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IMPACT OF DEFICIT IRRIGATION TIMING ON PHYSIOLOGICAL TRAITS, YIELD AND QUALITY OF SOME SUGAR BEET VARIETIES

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ABSTRACT

This study was conducted on a private farm located behind the Cairo-Alexandria Desert Road in Egypt's Southern Tahrir region (30°14'14.59"N, 30°46'53.90"E) during the 2021/2022 and 2022/2023 seasons using a drip irrigation system.

The objective of this study was to determine the sensitive period during the sugar beet growing season for deficit irrigation and its effect on the yield and quality of four multigerm sugar beet varieties (Faten, Dina, Scota, and Elmo). The treatments included irrigation at 100% ETc (the control) and irrigation deficit (65% ETc), which was applied during four growth periods: 15-30, 40-70, 100-130, and 160-190 days after planting (DAP). The experiment was set up using a randomized complete block design in a split-plot arrangement with three replications.

The highest root and sugar yields were achieved with irrigation at 100% ETc throughout the season. Early-season water stress (65% ETc from 15 to 30 DAP) significantly reduced yield potential, a deficit that could not be offset by late-season irrigation.

Physiological and biochemical responses, such as leaf relative water content, leaf area index, and proline accumulation, were examined and revealed that early stress resulted in irreversible damage.

Insignificant differences were observed between full irrigation and late season deficit treatment concerning root and sugar yields/fed, suggesting a partial compensatory response when water stress occurred later in the growing season. The findings emphasized the importance of water availability during the early growth stages for optimal sugar beet production under deficit irrigation conditions. Along late stress periods, the Elmo variety recorded higher proline concentration and showed more tolerance to water stress.

Key Words: Sugar beet, varieties, deficit irrigation time, sensitive period, yield, quality and Evapotranspiration.

INTRODUCTION

The increased demand for water in agriculture has raised concerns about the availability of water for irrigation, particularly in the newly reclaimed soils along the Cairo-Alexandria Desert Road. With increasing water demands, scientists are relying on science to determine how to use water more efficiently

(Tarkalson and King, 2017). In recent years, numerous studies have examined crop production under conditions of limited water availability. In this context, several studies have evaluated the effect of deficit irrigation on sugar beet crops. Drought generally impacts various morpho-physiological traits of beet varieties, including delayed and restricted fresh and dry weight **(Tan *et al.*, 2023)**; reduced leaf area **(Suminarti *et al.*, 2020)**; reduced leaf relative water content **(Zhang *et al.*, 2024)**; and electrolyte leakage or membrane damage **(Sattar *et al.*, 2024)**. However, little research exists on the timing of deficit irrigation for sugar beets during the growing season. For instance, **Carter *et al.* (1980)** concluded that irrigation could be eliminated late in the season (during the swelling growth stage) without reducing sucrose yield, provided that the soil contained at least 1.6 meters of water at field capacity and at least 200 millimeters of available water during the root swelling stage. They also suggested implementing seasonal deficit irrigation management strategies in August, September, and October, which could reduce seasonal irrigation requirements by up to 30% and decrease production costs. They also found that deficit irrigation reduces leaf growth and canopy cover without affecting root sucrose accumulation. Meanwhile, **Yonts *et al.* (2011)**, revealed that restricting irrigation in August resulted in sugar yields similar to those of full irrigation. Furthermore, drought tolerance is a complex, quantitative trait influenced by multiple genes **(Li *et al.*, 2023)**.

This study was aimed to evaluate the impact of deficit irrigation at various stages of the growing season on the physiological and quality traits, as well as the yields of roots, sugar, and water use efficiency of different sugar beet varieties.

MATERIALS AND METHODS

This study was conducted on a private farm located behind the Cairo-Alexandria Desert Road in the Southern Tahrir region of Egypt (30°14'14.59" N, 30°46'53.90" E) during the 2021/2022 and 2022/2023 seasons, utilizing a drip irrigation system.

This study was aimed to identify the sensitive stress period during the sugar beet growing season when deficit irrigation has the greatest impact on multigerm sugar beet varieties, examining this influence quantitatively and qualitatively. Using a randomized complete block design with a split-plot arrangement and three replications, twenty combinations were laid out among five deficit irrigation treatments. These included full irrigation at 100% ETc (the control treatment) and a 65% deficit of ETc. This deficit was applied during four growth periods: the initial stage (days 15-30), canopy development (days 40-70), root development and storage (days 100-130), and maturity (days 160–190) after planting. The treatments were applied using a drip irrigation system and were tested on four multigerm sugar beet varieties: Faten, Dina, Scota, and Elmo. The deficit irrigation treatments occupied the main plots, and the sugar beet varieties were randomly sown in the sub-plots. Regardless of the studied growth period, during which deficit irrigation at 65% ETc was practiced, sugar beet varieties were fully irrigated at 100% ETc.

