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ORIGINAL PAPER

Impact of water and salinity stresses on sugar beet productivity and quality under Wadi El Natrun conditions

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A R T I C L E I N F O

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A B S T R A C T

Water scarcity and salinity are among the most critical constraints affecting sugar beet (*Sultan Beta vulgaris L.*) production in arid regions of Egypt. To address the dual challenges of water scarcity and salinity in arid agricultural regions, a two-year field experiment (2022/2023 and 2023/2024) was conducted in Wadi El-Natrun to assess the interactive effects of irrigation regimes (IRs 100%, 80%, and 60% of crop evapotranspiration, ETc) and saline irrigation water (2.19, 4.38, and 6.57 dS m^{-1}) under two drip irrigation systems: surface (SDI) and sub-surface (SSDI). Results demonstrated that roots yield and quality attributes (length, diameter, fresh weight, purity, and sucrose content) significantly declined ($P < 0.05$) with increasing salinity and water deficit while impurity levels increased. The highest marketable yield (54.75 and 54.31 t ha^{-1} in the first and second seasons, respectively) was recorded under full irrigation (IRs 100%) with low salinity water (2.19 dS m^{-1}) using the SSDI system. Notably, the most significant values of water use efficiency (WUE) and irrigation water use efficiency (IWUE), reaching 12.36 and 12.06 kg m^{-3}, were obtained at IRs 80% with low salinity under SSDI treatment. Furthermore, the lowest yield response factor (Ky = 0.14 and 0.16) was observed under the same treatment, indicating the superior capacity of the SSDI system to sustain yield under moderate water-saving conditions. In addition, these results reveal that irrigating sugar beet in sandy soils with low-salinity water (2.19 dS m^{-1}) at 80% of the SSDI irrigation level can increase marketable sugar beet yield by approximately 10% and effectively reduce irrigation water consumption by approximately 26% compared to the control (traditional) treatment. Furthermore, when freshwater is unavailable, using moderately saline water (S2 = 4.38 dS m^{-1}) under the same treatment maintains acceptable yield levels and water use efficiency, making it a suitable alternative with a limited impact on crop yield and quality of no more than 4%. This strategy provides a practical and sustainable approach to irrigation in arid environments, contributing to national efforts to conserve water, enhance food security, and achieve sustainable agriculture in reclaimed desert regions.

1. Introduction

Sugar Beet (*Beta vulgaris L.*) is a key agricultural crop in Egypt that is a major source of sugar consumption for the country in areas with limited fresh water and increasing salinity (Abdelraouf et al., 2020). The saline and arid environment allows the growers to depend on saline water, which can add to the risk of increasing soil salinity resulting from either a limited water supply or both factors. When crops are subjected to varying sequences of environmental constraints, the area is flabbergasted that the crops are growing poorly; hence the overall yield is negatively impacted due to the impediments to physiological processes in the plant caused by the uptake of water by the roots, photosynthesis, and availability of nutrients (El-Fattah et al., 2019; Zhang et al., 2022). Salinity, water deficit, and/or combinations of the two cause osmotic stress that

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reduces the availability of water to the root zone (Furrok et al., 2020; Khan et al., 2020). The physiological impairments from the sequence of environmental constraints must lead to lower crop evapotranspiration (ETc) measured in mm, water use efficiency (WUE), and eventually root quality (Mahmoud et al., 2021b). Salinity can not only cause physiological drought, salinity, and osmotic stress, which would increase the overall energy and possible output "costs" along with subsequently causing even lower IWUE and agricultural crop productivity (Salem et al., 2019; Zhang et al., 2022). The result would be excessive water losses and a less-than-ideal crop (Zhang et al., 2021). The indicators for quantifying the seriousness of these effects are yield response factor (Ky), water stress coefficient (Ks), and adjusted crop evapotranspiration (ETc adj). Research shows, for example, that Ks declines sharply in high salinity, which adds to previous effects and would suggest Ks below 0.75 and likely lower than 0.5 at salinity above 8.0 dS/m for periods of combined drought stress at critical growth stages (El-Sayed et al., 2019; Mahmoud et al., 2021b). Ky follows similar trends and was reported to remain greater than 1.0 in saline and low water-stressed conditions, given that yield losses occur at the same ETc level for all restricted treatments. The Ky we measured with Ibrahim et al. (2019), for example, would have exceeded 1.0 during the root bulking stage, highlighting how sensitive the sugar beet crop was to water stress during this critical period of root growth. Mahmoud et al. (2021a) and El-Sayed et al. (2020) also recorded elevated Ky under salinity and water deficit, but serve as a good confirmation of these patterns. Since effective water management is critical to mitigate the influences of salinity and salutary drought, regulated deficit irrigation (RDI) applied during a crop less sensitive to stress will certainly maximize WUE without dramatically compromising yield if appropriate (Hassan et al., 2020; Ali and Mohamed, 2017). Harnessing drip irrigation systems, including surface drip irrigation (SDI) has been shown to improve Ks values, and mitigate stress by enhancing water application frequency at low volume to increase root-zone moisture and restrict saline accumulation (Fathy et al., 2018). Surface drip irrigation (SDI) and subsurface drip irrigation (SSDI) are both effective systems for growing sugar beets, especially in dry and saline conditions. The average irrigation efficiency (Ea) for SDI is 85–90 %, whereas SSDI is higher than 90% to 98% due to decreased evaporative loss as the water is delivered more directly to the crop with less water movement horizontally across the surface. For water use efficiency (WUE), SSDI outperforms SDI because SSDI maintains a drier, consistent moisture regime in the root zone, while minimizing other non-productive water losses (Omar and Salem, 2021). Both of these systems also rely heavily on stress coefficients. Generally, the water stress coefficient (Ks) should be higher for SSDI because the range of moisture in the soil is reduced, which supports continual plant growth. The salinity stress is also reduced better with SSDI because the salinity is washed downward away from the root zone. The yield response factor (Ky) is essential for sugar beet, as it reflects the ability of that crop to respond to water deficit. Under SSDI, Ky tends to be less than SDI, indicating an improved stress-buffering and more efficient water use (Ali et al., 2018; Zhao et al., 2021). Both SDI and SSDI produced some enhancement of sugar beet root diameter and sucrose content, in agreement with previous studies of sugar beet irrigation performance, but SSDI produced enhanced juice purity and total soluble solids (TSS) (El-Metwally et al., 2019). Sugar beet is reported to be one of the most sensitive crops to water deficit, and the impacts of scheduled water and salinity stress are most potent when experienced during critical stages of the crop development cycle (Ahmed and Ali, 2021). As previously recommended, it is essential to schedule irrigation effectively based on well-calibrated Kc, Ks and Ky values to produce the highest yield and quality (Omar et al., 2018). The principle of adopting both adaptive irrigation and the use of stress-resilient sugar beet cultivars is increasingly important in order to sustain quality performance from the crop under light or moderate water and salinity stress.

In this context, this research aims to evaluate the combined effects of water and salinity stresses on sugar beet marketable yield and root quality and to compare differences in evapotranspiration ($ET_{c\,adj}$), water use efficiency (WUE), irrigation water use efficiency (IWUE), yield response factor (Ky), and coefficient of water and salinity stresses (Ks) to surface and subsurface drip irrigated sandy soils. This comparison helps to identify best practices for improving sugar beet production and broader production resource efficiency within arid and saline agricultural conditions in Egypt.

2. Materials and methods

2.1. Experimental

Field experiments were carried out in the winter seasons of 2022/2023 and 2023/2024 at a privately owned farm (30° 23′ 37″ N, 30° 19′ 41″ E, 21 m b. s. l.) located 100 km southwest of Alexandria, in the Wadi El Natrun region of El-Beheira Governorate, Egypt. Three replicates were used in a split-split plot design for the experiments. The experimental area was divided into 50 m^2 plots to halt horizontal infiltration of water, with a bare 2 m strip between plots. As shown in Figure 1, sugar beet (*Sultan Beta vulgaris L.*) was irrigated using three different irrigation water stress levels (IRs 100%, 80% and 60% of crop evapotranspiration) and three different salinity stress levels of irrigation water (SWL) (S1 = 2.19, S2 = 4.38, and S3 = 6.57 dS m^{-1}), which represent a realistic salinity gradient observed in the Wadi El-

Natrun region. These levels simulate low, moderate, and high salinity stress typically found in local groundwater and drainage sources encountered during irrigation in sandy reclaimed soils under two irrigation systems: surface drip irrigation (SDI) and sub-surface drip irrigation (SSDI). Quality traits were evaluated for the winter sugar beet crop, such as marketable yield (MY) (t ha^{-1}), sucrose (S) (%), purity (P) (%), impurities (I) (%), fresh weight (FW) (kg $plant^{-1}$), length (L) (cm $plant^{-1}$), and diameter (D) (cm $plant^{-1}$). Yield and salinity stress indicators were also calculated for the winter sugar beet crop. Yield response factor (Ky), water use efficiency (WUE) (kg m^{-3}), irrigation water use efficiency (IWUE) (kg m^{-3}), adjusted crop evapotranspiration (ETc_{adj}) (mm), and overall water and salinity stress coefficient (Ks_{total}) characteristics were determined from winter sugar beet crop treatments and also included in all treatments for surface drip (SDI) and sub-surface drip irrigation (SSDI) related to salinity and irrigation water levels.

