation treatments (IFarmer, IGrowth-stage, I120%ETo, I100%ETo, I80%ETo, and I60%ETo) on chia seed yield, plant height, total carbohydrates, total protein, total oil content, seed's nutrients, applied irrigation water (AIW), water productivity (WP) and yield response factor (Ky). Results showed significant effect of the irrigation treatments on all tested parameters. Average AIW values for the respective treatments were 8036 m^3/ha, 7492 m^3/ha, 6081 m^3/ha, 5228 m^3/ha, 4376 m^3/ha and 3523 m^3/ha. The highest average seed yield of 3.15 t/ha was recorded for I120%ETo treatment, while the lowest value of 2.00 t/ha was recorded for the I60%ETo treatment. The highest WP of 0.598 kg/m^3 was recorded for I80%ETo. The Ky value of 0.78 was obtained. Therefore, applying appropriate agronomic management (e.g. proper amounts of irrigation water, and fertilizers through drip-fertigation technique) can achieve high chia seed yields. In case of water shortage, applying appropriate agricultural practices and I80%ETo can save 46% (3660 m^3/ha) of AIW without significant reduction in seed yield.

Keywords: Chia, Applied irrigation water, water productivity, yield response factor, carbohydrates, protein, oil content, Egypt

INTRODUCTION

Chia (*Salvia hispanica* L.) crop is a new herbaceous plant introduced to the Egyptian cultivation system to enrich it with new varieties of medicinal and aromatic plants (Salman *et al.*, 2019). It produces edible seeds and its economic value in the national and international market is very high. Chia seed has high nutritive and medicinal values, particularly rich in polyunsaturated fatty acids, omega-3 fatty acid or fish oil, high dietary fiber, protein, minerals, carbohydrates, protein, lipids, vitamins, and high level of antioxidants. Chia plants can grow in a wide range of well drained clay and sandy soils under all climatic conditions in rainfed and irrigated fields. It has reasonable salt and acid tolerance (Ayerza, 1995; Ixtaina *et al.*, 2008; Ayerza and Coates, 2009; Amato *et al.*, 2015; Bochicchio *et al.*, 2015; Ullah, 2016; Singh and Verma, 2022).

Throughout the world, water scarcity is increasing in frequency, intensity and magnitude which pose threats to the food security of millions of people. To attain sustainable agriculture, a balance between conserving the water supply and ensuring food security should be considered. Coping with this major challenge requires proper strategies for crop management, implementing advanced technologies to help farmers optimize water use, and adopting policies that encourage farmers to conserve water (Evans and Sadler, 2008). One approach for ensuring diversity and water saving and reduce water scarcity problem is cultivating some areas of the high-water-demanding crops with more water-efficient crop such as chia crop (Hufnagel *et al.*, 2020; Kirsch *et al.*, 2024). Peperkamp (2015) stated that chia is a plant characterized by low water requirement and well adapted to arid and semiarid regions. The plants grow very well in sandy loam, well-drained soils with a low nutrient content, moderate salinity, and soil having pH of 6-8.5. The duration of chia crop cycle is from 140 to 180 days (Yeboah *et al.*, 2014). Studies by Herman *et al.* (2016) showed diverse response of chia seed yield and water use efficiency (WUE) under deficit irrigation treatments in sandy loam soil. Results revealed that 20% deficit irrigation (80% ETo) did not affect chia yield. As for deficit irrigation (40–70% ETo), results showed reduction in chia seed yield and oil yield by 33 and 5%, respectively and increasing in WUE of oil yield by 27%. Results by Njoka *et al.* (2022) showed that high soil moisture content (89-93%) significantly increased chia vegetative growth and plant height increased by 65-180%, while 20-40% reduction of soil water decreased plant growth due to inhibition of cell enlargement or cell division.

In this study, we hypothesized that applying different amounts of irrigation water can considerably improve chia seed yield, chemical constituents and water productivity. As a new crop, there is no information available on water requirements of chia crop under Egyptian conditions. Therefore, the objectives of this field experiment were to determine the effect of irrigation treatments on chia seed yield, plant height, total carbohydrates (TC, %), total protein (TP, %), total oil content (%), macro-, secondary-, micro-nutrients, amounts of applied irrigation (AIW, m^3/ha), water productivity (WP, kg seed/m^3 applied water) and yield response factor (Ky).

MATERIALS AND METHODS

Experimental site description

A field experiment was conducted in a private farm (30°40' N latitude, 32°15' E longitude, and 10.0 m above mean sea level), Ismailia Governorate, Egypt, during the 2020/2021 and 2021/2022 winter growing seasons. The

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experimental site represents the newly reclaimed sandy soil of East Nile Delta region (Figure 1).

The site is characterized with cool winter with rare rainfall events. Mean monthly weather data at the experimental site for the period from 2015 to 2019 are presented in Table 1.

The data in Table 1 were used to calculate monthly reference evapotranspiration (ETo) values at the experimental site according to CROPWAT 8 model using the FAO-56 Penman-Monteith equation (Allen *et al*., 1998).

Samples from the upper 60 cm soil surface were collected at 15 cm interval to determine main soil physical parameters (particle size distribution, textural class and bulk density), hydro-physical constants (field capacity, wilting point, and available soil moisture) and some chemical properties (pH, ECe, and soluble cations and anions). Physical and chemical soil analyses were done according to the standard methods as described by Klute (1986) and Tan (1996). Soil samples were also analyzed for determining available macronutrients (N, P, and K) and the obtained values were 16.7, 5.5 and 65.1 mg kg^{-1}, respectively. Accordingly, the soil was characterized by low fertility and insufficient available water for plant growth. As for irrigation water, samples were collected from Ismailia branch which supplies irrigation water to the farm and the chemical analysis is given in Table 2.

