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Optimisation of irrigation strategy in sugar beet farming based on yield, quality and water productivity

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Abstract: Present experiments were conducted to determine the effects of different irrigation levels on yield, yield components and quality of drip-irrigated sugar beet under sub-humid conditions. Field experiments were conducted in the 2019 and 2021 growing seasons in the Bursa province of Turkey. Experiments were carried out in completely randomised blocks design with three replications. Irrigations were scheduled based on the replenishment of 100 (S1), 66 (S2), 33 (S3), and 0% (S4) of soil water depletion within the soil profile of 90 cm using 7-day irrigation intervals. In 2019, root yields varied between 29.32 (S4)–86.31 (S1) t/ha and sugar yields between 6.33–13.57 t/ha. In 2021, root yields varied between 26.18 (S4)–74.56 (S1) t/ha and sugar yields between 6.56–12.53 t/ha. Effects of different irrigation levels on investigated parameters were found to be significant ($P < 0.01$). The crop water consumption values were significantly related to root and sugar yields ($P < 0.01$). Based on present findings, S1 treatment was recommended to get the highest root and sugar yields. In case of limited water resources, S2 (33% water shortage) treatment with the highest water productivity and irrigation water productivity values could be recommended to ensure maximum efficiency from the applied irrigation water quantity.

Keywords: deficit irrigation; *Beta vulgaris* L.; crop evapotranspiration; sugar ratio; yield response factor

Sugar is a significant source of nutrients for humans. Sugar cane and sugar beet (*Beta vulgaris* L.) have emerged as the primary sources of sugar production (Rajaeifar et al. 2019). Sugar cane continues to dominate in world sugar supply due to high production levels in tropical regions. Sugar beet, on the other hand, can be characterised as a relatively new crop, which appeared in mild climate zones in the 19th century and became widely used only in the 20th century. In 2020, 88% of world sugar production came from sugar cane and 12% from sugar beet. Europe is the leading sugar beet producer with 62.1%; Asia is the second with 18.3%, America is the third with 13.0%, and Africa is the fourth with 6.6% of world production. Turkey produced 23.1 megatons (Mt) of 252.9 Mt of sugar produced in the world in 2020; this value corresponds to 9% of overall production (FAOSTAT 2021).

Root growth is the most important factor in sugar beet production. Sugar beet root growth is directly affected by irrigation. Especially in arid regions, sugar beet yield is closely related to irrigation water quantities, rainfalls throughout the growing season and irrigation scheduling (Dunham 1993). Excessive irrigations increase sugar beet yields but reduce the quality and sugar ratio (Masri et al. 2015). Since the quality components are important harvest parameters besides the yield in sugar beet production, it is very important to avoid both deficient or excessive irrigations and to optimise the amount of irrigation water. Deficit irrigation strategies are becoming increasingly important for the optimisation of irrigation practices.

Deficit irrigation is described as the irrigation method for plants with less water than is required for optimal growth. Deficit irrigation applications are

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used as an optimal approach against water shortages and yield reductions (Sepaskhah et al. 2006). Sugar beet is well-adapted to deficit irrigation (Kirda 2002). Crop tolerance to water stress due to morphological and physiological characteristics of the root system facilitates this adaptation capacity of sugar beet (Doorenbos and Kassam 1979).

There are several studies conducted in different climate zones and with different cultivars to optimise irrigation water quantities and determine the plant response of sugar beet to water deficits. Sugar beet crop water consumption (ET_c) values throughout a growing season ranged from 900 mm to 1 200 mm (Dunham 1993). Sugar beet yields were reported as between 61.34–90.33 t/ha by Topak et al. (2016), between 65.90–109.20 t/ha by Tarkalson and King (2017), between 46.17–100.21 t/ha, and by Mahmoud et al. (2018) under continental and arid climatic conditions. Increasing sugar ratios were reported with decreasing irrigation water quantities in arid climatic conditions (Li et al. 2019). It was determined that there was a linear relationship between ET_c and sugar beet root yield under semi-arid and arid climatic conditions (Uçan and Gençoğlan 2004, Süheri et al. 2007). In previous studies conducted by Tognetti et al. (2003) in the Mediterranean and Masri et al. (2015) in semi-arid conditions reported that 25% water deficits did not have significant effects on sugar beet yields. The yield response factor (k_y) was identified as 0.95 in semi-arid climatic conditions (Kiziloglu et al. 2006).