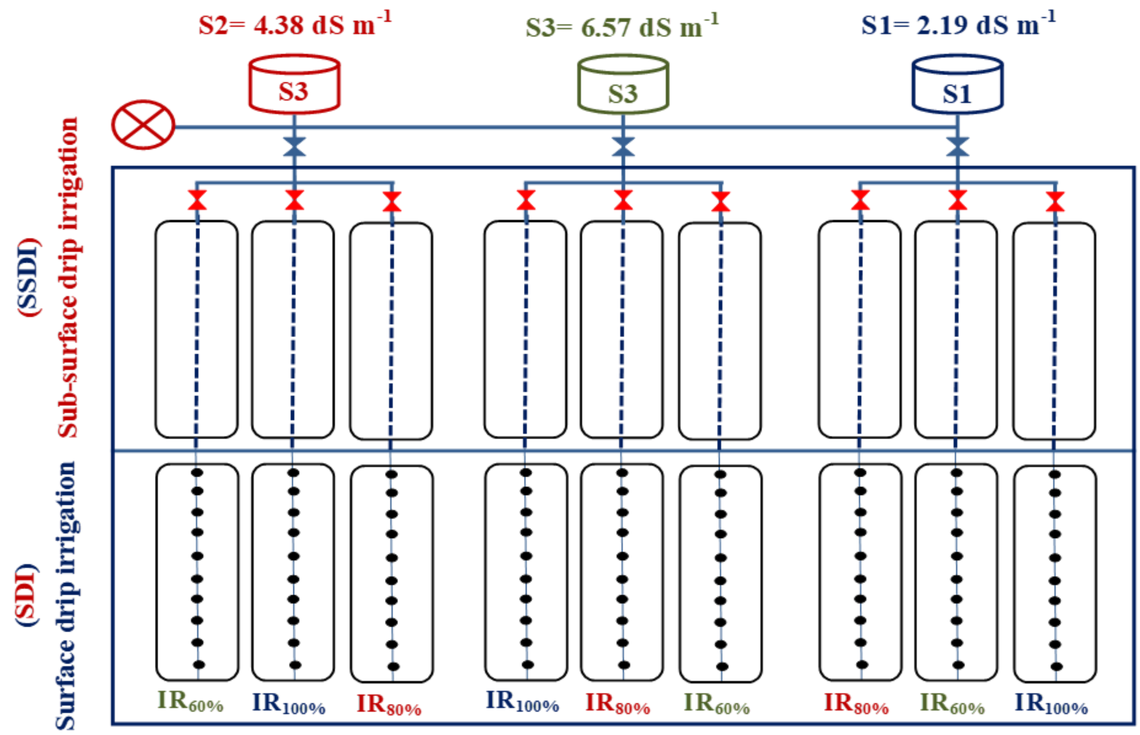


Fig. 1. Field experiment layout in Wadi El Natron, Behera Governorate.

2.2. Soil characteristics

Soil samples intended for planting were collected to determine the physical and chemical properties of the soil. The methods adhered to the protocol established by Page et al. (1982); Klute (1986) (Tables 1 and 2).

2.3. Preparation of irrigation water salinity levels

To create the saline water, well water (S1 = 2.19 dS m^{-1}) was combined with well water (S3 = 6.57 dS m^{-1}), which was determined using the equation (Ayers and Westcot, 1994):

$$EC_w\ (dS\ m^{-1})\text{of mix} = [S_1 (dS\ m^{-1})\ X\ \text{ratio used 1}] + [S_3 (dS\ m^{-1})\ X\ \text{ratio used 2}] \quad \ldots [1]$$

$$S_2 = (2.19 \times 0.50) + (6.57 \times 0.50) = 4.38\ dS\ m^{-1}$$

2.4. Quality of irrigation water

As illustrated in Table 3, the methods summarized by Ayers **and** Westcot (1994) were used to analyze the chemical makeup of irrigation water.

2.5. Reference evapotranspiration ETo

The reference evapotranspiration (ETo) displayed in Table 4 was estimated using the CropWat 8 program, utilizing the FAO 56 method and the Penman-Monteith equation (Allen et al., 1998).

2.6. Crop evapotranspiration

The crop evapotranspiration (ETc) (without stress) revealed in Table 5 was estimated using the formula below (Allen et al., 1998):

$$ETc = Kc_{FAO} \times ET_O \quad \ldots [2]$$

where:

ET_C: crop evapotranspiration (mm day^{-1}),
Kc_{FAO}: FAO No. 56 crop coefficient., and
ETo: Reference crop evapotranspiration (mm day^{-1}).

Table 1

Some of the experimental soil's physical attributes.

Soil depth cm	Particle size distribution %					Textural class	OM %	ρ_b g cm^{-3}	Ks cm h^{-1}	FC %	WP %	AW %
	C. sand	M. sand	F. sand	Silt	Clay							
0-20	5.41	19.52	66.63	5.08	3.36	S	0.43	1.58	12.45	17.59	5.23	12.36
20-40	5.18	18.75	65.91	5.42	4.74	S	0.41	1.56	13.28	18.62	5.47	13.15
40-60	4.86	18.19	65.75	5.67	5.53	S	0.39	1.54	13.62	19.27	5.69	13.58

Table 2

A few of the experimental soil chemical properties.

Soil depth cm	EC dS m^{-1}	pH	$CaCO_3$ %	CEC cmole kg^{-1}	Soluble ions (meq/l) in saturated soil paste extract							
					Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	CO_3^{--}	SO_4^{--}
0-20	7.63	7.97	16.45	7.71	45.76	4.15	27.52	8.87	37.89	8.74	-	39.67
20-40	7.86	7.79	15.21	7.74	46.92	4.39	28.17	9.12	38.54	9.17	-	40.89
40-60	7.98	7.65	14.83	7.8	47.19	4.52	28.75	9.34	39.17	9.39	-	41.24

Table 3

Some chemical analysis of water used for irrigation.

Sample	pH	EC dS m^{-1}	SAR	Soluble cations, meq l^{-1}				Soluble anions, meq l^{-1}			
				Na^+	K^+	Ca^{++}	Mg^{++}	CL^-	HCO_3^-	$CO_3^=$	$SO_4^=$
S1	7.63	2.19	4.29	9.81	1.64	5.86	4.59	10.91	4.46	-	6.53
S2	7.91	4.38	6.07	18.75	5.98	10.21	8.86	21.83	8.91	-	13.06
S3	8.17	6.57	7.94	29.18	9.52	13.73	13.27	32.25	13.37	-	20.08

Table 4

Determine the reference evapotranspiration, measured in mm day^{-1}, during Wadi El-Natrun's winter sugar beet growth season.

Seasons	Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr
2022/2023	ETo	4.81	3.63	2.95	2.78	3.96	4.74	5.89
2023/2024	mm day^{-1}	4.86	3.69	2.98	2.85	4.01	4.79	5.94

Table 5

Crop evapotranspiration, measured in mm day^{-1}, during the winter sugar beet development.

Planting date	21/10 to 19/11	20/11 to 18/1	19/1 to 19/3	20/3 to 18/4	21/10 to 18/4
Period length (day)	30	60	60	30	180
K_{CFAO} (-)	0.35	0.78	1.20	0.70	--------
Season 2022/2023					
ETo (mm)	121.88	181.42	237.08	162.9	703.28
$ET_{c100\%}$ (mm)	42.66	141.51	284.50	114.03	582.70
Eff. Rainfall (mm)	6	9	18	4	37
Season 2023/2024					
ETo (mm)	123.57	184.27	240.34	164.40	712.58
$ET_{c100\%}$ (mm)	43.25	143.73	288.41	115.08	590.47
Eff. Rainfall (mm)	5	8	16	3	32

2.7. Applied irrigation water (IRs)

The irrigation water stress levels (IRS) involved in the winter sugar beet crop as indicated in Table 6, were determined by employing the subsequent equation Keller and Karmeli, 1974):

$$IRs_{100,80,60\,\%} = (ETc - pe)(Kr/Ea) + LR \quad ... [3]$$

where:

$IRs_{100\,\%}$: Seasonal applied irrigation water (mm period^{-1}),

ETc: Crop evapotranspiration, mm period^{-1} (Table 5)

Pe: Adequate rainfall, mm season^{-1} (Table 5),

Kr: The adjustment factor for limited wetness for sugar beets with canopy 80% round coverage is Kr = 0.90 (Smith 1992),

Ea: 85% of surface drip irrigation and 95% of subsurface drip irrigation are efficient (Allen et al., 1998), and

LR: Leaching needs, at irrigation water salinity levels of 0.06, 0.13, and 0.20 x ETc), mm.

Table 6

Water stress levels of irrigation water (IRs), measured in mm during the winter growing cycle of sugar beets during the 2022–2023 season.