The experimental unit measured 12 m² and consisted of five ridges, each 4 m long, spaced 60 cm apart, with 20 cm of space between hills. This was done during the first week of October in both seasons. Thinning was executed at the four-leaf stage. Ammonium nitrate (33.5% nitrogen) was added at a rate of 120 kg N per fed, divided into five equal doses. The first dose was applied after thinning, and the remaining doses were applied at two-week intervals.

Phosphorus was added during land preparation in the form of calcium superphosphate (15% P_2O_5) at a rate of 200 kg/fed along with five tons of compost/fed. Potassium sulphate (48% K_2O) was applied at a rate of 48 kg/fed with the final nitrogen fertilizer application. All other agricultural practices were carried out according to the recommendations of the Sugar Crops Research Institute (SCRI). The soil type was sandy, containing 1.9%, 3.0%, and 95.1% clay, silt, and sand, respectively. It had a bulk density of 1.56 g/cm³, a field capacity of 15.2%, and a wilting point of 6.1%. The source of irrigation was an artesian well, whose water had a pH of 7.30 and an electrical conductivity (EC) of 5.0 dS/m^{-1}.

1. Calculating Irrigation Water Requirements:

The **Blaney and Criddle (1962**) method was used to determine irrigation water requirements.

$$IR_c = \frac{\left[\left(ET_0 \times K_c\right) \times Dd\right]}{Es}$$

Where: IRc = total actual irrigation water requirements (mm/interval); ETo = evapotranspiration (mm/day), calculated using the CROPWAT program **(Smith *et al.*, 1991)**; Kc = crop coefficient **(Doorenbos and Kassam, 1979)**; Dd = time intervals; and Es = system efficiency (%).

According to **Chapman and Pratt (1961)**, the experimental site's meteorological data in the Southern Tahrir region are shown in Table 1. Table 2 shows the values of the crop factor (Kc) throughout the growing seasons. Table 3 exhibits the average amounts of applied water (m³/fed-^{1}) during the four periods of sugar beet growth throughout the growing seasons under the drip irrigation system. Table 4 shows the amounts of water applied for the four water-deficient treatments.

Table (1): Meteorological data of the southern Tahrir region (average of 2021/22 and 2022/23 seasons)

Month	Max. temp. (C°)	Min. temp. (C°)	Relative humidity (%)	Wind speed (km/hr)	Sunshine (hr)	Evapotranspiration (ET°) (mm)
October	31.5	15.4	58	8.6	8.22	4.89
November	26.6	11.3	65	7.5	7.13	2.81
December	22.4	7.3	67	6.4	6.36	2.49
January	20.9	6.2	68	6.3	6.45	2.32
February	22.5	7.9	63	7.2	7.34	2.86
March	24.7	11.5	61	7.9	7.65	3.82
April	28.9	12.2	53	8.9	8.62	5.12
Average/year	25.4	10.2	62	7.5	7.40	3.47

Source: Southern Tahrir Meteorological Station

Table (2): Crop factor (K_c) throughout the growing season of sugar beet in the semi-arid region (FAO, 1979)

Initial		Crop development		Mid-season		Late-season		Total (days)
Time (days)	K_c	Time (days)	K_c	Time (days)	K_c	Time (days)	K_c	210
30	0.38	60	$0.38>K_c<1.3$	60	1.3	60	$1.3>K_c<0.8$	

Table (3): Applied irrigation water requirements, IWR (m^3/fed) at 100% Etc throughout each of the two growing seasons (2021/22 and 2022/23)

Days after planting (DAF)	Sugar beet growth period	Amount of water (m^3/feddan*)
1	Initial (15-30 DAP)	158.3
30		
31	Canopy development (40-70 DAP)	433.7
90		
91	Root development (100-130 DAP)	771.0
150		
151	Maturity (160-190 DAP)	1183.1
210		
Total seasonal IWR (m^3/fed)		2546.1

Feddan (fed) = 4200 m^2

Table (4): The seasonal amount of water for studied deficit irrigation treatments

Irrigation water levels	Deficit irrigation treatment	Amount of (m^3/fed)
65 % of Etc*	Water stress applied during 15-30 days after planting (DAP) atthe initial stage	2518.4
	Water stress applied during 40-70, DAP at canopy Development stage	2470.2
	Water stress applied during 100-130 DAP at development and storage root stage	2411.18
	Water stress applied during 160-190 DAP at maturity stage	2339.06

*ETc = crop evapotranspiration

2. Studied characters:

Random samples were taken from each subplot 90 and 180 days after planting to determine the following:

2. 1. Physiological and Biochemical traits:

2.1.1. Leaf area index

Five guarded sugar beets were sampled, and the foliage of each plant was used to determine leaf area (cm^2), according to the disk method described by **Watson (1958).**

Leaf Area Index (LAI) = Leaf Area (cm^2) / Plant Ground Area (cm^2)

2.1.2. Leaf Relative Water Content (LRWC)

LRWC% was estimated using **Weatherly's (1950)** method and calculated as follows:

LRWC (%) = [FW – DW] / [TW – DW] × 100

Where: FW, DW, and TW are the fresh weight, dry weight, and turgid weight, respectively.