There are limited studies about the effects of deficit irrigations on sugar beet yield and quality in sub-humid climate zone. Therefore, this study was conducted to investigate the effects of deficit irrigations on yield, yield components, quality, water productivity (WP) and irrigation water productivity (IWP) values of drip-irrigated sugar beet under sub-humid climate conditions. Present findings are expected to guide sugar beet growers in farming in the other sub-humid climate zones.

MATERIAL AND METHODS

Experimental site. Field studies were carried out during the growing seasons of 2019 and 2021 at the Research and Training Centre of the Faculty of Agriculture, Bursa Uludağ University, located in Bursa province of Turkey (latitude 40°13'33''N, 28°51'34''E; altitude 112 m a.s.l.). Bursa province has a dominant sub-humid climate with a long-term average annual air temperature of 14.6 °C and total precipitation of 708.7 mm. During the growing seasons of 2019 and 2021, mean air temperatures were 22.5 °C and 22.4 °C, relative humidity values were 65.6% and 66.2%, wind speeds (2 m height) were 2.8 m/s and 2 m/s, and total precipitations were 166.2 mm and 120 mm, respectively. Soil characteristics of the experimental site are provided in Table 1. Experimental soils were clay (C) in texture with an effective root depth of 90 cm for sugar beet and a water holding capacity of 163.3 mm. The irrigation water used in the study was classified as C_2S_1.

Experimental details. Sugar beet (*Beta vulgaris* L.) seeds (cv. KWS-Akazia) were sown at 3 cm soil depth with 45 cm row spacing and 20 cm on-row plant spacing on the 1^{st} of May in 2019 and the 3^{rd} of May in 2021. NPK compound fertiliser (15-15-15) (50 kg/ha) was applied to the plots immediately after sowing,

Table 1. Physical and chemical properties of soil layers of the experimental fields

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	Bulk density (g/cm^3)	Field capacity (%)	Permanent wilting point (%)
0–30	24.32	26.18	49.50	C	1.35	38.17	27.07
30–60	23.28	26.22	50.50	C	1.36	40.01	27.03
60–90	21.88	24.62	53.50	C	1.34	43.01	26.75
90–120	21.64	37.86	40.50	C	1.38	40.05	23.18

Soil depth (cm)	EC (dS/m)	pH	degree of saturation (%)	available P (mg/kg)	available K (mg/kg)	organic carbon (%)
0–30	0.45	6.1	101	35.6	184	0.72
30–60	0.45	6.4	109	14.0	144	0.43
60–90	0.79	7.1	110	32.4	156	0.57
90–120	0.64	8.0	101	27.6	100	0.17

EC – electrical conductivity

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and when the plants reached to 15 cm height, 70 kg N/ha additional urea fertiliser was applied. For both years, a total of 55 mm of irrigation water was applied by the sprinkler irrigation method for emergence and germination. Deficit irrigation treatments were initiated on the 26th of June in 2019 and the 23rd of June in 2021.

Experiments were carried out in completely randomised blocks design with 3 replications. Experimental plots were 6 m long and 2.25 m wide (13.5 m^2), with 6 rows per plot. A 2 m distance was provided between the plots and 3 m between the blocks. Four different irrigation treatments were created with different irrigation water levels. Irrigation treatments were determined according to the replenishment of 100% (S1), 67% (S2), 33% (S3) and 0% (S4) of soil water depletion within 90 cm soil profile in 7-day irrigation intervals. The drip irrigation method was used to irrigate the plants. Irrigation water was supplied through 16 mm lateral pipes (polyethylene) with pressure-regulated in-line emitters of 2 L/h under 1 atm pressure. A lateral line was placed in each row, and emitter spacing was 20 cm.

