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ORIGINAL ARTICLE

Response of Physiological Activities and Vine Performance of Field Grown ‘Sultan 7’ (*Vitis Vinifera* L.) Variety to Different Water Status in Mediterranean Conditions

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Abstract

This study was carried out to investigate the effects of different irrigation treatments (Ir100, Ir66, Ir33) on physiological activities and vine performance of the field-grown ‘Sultan 7’ variety. Overall, stomatal conductance (*gsw*) and net CO_2 assimilation (A) values were lower in the veraison–harvest than in the fruit set–veraison period regardless of irrigation treatments. In both periods, Ir33 was the most restrictive treatment on gas exchange parameters. However, *gsw* values under all treatments varied in the range of mild stress thresholds (150.39–381.01 mmol m^2 s^1). In this regard, vegetative growth parameters, particularly pruning wood weight and Ravaz index, were not influenced significantly by irrigation regimes, suggesting that *gsw* is a trustworthy parameter to detect the water stress level of vines. Although ‘Sultan 7’ vines reached severe stress levels according to midday leaf water potential (Ψ_{md}) values (between –1.51 and –1.64 MPa) under deficit irrigations, the vines remained at mild stress levels according to *gsw* values. This shows that ‘Sultan 7’ vines might be more resistant to stress conditions because they remained at the mild stress level even under deficit irrigation. Consequently, ‘Sultan 7’ dried grape growing can be achieved without reducing vine performance under deficit irrigation strategies in the experiment and water use efficiency can be increased by saving water.

Keywords Gas exchange · Leaf water potential · Vegetative development · Water stress · Climate change

Introduction

Climate change is one of the greatest challenges in viticulture. Particularly increasing temperatures and changes in precipitation patterns affect grape quality and yield (Van Leeuwen and Darriet 2016). However, these effects vary according to the growing regions, cultivars and production types (table grapes, dried grapes, wine, etc.) (Schultz 2016). Therefore, different varieties and production types should be investigated on a regional scale to reduce the negative impacts of climate change (Van Leeuwen et al. 2019). The Mediterranean basin is affected by adverse effects of climate change because of temperate, semi-arid and arid climatic features (Ferrise et al. 2016). Also, water use in the region is increasing to reduce environmental stress and guarantee higher yield-quality attributes. Therefore, water is recognized as the most vulnerable resource in this region (Dinis et al. 2022). For this purpose, there is a need to develop strategies to eliminate the weaknesses of the Mediterranean basin and to adapt to water scarcity.

Many studies, extensively reviewed by Medrano et al. (2015), focused on improving water use efficiency (WUE) in vineyards with different strategies, particularly deficit irrigation, partial root irrigation and partial root drying. Also, these strategies have suggested that significant reduction in the amount of water applied, although there is some cost reduction in yield. It is crucial to understanding vine physiology and improving plant water relations regarding to stomatal regulation under water stress. Stomatal conductivity, leaf and stem water potential measurements combined with soil moisture monitoring are effective in determining the water stress of vines (Romero et al. 2014). Tuccio et al. (2019) reported that stomatal conductivity is a successful physiological indicator in terms of both early detection and sensitivity in predicting the water status of grapevine. Cifre et al. (2005) stated that the optimum stomatal conductivity should be between 0.05 and 0.15 mol m^{-2} s^{-1} to increase the water use efficiency in the vine. Thus, rel-

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atively moderate yield loss and optimization of grape quality attributes are achieved compared to excessive irrigation. On the other hand, there are many gaps in how drought-adapted grapevines can resist physiologically water stress conditions. Therefore, considering the cultivars separately in different regions and examining their reactions under water stress conditions will enable us to be strong against future climatic problems (Soltekin and Altındisli 2022).

Deficit irrigation strategy is a promising tool that provides the balance between vegetative growth and yield-quality in many grape varieties. Moreover, the effects of water stress on the grapevine vary according to the cultivar, vineyard management and climatic conditions of the region (Mirás-Avalos and Araujo 2021). Many studies show that water deficits decrease yield (Williams et al. 2012; Keller et al. 2016) and vegetative development (Caruso et al. 2023) while enhancing grape composition and quality unless they are severe (Buesa et al. 2017).