Table 1: Mean monthly values (2015-2019) of solar radiation (Srad), maximum (Tmax), minimum (Tmin) air temperatures, wind speed (Ws), and dew point temperature (Td)

Month	Srad ($MJ\ m^{-2}\ day^{-1}$)	Tmax (°C)	Tmin (°C)	Ws ($m\ s^{-1}$)	Td (°C)
September	16.8	25.5	14.8	2.4	5.8
October	16.0	26.8	14.2	2.7	11.2
November	11.1	25.5	12.9	2.2	9.9
December	9.8	19.7	8.5	2.1	6.0
January	9.2	17.8	8.1	2.1	5.9
February	13.6	21.8	7.3	2.5	4.3
March	17.6	23.6	9.4	2.6	6.4

Table 2: Soil analysis of physical, hydro-physical, and some chemical properties and irrigation water analysis at the experimental site

Soil properties	Soil depth (cm)			
	0-15	**15-30**	**30-45**	**45-60**
Physical parameters				
Coarse sand, %	68.7	73.1	74.1	75.23
Fine sand, %	25.7	22.7	22.2	20.5
Silt, %	3.60	2.74	2.60	3.32
Clay, %	1.95	1.42	1.00	0.94
Textural class	Sandy	Sandy	Sandy	Sandy
Bulk density, g cm^{-3}	1.65	1.76	1.75	1.72
Hydro-physical parameters				
Field capacity, % v/v	15.2	13. 5	9.43	10.2
Permanent wilting point, % v/v	6.07	5.16	4.03	3.78
Available soil moisture, % v/v	9.10	8.32	5.40	6.40
Chemical parameters				
pH (1:2.5)	7.64	7.55	7.52	7.44
ECe, soil past extract, dS m^{-1}	0.55	0.53	0.51	0.49
Soluble cations, meq L^{-1}				
Ca^{2+}	1.30	1.26	1.28	1.32
Mg^{2+}	0.60	0.58	0.55	0.53
Na^{+}	2.05	2.06	1.66	1.67
K^{+}	0.20	0.22	0.16	0.20
Soluble anions, meq L^{-1}				
CO_3^{2-}	nd*	nd	Nd	nd
HCO_3^{-}	1. 35	1. 33	1. 20	1. 22
Cl^{-}	1.94	1.90	1.60	1.63
SO_4^{2-}	0.86	0.91	0.85	0.87
Irrigation water analysis				
pH	8.08			
EC, dS m^{-1}	0.36			
Soluble cations, meq L^{-1}				
Ca^{2+}	1.00			
Mg^{2+}	0.50			
Na^{+}	1.90			
K^{+}	0.18			
Soluble anions, meq L^{-1}				
CO_3^{2-}	nd*			
HCO_3^{-}	0.50			
Cl^{-}	2.50			
SO_4^{2-}	0.58			

**nd: not detected.*

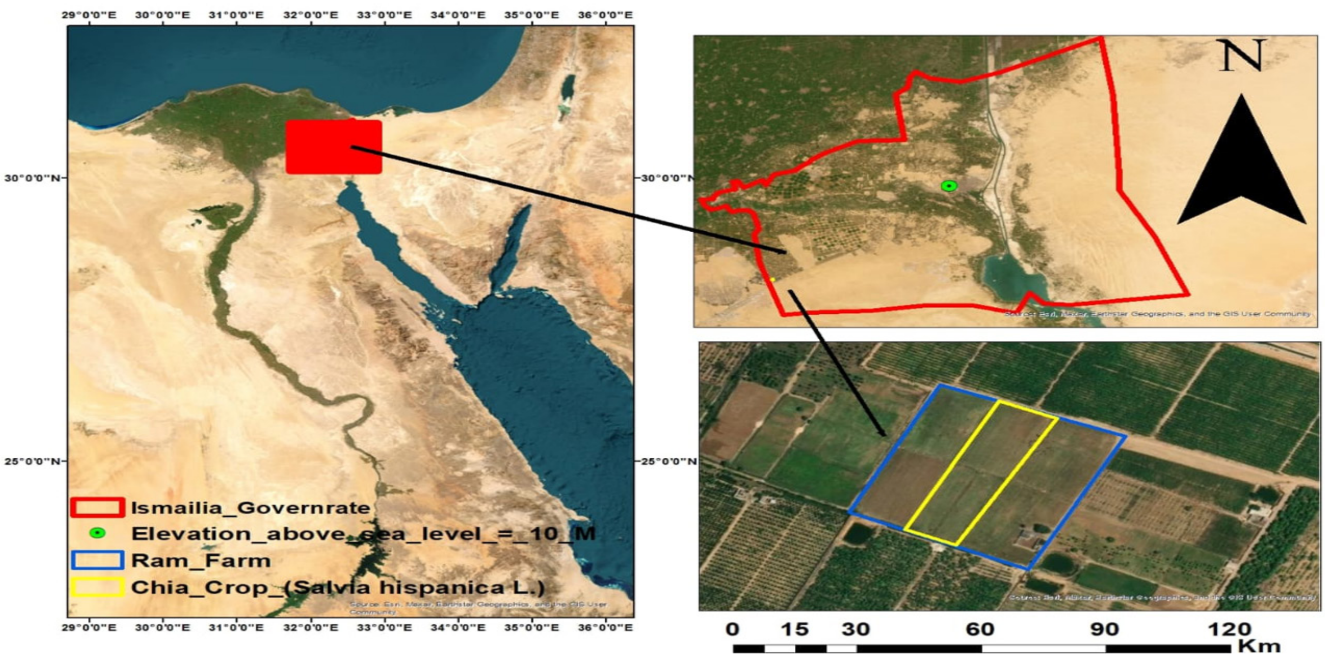

Figure 1: Location of the experimental site

Experimental design and tested treatments

The field experiment was implemented in a strip plot design with four replicates. Irrigation treatments were laid out in the horizontal plots. The plots area was 700 m^2.