Soil-water-crop relations. Water depletion within the root zone was monitored through regular soil samplings from 0.15, 0.45, and 0.75 m soil depth on a weekly basis and soil water content was checked by gravimetric method.

While the amount of irrigation water required to bring the available moisture to the field capacity was determined, the effective rooting depth of the sugar beet (90 cm) was taken into account and was calculated at 7-day intervals with the use of Eq. 1:

$$I = \frac{(FC - AW)}{100} \times \rho_b \times D \times P \quad (1)$$

where: I – irrigation water depth (mm); FC – field capacity (%); AW – available water in the soil (mm); ρ_b – bulk density (g/cm^3); D – effective rooting depth (mm); P – percentage of the wetted area (44%).

Crop water consumption (ET_c, mm) of different irrigation treatments was calculated at 7-day intervals using the following soil water balance equation (Eq. 2) (Garrity et al. 1982):

$$ET_c = I + P \pm \Delta S - D - R \quad (2)$$

where: I – irrigation water depth (mm); P – rainfall (mm); ΔS – change in soil water storage between different measurements (mm/90 cm) and D – deep percolation (mm); R – runoff (mm). Since irrigation applications were based on the principle of completing the deficient moisture within the root zone to the field capacity and the trial plots were surrounded by earthen embankments, runoff was neglected. Deep percolation was neglected based on soil water content measurements in the 90–120 cm soil profile.

Measurements and water-yield functions. At the end of the cultivation period, sugar beet plants of each plot were harvested by pulling the plant manually. Considering the side effects, two rows of each treatment and 50 cm at the beginning and end of each row were eliminated (harvested plot size = 6.75 m^2). Sugar beet harvest was carried out on the 1st of October for both years. At harvest, cleaned plants were separated into the root and leaves to determine the root and leaf yield. Afterwards, a random sample of 5 plants from each plot was taken to determine the root length (cm) and root diameter (cm). Following the measurements, samples were cut into pieces and oven-dried at 70 °C for 48 h to determine the leaf water content (%) and dry matter ratio (%) (Penuelas et al. 1993). The remaining samples were frozen and sent to the Central Research Institute of Food and Feed Control, Bursa, Turkey. In the laboratory, the sugar ratio was determined by Lane-Eynon method (Rajakylä and Paloposki 1983). Sugar yield was calculated with Eq. 3 according to the determined sugar ratio.

$$SY = RY \times SR \quad (3)$$

where: SY – sugar yield (t/ha); RY – root yield (t/ha); SR – sugar ratio (%).

The Stewart equation (Eq. 4) was used to determine the yield response factor (k_y), representing the relationship between relative yield decrease ($1 - Y_a/Y_m$) and relative ET_c deficit (Stewart et al. 1976, Doorenbos and Kassam 1979).

$$\left(1 - \frac{Y_a}{Y_m}\right) = k_y\left(1 - \frac{ET_a}{ET_m}\right) \quad (4)$$

where: Y_a – actual yield (under deficit irrigation conditions); Y_m – maximum yield (under full irrigation conditions); ET_a – actual seasonal evapotranspiration (under deficit irrigation conditions); ET_m – maximum seasonal evapotranspiration (under full irrigation conditions).