IS	SWL (dS m^{-1})	IRs (%)	Water stress levels of irrigation water, mm				
			Growth Stages				
			Initial	Development	Mid	Late	Seasonal
SDI	S1	100	41.35	148.70	299.05	123.27	612.37
		80	33.08	118.96	239.24	98.62	489.90
		60	24.81	89.22	179.43	73.96	367.42
	S2	100	44.20	158.15	318.06	130.89	651.30
		80	35.36	126.52	254.45	104.71	521.04
		60	26.52	94.89	190.84	78.53	390.78
	S3	100	47.43	168.88	339.63	139.53	695.47
		80	37.94	135.10	271.70	111.62	556.36
		60	28.46	101.33	203.78	83.72	417.29
SSDI	S1	100	37.26	133.93	269.35	111.00	551.54
		80	29.81	107.14	215.48	88.80	441.23
		60	22.36	80.36	161.61	66.60	330.93
	S2	100	40.11	143.38	288.36	118.62	590.47
		80	32.09	114.70	230.69	94.90	472.38
		60	24.07	86.03	173.02	71.17	354.29
	S3	100	43.34	154.11	309.93	127.27	634.65
		80	34.67	123.29	247.94	101.82	507.72
		60	26.00	92.47	185.96	76.36	380.79

S1 =2.19 dS m^{-1} S2= 4.38 dS m^{-1} S3= 6.57 dS m^{-}

2.8. Adjusted (actual) crop evapotranspiration

The adjusted crop evapotranspiration ETc_{adj} under water (or salinity) stress conditions was calculated using the formula below (Allen et al., 1998):

$$ET_{adj} = ETc \times Ks_{\,total} \quad ... [4]$$

where:

$K_{s\,total}$: Total water and salinity stresses coefficient was determined using the following equation (Allen et al., 1998):

$$Ks_{total} = \left[1 - \frac{b}{Ky \times 100}(ECe - ECe_{thrshold})\right] \times \left[\frac{TAW - Dr}{TAW - RAW}\right](-) \quad ... [5]$$

where:

b: Reduction in yield per increase in ECe; for sugar beet b= 5.9 % / dS m^{-1}, table 23 FAO56

ECe: Mean electrical conductivity of the saturation extract for the root zone, dS m^{-1}

$ECe_{threshold}$: Electrical conductivity of the saturation extract at the threshold of ECe when crop yield first reduces below Ym; for sugar beet $Ece_{threshold}$ = 7 dS m^{-1}, Table 23 FAO56

Ky: Yield response factor; for sugar beet Ky= 1, table 24 FAO56

TAW: Total available soil water in the root zone, mm.

Dr: Root zone depletion, mm

RAW: Readily available water, mm

Total available water was determined using the following equation (Allen et al., 1998):

$$TAW = 1000\ (\theta_{FC} - \theta_{PWP}) \times Z_r \quad \dots [6]$$

where:

θ_{FC}: The water content at field capacity, %
θ_{PWP}: The water content at wilting point, %
Z_r: Rooting depth, m.

Readily available water was determined using the following equation (Allen et al., 1998):

$$RAW = TAW \times P \quad \dots [7]$$

where:

P: fraction of TAW that a crop can extract from the root zone without suffering water stress (-); for sugar beet p= 0.55, Table 22 FAO56.

If Dr ≤ RAW, there is no water stress, and Ks water = 1, meaning the plant can access water easily.

If Dr > RAW, water stress begins, and Ks water gradually decreases.

If Dr = TAW, then Ks water = 0, indicating severe water stress for the plant.

2.9. Water use efficiency (*WUE*) and irrigation water use efficiency (*IWUE*)

WUE and IWUE were determined by the equations [8] and [9] (Howell et al., 2001, Michael, 1978):

$$WUE = \frac{MY}{ETc_{adj}} \quad \dots [8]$$

$$IWUE = \frac{MY}{IR} \quad \dots [9]$$

where:

WUE and IWUE: Water use efficiency and irrigation water use efficiency ($kg\ m^{-3}$),
MY: Marketable sugar beet crop yield ($t\ ha^{-1}$) and
IR: Seasonal applied irrigation water, m^3, (Tables 6 and 7).

Table 7

Water stress levels of irrigation water (IRs), measured in mm during the winter growing cycle of sugar beets during the 2023–2024 season.

IS	SWL ($dS\ m^{-1}$)	IRs (%)	Water stress levels of irrigation water, mm				
			Growth Stages				
			Initial	Development	Mid	Late	Seasonal
SDI	S1	100	43.07	152.24	305.54	125.50	626.35
		80	34.46	121.79	244.43	100.40	501.08
		60	25.84	91.34	183.32	75.30	375.80
	S2	100	45.96	161.85	324.82	133.19	665.82
		80	36.77	129.48	259.86	106.55	532.66
		60	27.58	97.11	194.89	79.91	399.49
	S3	100	49.23	172.74	346.68	141.92	710.57
		80	39.38	138.19	277.34	113.54	568.45
		60	29.54	103.64	208.01	85.15	426.34
SSDI	S1	100	38.80	137.11	275.18	113.01	564.10
		80	31.04	109.69	220.14	90.41	451.28
		60	23.28	82.27	165.11	67.81	338.47
	S2	100	41.69	146.72	294.45	120.70	603.56
		80	33.35	117.38	235.56	96.56	482.85
		60	25.01	88.03	176.67	72.42	362.13
	S3	100	44.97	157.62	316.32	129.42	648.33
		80	35.98	126.10	253.06	103.54	518.68
		60	26.98	94.57	189.79	77.65	388.99

S1 =2.19 $dS\ m^{-1}$ S2= 4.38 $dS\ m^{-1}$ S3= 6.57 $dS\ m^{-1}$

2.10. Yield response factor (*Ky*)

The Ky was calculated using equation [10] provided by Allen et al. (1998).

$$\left(1 - \frac{Ym}{Ya}\right) = Ky \times \left(1 - \frac{ET - ETc_{adj}}{ETc}\right) \quad (-) \quad \dots [10]$$

where:

Ym: maximum expected crop yield when ECe < $ECe_{threshold}$, $t\ h^{-1}$,
Ky: Factor for yield response,
ETc_{adj}: Adjusted crop evapotranspiration (without stress), mm $season^{-1}$ and
Ya: actual crop yield, $t\ h^{-1}$

3. Results and discussions

3.1. Effect of SWL and IRs on quality parameters for sugar beet roots under SDI and SSDI irrigation systems

The data illustrated in Tables 8 and 9 present that the quality parameters of sugar beet roots length (L) cm plant^{-1}, diameter (D) cm plant^{-1}, fresh weight (FW) kg plant^{-1} purity (P%) and sucrose content (S%) decreased as irrigation water stress levels (IRs) and salinity levels of irrigation water (SWL) increased across all treatments. At the same time, impurities (I%) exhibited an increasing trend with higher IRs and SWL under both surface drip irrigation (SDI) and sub-surface drip irrigation (SSDI) systems. Notably, the SSDI system had a more apparent effect on all treatments than the SDI system. A consistent pattern was observed during the 2022–2023 and 2023–2024 growing seasons. The highest values of L, D, FW, P and S were recorded under full irrigation (IRs 100%) with the lowest salinity level (S1 = 2.19 dS m^{-1}) using the SSDI system, reaching 39.87 cm, 14.87 cm, 0.89 kg plant^{-1}, 92.83% and 18.85% respectively, in the first season, and 39.15 cm, 14.59 cm, 0.86 kg plant^{-1}, 92.41% and 18.38% respectively, in the second season. The highest stress conditions (IRs 60%, S3 = 6.57 dS m^{-1}) with the SDI system, gave the lowest values were 12.72 cm, 5.76 cm, 0.45 kg plant^{-1}, 58.76% and 9.68%, respectively, in the first season, and 11.31 cm, 5.61 cm, 0.43 kg plant^{-1}, 58.09% and 9.46% respectively, in the second season. On the other hand, the highest I values were recorded under IRs 60% and S3 = 6.57 dS m^{-1} using the SDI system, reaching 6.79% and 6.83% for both seasons, respectively. Meanwhile, the lowest values of these parameters were observed under full irrigation (IRs 100%) with the lowest salinity level (S1 = 2.19 dS m^{-1}) using the SSDI system, with I value of 1.46% and 1.51% for both seasons respectively. Sugar beet root quality traits (L, D, FW, P%, and S%) gradually declined with increasing irrigation deficit (IRs) and salinity levels (SWL). The decrease in quality was caused by osmotic stress and ion toxicity limits to water uptake, nutrient uptake, and physiological functions (photosynthesis and sugar accumulation) (Furrok et al., 2020; Khan et al., 2020; Mahmoud et al., 2021b). Embracing sub-surface drip irrigation (SSDI) had higher significance with adequate moisture levels in the root zone, allowing higher root development and sucrose content due to less salinity accumulation and more nutrient availability compared to surface drip (SDI) (Omar and Salem, 2021; El-Metwally et al., 2019). In contrast, under SDI system at severe water and salinity stress (IRs 60%, S3 = 6.57 dS m^{-1}), had the lowest quality values coupled with the highest impurity levels due to disturbed nutrient balance and salinity toxicity (El-Fattah et al., 2019; Zhang et al., 2022). The study concluded that SSDI with full or moderate irrigation (IRs 80 – 100%) using low saline water (S1) is the most effective way to maintain sugar beet root quality traits in arid and saline environments.