2.1. 3. Proline content in leaves (mg/g of fresh weight) was determined using the ninhydrin method cited by **Bates *et al.* (1973).**

2.2. Soil-water-crop relations:

Water use efficiency (WUE) (kg roots and/or sugar/m^3):

WUER = root yield (kg fed^{-1})/consumed irrigation water (m^3 fed^{-1})

WUES = sugar yield (kg fed^{-1})/consumed irrigation water (m^3 fed^{-1}), as shown by **Stan hill (1986).**

2. 3. Quality parameters:

A random sample of ten roots was taken from each sub-plot at harvest (210 DAP). The roots were then cleaned and sent to the Sugar Beet Laboratory at Nubaria Sugar Factory in El-Beheira Governorate, Egypt to determine the following:

2.3.1. Juice impurities: The Sugar Company's automatic analyzer was used to determine the concentrations of three elements in sugar beet roots: alpha-amino nitrogen (α-amino N), sodium (Na), and potassium (K), This method is described by **Cooke and Scott (1993)**.

2.3.2. Sucrose percentage: was estimated in fresh macerated roots using a saccharometer and lead acetate extract as reported by **Carruthers *et al.* (1962)**.

2.3.3. The extractable sugar percentage (ES %) was estimated using the following equation of **Reinefeld *et al.* (1974)**:

$$ES\% = pol\ \% - [0.343(K + Na) + 0.094\ \alpha\text{-amino N} + 0.29].$$

Where**:** Pol. % = sucrose percentage

2.3.4. Juice purity percentage = (ES% /pol.) × 100

2.4. Yields

2.4.1. Root yield/fed:

At harvest, root weight per plot was determined in kilograms and converted to tons per fed.

2.4.2. Sugar yield/fed:

Sugar yield (tons per fed) = root yield (tons per fed) × (extractable sugar percentage/100).

2.5. Statistical analysis:

The collected data were subjected to statistical analysis according to the methods outlined by **Snedecor and Cochran (1994).** Treatment means were compared. The least significant difference (LSD) at the 5% probability level was used for this comparison.

RESULTS AND DISCUSSION

Leaf area index, leaf relative water content and proline content in leaves as affected by the evaluated deficit irrigation treatments and the tested sugar beet varieties

The data in Table 5 revealed that the leaf area index (LAI) of sugar beets irrigated with 65% ETc during the initial growth period (15-30 days after planting [DAP]) decreased markedly by 2.71 and 2.67 at 90 DAP and by 2.62 and 2.83 at 180 DAP, compared to the control, which received full irrigation at 100% ETc in the first and second seasons, respectively. A similar pattern was observed for leaf relative water content (LRWC), which decreased by 13.98% and 14.98%, and 14.18% and 17.07% at 90 and 180 days after planting (DAP), respectively. The results demonstrated that W4 was appreciably superior to W3 in LAI at 90 DAP in the second season, compared to the control (fully irrigated at 100% ETc) in the first and second seasons. Researchers also observed this model for leaf relative water content (LRWC), which decreased by 13.98%-14.98% and 14.18%-17.07% at 90 and 180 days after planting (DAP) in both seasons, respectively. The findings demonstrated that, except for the appreciable superiority of W4 over W3 in LAI at 90 DAP in the 2nd season, as well as the significant increase of W3 over W4 at 180 DAP in the 1st one, the difference between the mid and late water stress treatments (periods of 100-130 and 160-190 DAP) was insignificant. Moreover, the results pointed to a substantial increase in LRWC in beets as affected by W4 compared with those treated with W3, at 180 DAP, in both seasons, without any significant variance in LRWC between W4 and W5 at 90 and/or 180 DAP. These findings may be attributed to the decrease in photosynthetic rate caused by the reduction in leaf area due to severe water stress. Moreover, it may be due to the reduction in LAI and LRWC % occurred under water shortage conditions early in the season (15-30 DAP) in October, along with a maximum temperature of 30.4 ^{0}C and evapotranspiration (ET_0) of 4.98 mm (Table 1). In addition, the simultaneous occurrence of high temperatures and water deficit at the early growth stage can accelerate the transpiration rate, water loss from leaves, and reduce osmotic potential **(Hussain *et al.*, 2018)**. Additionally, it may hinder a plant's ability to absorb water from the soil and decrease the flow of water from the xylem to the mesophyll cells in the leaves, resulting in a decrease in LRWC. **(Chołuj *et al.*, 2008)**. Early-season severe water stress can result in irreversible physiological damage to plants. One potential reason for a decrease in leaf area is severe water stress, which would result in a reduction in photosynthesis. **(Tarkalson and King, 2017)**.