There are many reports dealing with water deficits in wine and table grape varieties, but there is still a lack of information on how the varieties used in dried grape production will behave under deficit irrigation conditions. The region where this study is carried out has Mediterranean climate characteristics and the common production type in this region is dried grape growing. Therefore, the importance of adaptation studies against expected water scarcity has increased even more.

Based on the previous literature, this study hypothesized that deficit irrigation under Mediterranean conditions will exhibit higher water use efficiency and may be an alternative strategy to full irrigation by maintaining the balance between water requirement and physiological activities. In this regard, the study aimed to answer the following research questions: (1) What was the agronomic response of 'Sultan 7' (*Vitis vinifera* L.) variety to different water status under Mediterranean conditions? (2) How did deficit irrigations affect the leaf water potential and physiological parameters during the growing seasons? By addressing these questions, the study examined the efficiency of deficit irrigation practices first time in 'Sultan 7' dried grape growing under Mediterranean conditions and presented results that will support further studies.

Materials and Methods

Location, Plant Material and Agronomic Practices

The study was undertaken in an experimental vineyard of Viticulture Research Institute, Manisa province (lat. 38°38′2.09″N; long. 27°24′0.65″E; 39 m.a.s.l.) located in western Türkiye. Experiment was conducted in a Mediterranean climatic condition (Teker and Altindisli 2021) over two consecutive seasons during 2019 and 2020. The vineyard was planted in 2015 with 'Sultan 7' (*Vitis vinifera* L.) variety grafted on 1103 Paulsen rootstock at 2m × 3m (vine × row) spacing in a north–south orientation with a density of 1666 vines ha^{-1}. 'Sultan 7' is a seedless dried grape variety with high yield and drying efficiency. It is developed and registered by the Manisa Viticulture Research Institute after clonal selection studies of 'Sultani Seedless'. In recent years, 'Sultan 7' has started to be grown in larger areas of Türkiye as an aim of 'Sultana' (raisin) production. The soil in the experimental site has a sandy loam (SL) and loamy texture (L) in a depth of 0–60 cm and 60–90 cm, respectively. The soil characteristics of the experimental site are given in Table S1. All vines were hand-pruned leaving six canes per vine with 15 buds (90 bud $vine^{-1}$). Y-shaped (six wires) training system was used and trained as a goblet system with 110 cm above the soil surface. The same fertilization program was applied to all treatments. Also, standard cultural practices such as leaf removal and topping were performed during the study.

Irrigation Treatments and Experimental Setup

In the study, 'Sultan 7' vines were subjected to three different irrigation regimes: Ir100, soil water content in the functional rooting depth (90 cm) was replenished to field capacity; Ir66, applying 66% water of Ir100; Ir33, applying 33% water of Ir100. All irrigation treatments started when the available water decreased 50% in the functional rooting depth (90 cm) and continued with an interval of 1 week until harvest. Therefore, irrigation treatments carried out between 14 June and 16 August in 2019 (10 times), and between 19 June and 21 August in 2020 (10 times). Moreover, sub-surface drip irrigation systems were used in the study. Drip laterals were buried 40 cm below the soil surface and two drip laterals were placed at 50 cm apart from each vine row.

The trial was set in a randomized block design. There were three replications in each treatment and six vines in each replication. Furthermore, three long vine rows (54 vines per row) were used for each treatment in the study. The middle vine row was used for data collection and other two rows were used as buffer rows in an aim to prevent effecting of irrigation regimes with each other. Therefore, a total of 486 vines were used in the experiment, but data collected from 162 of them. During the experiment, all irrigation treatments were conducted according to the soil water variation. Therefore, the soil water content (SWC) was monitored weekly, 1 day before the irrigation. SWC in functional rooting depth (90 cm) with 30 cm increments during the irrigation season was also measured weekly by the gravimetric method. Additionally, a Sentek Drill&Drop probe (Sentek Inc., Stepney, Australia) was used to monitor SWC in the study. The Sentek Drill&Drop probe was down to 90 cm depth with monitoring at 5, 15, 25, 35, 45, 55, 65, 75, 85 cm. Measurements were logged at 1 h interval and the probe was calibrated for soil conditions using the procedure detailed by the manufacturer.