Eqs. 5 and 6 were used to determine the water productivity (WP, kg/m^3) (Bos 1980, Pereira et al. 2012) and irrigation water productivity (IWP, kg/m^3) (Bos 1985, Pereira et al. 2012) of each treatment.

$$WP = \frac{Y}{ET} \quad (5)$$

$$IWP = \frac{Y - Y_0}{I} \quad (6)$$

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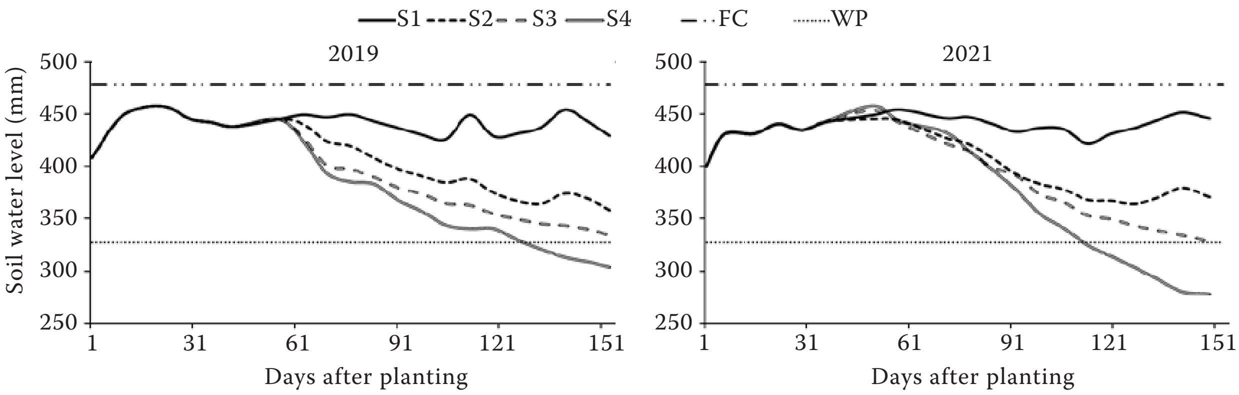

Figure 1. Seasonal changes of soil water level. S1 – 100, S2 – 66, S3 – 33, S4 – 0% of soil water depletion; WP – water productivity; FC – field capacity

where: Y – root yield of the treatment; Y_0 – root yield of non-irrigated treatment (S4); ET – seasonal evapotranspiration by treatment; I – seasonal irrigation water amount by treatment.

Statistical analysis. Variance analysis was conducted at 0.01 and 0.05 probability levels to determine the effects of irrigation treatments on yield, agronomic traits, quality and WP of sugar beet. Significant means were compared with the use of the least significant difference (*LSD*) test at a 0.05 significance level. Regression analysis was conducted to identify the relations among water, yield and quality.

RESULTS AND DISCUSSION

Irrigation water applied and crop water consumption. Figure 1 shows seasonal soil water level fluctuations for both years. The amount of precipitation measured from sowing to harvest was 166.6 mm in the first year and 120.0 mm in the second year. Seasonal ET_c values varied between 326.3–896.9 mm in 2019 and 387.3–830.0 mm in 2021 (Table 2). Köksal et al. (2011) conducted a study under semi-arid climate conditions and reported IRR as between 65–865 mm and seasonal ET_c values as between 338.5–1009.9 mm. Tarkalson et al. (2018) reported IRR of sugar beet in 2011, 2012 and 2016 respectively as 781, 755 and 686 mm and seasonal ET_c values as 879, 767 and 857 mm, respectively. Tarı et al. (2016) reported the IRR of sugar beet as between 279–668 mm and seasonal ET_c values as between 767–821 mm. Present findings on IRR, and ET_c values comply with the results of previous studies.

Yield, yield components and quality. The differences between the irrigation treatments were found to be significant at 0.01 level for all parameters in both years. Root yield values varied between 29.32–86.31 t/ha in 2019 and 26.18–74.56 t/ha in 2021 (Table 3). Decreasing root yields were observed with increasing water deficits. Several studies indicated that different irrigation levels had significant effects on sugar beet root yields (Köksal et al. 2011, Topak et al. 2016). Tognetti et al. (2003) determined the maximum root yield of sugar beet as 78.70 t/ha under full irrigation conditions in Italy. Topak et al. (2011) reported the highest root yield as 77.30 t/ha for full irrigations and the lowest as 28.10 t/ha for 75% water deficits. Present values on root yields comply with the findings of previous studies.