The tested irrigation treatments were as follows:

- **I_F:** Farmer treatment (control). The farmer applied irrigation and fertilizer amounts without interference from the researchers.
- **I_G:** Applying water according to growth stages of chia crop.

According to BBCH scale description (Meier, 2018) and the specific growth stages defined for chia crop by Brandán *et al.* (2019), the growth stages (day) are: germination (10-15); leaf appearance (7-10); shoot appearance (7-10); inflorescence growth (7-10); flowering (25-30); fruit development (35-40); ripening (35-40); and senescence (30). In this treatment, applied irrigation water increased gradually from 100% ETo during germination to 140% ETo until mid-ripening stage, then decreased gradually to 120% ETo by the end of the season.

I_{120}: Irrigation with amounts of water equal to 120% ETo.
I_{100}: Irrigation with amounts of water equal to 100% ETo.
I_{80}: Irrigation with amounts of water equal to 80% ETo
I_{60}: Irrigation with amounts of water equal to 60% ETo

Irrigation treatments started 25 days from sowing chia seeds and stopped 5 days before harvest. Irrigation event was carried out every 3 days.

Cultural practices

Chia *(Salvia hispanica L.)* seeds were sown on 15 September of 2020 and 2021 winter seasons. Plants were harvested on 20 March 2023 and 2024. Seeds were banded under drip lateral lines spaced 30 cm apart between seeds and 30 cm apart between rows achieving plant density of 60,000 plants/ha. The crop was irrigated by a surface drip irrigation system. Fresh water from Ismailia branch was the source of irrigation water. The surface drip system consists of:

- Irrigation pump (60 hp) with discharge rate of 100 m^3 h^{-1} ;
- Sand and screen filters and a venturi fertilizer injector. Fertilizers were applied in 80% of irrigation time (fertigation).

The conveying pipeline system consists of:

- 160 mm PVC main line;
- 110 mm PVC sub-main line;
- 50.8 mm PVC sub sub-main line.

The drip lateral lines of 16 mm diameter are connected to the sub sub-main line. Each lateral line is 24 m long spaced at 30 cm apart. The lateral lines were equipped with build-in emitters of 4 L h^{-1} discharge rate spaced at 0.30 m. Each lateral has 16 mm PE valve to control the application of irrigation water and the applied mineral fertilizers.

Macro and micro-nutrients were added through the irrigation water in 80% of irrigation time using the venture injector (fertigation technique). According to the findings of Taha (2012), all macronutrient fertilizers were added in equal doses (3 doses per week). The fertigation started 25 days from sowing in both growing seasons. Nitrogen fertilizer (ammonium nitrate, 33.5% N) was added at a rate of 120 kg N/ha, potassium fertilizer (potassium sulphate, 48% K_2O) was added at a rate of 60 kg K_2O/ha, and phosphorus was added at a rate of 80 kg P_2O_5/ha as phosphoric acid (60%). Micro-nutrients, i.e. Fe, Zn and Mn (EDTA, 13%), were also added 15 days before and during flowering at the rate of 600:600:600 g/ha using a regular hand sprayer. All other practices used for growing chia crop including weeds and pest management were followed.

The duration of the chia crop cycle in most cases ranges from 140 to 180 days (Coates and Ayerza, 1996). In our study, the crop cycle was 185 days.

Measurements of plant height and crop yield

Plant height (cm) growth attribute of chia crop was measured twice, from soil surface up to the top, after 45 and 60 days from sowing. At harvest time, all plants representing each treatment were collected to determine seed yield/plot and then yield/ha.

Chemical analysis

At harvest, samples from chia seeds were collected from all treatments to determine total carbohydrate (TC, %), crude fiber (CF, %), crude protein (CP, %), and oil content during 2021 and 2022 seasons. Total carbohydrate percentage was determined in plants using colorimetric method as described by Herbert *et al.* (1971).

As for crude protein, the nitrogen content of the collected samples was determined by Kjeldahl N (AOAC, 1999) and the value recorded for nitrogen was then multiplied by 6.25 to determine CP of the sample.

Irrigation water measurements and crop-water relations

The following parameters were considered in this study:

Applied irrigation water (AIW)

The amount of applied irrigation water was calculated according to the equation given by Vermeiren and Jopling (1984) as follows:

$$AIW = \frac{ETo \ x \ Kr \ x \ A \ x \ Iinterval}{Ea \ (1 - LR)}$$

where:

AIW = applied irrigation water (m^3).
ETo = reference crop evapotranspiration (mm/d**).**
Kr = ground cover reduction factor (= 0.7 according to Keller and Karmeli, 1975).
$I_{interval}$ = irrigation interval (3 days under experimental conditions).
A = irrigated area (m^2)
Ea = irrigation efficiency = K1 x K2

where:

K1 = emitter distribution uniformity (= 0.89 and 0.91 in the 1st and 2nd seasons, respectively)
K2 = drip irrigation system efficiency (= 0.90 at the experimental site).
LR = leaching requirements (was not considered in this study to avoid the effect of excess leaching water on deficit irrigation treatments).

Yield response factor (Ky)

The yield response factor, which links relative yield decrease to relative applied irrigation water deficit, was expressed by the standard formulation given by Vaux and Pruitt (1983).

Crop water productivity (WP)

Crop water productivity, relates unit of crop yield to unit of water applied, was calculated according to Zhang (2003).

Statistical analysis

The obtained data were statistically analyzed according to (MSTAT-C) computer software package. Least significant differences (LSD) method was used to test the differences between treatment means at 5% level of probability as described by Snedecor and Cochran (1980).

RESULTS AND DISCUSSION

Reference crop evapotranspiration (ETo)

The calculated reference evapotranspiration (ETo) values at the experimental site during the growing seasons are illustrated in Figure 2. Results indicated that, the ETo value for irrigation season (15 Sep. – 20 Mar.) was 439 mm. Results presented in this figure show that, the highest mean ETo values were 4.7 and 4.2 mm/day during September and March, respectively. The lowest mean ETo values were 2.4 and 2.1 mm/day during the winter months of December and January, respectively.