Table 8

Impact of IR and SWL on sugar beet root length, diameter, and fresh weight of sugar beet root grown during the 2022–2023 and 2023–2024 seasons under SDI and SSDI irrigation systems.

IS	SWL (dS m^{-1})	IRs (%)	Root length (cm plant^{-1})		Root diameter (cm plant^{-1})		Root fresh weight (kg plant^{-1})	
			1st	2nd	1st	2nd	1st	2nd
SDI	S1	100	36.06c	35.39c	13.45c	13.19c	0.81b	0.79b
		80	33.89e	33.27e	12.59e	12.35e	0.75d	0.73d
		60	24.32j	23.81j	9.73k	9.53k	0.53g	0.51k
	S2	100	32.45g	31.83g	11.92g	11.69g	0.71e	0.69e
		80	29.73h	29.19h	10.85i	10.64i	0.64g	0.62h
		60	18.87m	18.45m	7.71n	7.55n	0.42j	0.40n
	S3	100	27.31i	26.74i	9.52l	9.32l	0.62h	0.60i
		80	23.95k	23.47k	8.64m	8.46m	0.56i	0.54j
		60	12.72o	11.31n	5.76o	5.61o	0.45l	0.43m
SSDI	S1	100	39.87a	39.15a	14.87a	14.59a	0.89a	0.86a
		80	37.42b	36.73b	13.93b	13.67b	0.82b	0.79b
		60	27.29i	26.69i	11.85g	11.62g	0.69f	0.67f
	S2	100	35.54d	34.87d	13.17d	12.92d	0.78c	0.76c
		80	32.61f	31.98f	12.02f	11.79f	0.70e	0.67f
		60	21.16l	20.67l	9.63k	9.45k	0.57i	0.55j
	S3	100	32.32g	31.72g	11.62h	11.40h	0.68f	0.65g
		80	29.85h	29.31h	10.67j	10.47j	0.61h	0.59i
		60	23.98k	23.49k	7.56n	7.39n	0.49k	0.47l

S1 =2.19 dS m^{-1} S2= 4.38 dS m^{-1} S3= 6.57 dS m^{-1}

Table 9

Impact of IR and SWL on the purity, impurities and sucrose of sugar beet root grown during the 2022–2023and 2023–2024 seasons under SDI and SSDI irrigation systems.

IS	SWL (dS m^{-1})	IRs (%)	Purity (%)		Impurities (%)		Sucrose (%)	
			1st	2nd	1st	2nd	1st	2nd
SDI	S1	100	87.69c	87.35c	2.41c	2.45c	17.17c	16.94c
		80	84.53e	83.97e	2.85e	2.89e	15.59d	15.16d
		60	75.85k	75.23i	3.78j	3.81j	11.86l	11.58l
	S2	100	83.95f	83.71e	2.93e	2.97e	15.31e	15.24e
		80	79.21h	78.56g	3.47h	3.51h	13.23i	12.87i
		60	67.43n	66.54l	5.12m	5.16m	10.59n	10.27n
	S3	100	76.59j	76.07h	4.17k	4.21k	13.64h	13.39h
		80	67.23n	66.52l	5.56o	5.61o	11.41m	11.15m
		60	58.76p	58.09n	6.79p	6.83p	9.68o	9.46o
SSDI	S1	100	92.83a	92.41a	1.46a	1.51a	18.85a	18.38a
		80	89.75b	89.28b	1.97b	2.01b	17.21b	16.75b
		60	78.97i	78.13g	3.31g	3.34g	12.43j	11.94j
	S2	100	86.62d	86.09d	2.65d	2.69d	17.15c	16.67c
		80	82.48g	81.91f	3.09f	3.13f	14.57f	14.16f
		60	73.53l	72.69j	4.27k	4.32k	11.87l	11.49l
	S3	100	79.46h	78.78g	3.67i	3.71i	14.19g	13.76g
		80	71.81m	70.81k	4.84l	4.87l	12.34k	11.82k
		60	62.19o	61.57m	5.45n	5.49n	8.96p	8.79p

S1 =2.19 dS m^{-1} S2= 4.38 dS m^{-1} S3= 6.57 dS m^{-1}

3.2. Effect of SWL and IRs on Ks_{total} for sugar beet roots under SDI and SSDI irrigation systems

Data in Table 10 shows that the total water and salinity stress coefficient (Ks_{total}) varied significantly by irrigation regime and salinity level (SWL) in both SDI and SSDI systems over the four growth stages of sugar beet Initial (I), Development (D), Mid (M), and Late (L). The highest Ks_{total} values 1.00, 1.00, 1.00, 1.00 for both seasons respectively, would all occur under full irrigation (IRs 100%) and low salinity (S1 = 2.19 dS m^{-1}) using the SDI system, indicating minimal stress and optimal crop conditions. In comparison, the lowest values of I , D, M and L were 0.61, 0.48, 0.43, 0.59 in the first season 0.61, 0.48, 0.43, 0.62 in the second season occurred under SSDI at IRs 60% and high salinity (S3 = 6.57 dS m^{-1}), which resulted in compounded water and salinity stress, particularly during the development and mid stages. Ks_{total} values decreased steadily because of higher salinity and less irrigation, especially under the SDI system, which consistently had lower coefficients than SSDI under the same conditions. This trend was even more marked during the developmental and mid-growth stages, which are the most sensitive to moisture and nutrient availability. For instance, Ks_{total} was as low as 0.48 under SSDI during the developmental stage at only IRs 60% and high salinity (S3). During the mid-stage, it further dropped to 0.43 under the same treatment, reinforcing the sensitivity of these stages to the productivity of sugar beets. Interestingly, SSDI also maintained higher Ks_{total} under most treatments compared to the lower irrigation amounts of SDI, suggesting efficient water uptake and less overall salinity within the root zone. This could be because SSDI delivered water more localized and deeper in the soil profile than SDI, which would reduce surface evaporation and alleviate salinity crusting, thereby balancing the moisture again within the root zone (Omar and Salem, 2021; El-Metwally et al., 2019). Also, higher Ks values under SSDI supported previous findings of Fathy et al. (2018); Mahmoud et al. (2021b), who demonstrated that SSDI enhances moisture uniformity while mitigating salinity stress due to osmotic stresses. From a physiological perspective, the decrease in Ks_{total} due to combinations of water-saline stresses is a function of their restriction on root water uptake and transpiration and inhibition of photosynthesis due to ion toxicity and osmotic stress (Zhang et al., 2022; Furrok et al., 2020). The effects of stress are enhanced during the critical growth stage (development and mid) when these stresses result in lower evapotranspiration (ET_{Cadj}) and yield and quality loss. Therefore, it is important to keep Ks_{total} above 0.75 to maintain growth under stress, which could be achieved using SSDI with moderate amounts of irrigation with low to moderate salinity. In conclusion, SSDI at IRs 80–100% under low or moderate salinities maintained Ks_{total} above other trials at each growth stage, which supports SSDI as both a water-efficient and stress-mitigating irrigation approach in saline, arid environments like Wadi El-Natrun.

Table 10

Impact of IR and SWL on the total water and salinity stress coefficient for all sugar beet growth stages during the 2022–2023 and 2023–2024 seasons.

IS	SWL (dS m^{-1})	IRs (%)	Total water and salinity stress coefficient, (-)							
			Growth Stages							
			Initial		Development		Mid		Late	
			1st	2nd	1st	2nd	1st	2nd	1st	2nd
SDI	S1	100	1.00a	1.00a	1.00a	1.00a	1.00a	1.00a	1.00a	1.00a
		80	0.91e	0.92e	0.81f	0.81f	0.77g	0.77g	0.89e	0.90.e
		60	0.78j	0.81i	0.61l	0.61l	0.57m	0.57m	0.72k	0.74k
	S2	100	1.00a	1.00a	1.00a	1.00a	0.98b	0.98b	1.00a	1.00a
		80	0.89f	0.90f	0.79g	0.79g	0.75h	0.75h	0.87f	0.87f
		60	0.76k	0.78k	0.58m	0.60m	0.54n	0.54n	0.69l	0.70l
	S3	100	0.97c	0.97c	0.95b	0.95b	0.94c	0.94c	0.97b	0.98b
		80	0.83h	0.86g	0.76h	0.78h	0.73i	0.73i	0.83g	0.84g
		60	0.72l	0.72l	0.53o	0.56n	0.50o	0.51o	0.67m	0.67m
SSDI	S1	100	0.99b	1.00a	0.92c	0.91c	0.91d	0.90d	0.97b	0.98b
		80	0.86g	0.86g	0.72i	0.74i	0.70j	0.70j	0.82h	0.83h
		60	0.71m	0.72l	0.55n	0.54o	0.50o	0.50p	0.66n	0.65n
	S2	100	0.97c	0.98b	0.90d	0.89d	0.88e	0.87e	0.95c	0.95c
		80	0.83h	0.83h	0.69j	0.69j	0.66k	0.66k	0.79i	0.79i
		60	0.69n	0.70m	0.51p	0.51p	0.47p	0.47q	0.62o	0.62o
	S3	100	0.94d	0.94d	0.84e	0.84e	0.82f	0.82f	0.91d	0.91d
		80	0.79i	0.79j	0.66k	0.66k	0.62l	0.61l	0.75j	0.76j
		60	0.61o	0.61n	0.48q	0.48q	0.43q	0.43r	0.59p	0.62p