Under deficient water, sugar beet utilizes osmotic compounds to alleviate drought stress. Proline has a role in adjusting cellular osmotic potential It may protect cells from dehydration by stabilizing membranes, proteins, and subcellular structures, as well as by destroying free radicals. **Ozturk and Demir (2002) ; Blum (2017)**.

Data from the same Table indicates that, at 90 DAP, maximum leaf proline content was recorded when beets were exposed to deficit irrigation earlier in the growing season (15-30 DAP, W2), where leaves significantly contained 2.33 and 2.54% (in both seasons, respectively) more than those unstressed (fully irrigated, W1) throughout the whole season. Meanwhile, there was insignificant variance between W2 and W3 as well as W4 and W5 in their influence on proline content. The same trend was observed at 180 DAP. These results are in arrangement with those of **Tarkalson and King (2017)**, who found that severe water stress at the start of the season can cause lasting harm to the plants' physiological processes that cannot be reversed.

The results show that the tested varieties did not exhibit a significant difference in LAI during the first season, either at 90 or 180 DAP. However, the Elmo variety showed the appreciable superiority in LAI in the 2nd season, over the other three, while, insignificant variance was detected between Faten, Dina and Scota.

Results in Table 5 pointed to a substantial superiority of Elmo beet variety in LRWC over the other varieties tested at 180 DAP in the 2nd season, without significant difference with Scota variety. Additionally, the evaluated varieties did not vary significantly in LRWC at 90 DAP in the first and second seasons, nor at 180 DAP in the first season. These results align with those mentioned by **El-Kady *et al.* (2021)**, who found that Amina variety surpassed the others with respect to LRWC%. Additionally, **Kaya and Ergin (2025)** stated that relative water content can effectively be used to select drought-tolerant beet genotypes.

Table (5): Leaf area index (LAI), leaf relative water content (LRWC %) and proline (mg/g fresh weight) for the studied irrigation treatments and sugar beet varieties in 2021/22 and 2022/23 seasons.

Treatment	Leaf area index				Leaf relative water content %				Proline (mg/g)			
	90 DAP		180 DAP		90 DAP		180 DAP		90 DAP		180 DAP	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Water stress (65% Etc) periods (A)												
W1* (control)	4.80	4.26	6.29	6.75	87.89	85.61	87.99	88.21	4.05	3.84	3.78	3.67
W2*	2.09	1.59	3.67	3.92	73.91	70.63	73.81	71.14	6.38	6.38	6.24	6.29
W3*	3.47	2.67	6.09	5.37	80.72	78.04	76.14	75.09	6.06	5.88	6.02	6.09
W4*	3.70	3.92	5.09	5.53	84.53	81.88	84.17	84.40	4.51	4.29	4.93	5.09
W5*	3.99	3.92	4.78	5.75	86.59	84.64	84.62	85.60	4.34	4.21	5.00	4.78
LSD at 5%	0.82	0.65	0.74	0.74	8.13	9.35	5.94	7.29	0.68	0.71	0.75	0.74
Sugar beet varieties (B)												
Faten	3.76	3.01	5.60	4.77	81.67	79.23	79.14	78.76	4.57	4.41	4.78	4.80
Dina	3.72	2.89	5.58	4.73	82.44	79.64	80.22	79.71	4.74	4.58	4.72	4.71
Scota	3.41	3.07	5.32	4.94	83.38	80.38	82.56	81.31	5.42	5.30	5.61	5.59
Elmo	3.95	3.73	5.75	5.54	83.43	81.38	83.47	83.78	5.53	5.40	5.67	5.64
LSD at 5%	NS	0.44	NS	0.44	NS	NS	NS	3.06	0.35	0.33	0.27	0.30

W1: 100% ETc applied during initial growth period; W2: 65% Etc applied during initial growth period (15-30 DAP); W3: 65% ETc applied during development (40-70 DAP); W4: 65% ETc applied during mid-season (100-130 DAP); W5: 65% ETc applied during maturity (160-190 DAP).

The Elmo sugar beet variety recorded the highest mean proline percentage values at 90 and/or 180 days after planting (DAP) compared to the other three varieties in the first and second seasons. There was no statistical variance between Elmo and Scota in this trait. Meanwhile, an insignificant difference in proline content was detected between Faten and Dina at 90 and 180 DAP in both seasons. These results align with those reported **by Farkhondeh *et al.* (2012)**, who found that the Dorotea cultivar had higher proline levels. The differences among varieties in the aforementioned traits are likely due to gene makeup **(El-Kady *et al.*, 2021)**.