Data Collection

EL stages of phenological periods were observed according to Lorenz et al. (1995), and the dates were recorded during the experimental years. On the other hand, degree-days were calculated using the base temperature of 10 °C. In this regard, day of the years (DOY) for phenological stages, growing degree-days and accumulation of degree-days were determined. Climatic data was collected from the climate station (iMETOS Pessl Instruments, Austria) in the Institute. The total irrigation quantity was determined based on the pre-irrigation soil water content in 90 cm soil depth according to the following equation: I = (FC-SWC)*A*W, where I is the irrigation water (mm), FC is soil water content at field capacity (mm), SWC is soil water content at the day before irrigation (mm), W is wetting percentage (%) and A is surface area of the plot (m^2). Evapotranspiration (ET) was calculated with the following equation: ET = I + $P \pm \Delta$SW-Dp-Roff, where ET is evapotranspiration (mm), I is the irrigation water (mm), P is precipitation (mm), ΔSW is the change in the soil water content (mm), Dp is deep percolation (mm) and Roff is amount of runoff (mm). Dp and Roff were assumed to be ignored (Çolak and Yazar 2017). WUE was determined as vine yield divided by seasonal ET (Howell et al. 1995). Grapevine water status was monitored by measuring midday leaf water potential (Ψ_{md}) using a Scholander Pressure Chamber (Skye Instrument Co., UK) between 12:00 h and 13:30 h during the experimental years (Williams et al. 2012). Three fully expanded and undamaged leaf chosen from the mid-upper and sunlit side of the canopy from each replication. All measurements were carried out before the irrigation day, weekly. Leaf gas exchange measurements were carried out by LI-6800 portable photosynthesis system (Li-Cor Inc., Lincoln, NE, USA). It was fitted with 3 × 3 cm^2 cuvette head and reference CO_2 concentration was controlled at 400 μmol mol^{-1} inside the leaf cuvette. The photosynthetic photon flux density (PPFD) was 1000 μmol m^{-2} s^{-1}, the air flow rate was 500 μmol s^{-1} and the leaf temperature was maintained at 25–30 °C. All measurements were conducted in healthy and fully expanded leaves well exposed to direct sunlight between 10:00 and 12:00 h during the study (Zufferey et al. 2018). Three leaves were selected in all replications for all measurements. Net CO_2 assimilation (A; μmol CO_2 m^2 s^1), stomatal conductance (*gsw*; mmol m^2 s^1), transpiration (E; mmol m^2 s^1) were measured by infrared gas analyzer (IRGA). All measurements were conducted before the irrigation day, weekly. In addition, intrinsic water use efficiency (WUE_i, A/*gsw*; μmol CO_2 mol^{-1} H_2O) and instantaneous water use efficiency (WUE_{inst}, A/E; mmol CO_2 mol^{-1} H_2O) were calculated by considering the parameters A, E and *gsw* (Schultz and Stoll 2010).

Statistical Analysis

JMP Pro 13.2.1 statistical software was used regarding to the randomized block design for determining differences among irrigation treatments and years. When the irrigation factor was statistically significant at $P \leq 0.05$, $P \leq 0.01$ or $P \leq 0.001$, differences between treatments were identified by LSD test. In addition, the principal component analysis (PCA) by using SPSS Statistics 22.0 (IBM SPSS, US) was conducted to evaluate the behaviour of the physiological activities of grapevines in relation to different irrigation treatments.

Results

Meteorological Conditions of the Experimental Site and Phenological Stages

Rainfall and mean air temperature variation of both growing seasons are presented in Fig. 1 to evaluate weather patterns during the experimental years. Typical Mediterranean climatic conditions were observed in the experimental site throughout the experimental years. The highest mean temperature was recorded in August (28.41 °C) and July (28.77 °C) in the 2019 and 2020 season, respectively. Lower rainfall was experienced (115 mm) in 2019 than in 2020 (155 mm) in the vegetation period (March–September).