Effect on applied irrigation water (AIW)

Results in Table 3 show the effect of tested irrigation treatments on amounts (m^3/ha) and the savings in applied irrigation water (%) to chia crop. The 2-year average AIW values were 8036 m^3/ha, 7492 m^3/ha, 6081 m^3/ha, 5228 m^3/ha, 4376 m^3/ha and 3523 m^3/ha for the farmer practice, irrigation according to growth stage, 120%, 100%, 80%, and 60% ETo treatments, respectively. It is clear from the results that amounts of AIW in the first season were higher than the amounts in the second season due to the lower application efficiency (Ea) of 80% in the 1st season and higher application efficiency of 82% in the 2nd season. The 2-yrs. average water saved were 7, 24, 35, 46 and 56% for the respective treatments less than farmer practice. The obtained results reflect the need of extension services to the farmers growing newly cultivated crops such as chia crop to avoid excess of irrigation water, reduce the cost of fertilizers added and energy used for irrigation and to decrease the negative effect on crop yield. The obtained results were higher than those reported by Harisha *et al.* (2024) who stated that average supplied irrigation water for chia crop of 2042 and 3433 m^3/ha were recorded for $I_{50\%}$ and $I_{100\%}$ irrigation treatments, respectively. The differences in amounts of water applied could be due to climate parameters, soil type and length of growing season.

Effect on chia seed yield and water productivity

Results indicated that chia seed yields were significant affected by irrigation treatments in the two growing

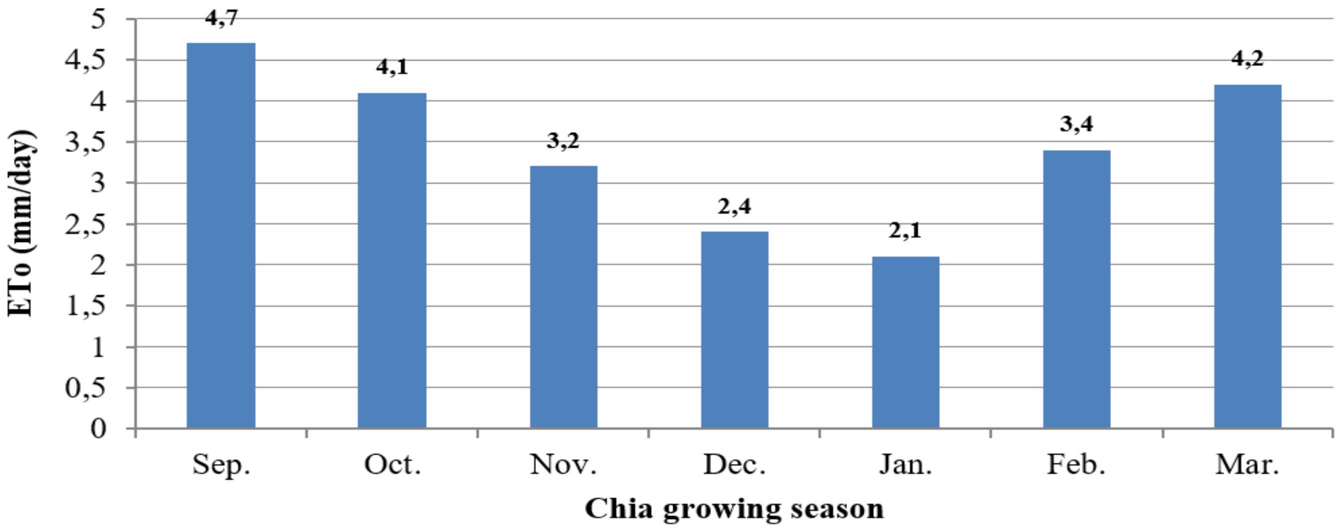

Figure 2: Reference crop evapotranspiration (mm/day) during chia growing season

Table 3: Effect of tested irrigation treatments on the amounts of applied irrigation water (AIW) and water saved (%) by chai crop during 2020/21 and 2021/22 seasons

Irrigation treatment	2020/21		2021/22		2-yr. average	
	AIW (m^3 ha^{-1})	Saving (%)	AIW (m^3 ha-^{1})	Saving (%)	AIW (m^3 ha^{-1})	Saving (%)
I_F	8176	0	7896	0	8036	0
I_G	7575	7.4	7409	6.2	7492	7.0
$I_{120\ \%\ ETo}$	6148	24.8	6013	23.8	6081	24.0
$I_{100\%\ ETo}$	5286	35.3	5170	34.5	5228	35.0
$I_{80\%\ ETo}$	4424	45.9	4327	45.2	4376	46.0
$I_{60\%\ ETo}$	3562	56.4	3484	55.9	3523	56.0

seasons. The highest 2-yrs average seed yield of 3.15 t/ha was recorded for the 120% ETo treatment, while the lowest value of 1.99 t/ha was recorded for the 60% ETo treatment (Table 4). Results showed that seed yields of the 2nd seasons were higher than seed yields of the 1st season. Also, there were no significant differences between seed yields recorded for I_F, I_G, $I_{120\%}$, $I_{100\%}$ and $I_{80\%}$ treatments in the 2nd season. The obtained result can be explained by the fact that application efficiency (Ea) of irrigation water was higher in the 2nd season with direct effect on improving fertilizer application efficiency and increasing seed yields. Also, it could be stated that, applying appropriate agronomic conditions (e.g. proper amounts of irrigation water, and applying fertilizer by fertigation technique) can achieve high chia seed yields. From the obtained results of the 2nd season it could be recommended, in case of water shortage, that applying good agricultural practices can save 46% of applied irrigation water ($I_{80\%ETo}$) without significant reduction in chia seed yield. The obtained seed yields were close to what was reported by Yeboah *et al.* (2014) and Sosa *et al.* (2017). They reported that the maximum attainable seed yield of chia crop is close to 3.0 t/ha. The results were also close to those reported by Harisha *et al.* (2023), who concluded that deficit irrigation at $I_{25\%}$, $I_{50\%}$ and $I_{75\%}$ led to 3.3, 20.1 and 55.3% reductions in seed yield.