Water Use Efficiency as affected by the evaluated deficit irrigation treatments and the tested sugar beet varieties

The results in Table 6 showed that water use efficiency, determined as kg of roots and sugars per m^3, was significantly affected by the timing of deficit irrigation in both seasons. Beets that suffered from a shortage of irrigation during the initial growth period (15-30 days after planting [DAP]) recorded the lowest WUE values, while deficit irrigation, where water was given to sugar beets later in the maturity period (160-190 DAP), led to the highest WUE values, estimated on either a root or sugar basis, compared with other deficit irrigation treatments in both seasons.

Table 6 also showed that the tested sugar beet varieties varied markedly in WUE calculated on a root basis in the first season. The Elmo and Scota varieties utilized one cubic meter of water efficiently to produce one kilogram of roots, with an insignificant difference between them. The Dina and Elmo varieties were less efficient, recording lower WUE values without a significant difference between them. This trait's variation among different varieties may be explained by differences in their gene makeup.

Table (6): Water use efficiency (kg root and/or sugar/m^3water) for the studied irrigation treatments and sugar beet varieties in 2021/2022 and 2022/2023 seasons.

Treatment	Water use efficiency (kg root/m^3 water)		Water use efficiency (kg sugar/m^3 water)	
	1st	2nd	1st	2nd
Water stress (65% Etc) periods (A)				
W1* (control)	1.005	0.948	0.153	0.138
W2*	0.579	0.575	0.104	0.110
W3*	0.936	0.805	0.150	0.115
W4*	1.020	0.914	0.155	0.130
W5*	1.068	1.009	0.162	0.146
LSD at 5%	0.05	0.07	0.16	0.011
Sugar beet varieties (B)				
Faten	0.885	0.823	0.144	0.128
Dina	0.891	0.835	0.142	0.131
Scota	0.947	0.872	0.146	0.130
Elmo	0.964	0.871	0.147	0.123
LSD at 5%	0.05	NS	NS	NS

W1: 100% ETc applied during initial growth period; W2: 65% Etc applied during initial growth period (15-30 DAP); W3: 65% ETc applied during development (40-70 DAP); W4: 65% ETc applied during mid-season (100-130 DAP); W5: 65% ETc applied during maturity (160-190 DAP).

Root mineral composition and impurity accumulation as affected by the evaluated deficit irrigation treatments and the tested sugar beet varieties

The data in Table 7 revealed significant differences among the water stress treatments in their effects on the root content of potassium in the second season, sodium in the first season, and alpha amino-N in both seasons. The results showed that beets that were fully irrigated throughout the growing season (control) had the lowest levels of these three impurities. Furthermore, there was no significant difference in impurities between plants that were not water-stressed (control) and those that were water-stressed at 65% ETc during maturity (160-190 DAP). However, it was observed that plants stressed by water earlier, during the initial growth period (15-30 DAP), had the highest concentrations of the three impurities. These results may be due to the fact that limited irrigation can trigger the accumulation of certain solutes, such as K, Na, and amino acids, in the sugar beet root. These solutes are considered "compatible solutes" that may help the plant cope with stress **(Rover and Buttner, 1999)**.

Results cleared that Elmo variety showed the significant superiority in root potassium content over the other three varieties in both seasons without a substantial variance with Scota in the 1st one (Table 7). However, the roots of Faten variety contained the lowest K % without a statistical variance with Dina in both seasons. Concerning Na and alpha amino-N, insignificant differences among the evaluated beet varieties were detected in the 1st and/or the 2nd seasons.

Table (7): Potassium, sodium and alpha amino-N percentages in sugar beet roots as affected by the studied irrigation treatments and sugar beet varieties in 2021/2022 and 2022/2023 seasons.

Treatment	K%		Na%		Alpha amino-N%	
	1st	2nd	1st	2nd	1st	2nd
Water stress (65% Etc) periods (A)						
W1* (control)	**5.41**	**4.29**	**1.55**	**1.34**	**1.58**	**1.34**
W2*	**6.23**	**5.72**	**2.61**	**2.20**	**2.92**	**2.95**
W3*	**6.16**	**5.64**	**2.40**	**2.05**	**2.79**	**2.79**
W4*	**5.71**	**5.58**	**2.05**	**1.86**	**2.31**	**1.54**
W5*	**5.57**	**5.18**	**2.02**	**1.38**	**1.98**	**1.53**
LSD at 5%	**NS**	**0.92**	**0.57**	**NS**	**0.44**	**0.98**
Sugar beet varieties (B)						
Faten	**5.57**	**4.79**	**2.29**	**1.65**	**2.37**	**2.10**
Dina	**5.64**	**4.87**	**2.06**	**1.72**	**2.27**	**2.12**
Scota	**6.01**	**5.18**	**2.06**	**1.84**	**2.34**	**1.98**
Elmo	**6.04**	**6.29**	**2.10**	**1.85**	**2.28**	**1.92**
LSD at 5%	**0.39**	**0.45**	**NS**	**NS**	**NS**	**NS**

W1: 100% ETc applied during initial growth period; W2: 65% Etc applied during initial growth period (15-30 DAP); W3: 65% ETc applied during development (40-70 DAP); W4: 65% ETc applied during mid-season (100-130 DAP); W5: 65% ETc applied during maturity (160-190 DAP).