Although the amount of total rainfall was higher in 2020, particularly no rainfall was registered between mid-June to September. Also, specific dates for each phonological stage are given in terms of DOY in Table 1. Dates of bud-break, flowering and fruit set were very close to each other in both years. The highest difference was occurred in terms of harvest date and 2019 had 12 days earliness compared to 2020 season. Furthermore, 2020 season had 16 days longer growing period compared to 2019 and average growing period was found 251 days in the study.

Soil and Water Relations

In both growing seasons, soil water measurements were conducted on the day before the irrigation. The gravimetric and Drill&Drop results on the day before the irrigation are given in Table S2. 'Sultan 7' vines in plots were irrigated 10 times in each year over the irrigation period of the experiment. The soil moisture variation graph (the day before irrigation at 1-week intervals), in 90 cm depth was given

Fig. 1 Monthly rainfall and mean air temperature variation during the experimental years

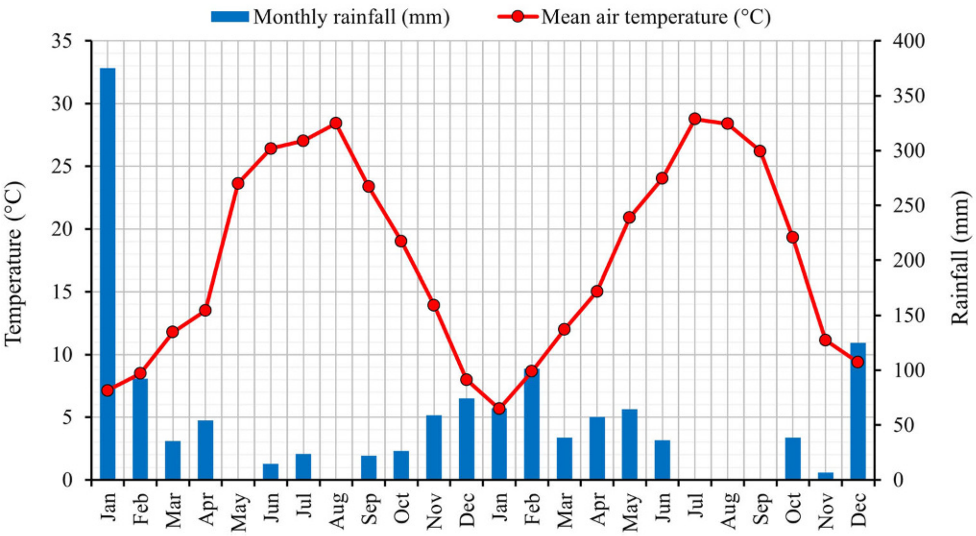

Table 1 Beginning of phenological stages, growing period, and accumulation of degree-days between bud break and harvest

	Bud break (EL-05)	Flowering (EL-23)	Fruit set (EL-27)	Veraison (EL-35)	Harvest (EL-38)	Growing period (days)	Degree-day accumulation
2019	79 (20 Mar)	140 (20-May)	147 (27 May)	193 (12 Jul)	233 (21 Aug)	243	1951
2020	76 (16 Mar)	139 (18-May)	145 (24 May)	202 (20 Jul)	245 (1 Sep)	259	2089
Avg.	78	140	146	198	239	251	2020

Dates of the stages were determined by representative 50% of each stage. Degree-days were calculated according to the base temperature of 10 °C. Dates are expressed in day of the year

in Fig. S1 for the 2019 and 2020 seasons. SWC tended to decrease towards the end of the season, particularly by Ir33 and Ir66. The amount of total irrigation, ET, WUE (yield per unit ET) for fresh grapes (WUE_{FG}) and dried grapes (WUE_{DG}) during the experimental period are given in Table 2. In 2019, the amount of irrigation water applied between the fruit set–veraison (F–V) period was higher than that between the veraison–harvest (V–H) period. In 2020, the amounts of irrigation water applied in both periods were very close to each other. ET increased with the amount of irrigation water applied. ET values were 26.5% higher under Ir100, 27.1% higher under Ir66 and 28.3% higher under Ir33 in 2020 compared with 2019. On average, WUE_{FG} from the Ir66 and Ir100 treatments were respectively 56.3 and 90.4% lower than that from Ir33. Average value of WUE_{DG} from the Ir33 was 55.9 and 90.1% higher than Ir66 and Ir100 treatments, respectively.