A second order polynomial equation was used to explain the association between seed yields (t/ha) and applied irrigation water (m^3/ha) for all tested treatments. The obtained 2nd order degree polynomial equation explaining seed yield – AIW relation is illustrated in Figure 3 and expressed as:

$$Yield\left(\frac{t}{ha}\right) = -10^{-7}(AIW)^2 + 0.0018\,(AIW) - 2.5944 \qquad R^2 = 0.8259$$

The coefficient of determination value ($r^2 = 0.8259$) indicates that the developed relation can effectively explain the relation between seed yields and applied irrigation water.

Results in Table 4 showed also that water productivity values increased with decreasing amounts of applied irrigation water, except for the $I_{60\%ETo}$ treatment. The 2-yrs. average WP values varied between 0.343 and 0.598 kg seeds/m^3. The highest WP for seeds was recorded for $I_{80\%ETo}$ (0.598 kg/ m^3), followed by $I_{60\%ETo}$ (0.565 kg/ m^3), $I_{100\%ETo}$ (0.552 kg/m^3), $I_{120\%ETo}$ (0.518 kg/m^3), and the lowest values were recorded for I_G (0.404 kg/m^3) and I_F (0.343 kg/m^3). The obtained results were close to those reported by Tezara *et al.* (2002), who indicated that deficit irrigation improved the WP to the extent of 12.8, 25.4 and 17.5% at severe (I_{25}), moderate (I_{50}) and mild (I_{75}) stress conditions, respectively, compared to no stress (I_{100}). Results can be also explained by the statement of Harisha *et al.* (2023) who indicated that, the increase in WP in the less amounts of applied water treatments could be due to increasing net assimilation or decreasing transpiration.

Table 4: Chia yield (t/ha) and water productivity (kg/m³) as affected by irrigation treatments in 2020/2021 and 2021/2022 growing seasons

Irrigation Treatment	Yield (t/ha)				WP (kg seed/m³)			
	2020/21	2021/22	2-yrs. Average		2020/21	2021/22	2-yrs. Average	
			Yield	Reduct. (%)			WP	Reduct. (%)
I_F	2.56 b	2.94 a	2.75	12.5	0.31	0.37	0.343	42.6
I_G	2.74 ab	3.30 a	3.02	4.00	0.36	0.45	0.404	32.4
$I_{120\%\ ETo}$	3.04 a	3.25 a	3.15	0	0.50	0.54	0.518	13.3
$I_{100\%\ ETo}$	2.80 ab	2.97 a	2.88	8.34	0.53	0.57	0.552	7.6
$I_{80\%\ ETo}$	2.42 b	2.80 a	2.61	17.0	0.55	0.65	0.598	0
$I_{60\%\ ETo}$	1.87 c	2.10 b	1.99	36.8	0.53	0.60	0.565	5.5

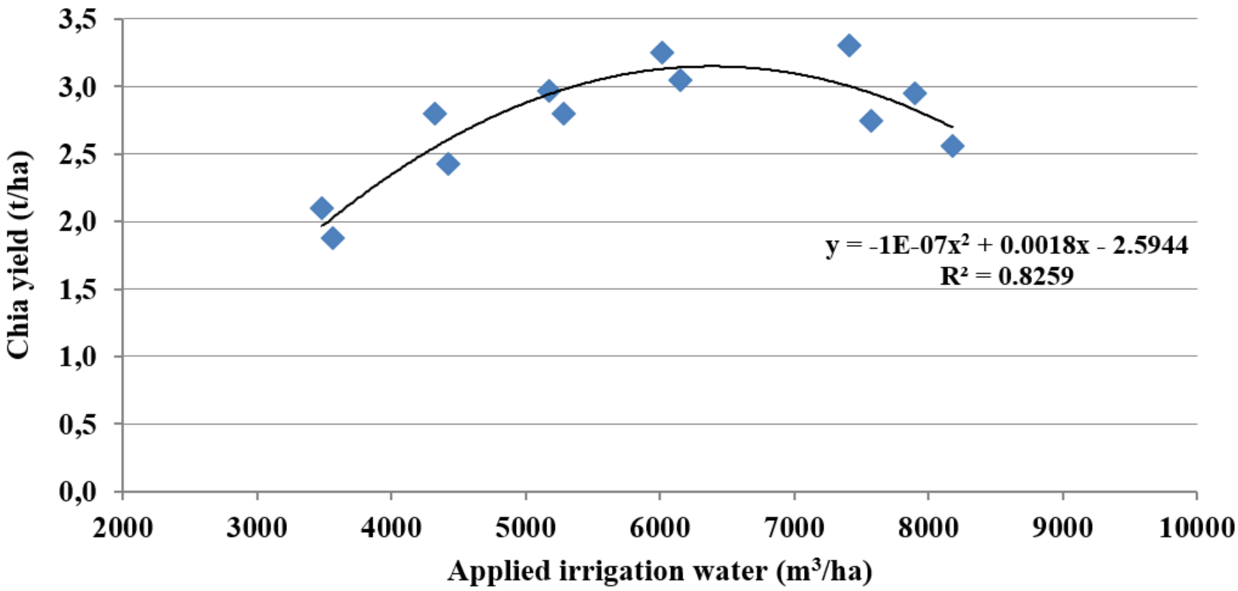

Figure 3: The 2nd order equation describing the relation between seed yield and AIW

Effect on yield response factor (Ky)

The relation between relative yield reduction and relative reduction in applied irrigation water (i.e. Ky) is illustrated in Figure 4. The linear equation governing this relation is expressed as:

$$Y = 0.7803\,X, \;\; r^2 = 0.9226$$

where:

Y: represents relative yield reduction ($1 - Y_a/Y_m$). In this study, Ym represents the yields obtained from $I_{120\%\ ETo}$ treatment, while Ya represents the yields obtained from $I_{100\%\ ETo}$, $I_{80\%\ ETo}$, and $I_{60\%\ ETo}$ treatments.