Sucrose, purity, extractable sugar percentages, roots and sugar yields/fed of the tested sugar beet varieties as affected by the evaluated deficit irrigation treatments

In Table 8 data revealed that, except for purity%, in the 1st season, sucrose and sugar extracted %, as well as, root and sugar yields/fed were substantially influenced by the applied irrigation regimes in both seasons. The data showed that, supplying beets with water at 65% Etc during the initial growth period (15-30 DAP) resulted in the highest sucrose % compared with the other studied water stress periods, in both seasons. In the 1st season, W2 caused increases in sucrose % amounted to 3.75, 2.35, 3.46 and 3.53 %, corresponding to 5.57, 4.96, 5.18 and 5.28 in the 2nd one, compared with W1, W3, W4 and W5, respectively. Meantime, insignificant statistical variance was found among sucrose % as affected by W1, W3, W4 and W5, in both seasons. Moreover, applying W1 led to the lowest values of this trait, which may be attributed to the fact that sucrose is determined as a percentage in the fresh roots, where the higher water content, the lower sucrose % in roots of beets fully irrigated at 100% ETc throughout the growing season. It can be observed that, extractable sugar % had the same tendency, in both seasons. Purity % was markedly affected by the studied deficit irrigation treatments in the 2nd season. Applying W1 resulted in the highest purity %, without significant difference with W2. Meanwhile, there was insignificant variance between W3 and W4 in this trait. Applying irrigation at 100 % ETc throughout the growing season (W1) significantly led to the production of the maximum root yield/fed over those produced by the other deficit irrigation treatments in both seasons. In the 1st one, W1 attained increases of 11.02, 2.47, 1.00 and 0.60 ton/fed in root yield over that harvested in the case of using W2, W3, W4 and W5 for sugar beet irrigation, successively, corresponding to 9.65, 4.25, 2.11 and 0.53 ton/fed in the 2nd season. An appreciable increase in sugar yield amounted to 1.26 ton/fed was gained, in comparison to W2, in addition to insignificant increases of 0.19, 0.16 and 0.10 ton of sugar/fed in the case of using W1 for sugar beet irrigation, compared with W3, W4 and W5, respectively, in the 1st season. In the 2nd one, marked increases of 0.73 and 0.67 ton of sugar were produced when W1 was applied, compared with W2 and W3, successively. Meanwhile, insignificant variance was noticed between W1 and both of W4 and W5, as well as between W2 and W3, in their effect on sugar yield. These results are consistent with those of **Tarkalson and King (2017)**, who determined that water availability and reduced water stress early in the season were critical for maximizing yield under water-deficit conditions. Additionally, the timing of water stress may affect sugar beet nitrogen (N) uptake, internal processing, and sucrose production.

Concerning the differences among the tested varieties in the determined traits illustrated in Table 8, the four varieties differed substantially in sucrose and extractable sugar percentages in both seasons, while sugar yield/fed did not significantly differ. Similarly, the evaluated varieties were insignificantly different in purity % (in the 1st season) and root yield/fed (in the 2nd season).

Table (8): Sucrose, purity, extractable sugar percentages and root and sugar yield (ton/fed.) for the studied irrigation treatments and sugar beet varieties in 2021/22 and 2022/23 seasons.

Treatment	Sucrose%		Purity %		Extractable Sugar%		Root yield (ton fed-1)		Sugar yield (ton fed-1)	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Water stress (65% Etc) periods (A)										
W1* (control)	18.05	16.86	84.33	86.07	15.22	14.51	25.59	24.14	3.89	3.51
W2 *	21.80	22.43	83.37	85.32	18.20	19.14	14.57	14.49	2.63	2.78
W3*	19.45	17.47	82.01	81.65	15.96	14.28	23.12	19.89	3.70	2.84
W4 *	18.34	17.25	82.69	82.69	15.17	14.26	24.59	22.03	3.73	3.14
W5 *	18.27	17.15	83.07	84.24	15.19	14.46	24.99	23.61	3.79	3.41
LSD at 5%	1.43	1.61	NS	1.70	1.52	1.48	1.23	1.72	0.28	0.39
Sugar beet varieties (B)										
Faten	19.84	18.53	83.77	85.43	16.64	15.84	21.65	20.17	3.53	3.13
Dina	19.26	18.64	83.64	85.13	16.12	15.89	21.81	20.46	3.48	3.21
Scota	18.83	18.08	82.57	83.99	15.55	15.20	23.22	21.37	3.58	3.19
Elmo	18.78	17.67	82.40	81.43	15.48	14.40	23.61	21.34	3.61	3.01
LSD at 5%	0.73	0.53	NS	0.98	0.79	0.51	1.26	NS	NS	NS