S1 =2.19 dS m^{-1} S2= 4.38 dS m^{-1} S3= 6.57 dS m^{-1}

3.3. Effect of SWL and IRs on ETcadj for sugar beet roots under SDI and SSDI irrigation systems

Table 11 and Figs. 2 and 3 present that the adjusted crop evapotranspiration (ET_{cadj}) across different growth stages (initial, development, mid, late) and the overall growing season for sugar beet consistently declined with decreasing irrigation levels (IRs) and increasing salinity levels (SWL) across all treatments. The SSDI irrigation system also demonstrated greater efficiency in regulating irrigation water applications than the SDI system, a trend observed throughout the 2022–2023 and 2023–2024 seasons. The highest ET_{cadj} values recorded in the first season were 42.66, 141.51, 284.50, 114.03, and 582.70 mm across the respective growth stages, while in the second season, they were 43.25, 143.73, 288.41, 115.08, and 590.47 mm. These values corresponded to full irrigation (IRs 100%) and the lowest salinity level (S1 = 2.19 dS m^{-1}) under SDI irrigation treatment. Conversely, the lowest ET_{cadj} values in the first season were 25.95, 67.36, 121.71, 66.71, and 281.73 mm, while in the second season, they were 26.31, 68.99, 123.38, 70.81, and 289.49 mm, recorded under IRs 60%, S3 = 6.57 dS m^{-1}, and SSDI irrigation. These results may stem from the combined effects of water deficit and salinity stress on the primary physiological aspects of sugar beet. Salinity-induced osmotic stress and ion toxicity reduce the availability of water to plant roots, which can limit water establishment during critical physiological processes and, as a result, cause a stop in transpiration and photosynthesis and negatively affect ET_{cadj} (Zhang et al., 2022; Furrok et al., 2020). If salinity is high, it can increase the impacts of water deficit stress when plants are presented with deficit irrigation because the osmotic gradient decreases, reducing stomatal conductance and photosynthetic production. There is also an impact on the irrigation system. SSDI has been shown to allow, with reasonable precision, the placement of water into the crop root zone, decrease surface evaporation from within the SDI method, and reduce salinity accumulation in the root zone (Omar and Salem, 2021; El-Metwally et al.; 2019). Efficiently watering the root zone allows moisture to be available when the plants need it, thereby supporting weak, stressed physiological actions. Sugar beet physiological functions can continue under moderate combined water and salinity stress, provided nutrient and moisture availability are maintained. Alternatively, surface drip irrigation creates a non-uniform soil moisture profile compared to other systems, as well as contributes to evaporative losses, and as a result, stress conferred by salinity is worsened with SDI (Mahmoud et al., 2021b; Fathy et al., 2018). Previous research has also confirmed that the development and mid-growth stages are particularly vulnerable to water and salinity stress, which also explains the larger drops in ET_{cadj} at these points (Ali et al., 2018; El-

Sayed et al., 2019). Under these conditions, lower values of total water and salinity stress parameters reflected a larger physiological toll on the crop and less water use efficiency (Hassan et al., 2020; Mahmoud et al., 2021a). Therefore, integrated water-salinity management, especially SSDI with moderate irrigation and low-moderate salinity, offers an exciting new avenue to maintain plant performance and water productivity under arid and saline field environments.

Table 11

Impact of IR and SWL on adjusted crop evapotranspiration, (mm) for all sugar beet growth stages throughout the 2022–2023 and 2023–2024 seasons.

IS	SWL (dS m^{-1})	IRs (%)	Adjusted crop evapotranspiration, (mm)							
			Growth Stages							
			Initial		Development		Mid		Late	
			1st	2nd	1st	2nd	1st	2nd	1st	2nd
SDI	S1	100	42.66a	43.25a	141.51a	143.73a	284.50a	288.41a	114.03a	115.08a
		80	38.91d	39.79d	114.27f	116.06e	219.61g	222.62g	101.49e	103.57d
		60	33.27h	34.91h	86.41k	88.38j	160.97l	163.18l	82.10j	84.93i
	S2	100	42.66a	43.25a	141.51a	143.73a	277.54b	281.35b	114.03a	115.08a
		80	37.78e	38.73e	112.21f	113.97f	212.29h	215.68h	99.67f	100.52e
		60	32.22i	33.85i	82.02l	85.72j	154.34m	156.46m	78.53k	80.22j
	S3	100	41.56b	42.14b	134.92b	136.88b	267.66c	271.34c	110.61b	112.78b
		80	35.50g	37.37f	108.06g	111.48f	207.40h	210.91h	94.25g	97.12f
		60	30.75j	31.18j	75.15m	80.33k	143.67n	146.75n	76.19l	77.33k
SSDI	S1	100	42.23a	43.25a	130.19c	130.79c	258.90d	259.57d	111.09b	112.55b
		80	36.87f	37.38f	101.89h	106.07g	197.88i	203.17i	93.67g	95.29g
		60	30.46j	31.14j	77.60m	78.00l	142.39n	143.66n	74.71l	75.28l
	S2	100	41.38b	42.24b	126.66d	127.31c	250.67e	251.22e	108.33d	109.53c
		80	35.26g	36.05g	98.24i	99.78h	188.11j	190.70j	89.66h	90.49h
		60	29.35k	30.10k	72.62n	73.19m	132.92o	134.46o	70.24m	71.72m
	S3	100	39.96c	40.48c	119.55e	120.04d	232.44f	235.63f	103.93e	104.88d
		80	33.72h	34.33h	93.57j	95.18i	176.85k	177.14k	85.00i	86.92i
		60	25.95l	26.31l	67.36o	68.99n	121.71p	123.38p	66.71n	70.81m

S1 =2.19 dS m^{-1} S2= 4.38 dS m^{-1} S3= 6.57 dS m^{-1}

3.4. Effect of SWL and IRs on MY for sugar beet roots under SDI and SSDI irrigation systems

Figs. 2 and 3 indicate that the marketable yield (MY) production (t ha^{-1}) of sugar beet roots declines as irrigation levels (IRs) decrease and salinity levels (SWL) increase across all treatments. Additionally, the SSDI irrigation system significantly enhanced MY values compared to the SDI irrigation system under water and salinity stress conditions throughout the 2022/2023 and 2023/2024 seasons. The highest MY values were 54.75 and 54.31 t ha^{-1} in the first and second seasons under full irrigation (IRs 100%), with the lowest salinity level (S1 = 2.19 dS m^{-1}) using the SSDI system. Conversely, the lowest MY values were observed at 16.15 and 15.89 t ha^{-1} in the respective seasons under IRs 60%, S3 = 6.57 dS m^{-1} with the SDI system. These findings may be attributed to the combined physiological effects of salinity stress and water deficit stress on the productivity and growth of sugar beet plants. Salinity causes osmotic pressure and ion toxicity (primarily Na^+ and Cl^- ions). It drastically impacts root zone water availability and root membrane functionality, lowering water availability and nutrient uptake. Reduced uptake of nutrients and water will impact photosynthesis and restrict cell expansion, especially under low irrigation conditions, resulting in limited biomass accumulation and a marketable yield (Furrok et al., 2020; Zhang et al., 2022). Regarding salinity, irrigation deficits are also more problematic because salinity diminishes the soil-plant water potential gradient and worsens drought conditions. As a result, nutrient uptake and water availability are diminished under poor water conditions, and the crops experience greater metabolic disruption, especially during important times of growth like sugar storage and root bulking (El-Fattah et al., 2019; Mahmoud et al., 2021b). The improved yields under SSDI may be attributed to its higher efficiency in delivering water directly to the root zone under stress conditions. SSDI applies water directly to the effective root zone, minimizes evaporative losses and salinity accumulation near the crown area, and provides a better soil moisture profile. These attributes assist in maintaining physiological functions and reducing osmotic stress, even with moderate reductions in water availability (Omar and Salem, 2021; El-Metwally et al., 2019). The findings reiterate the importance of irrigation strategies and salinity management when considering sugar beet yield in arid environments. The ability to apply regulated deficit irrigation using SSDI, particularly under conditions of low to moderate salinity, allows for improvements to water use efficiency while buffering yield loss in saline-prone conditions (Ali and Mohamed, 2017; Fathy et al., 2018; Zhao et al., 2021). Thus, integrating SSDI with regulated deficit irrigation offers a practical strategy to sustain sugar beet productivity under water-saline stress in arid agro-ecosystems.