Physiological Activities

The repeated measurements of midday leaf water potential (Ψ_{md}) and gas exchange parameters were averaged for the F–V and V–H periods. Table 3 shows the variation of Ψ_{md} for each treatment according to the different periods of experimental years. In both periods, Ψ_{md} generally decreased as the irrigation water supply decreased during the experimental years. Nevertheless, in the F–V period of 2019, Ir100 and Ir66 had higher Ψ_{md} values (less negative) and were statistically ($P \leq 0.05$) in the same level group. After this period, between V–H, Ir100 was associated with the highest Ψ_{md} and Ir33 maintained the lowest Ψ_{md}. In both periods of the 2020, Ψ_{md} was consistently lower (more negative) in Ir33 and the increased water supply led to higher Ψ_{md} values. Also, in both periods of 2020, ‘Sultan 7’ grapevines exhibited higher Ψ_{md} in comparison to the 2019. On average, Ir33 and Ir66 had lower Ψ_{md} values (more negative) and were statistically in the same level group during the F–V period. However, Ir100 continued to be associated with the highest average Ψ_{md}, while Ir33 maintained the lowest average Ψ_{md} values during the V–H period.

The seasonal course of net CO_2 assimilation (A) and stomatal conductance (*gsw*) of ‘Sultan 7’ grapevines in all treatments was similar and decreasing consistently with the decrement of irrigation water supply in both experimental years (Table 4). The Ir100 vines had significantly ($P \leq 0.001$) higher A and *gsw* values than Ir66 and Ir33 in both growing seasons. Nevertheless, from V–H, ‘Sultan 7’ vines showed lower A and *gsw* than F–V. Average values of A during F–V period were reduced 11.87% in Ir66 and 19.54% in Ir33 compared with Ir100. Additionally, average values of A during V–H period were reduced 9.83% in Ir66

Table 2 The amount of total irrigation, evapotranspiration (ET), WUE_{FG} and WUE_{DG} under different treatments were calculated in each growing season and average of the years

		Total irrigation (mm vine^{-1})			WUE_{FG}	WUE_{DG}	ET + Dp
		F–V	V–H	F–H	(kg m^{-3})	(kg m^{-3})	(mm)
2019	Ir100	304	265	569	4.08^{c}	0.99^{b}	714
	Ir66	201	175	376	4.81^{b}	1.19^{b}	520
	Ir33	100	87	188	7.62^{a}	1.92^{a}	332
	Significance	–	–	–	**	**	–
2020	Ir100	351	362	713	3.83^{c}	0.83^{b}	903
	Ir66	232	239	471	4.81^{b}	1.03^{b}	661
	Ir33	116	119	235	7.43^{a}	1.55^{a}	426
	Significance	–	–	–	**	**	–
Avg	Ir100	328	313	641	3.95^{c}	0.91^{b}	809
	Ir66	216	207	423	4.81^{b}	1.11^{b}	591
	Ir33	108	103	212	7.52^{a}	1.73^{a}	379
	Significance	–	–	–	**	**	–

LSD test determined significant difference between the treatments for WUE values

Values with different letter are significantly different in terms of each parameter ($n = 9$)

F fruit set, *V* veraison, *H* harvest; WUE_{FG} Yield/ET for fresh grapes, WUE_{DG} Yield/ET for dried grapes

**Represents significant effect at $P \leq 0.01$

Table 3 Mean values of midday leaf water potential (Ψ_{md}) during the period from fruit set to veraison (F–V) and from veraison to harvest (V–H) during the experimental years for 'Sultan 7' grapevines subjected to different irrigation treatments