X: represents relative reduction in applied irrigation water ($1 - AIW_a/AIW_m$). The AIWm represents the applied irrigation water for the $I_{120\%ETo}$ treatment, while AIWa represents the applied irrigation water for the $I_{100\%ETo}$, $I_{80\%ETo}$, and $I_{60\%ETo}$ treatments.

The constant 0.7803 represents the crop response factor (K_y) under the experimental conditions. Since Ky value is less than 1.0, the chia crop can be considered as moderately tolerant to deficit irrigation and the relative reduction in yield is less than the relative reduction in applied water. The coefficient of determination (r^2) value of 0.9226 indicates that the developed relation can predict with high confidence level the relative yield reduction due to relative reduction in applied irrigation water at the experimental site and other locations with similar conditions.

Effect on plant height, total carbohydrates, total protein and oil percentage

Results in Table 5 showed significant effect of the tested irrigation treatments on plat height, total carbohydrates, total protein and oil percent in the two seasons. The highest plant height values of 60.2 and 62.0 cm after 45 days and 88.2 and 90.0 cm after 60 days from sowing were recorded for I_G treatment in the 2020/21 and 2021/22 seasons, respectively. The lowest values of 42.0 cm (30.3% reduction) and 44.0 cm (29% reduction) after 45 days and 65.4 cm (25.9% reduction) and 66.6 cm (26% reduction) after 60 days from sowing were recorded for $I_{60\%}$ treatment in the 2020/21 and 2021/22 seasons, respectively. Results showed that, decreasing amounts of applied water significantly reduced plant growth. The obtained results were close to those reported by El-Serafy *et al.* (2020) who indicated that chia plant height varied between 47 and 67 cm. Also, the results were in line with those of Harisha *et al.* (2024), who reported that irrigation levels significantly influenced the plant height of chia crop since deficit irrigation (I_{50}) reduced the plant height by 9.6, 14.4 and 11.0% at 30, 60 and 90 days after sowing, respectively as compared to 100% irrigation treatment (I_{100}). Results of this research were similar to those given by Soliman *et al.* (2024) who showed that plant heights were 51.1 and 69.5 cm.

Table 5: Effect of tested irrigation treatments on plant height (cm) after 45 and 60 days from planting, total carbohydrate, total protein and oil percent of chai crop during 2020/21 and 2021/22 seasons

Irri. Treat.	Plant height (cm)				Total carbohydrate (%)		Total protein (%)		Total oil (%)	
	After 45 days		After 60 days							
	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22	2020/21	2021/22
I_F	53.0 bc	55.0 bc	76.4 bc	76.4 bc	45.5 cd	46.7 d	9.35 d	9.60 d	11.2 d	11.5 d
I_G	60.2 a	62.0 a	88.2 a	90.0 a	59.4 a	61.3 a	11.7 a	12.9 a	14.6 a	15.1 a
$I_{120\ \%}$	56.6 ab	58.4 ab	80.0 b	82.0 b	53.6 ab	54.8 b	11.1 b	11.2 b	13.2 b	13.5 b
$I_{100\%}$	55.2 ab	54.0 cd	75.0 c	76.6 bc	48.2 bc	50.1 c	9.9 b	10.3 c	11.9 c	12.4 c
$I_{80\%}$	48.0 cd	50.0 d	70.2 d	71.4 cd	40.4 de	42.0 e	8.30 e	8.63 e	9.97 e	10.3 e
$I_{60\%}$	42.0 d	44.0 e	65.4 e	66.6 d	34.8 e	36.3 f	7.15 f	7.40 f	8.60 f	8.87 f