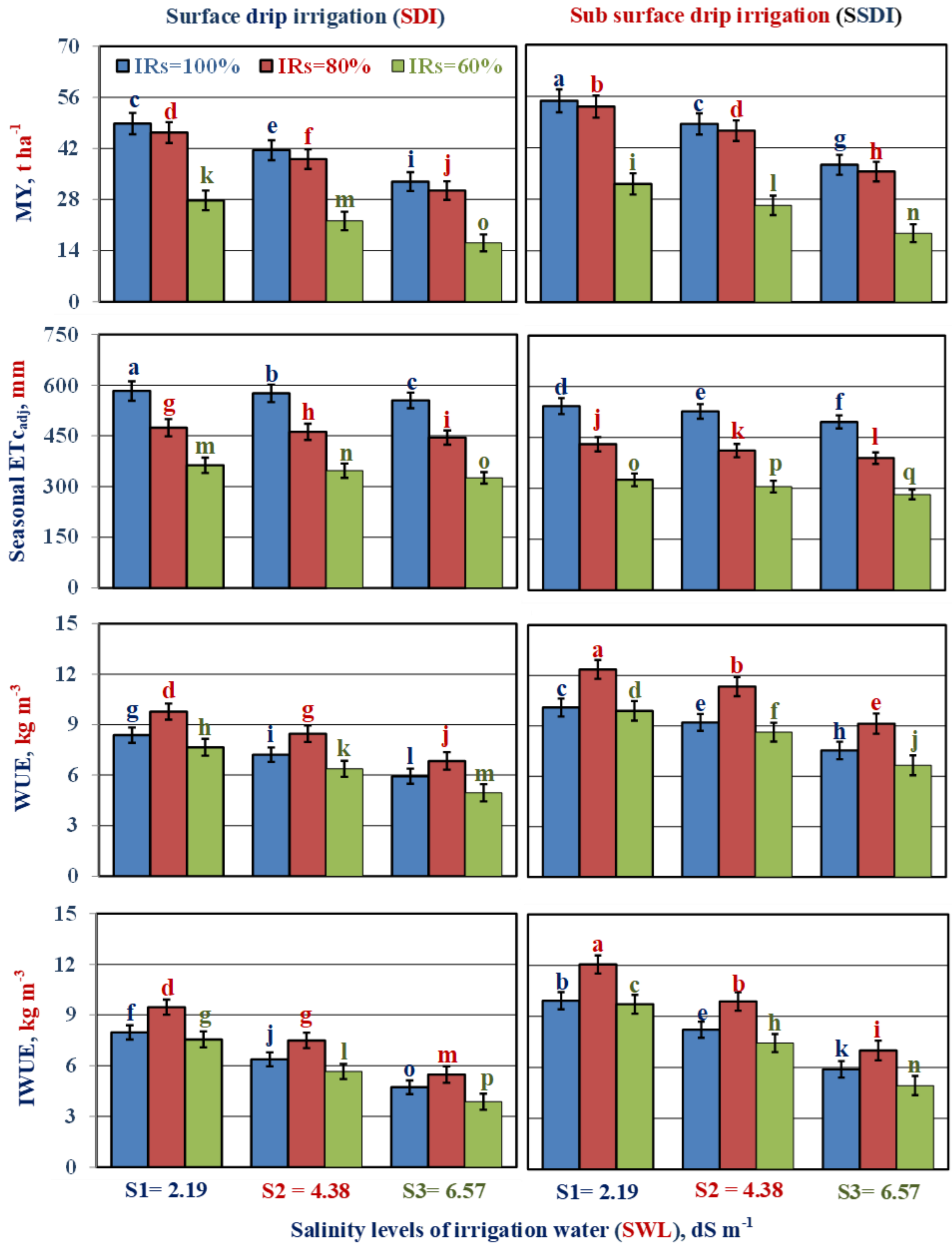


Fig. 2. Impact of salinity levels of irrigation water (SWL) and added irrigation water levels (IRs) on marketable yield (MY) of sugar beet roots, seasonally adjusted evapotranspiration (ETcadj), water use efficiency (WUE), and irrigation water use efficiency (IWUE) under SDI and SSDI irrigation systems for the 2022–2023 seasons.