		Periods	
Year	Treatment	F–V	V–H
2019	Ir100	-1.38 ± 0.01^{a}	-1.52 ± 0.03^{a}
	Ir66	-1.41 ± 0.05^{a}	-1.58 ± 0.05^{b}
	Ir33	-1.45 ± 0.03^{b}	-1.64 ± 0.02^{c}
	P	*	***
	LSD	0.041	0.028
	CV (%)	–1.67	–1.01
2020	Ir100	-1.33 ± 0.04^{a}	-1.45 ± 0.03^{a}
	Ir66	-1.38 ± 0.03^{ab}	-1.51 ± 0.03^{ab}
	Ir33	-1.41 ± 0.04^{b}	-1.56 ± 0.05^{b}
	P	*	*
	LSD	0.061	0.059
	CV (%)	–2.57	–2.26
Avg.	Ir100	-1.35 ± 0.02^{a}	-1.49 ± 0.02^{a}
	Ir66	-1.40 ± 0.04^{b}	-1.55 ± 0.02^{b}
	Ir33	-1.43 ± 0.03^{b}	-1.60 ± 0.03^{c}
	P	***	***
	LSD	0.036	0.052
	CV (%)	–2.47	–3.18

For each parameter, means are separated by LSD test

Values with different letter are significantly different and no letters indicate no differences. In the analysis of variance, *ns*, *, ** or *** indicate non-significance, significance at $P \leq 0.05$, $P \leq 0.01$ or $P \leq 0.001$, respectively. Values are means ± standard deviation ($n = 9$)

and 21.80% in Ir33 compared with Ir100. In both periods of 2019, irrigation treatments had significant effects ($P \leq 0.001$) on transpiration (E) of 'Sultan 7' vines and the highest E values were obtained under Ir100. In contrast, from F–V of 2020, there were no significant differences in the E between treatments. However, in V–H period, E values decreased significantly ($P \leq 0.01$) in water deficits compared to full irrigation. There was no gain in WUE_{inst} at lower irrigation regimes except 2019 growing season. Nonetheless, WUE_i was usually higher in Ir33 than in the other irrigation treatments. Moreover, WUE_{inst} and WUE_i increased with water stress and reached to maximum values in particularly V–H period under Ir33 with 5.12 ± 1.56 mmol CO_2 mol^{-1} H_2O and 77.40 ± 19.49 µmol CO_2 mol^{-1} H_2O, respectively.

Principal component analysis (PCA) was carried out to examine the effects of different irrigation regimes on photosynthetic activities for 'Sultan 7' (Fig. 2). The result is suitable for PCA as the Kaiser–Mayer–Olkin measure of sampling adequacy (KMO) is 0.669 and this indicates that the data meet the requirements (KMO > 0.6) were suitable for further testing. The cumulative resolution of PC1 and PC2 for all the parameters involved in the analysis was 65.94 and 15.17%, respectively. The common cumulative variance of the first two components was calculated as 81.11% which were better components for evaluating physiological parameters treated with irrigation regimes as given in Fig. 2. Also, PCA component plot and PCA scatter plot matrix are exhibited in Fig. 2a and b, respectively. All parameters except WUE_i, WUE_{inst} and Ci were positively scored in PC1 and were represented by Ir100 and Ir66. In addition, Ca, WUE_i and WUE_{inst} were the most representative in the positive side of PC2. There was a strong positive correlation be-

Table 4 Net CO_2 assimilation (A), stomatal conductance (*gsw*), transpiration (E), instantaneous water use efficiency (WUE_{inst}) and intrinsic water use efficiency (WUE_i) values of 'Sultan 7' grapevines during the period from fruit set to veraison (F–V) and from veraison to harvest (V–H) in experimental years