The leaf yields varied between 6.25–11.87 t/ha in 2019 and 4.07–9.50 t/ha in 2021 (Table 3). It was determined that leaf yield of sugar beet was water-stress tolerant, but at higher water stress scenarios, such as 66% water deficit (S3) or non-irrigated (S4),

Table 2. Seasonal irrigation water quantities (IRR) and crop water consumptions (ET_c)

Year	Treatment	IRR	ETc
		(mm)	
2019	S1	750.3	896.9
	S2	545.4	751.2
	S3	340.0	558.7
	S4	135.0	362.3
2021	S1	765.7	830.0
	S2	563.8	705.0
	S3	361.9	547.0
	S4	160.0	387.3

S1 – 100, S2 – 66, S3 – 33, S4 – 0% of soil water depletion

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Table 3. Root and leaf yield, yield components and quality parameters of treatments

Year	Treatment	Root yield (t/ha)	Leaf yield (t/ha)	Root length (cm)	Root diameter (cm)	Leaf water content (%)	Dry matter ratio (%)	Sugar rate (%)	Sugar yield (t/ha)
2019	S1	86.31^{a}	10.45^{a}	24.5^{a}	14.7^{a}	78.0^{a}	26.1^{c}	15.7^{bc}	13.57^{a}
	S2	76.23^{b}	11.87^{a}	23.9^{a}	12.2^{b}	76.9^{a}	27.3^{bc}	15.9^{b}	12.12^{b}
	S3	50.28^{c}	7.86^{b}	21.2^{b}	11.4^{b}	72.4^{b}	29.2^{b}	17.1^{a}	12.04^{b}
	S4	29.33^{d}	6.25^{c}	19.7^{c}	9.4^{c}	65.1^{c}	33.2^{a}	15.2^{c}	6.64^{c}
	$LSD_{0.05}$	7.989	1.642	1.241	1.112	3.193	2.034	0.555	1.384
	F-test	**	**	**	**	**	**	**	**
2021	S1	74.57^{a}	9.50^{a}	25.2^{a}	13.5^{a}	72.2^{a}	30.9^{bc}	16.3^{c}	12.53^{a}
	S2	63.57^{b}	8.92^{a}	22.7^{b}	11.4^{b}	66.4^{ab}	30.3^{c}	16.7^{b}	10.67^{b}
	S3	42.36^{c}	5.05^{b}	21.9^{b}	9.1^{c}	62.7^{b}	33.5^{ab}	18.0^{a}	10.21^{b}
	S4	26.19^{d}	4.07^{b}	20.0^{c}	7.7^{c}	54.2^{c}	36.3^{a}	16.0^{d}	6.56^{c}
	$LSD_{0.05}$	6.766	2.082	0.827	1.786	6.260	2.954	0.274	1.036
	F-test	**	**	**	**	**	**	**	**

Indicate significant differences at $P < 0.05$ using the least significant difference (*LSD*) test. **Significant at 1% probability level ($P < 0.01$); S1 – 100, S2 – 66, S3 – 33, S4 – 0% of soil water depletion

values decreased. In a study with parallel findings, Mahmoud et al. (2018) reported the highest leaf yield value as 7.71 t/ha in 30% deficit irrigations and the lowest value as 1.20 t/ha in the least-irrigated treatment. Maralian et al. (2008) examined the leaf yield of sugar beet under different water-deficit levels. They reported leaf yield values as 25.03–28.96 t/ha, with the greatest yield from 30% water deficits. Differences in leaf yields from the present values were attributed to differences in climate conditions and sugar beet cultivars.