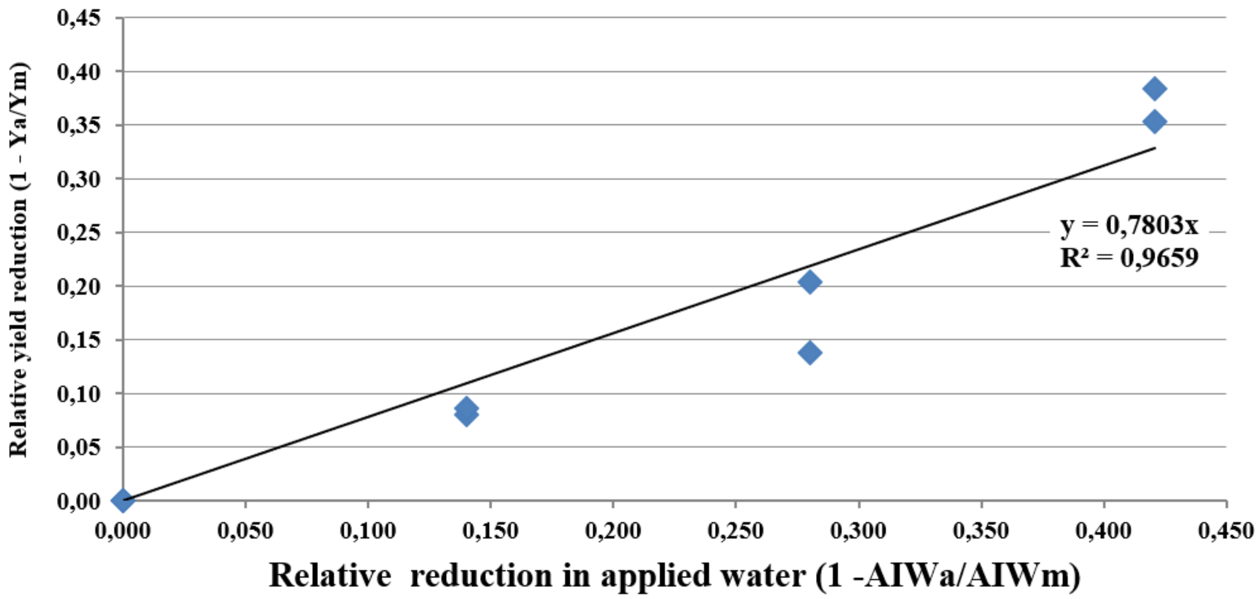

Figure 4: Yield response factor (Ky) of chia crop

Results revealed that the highest carbohydrates (%) values of 59.4 and 61.3% were recorded for I_G treatment in the 2020/21 and 2021/22 seasons, respectively. The lowest values of 34.8 and 36.3% were recorded for the $I_{60\%}$ treatment in the 2020/21 and 2021/22 seasons, respectively (Table 5). The obtained results were within the range of carbohydrate values reported by Ixtaina *et al.* (2008 and 2011) who stated that carbohydrate contents of chia seeds varied from 26 to 41%. The results were similar to carbohydrate content of 42.1% as reported by USDA (2018).

Protein contents (%) were significantly affected by irrigation treatments (Table 5). Results showed that, the highest protein content (%) values of 11.7 and 12.9% were recorded for I_G treatment in the 2020/21 and 2021/22 seasons, respectively. The lowest values of 7.1 and 7.4% were recorded for the $I_{60\%}$ treatment in the 2020/21 and 2021/22 seasons, respectively. The obtained results were close to chia seed protein values of (15 - 25%) as reported by Ixtaina *et al.* (2008 and 2011), (18.2 – 25.3%) as reported by da Silva *et al.* (2014 and 2017), 16.5% as reported by USDA (2018), and 17.1% as reported by Varban *et al.* (2022).

Results in Table 5 indicated that oil contents (%) in chia seeds were significantly influenced by irrigation treatments. The highest oil content (%) values of 14.6 and 15.1% were recorded for I_G treatment in the 2020/21 and 2021/22 seasons, respectively. Oil contents of the I_F, $I_{120\%}$, $I_{100\%}$, $I_{80\%}$, $I_{60\%}$ treatments were 23.7, 10.2, 18.5, 31.8, and 41.4% less than I_G treatment, respectively. The lowest values of 8.6 and 8.9% were recorded for the $I_{60\%}$ treatment in the 2020/21 and 2021/22 seasons, respectively. The reduction in oil content is directly related to the reduction in seed yield. The obtained results were similar to the oil contents in chia seeds reported by El-Serafy *et al.* (2020) who indicated that oil content varied between 15 and 13% for 15 Sep. and 1 Oct. sowing dates, respectively. The obtained results were also close to the results reported by Harisha *et al.* (2023) who stated that deficit irrigation at $I_{25\%}$, $I_{50\%}$, and $I_{75\%}$ led to 42.5, 22.5 and 4.2% reduction in oil yield compared to $I_{100\%}$.

Generally, the obtained results were in line with those reported by Furtado *et al.* (2016) who stated that plant growth reduction and accumulation of dry matter under deficit irrigation could be attributed to the decrease in water and nutrient uptake due to stomata closure, poor transpiration and low turgor pressure, which reduced photosynthesis and cell expansion.

Effect on macro-, secondary-, and micro-nutrients

Results in Tables 6 and 7 indicated significant effect of irrigation treatments on the measured macro-, secondary, and micro-nutrients in chia seeds. Results in Table 6 revealed that, the highest nitrogen values of 1.87 and 2.07% were recorded for I_G treatment, while the lowest values of 1.15 and 1.19% were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The obtained results were close to N% value of 2.98% as reported by Abd Elhamed and Abd El-Khalek (2022). The highest P (%) values of 0.32 and 0.31% were recorded for I_G treatment, while the lowest values of 0.17 and 0.18% were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The obtained results were close to P% value of 0.45% as reported by Abd Elhamed and Abd El-Khalek (2022). The highest potassium (%) values of 0.73 and 0.75% were recorded for I_G treatment, while the lowest values of 0.43 and 0.44 % were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The results of this study were close to K (%) values of 0.66-0.81% as reported by ESFA (2009), 0.73 % as reported by Jin *et al.* (2012), 0.41 % as reported by USDA (2018), and 0.32-0.53 % as reported by Mohamed *et al.* (2019). The highest Ca (%) values of

Table 6: Effect of tested irrigation treatments on N, P, K, Ca, and Mg (%) in chia seeds during 2020/21 and 2021/22 growing seasons

Irr. Treat.	N (%)		P (%)		K (%)		Ca (%)		Mg (%)	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
I_F	1.50 abc	1.54 bc	0.23 bc	0.23 bcd	0.56 c	0.57 bc	0.57 bc	0.59 bc	0.34 bc	0.35 bc
I_G	1.87 a	2.07 a	0.32 a	0.31 a	0.73 a	0.75 a	0.74 a	0.77 a	0.44 a	0.45 a
$I_{120\%}$	1.77 a	1.81 ab	0.27 ab	0.27 ab	0.66 ab	0.66 ab	0.67 ab	0.68 ab	0.4 ab	0.40 ab
$I_{100\%}$	1.59 ab	1.65 bc	0.24 bc	0.25 bc	0.59 bc	0.61 bc	0.60 bc	0.57 bc	0.36 bc	0.37 bc
$I_{80\%}$	1.33 bc	1.38 cd	0.20 cd	0.21 cd	0.45 d	0.51 cd	0.51 cd	0.52 cd	0.30 cd	0.31 cd
$I_{60\%}$	1.15 c	1.19 d	0.17 d	0.18 d	0.43 d	0.44 d	0.44 d	0.45 d	0.26 d	0.27 d

Table 7: Effect of tested irrigation treatments on Mn, Zn, Fe, B, and Cu (%) in chia seeds during 2020/21 and 2021/22 growing seasons