Fruit set–Veraison						
		A $(\mu mol\ CO_2\ m^2\ s^1)$	*Gsw* $(mmol\ m^2\ s^1)$	*E* $(mmol\ m^2\ s^1)$	WUE_{inst} $(mmol\ CO_2\ mol^{-1}\ H_2O)$	WUE_i $(\mu mol\ CO_2\ mol^{-1}\ H_2O)$
2019	Ir100	17.33 ± 1.73^{a}	381.01 ± 69.83^{a}	6.97 ± 1.02^{a}	2.55 ± 0.47^{b}	46.94 ± 9.80
	Ir66	15.73 ± 1.71^{b}	341.43 ± 82.23^{b}	6.02 ± 1.32^{b}	2.75 ± 0.70^{ab}	48.51 ± 11.78
	Ir33	14.34 ± 2.06^{c}	289.43 ± 79.17^{c}	4.98 ± 1.48^{c}	3.13 ± 0.95^{a}	52.38 ± 12.57
	P	***	***	***	*	ns
	LSD	0.827	27.475	0.579	0.383	–
	CV (%)	7.08	11.02	13.06	18.40	13.74
2020	Ir100	17.36 ± 1.17^{a}	371.23 ± 78.21^{a}	5.24 ± 1.32	3.59 ± 1.29	48.74 ± 11.40^{b}
	Ir66	14.84 ± 1.42^{b}	284.39 ± 64.76^{b}	4.15 ± 1.34	3.95 ± 1.40	54.04 ± 9.55^{ab}
	Ir33	13.59 ± 1.21^{c}	236.74 ± 50.97^{c}	4.40 ± 3.07	3.95 ± 1.68	58.87 ± 8.78^{a}
	P	***	***	ns	ns	**
	LSD	0.648	38.747	–	–	6.114
	CV (%)	5.70	17.62	40.96	29.53	15.33
Avg.	Ir100	17.35 ± 1.45^{a}	376.12 ± 73.02^{a}	6.10 ± 1.46^{a}	3.07 ± 1.09	47.84 ± 10.48^{b}
	Ir66	15.29 ± 1.61^{b}	312.91 ± 78.30^{b}	5.09 ± 1.62^{b}	3.35 ± 1.25	51.27 ± 10.90^{ab}
	Ir33	13.96 ± 1.70^{c}	263.08 ± 70.70^{c}	4.69 ± 2.39^{b}	3.54 ± 1.41	55.62 ± 11.15^{a}
	P	***	***	**	ns	*
	LSD	0.815	36.778	0.895	–	5.467
	CV (%)	10.11	22.58	32.70	43.47	20.65
Veraison–Harvest						
		A $(\mu mol\ CO_2\ m^2\ s^1)$	*Gsw* $(mmol\ m^2\ s^1)$	*E* $(mmol\ m^2\ s^1)$	WUE_{inst} $(mmol\ CO_2\ mol^{-1}\ H_2O)$	WUE_i $(\mu mol\ CO_2\ mol^{-1}\ H_2O)$
2019	Ir100	13.97 ± 1.34^{a}	283.49 ± 44.31^{a}	3.59 ± 0.68^{a}	3.97 ± 0.51^{b}	50.24 ± 8.06^{c}
	Ir66	12.81 ± 1.40^{b}	214.77 ± 46.50^{b}	3.13 ± 0.55^{b}	4.16 ± 0.51^{b}	61.86 ± 13.26^{b}
	Ir33	11.23 ± 1.28^{c}	165.32 ± 46.34^{c}	2.45 ± 0.21^{c}	4.61 ± 0.46^{a}	71.47 ± 15.45^{a}
	P	***	***	***	***	***
	LSD	0.547	29.354	0.298	0.271	7.956
	CV (%)	5.84	17.95	13.20	8.66	17.59
2020	Ir100	14.13 ± 2.07^{a}	259.10 ± 95.83^{a}	3.21 ± 0.79^{a}	4.65 ± 1.31	59.77 ± 17.67^{b}
	Ir66	12.47 ± 1.49^{b}	194.87 ± 80.85^{b}	2.57 ± 0.68^{b}	5.07 ± 0.91	69.81 ± 16.31^{ab}
	Ir33	10.67 ± 1.44^{c}	150.39 ± 58.28^{c}	2.29 ± 0.81^{b}	5.12 ± 1.56	77.40 ± 19.49^{a}
	P	***	***	**	ns	**
	LSD	0.470	42.091	0.470	–	10.701
	CV (%)	4.509	25.048	21.190	25.324	18.597
Avg.	Ir100	14.04 ± 1.67^{a}	272.65 ± 71.38^{a}	3.42 ± 0.74^{a}	4.27 ± 0.99	54.47 ± 13.80^{c}
	Ir66	12.66 ± 1.42^{b}	205.93 ± 63.50^{b}	2.88 ± 0.67^{b}	4.56 ± 0.84	65.39 ± 14.95^{b}
	Ir33	10.98 ± 1.36^{c}	158.69 ± 51.48^{c}	2.38 ± 0.56^{c}	4.83 ± 1.10	74.11 ± 17.27^{a}
	P	***	***	***	ns	***
	LSD	0.807	33.732	0.342	–	8.124
	CV (%)	11.86	29.31	21.80	20.22	23.17