Root lengths of experimental treatments varied between 19.7–24.5 cm in the first year and between 20.0–25.2 cm in the second year (Table 3). Increasing IRR significantly increased the root length of sugar beet. Khozaei et al. (2020) stated that the root length values ranged from 16.43 to 25.69 cm. Hussein et al. (2008) reported that the root length values varied between 16.3–24.0 cm. Özbay and Yıldırım (2019) found higher root lengths in sugar beet and reported the maximum root length as 27.4 cm (full-irrigated) and the minimum as 25.2 (33% water deficit applied).

Both in 2019 and 2021, the greatest root diameters (14.7 cm and 13.5 cm) were obtained from S1 treatments and the lowest values (9.4 cm and 7.7 cm) from S4 treatments (Table 3). Increasing root diameters were seen with increasing IRR. Similar findings were also reported in previous studies (Kiymaz and Ertek 2015, Khozaei et al. 2020). Hussein et al. (2008) reported the variation range of root diameter as 5.20–6.35 cm. Differences in root diameters were mainly attributed to differences in irrigation schedules, climate conditions, sugar beet cultivars and measurement techniques.

Leaf water content values ranged between 54.2% and 78.0% over the study period (2019–2021) (Table 3). In both years, the lowest and highest leaf water content values were reached at non and full-irrigated treatments, respectively. Tsialtas et al. (2011) reported significant effects of different irrigation regimes on leaf water contents.

The highest dry matter ratios (33.2% in 2019 and 36.3% in 2021) were obtained from S4 treatments, while the lowest dry matter ratio was obtained from S1 treatments (26.1%) in 2019 and S2 treatments (30.3%) in 2021 (Table 3). Hussein et al. (2008) reported dry matter ratios of sugar beet as between 27.1–30.4% and indicated increasing values with decreasing IRR. It was indicated in the other studies with different findings that different irrigation regimes did not have significant effects on dry matter ratios of sugar beet (Kiymaz and Ertek 2015), and such a case was attributed to differences in climate, variety and IRR.

Sugar ratios varied between 15.2–17.1% in the first year and 16.0–18.0% in the second year (Table 3). The greatest values were obtained from S3 treatments in both years, followed by S2 treatments, and the lowest values were seen in S4 treatments. Özbay and Yıldırım (2019) reported sugar ratio values varied from 16.66, 16.62 and 18.97%, respectively,

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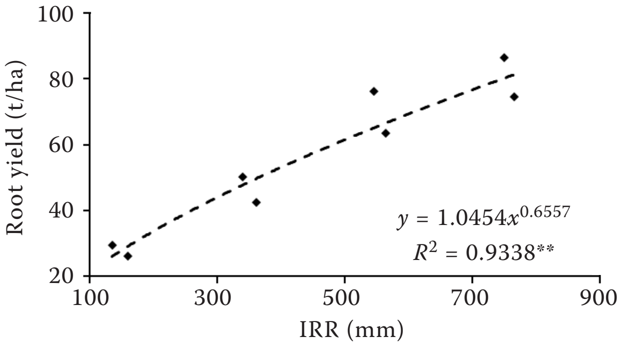


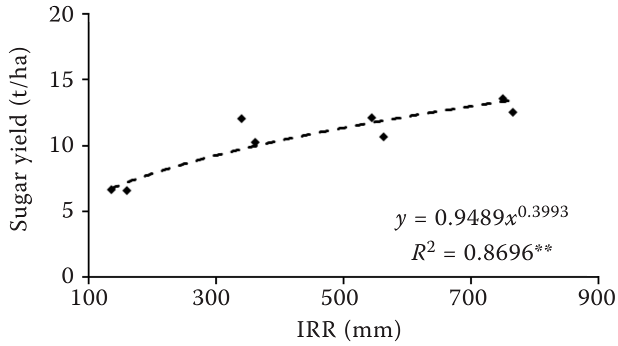


Figure 2. Relationships of root and sugar yields (t/ha) with irrigation water quantity (IRR). **Significant at 1% probability level ($P < 0.01$)