W1: 100% ETc applied during initial growth period; W2: 65% Etc applied during initial growth period (15-30 DAP); W3: 65%ETc applied during development (40-70 DAP); W4: 65% ETc applied during mid-season (100-130 DAP); W5: 65%ETc applied during maturity (160-190 DAP).

Data in Table 8 showed also that, Faten variety contained the highest sucrose % over the other three varieties in the 1st season. It recorded 1.01% and 1.06% higher than that given by Scota and Elmo, respectively. Meantime, insignificant variance in sucrose % between Faten and Dina was detected in this trait. In the 2nd season, Dina variety exhibited the highest sucrose %, without statistical difference with Faten and/or Scota. Dina recorded 0.86% higher than that of Elmo. Faten variety had the highest purity %, without significant difference with Dina. Faten recorded 1.44 % and 4.00 % over that shown by Scota and Elmo, respectively, in the 2nd season. The highest extractable sugar % was given by Faten beet variety, with insignificant variance with that recorded by Dina. Faten gave 0.89 % and 1.16 % higher than shown by Scota and Elmo, respectively, in the 1st season. A similar line was recorded in the 2nd one. Furthermore, it should be noted that Elmo variety had the lowest sucrose, extractable sugar percentage, and purity values compared to the other three tested varieties. Nevertheless, Elmo variety appeared the superiority in root yield over the other three varieties. It attained 1.96 and 1.80 ton of roots/fed higher than that produced by Faten and Dina. Meantime, insignificant variance was found between Elmo and Scota in root yield, as well as between Faten and Dina.

These results align with those of **El-Kady *et al.* (2021),** who found that Sharelston variety significantly surpassed the others studied in terms of sucrose, extractable sugar percentages, and purity in both seasons. Conversely, Amina variety outperformed the others in root yield.

Interaction Effects: Variety × Deficit irrigation period

As shown in Table 9, the interaction between the studied deficit irrigation periods and sugar beet varieties significantly affected proline content at 180 days after planting (DAP) in both seasons. In the 1st one, not significant variance was detected between W1 and W4 in their effect on proline content in leaves of Faten variety. However, the difference between W1 and W4 succeeded in reaching the level of significance, where a higher content of proline was recorded by the application of W4 over that produced by W1 for Dina, Scota and Elmo varieties. In the 2nd season, the application of W4 substantially resulted in higher proline content than that recorded by W2. On the contrary, there is insignificant variance between W2 and W4 in their influence on the determined proline content in Scota and Elmo varieties. **Islam *et al.*, (2020)** noted that drought-tolerant sugar beet varieties exhibited higher proline levels in their leaves than sensitive varieties in response to water stress.

Table (9): Proline (mg/g fresh weight) at 180 days for study irrigation treatment x variety interaction effect for stared measurements in 2021/22 and 2022/23 seasons.

Water treatment	Proline at 180 days							
	1st season				2nd season			
	Sugar beet varieties							
	Faten	Dina	Scota	Elmo	Faten	Dina	Scota	Elmo
W1* (control)	5.00	4.56	5.16	5.28	4.93	4.41	4.95	4.85
W2 *	4.02	4.07	5.86	5.78	4.23	4.21	5.93	5.97
W3*	3.62	3.33	4.03	4.13	3.48	3.23	3.91	4.04
W4 *	5.56	5.84	6.28	6.40	5.62	5.86	6.33	6.56
W5 *	5.70	5.80	6.74	6.74	5.75	5.82	6.75	6.83
LSD at 5%	0.60				0.67			

W1: 100% ETc applied during initial growth period; W2: 65% Etc applied during initial growth period (15-30 DAP); W3: 65% ETc applied during development (40-70 DAP); W4: 65% ETc applied during mid-season (100-130 DAP); W5: 65% ETc applied during maturity (160-190 DAP).

Data in Table (10) suggested that, the interaction between sugar beet varieties and stress timing significantly affected root impurities in terms of alpha amino nitrogen in the 1st season and extractable sugar in the second one. It was observed that the Faten variety contained the highest percentage of nitrogen (N%) when stressed early (15-30 DAP) at 65% ETc, whereas fully irrigated plants (which received 100% ETc throughout the growing season) achieved the lowest mean values for this trait among the tested varieties. The four sugar beet varieties responded differently to water stress at different stages of their life cycle in terms of extractable sugar. In contrast the results cleared that, the performance of each of these varieties was almost the same without significant variance if they were unstressed (fully irrigated) in the 2nd season.