Irr. Treat.	Mn (ppm)		Zn (ppm)		Fe (ppm)		B (ppm)		Cu (ppm)	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
I_F	39.1 bc	40.2 bc	59.5 b	61.0 bc	66.2 bc	68.0 bc	29.1 bc	29.9 cd	5.36 bcd	5.51 bc
I_G	51.1 a	52.7 a	76.9 a	80.1 a	86.4 a	89.3 a	38.0 a	39.2 b	7.22 a	7.23 a
$I_{120\%}$	46.0 ab	47.1 ab	70.0 ab	71.5 ab	77.9 ab	80.0 ab	34.2 ab	35.0 a	6.31 ab	6.46 ab
$I_{100\%}$	41.5 bc	43.1 bc	63.0 b	65.5 bc	70.1 bc	73.0 bc	30.8 bc	32.0 c	5.68 bc	5.91 bc
$I_{80\%}$	34.7 cd	36.1 cd	47.3 c	54.8 cd	58.8 cd	61.1 cd	25.8 cd	26.8 cd	4.76 cd	4.95 cd
$I_{60\%}$	29.9 d	31.0 d	45.5 c	47.1 d	50.6 d	52.4 d	22.2 d	23.0 d	4.28 d	4.25 d

0.57 and 0.59 % were recorded for I_G treatment, while the lowest values of 0.44 and 0.45% were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The obtained Ca (%) values were in close agreement with those reported by EFSA (2009) of 0.50-0.77%, Jin *et al.* (2012) of 0.46 %, USDA (2018) of 0.63%, and Mohamed *et al.* (2019) of 0.57-0.59 %. The highest Mg (%) values of 0.44 and 0.45 % were recorded for I_G treatment, while the lowest values of 0.26 and 0.27 % were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The obtained Mg (%) values in this study were in line with those reported by EFSA (2009) of 0.32-0.40 %, Jin *et al.* (2012) of 0.45%, USDA (2018) of 0.33 %, and Mohamed *et al.* (2019) of 0.29-0.30%.

Results in Table 7 showed that, the highest Mn values of 51.1 and 52.7 ppm were recorded for I_G treatment, while the lowest values of 29.9 and 31.0 ppm were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The obtained results were in line with Mn value of 37.9 ppm as reported by Jin *et al.* (2012). The obtained values were higher than Mn (ppm) value of 27 ppm as reported by USDA (2018). The highest Zn (ppm) values of 76.9 and 80.1 ppm were recorded for I_G treatment, while the lowest values of 45.5 and 47.1 ppm were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The results of this study were close to Zn (ppm) values of 37-79 ppm as reported by ESFA (2009), 64.7 ppm as reported by Jin *et al.* (2012), 46 ppm as reported by USDA (2018), and 37.6-51.9 ppm as reported by Mohamed *et al.* (2019). The highest Fe (ppm) values of 86.4 and 89.3 ppm were recorded for I_G treatment, while the lowest values of 50.6 and 52.4 ppm were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The results of this study were close to Fe (ppm) values of 63-99 ppm as reported by ESFA (2009), 91.8 ppm as reported by Jin *et al.* (2012), 77 ppm as reported by USDA (2018), and 53.9-0.71 ppm as reported by Mohamed *et al.* (2019). The highest B (ppm) values of 38.0 and 39.2 ppm were recorded for I_G treatment, while the lowest values of 22.2 and 23.0 ppm were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The obtained B (ppm) values were higher than those reported by Abd Elhamed and Abd El-Khalek (2022) of 18.7-20.0 ppm. The highest Cu (ppm) values of 7.22 and 7.23 ppm were recorded for I_G treatment, while the lowest values of 4.28 and 4.25 ppm were recorded for $I_{60\%}$ treatment in the 1st and 2nd seasons, respectively. The obtained Cu (ppm) values in this study were in line with those reported by EFSA (2009) of 2.0-19.1 ppm, USDA (2018) of 9.0 ppm and Mohamed *et al.* (2019) of 7.48-9.36 ppm.

Results showed that there were no significant differences between all measured macro- and secondary-nutrients (%) for I_G and $I_{120\%}$ treatments in the two seasons. Also, all measured values of macro- and secondary-nutrients (%), and micro-nutrients (ppm) were higher in the 2nd season compared with the 1st season. These results were due to higher irrigation application efficiency value in the 2nd season with direct effect on improving the availability and uptake of fertilizers injected through fertigation technique. Results also indicated that decreasing the amounts of applied water (i.e. $I_{100\%ETo}$, $I_{80\%ETo}$ and $I_{60\%ETo}$) decreased nutrient contents in chia seeds. The obtained results can be explained as nutrient availability may be limited since the decrease of soil moisture delays minerals' dissolution and reduces the concentration in soil solution, while adequate moisture (i.e. I_G and $I_{120\%ETo}$) ensures nutrients distribution uniformity and uptake. Excess irrigation (i.e. I_F) led to nutrients leaching from the root zone with direct effect on uptake and plant growth.

CONCLUSION

Chia (*Salvia hispanica* L.) crop is a new herbaceous plant introduced to the Egyptian cultivation system. No information is available on water requirements of chia crop under these conditions. Results indicated significant effect of irrigation treatments on chia seed yield, plant height, total carbohydrates, total protein, total oil content, macro-, secondary-, micro-nutrients, amounts of applied irrigation and water productivity. Results showed significant effect of the irrigation treatments on all tested parameters. Chia crop response factor was 0.78 indicating moderately tolerant to deficit irrigation. From the obtained results it could be concluded that applying appropriate agronomic conditions (e.g. proper amounts of irrigation water, and applying fertilizer through drip-fertigation technique) can achieve high chia seed yields. In case of water shortage, applying good agricultural practices and $I_{80\%ETo}$ can save 46% (3660 m^3/ha) of applied irrigation water without significant reduction in chia seed yield.

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