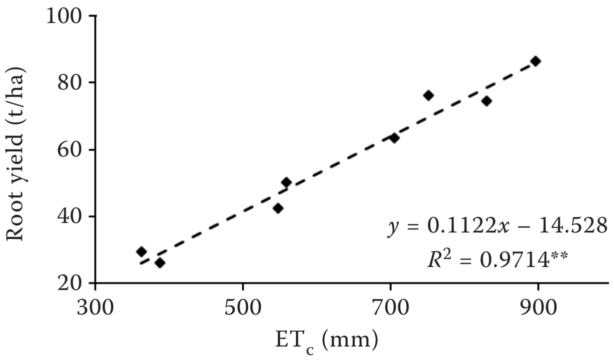
for 100, 66 and 33% irrigation treatments. Li et al. (2019) reported the highest sugar ratios of sugar beet in treatments where irrigations were initiated when 50% of the field capacity was depleted. Masri et al. (2015) found that water deficits did not have any significant effects on the sugar ratio of sugar beet plants irrigated with sprinkler irrigation. Still, the greatest sugar ratio was obtained from the 25% water deficit applied with the drip irrigation system.

Sugar yields varied between 6.33–13.57 t/ha in the first year and between 6.56–12.53 t/ha in the second year (Table 3). In both years, the greatest values were obtained from S1 treatments, and the lowest values were seen in S4 treatments. Irrigation levels had significant effects on sugar yields of sugar beet (Zarski et al. 2020). Mahmoodi et al. (2008) determined the highest sugar yield as 9.54 t/ha under full irrigation conditions and the lowest sugar yield as 7.73 t/ha under heavy water stress conditions. Mahmoud et al. (2018) obtained the highest sugar yield (10.14 t/ha) from 30% water deficits and the lowest sugar yield (8.37 t/ha) from 70% water deficits. Differences in sugar yield values were mainly attributed to differences in irrigation programs.

Water-yield relations. The determination coefficient was identified as $R^2 = 0.93$ ($P < 0.01$) for the exponential relationships between root yield and IRR and as $R^2 = 0.87$ ($P < 0.01$) for the exponential relationships between sugar yield and IRR (Figure 2). Uçan and Gençoğlan (2004) found linear relations between IRR and root yield and indicated the determination coefficients as $R^2 = 0.96$ and $R^2 = 0.96$, respectively, for the first and the second year of study. Tarı et al. (2016) reported that there were polynomial ($R^2 = 0.70$) and linear ($R^2 = 0.89$) relations between IRR and sugar yield.

Significant relationships were encountered between the root yield and ET_c values (linear, $R^2 = 0.97$) ($P < 0.01$) and between sugar yield and ET_c (logarithmic, $R^2 = 0.87$) ($P < 0.01$) (Figure 3). Present linear relations between root yield ET_c were similar to the findings of previous studies (Kiziloglu et al. 2006, Topak et al. 2011). Süheri et al. (2007) and Tarkalson and King (2017) also reported linear relationships between sugar yield, and ET_c.

The yield response factor (k_y) was identified as 1.09 in 2019 and 1.21 in 2021. The k_y value determined using the combined data of 2 years was 1.14



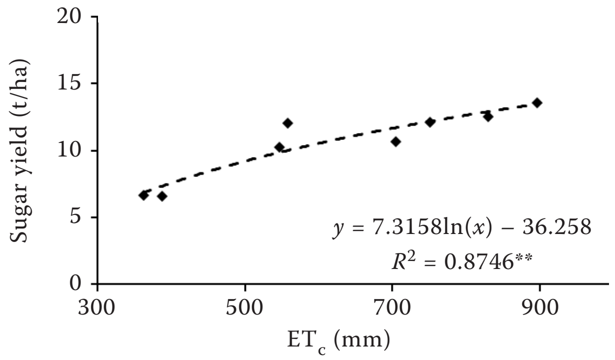


Figure 3. Relationships of root and sugar yields (t/ha) with crop water consumptions (ET_c). **Significant at 1% probability level ($P < 0.01$)