However, plants that continue to be exposed to water stress throughout their life span making it perform better in terms of extractable sugar %. At the same time, exposure of Elmo variety to late stress had the most negative impact on its performance. Then it achieved the lowest value for the extractable sugar, highlighting its sensitivity to water shortage, during the latter growth stages.

Table (10): Alpha amino nitrogen and extractable sugar% forthe studied irrigation treatments x sugar beet varieties in in 2021/22 and 2022/23 seasons

Water treatment	Alpha amino-N				Extractable Sugar%			
	1st season				2nd season			
	Sugar beet varieties							
	Faten	Dina	Scota	Elmo	Faten	Dina	Scota	Elmo
W1* (control)	1.38	1.42	1.81	1.70	14.80	14.37	14.88	13.98
W2 *	3.52	2.93	2.57	2.63	19.42	20.38	18.50	18.26
W3*	2.86	2.84	2.84	2.62	15.54	14.76	13.59	13.24
W4 *	2.02	2.24	2.60	2.40	14.18	14.95	14.14	13.78
W5 *	2.04	1.93	1.89	2.05	15.23	14.98	14.88	12.75
LSD at 5%	0.45				1.15			

W1: 100% ETc applied during initial growth period; W2: 65% Etc applied during initial growth period (15-30 DAP); W3: 65% ETc applied during development (40-70 DAP); W4: 65% ETc applied during mid-season (100-130 DAP); W5: 65% ETc applied during maturity (160-190 DAP).

CONCLUSION

Under the conditions of the present work, the two commercial sugar beet varieties, namely Elmo and Scota showed higher tolerance to delayed 65% ETc water stress (during 100-130 and 160-190 DAP) over the other two (Dina and Faten). Supplying sugar beets with full irrigation water (at 100% ETc) throughout the growing season was necessary to maximize sugar beet root and sugar yield compared to causing much water stress early and applying water latter in the season.

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تأثير توقيت عجز الري على الصفات الفسيولوجية والإنتاجية والجودة لبعض أصناف بنجر السُكَّر

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تمت هذه الدراسة فى مزرعة خاصة فى طريق القاهرة الأسكندرية الصحراوى بمنطقة جنوب التحرير بمصر فى موسمى الزراعة 2022/2021 و 2023/2022.

هدفت هذه الدراسة إلى تحديد فترة الإجهاد المائى الحساسة لنقص الري خلال موسم نمو بنجر السُكَّر وتأثيرها على حاصل وجودة أربعة أصناف عديدة الأجنة من بنجر السُكَّر (فاتن، دينا، سكوتا، وإلمو). شملت المعاملات الري بالتنقيط بنسبة 100% من النتح–بخر للمحصول (المُقارنة) والري بالتنقيط بنسبة 65%من النتح–بخر للمحصول، والذي تم تطبيقه على أربع فترات نمو [(15–30)، (40–70)، (100–130)، (160–190) يومًا بعد الزراعة]. تم إستخدام تصميم القطاعات الكاملة العشوائية بترتيب القطع المنشقة، فى ثلاث مكررات.

أشارت النتائج إلى أن الري طوال الموسم بنسبة 100٪ من النتح–بخر للمحصول حقق أعلى إنتاجية للجذور والسُكَّر/فدان، في حين أدى الإجهاد المائي في بداية الموسم (65٪ من ETc عند 15–30 يومًا بعد الزراعة) إلى نقصٍ للقدرة المحصولية للبنجر بشكلٍ كبير، وهو ما لا يمكن تعويضه عن طريق الري في أواخر الموسم.

تم تحديد الإستجابة الفسيولوجية والكيميائية الحيوية للبنجر، مثل المُحتوى النسبي للماء بالأوراق، ودليل مساحة الأوراق، ومحتوى البرولين، مما كشف أن الإجهاد المُبكِّر أدى إلى ضرر لا رجعة فيه. لوحظت فروق طفيفة بين الري الكامل (المقارنة) ومعاملات نقص الماء في أواخر الموسم فيما يتعلق بإنتاجية الجذور والسُكَّر بالفدان، مما يشير إلى إستجابة تعويضية جزئية عند حدوث الإجهاد المائي في وقت متأخر من موسم النمو.

تُسلّط النتائج الضوء على أهمية توافر المياه خلال مراحل النمو المُبكِّرة لتحقيق إنتاج أمثل لبنجر السُكَّر المُعرَّض لظروف عجز الريّ. سجّل الصنف "إلمو" تركيزاً أعلى من البرولين وأظهر تحمُّلًا أكبر للإجهاد المائي.