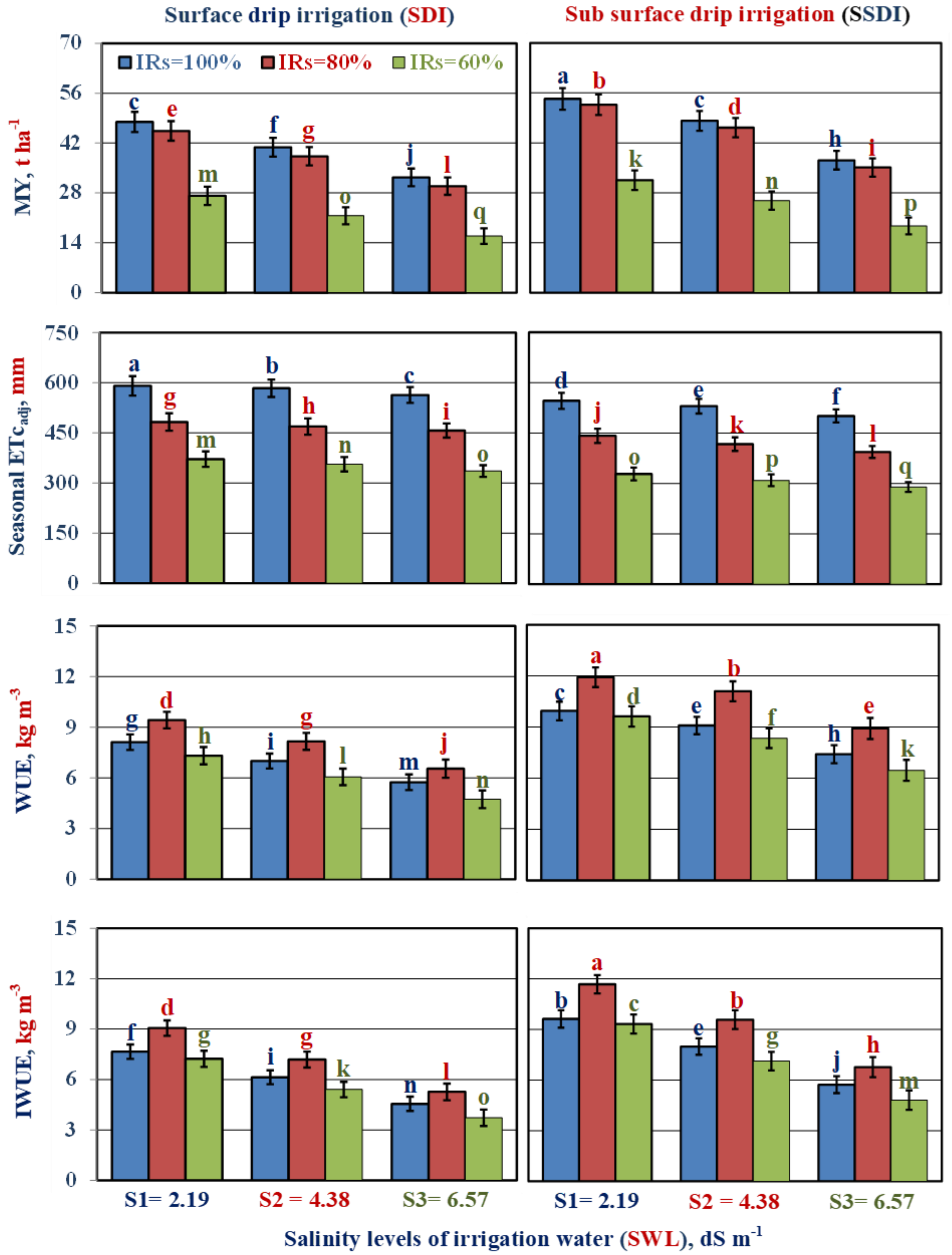


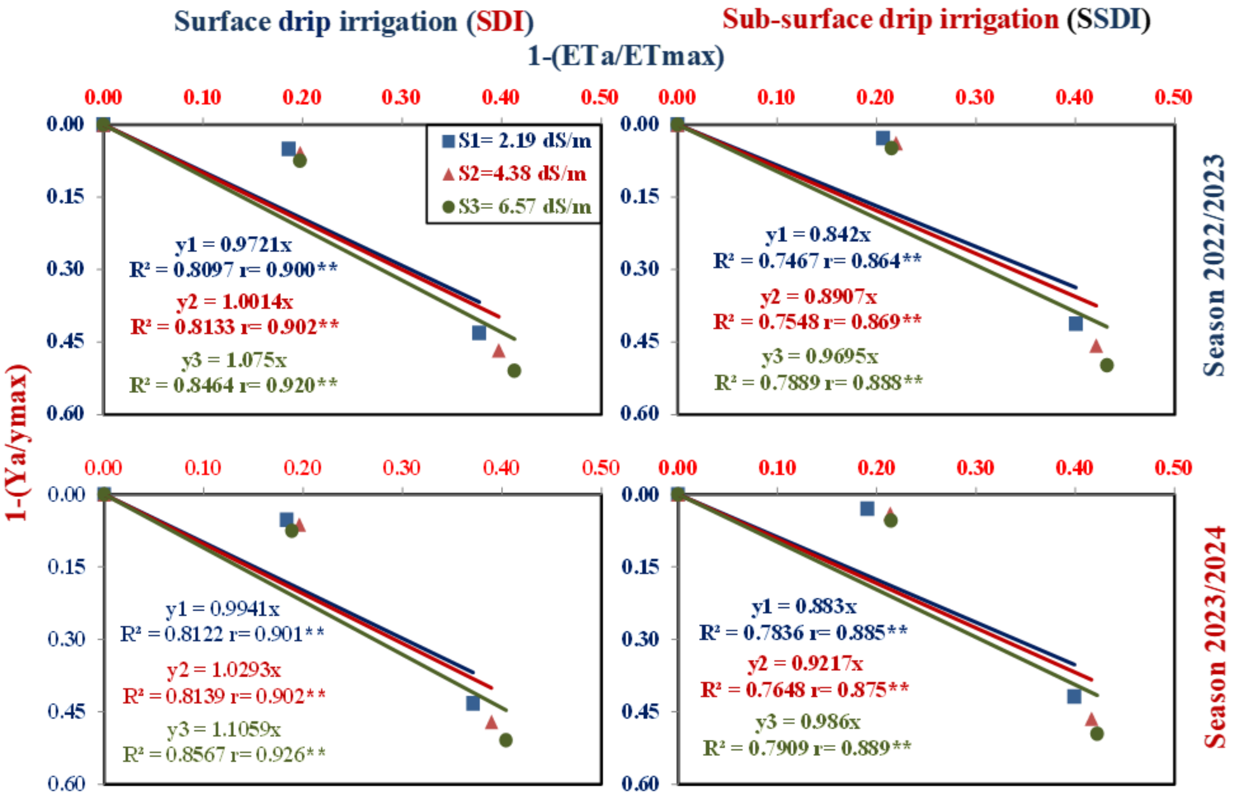
Fig. 3. Impact of salinity levels of irrigation water (SWL) and added irrigation water levels (IRs) on marketable yield (MY) of sugar beet roots, seasonally adjusted evapotranspiration (ETcadj), water use efficiency (WUE), and irrigation water use efficiency (IWUE) under SDI and SSDI irrigation systems for the 2023–2024 seasons.

3.5. Effect of SWL and IRs on WUE and IWUE for sugar beet roots under SDI and SSDI irrigation systems

Figs. 2 and 3 illustrate that the highest values of water use efficiency (WUE) and irrigation water use efficiency (IWUE) for sugar beet roots were observed at 12.36 kg m^{-3} and 12.06 kg m^{-3} in the first season and 11.92 kg m^{-3} and 11.68 kg m^{-3} in the second season respectively, under IRs 80% and low salinity (S1 = 2.19 dS m^{-1}) using the SSDI system. In contrast, the lowest WUE and IWUE values were 4.96 and 3.87 kg m^{-3} in the first season and 4.73 and 3.73 kg m^{-3} in the second season under severe water stress (IRs 60%) and high salinity (S3 = 6.57 dS m^{-1}) using SDI. Notably, under IRs, 80% and S1 with SSDI, WUE, and IWUE increased by 47.60 and 51.27% in the first season and 46.86 and 52.55% in the second season, compared to the conventional treatment (IRs 100%, S1, SDI). These improvements may be attributed to SSDI's enhanced capability to deliver water precisely and uniformly within the crop root zone, reducing non-beneficial water losses such as surface evaporation and deep percolation. This promotes consistent root moisture availability, supporting optimal physiological processes and metabolic efficiency in sugar beet plants (Omar and Salem, 2021; El-Metwally et al., 2019). Under moderate deficit irrigation (80% ETc), sugar beet exhibits a degree of resilience without significant compromise to photosynthesis or stomatal conductance, thereby maintaining higher WUE and IWUE (Mahmoud et al., 2021a). However, under more severe stress (60% ETc) and salinity (S3), plants experience dual stress osmotic and drought, which intensifies physiological disruption, particularly in processes like nutrient uptake, sugar accumulation, and root expansion (Furrok et al., 2020; Zhang et al., 2022). Moreover, salinity reduces water uptake by damaging root membranes through sodium and chloride toxicity, further decreasing yield and water productivity (Khan et al., 2020; El-Fattah et al., 2019). The SSDI system helps counteract these effects by minimizing salinity accumulation near the root zone through deeper, more controlled water delivery (Ali et al., 2018; Zhao et al., 2021). Therefore, integrating SSDI with regulated deficit irrigation, particularly at IRs 80%, represents an effective strategy to optimize WUE and IWUE while sustaining yield and resource efficiency in arid and saline environments. These insights suggest that adopting SSDI at 80% ETc under low salinity can serve as a practical irrigation strategy to improve water savings without compromising yield, which is particularly valuable for farmers in arid regions facing water scarcity.

3.6. Effect of SWL and IRs on Ky for sugar beet roots under SI and SDI irrigation systems

The data presented in Fig. 4 illustrates a linear relationship between the relative reduction in actual evapotranspiration, 1 - (ETa/ETmax), and the relative decline in yield, 1 - (Ya/Ymax), for winter sugar beet roots. This relationship was highly significant during the 2022/2023 season, with crop yield response factor (Ky) values of r = 0.900, 0.902, and 0.920 for salinity levels S1 = 2.19, S2 = 4.38, and S3 = 6.57 dS m^{-1} respectively, under surface drip irrigation (SDI). Similarly, under subsurface drip irrigation (SSDI), Ky values were recorded as r = 0.864, 0.869, and 0.888 for the same salinity levels. Figure 4 also indicates that during the 2023/2024 season, the trend between 1 - (ETa/ETmax) and 1 - (Ya/Ymax) remained consistent under varying water and salinity stress conditions for both SDI and SSDI systems. Furthermore, Fig. 5 shows that Ky values rose when irrigation water stress (IRs) and salinity levels (SWL) increased for all treatments. The SSDI system continuously functioned better than the SDI system, which led to lower Ky values and demonstrated its greater effectiveness in reducing the effects of water stress. The lowest Ky values were 0.14 and 0.16 for the first and second seasons, respectively, under the treatment IRs, 80%, S1 = 2.19 dS m-1 and SSDI. On the other hand, the treatment IRs 60%, S3 = 6.57 dS m-1 under SDI, gave the highest Ky values of 1.57 and 1.59 for the first and second seasons, respectively. These observations may be attributed to the heightened sensitivity of Ky under dual stress conditions, especially in the case of surface drip irrigation (SDI). Ky represents the proportional yield reduction relative to the adjusted seasonal evapotranspiration (ETcadj), and serves as a sensitive indicator of crop vulnerability to water and salinity stress (El-Sayed et al., 2019; Mahmoud et al., 2021b). Regarding SDI, the reduced leaching capacity and heterogeneous moisture distribution likely contributed to salinity accumulation in the root zone, which exacerbated osmotic stress and physiological effects associated with nutrient uptake and photosynthesis (Zhang et al., 2022; El-Fattah et al., 2019). This was likely to have increased Ky values since plants under stress conditions could not mitigate the effect of two sources of stress. In comparison, SSDI had lower values of Ky due to the hydrologic regime of the irrigation system keeping the bulk of the moisture and placing drainage vertically (I.e. facilitating vertical salinity leaching beyond the root zone) while reducing losses of non-productive water (Omar and Salem, 2021; Fathy et al., 2018). The improved irrigation efficiency of SSDI guarantees greater consistency in plants' water uptake and reduced yield loss due to stress, even under reduced irrigation volume. The results align with previous research findings regarding improved stress-buffering using SSDI and water use efficiency where Ky serves not only as an indicator of water deficit but also as a responsive parameter reflecting the interaction between irrigation method and salinity (Ali et al., 2018; Zhao et al., 2021; Ibrahim et al., 2019). Strategic irrigation management aimed at minimizing Ky values under combined stress conditions is therefore essential to ensure sustainable sugar beet productivity in arid and saline environments (Omar et al., 2018; Hassan et al., 2020).



*y1 at S1= 2.19 dS m^{-1} y2 at S2= 4.38 dS m^{-1} y3 at S2= 6.57 dS m^{-1}

Fig. 4. Relationship between adjustments to evapotranspiration stress (ETcadj), mm season^{-1}, and the decline in marketable yield (MY) for sugar beet roots at varying salinity levels of irrigation water (SWL) and irrigation systems (IS) during the seasons 2022/2023–2023/2024.