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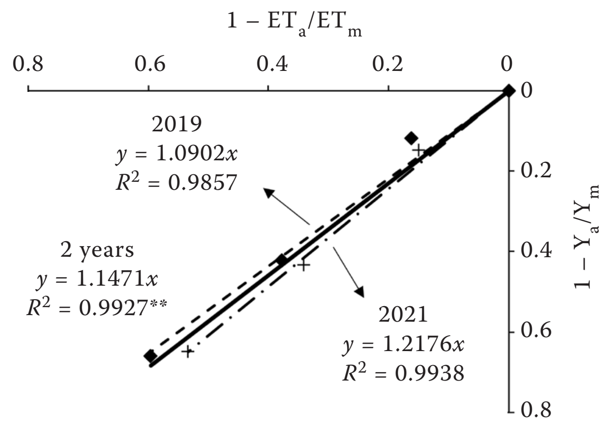

Figure 4. Relationships between relative root yield reduction and relative crop water consumption deficit. ET_a – actual seasonal evapotranspiration; ET_m – maximum seasonal evapotranspiration; Y_a – actual yield; Y_m – maximum yield

(Figure 4). In previous studies, the k_y values of sugar beet were determined as 0.73 and 1.32 by Uçan and Gençoğlan (2004), 0.95 by Kiziloglu et al. (2006), 0.93 by Topak et al. (2011), as 1.0 by Tarkalson et al. (2018) and as 1.1 and 0.8 by Khozaei et al. (2020). The differences in k_y values were mainly attributed to differences in climate characteristics, irrigation regimes and sugar beet cultivars.

Water and irrigation water productivity. Effects of irrigation treatments on WP values were found to be significant at a 0.05 level in both years. WP values varied between 7.45–9.57 kg/m^3 and IWP values varied between 9.04–10.34 kg/m^3 (Table 4). S2 treatments yielded the highest WP and IWP values in both years, although there were no significant differences between S1 and S2 treatments. The greatest WP value is not always found in the treatment with the highest ET_c (Fabeiro et al. 2003). Süheri et al. (2007) reported WP values of sugar beet as between 3.0–10.0 kg/m^3 and IWP values as between 5.9–14.2 kg/m^3. Topak et al. (2011) reported WP values of 7.4–8.3 kg/m^3 and IWP values of 7.9–11.5 kg/m^3 in sugar beet. Topak et al. (2016) reported significant effects of different irrigation treatments on WP values of sugar beet and indicated the greatest WP value for 50% water deficits. The similar range of WP values of sugar beet was reported by Dunham (1993) and Kiziloglu et al. (2006).

Table 4. Water productivity (WP) and irrigation water productivity (IWP) values (kg/m^3) for both years

Treatment	WP		IWP	
	2019	2021	2019	2021
S1	9.62^a	8.98^a	8.67	7.36
S2	10.14^a	9.01^a	11.43	9.26
S3	8.94^{ab}	7.74^{ab}	10.08	8.01
S4	8.09^b	6.76^b	–	–
$LSD_{0.05}$	1.401	1.627		
F-test	*	*		

Indicate significant differences at $P < 0.05$ using the least significant difference (*LSD*) test. *Significant at 5% probability level ($P < 0.05$). S1 – 100, S2 – 66, S3 – 33, S4 – 0% of soil water depletion

For sugar beet cultivation irrigated by drip irrigation method in sub-humid climate conditions, full irrigation (S1) treatment is recommended to get the highest root and sugar yields. In case of limited water resources, S2 treatment (33% water shortage) with the highest WP and IWP values can also be recommended as an irrigation strategy to ensure the maximum efficiency of applied irrigation water quantity.

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