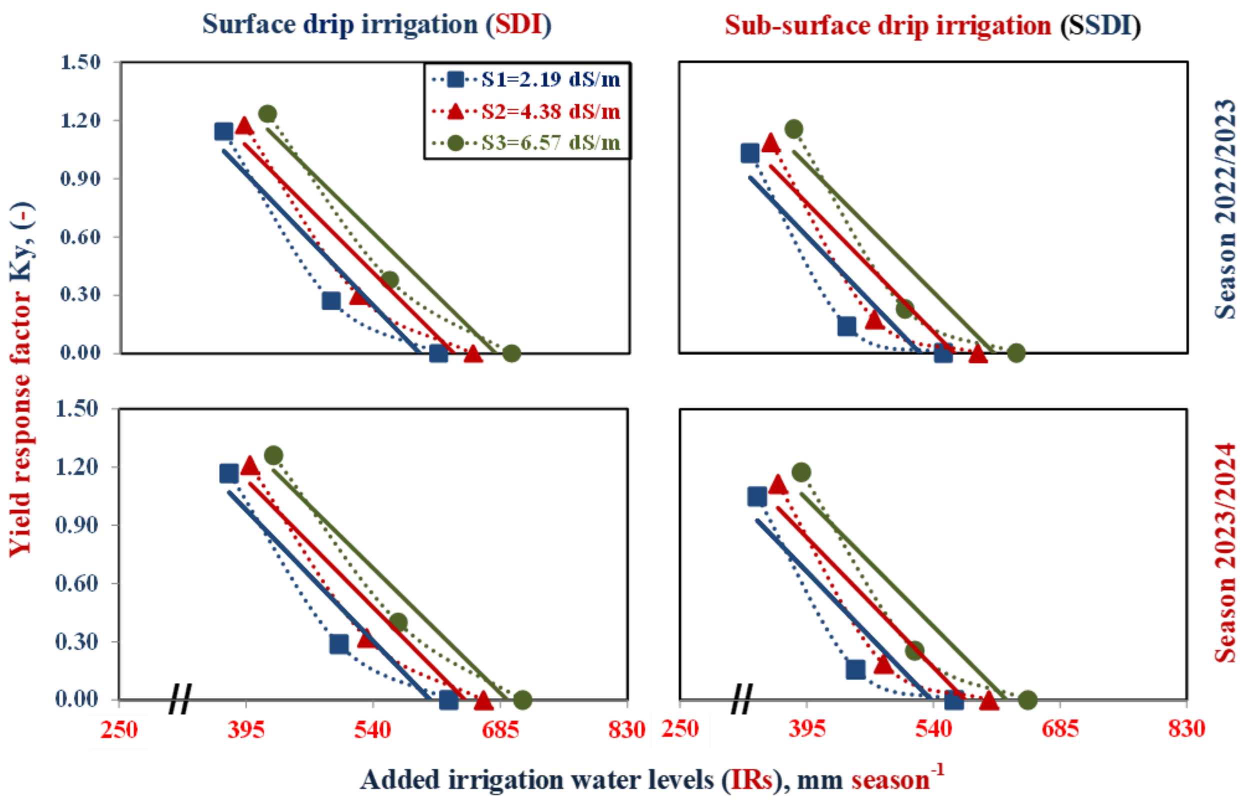


Fig. 5. Impact of varying salinity levels of irrigation water (SWL) and irrigation systems (IS) on sugar beet root yield response factor (Ky) for seasons 2022/2023-2023/2024 at additional irrigation water levels (IRs), mm season^{-1}.

4. Conclusion

This study concluded that the production of sugar beet in the sandy soils and dry conditions of Wadi El-Natrun, Egypt, was impacted by a deficit of irrigation water and salinity stress, both of which impaired crop productivity, root quality and water use efficiency. The most suitable treatment was achieved using a subsurface drip irrigation (SSDI) system with IRs= 80% irrigation level and low salinity water (S1 = 2.19 dS m^{-1}) which produced a 10% increase in marketable sugar beet productivity, 26% less actual water consumption and a 12% improvement in water use efficiency compared to the control treatment (full irrigation IRs = 100% and S1 = 2.19 dS m^{-1} using SDI). The study also showed that, provided low salinity water was unavailable, moderate salinity water (S2 = 4.38 dS m^{-1}) with IRs=80% irrigation level under SSDI gave adequate productivity and water use efficiency. High or very high salinity levels combined with water deficit produced significant yield reductions when using SDI. The results highlight the utility of implementing an irrigation strategy using SSDI at 80% IR value and with low and moderately saline (S1, S2) water resources as a sustainable solution to improve water productivity and salinity management in harsh conditions of arid regions such as Wadi El-Natrun. Moreover, if moderately saline water is used, a reasonable productivity of sugar beet can still be maintained at acceptable quality and salinity levels for sustainable agricultural productivity in limited water resources and high salinity environments.

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تأثير الإجهاد المائي والملحي على إنتاجية وجودة بنجر السكر تحت ظروف وادي النطرون

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الملخص العربي

يعد الإجهادان المائي والملحي من اهم العوامل المؤثرة سلبًا على جودة وإنتاجية المحاصيل، الأمر الذي استدعى تنفيذ هذه التجربة الحقلية لدراسة تأثير كميات مياه الري المضافة تحت مستويات ملوحة مختلفة على جودة وإنتاجية محصول بنجر السكر وكذلك معامل الإجهاد المائي والملحي وكفاءة الاستهلاك المائي والأروائي ومعامل استجابة المحصول لنقص المياه، لتحديد أنسب كمية مياه ري لكل مستوى ملوحة. أجريت هذه التجربة في منطقة وادي النطرون بمحافظة البحيرة – جمهورية مصر العربية وكانت إحداثياتها كالتالي (٣٠° ٢٣´٣٧" شمالا: ٣٠° ١٩´٤١" شرقا) وارتفاع ٢١ متر تحت مستوى سطح البحر. خلال الموسمين (٢٠٢٢/٢٠٢٣ – ٢٠٢٣/٢٠٢٤) أُستخدم تصميم القطع المنشقة مرتين، بثلاث مكررات لكل معاملة وتم ري محصول بنجر السكر باستخدام ثلاث كميات من مياه الري المضافة (١٠٠ , ٨٠ , ٦٠٪) وثلاث مستويات من ملوحة مياه الري المضافة (٢,١٩ , ٤,٣٨ , ٦,٥٧ ديسيسمنز/متر) تحت نظامي الري بالتنقيط السطحي وتحت السطحي.

أظهرت النتائج أن إنتاج الجذور وجودتها (الطول، القطر، الوزن الطازج، النقاء، ونسبة السكروز) انخفضت بشكل ملحوظ ($P < 0.05$) مع زيادة الملوحة ونقص مياه الري، في حين ارتفعت نسبة الشوائب. وحقق نظام الري بالتنقيط التحت سطحي عند الري الكامل ١٠٠٪ بمياه منخفضة الملوحة (٢,١٩ ديسيسمنز/متر) أعلى إنتاجية لمحصول بنجر السكر (٥٤,٧٥ و٥٤,٣١ طن/هكتار) لكلا الموسمين على التوالي. كما حقق نظام الرى بالتنقيط التحت سطحي عند كمية مياه الري المضافة ٨٠٪ أعلى كفاءة للاستهلاك المائي والإروائي لبنجر السكر (١٢,٣٦ و١٢,٠٦كجم/م٣) للموسم الأول (١١,٩٢ و١١,٦٨كجم/م٣) للموسم الثاني ومع أدنى قيم لمعامل استجابة الغلة للإجهاد المائي (٠,١٤ و٠,١٦) لكلا الموسمين على الترتيب مما يدل على كفاءة استخدام نظام الري بالتنقيط السطحي في الحفاظ على الإنتاجية تحت ظروف ملوحة منخفضة وتوفير معتدل في كميات مياه الري المضافة. كما أثبتت الدراسة أن الري بمياه ري متوسطة الملوحة (٤,٣٨ ديسيسمنز/متر) وكمية مياه ري مضافة ٨٠٪ باستخدام نظام الري بالتنقيط تحت السطحي حققت إنتاجية مقبولة وكفاءة جيدة في استخدام المياه مما يجعلها خيارًا مناسبًا في حالة ندرة المياه العذبة. في المقابل أدى أضافة مياه الري مرتفعة الملوحة (٦,٥٧ ديسيسمنز/متر) ونقص الري الحادعند٦٠٪ من مياه الري المضافة عند تطبيق نظام الري بالتنقيط السطحي إلى خسائر كبيرة في المحصول وارتفاع معامل استجابة المحصول مما يعكس ارتفاع حساسية النبات للإجهاد المركب. كما اوضحت النتائج أن ري بنجر السكر بمياه ري منخفضة الملوحة ومستوى عجز مناسب من كميات مياه الري المضافة٨٠٪ وتطبيق نظام الري بالتنقيط تحت السطحي يزيد من انتاجية محصول البنجر القابل للتسويق بحوالى ١٠٪ ويوفر في أستهلاك مياه الري الفعلى بحوالى ٢٦٪ مقارنةً بالري بالمعاملة التقليدية (الري الكامل ١٠٠٪ بمياه منخفضة الملوحة (٢,١٩ ديسيسمنز/متر) تحت نظام الرى بالتنقيط السطحى). ويمثل هذا الأسلوب خيارًا عمليًا ومستدامًا لإدارة الري والملوحة في الأراضي الرملية الجافة مثل وادي النطرون، ويعزز جهود الدولة نحو ترشيد استهلاك مياه الري ومن ثم تحقيق الأمن الغذائي والزراعة المستدامة في الأراضي المستصلحة.

لذا توصي الدراسة باستخدام مياه منخفضة أو معتدلة الملوحة (٢,١٩ أو ٤,٣٨ديسيسمنز/متر) مع مستوى مياه ري مضافة ٨٠٪، وتطبيق نظام الري بالتنقيط تحت السطحي واستخدامها كاستراتيجية مثلى لإنتاج بنجر السكر بشكل مستدام في البيئات الجافة والمالحة دعمًا لسياسات الإدارة المتكاملة للمياه وتحقيق الاستدامة الزراعية.