For each parameter means are separated by LSD test

Values with different letter are significantly different and no letters indicate no differences. In the analysis of variance. *ns*, *, ** or *** indicate non-significance, significance at $P \leq 0.05$. $P \leq 0.01$ or $P \leq 0.001$, respectively. Values are means ± standard deviation ($n = 15$)

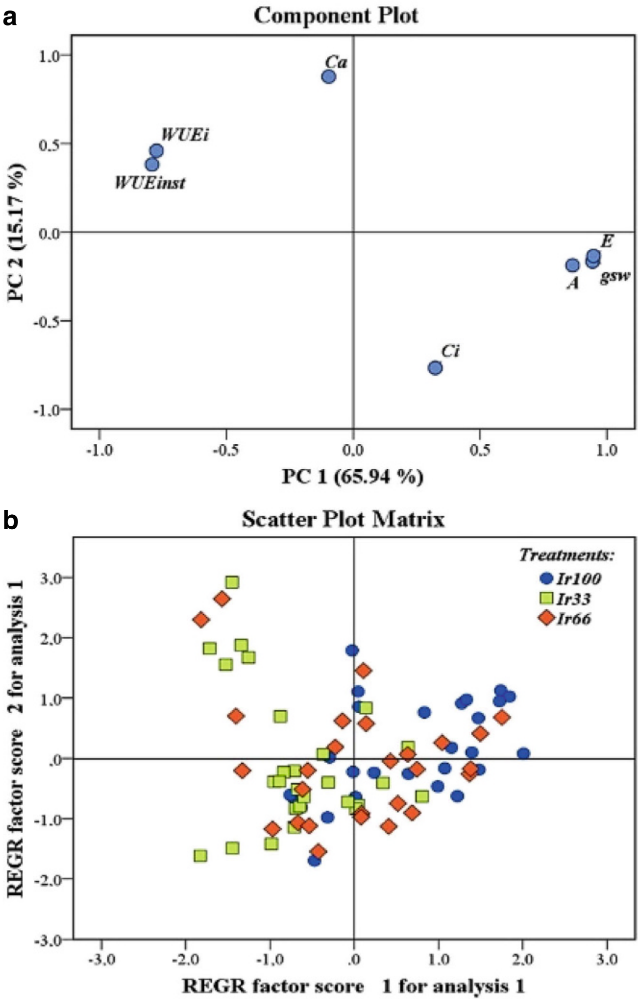

Fig. 2 Principal component analysis conducted for the physiological activities of 'Sultan 7' vines treated with different irrigation regimes. Average values ($n = 81$ for each parameter) of both experimental years are used to carry out component plot analysis (**a**) and building of scatter plot matrix (**b**) with component 1 and component 2. *REGR* regression, *A* net CO_2 assimilation, *gsw* stomatal conductance, *E* transpiration, *Ci* intercellular CO_2 concentration, *Ca* ambient CO_2 concentration, WUE_{inst} instantaneous water use efficiency, WUE_i intrinsic water use efficiency

tween A, E and *gsw* as well as between WUE_i and WUE_{inst}. On the other hand, negative correlations were determined between *gsw* and WUE_i with between E and WUE_{inst}. It was found that A, E and *gsw* of 'Sultan 7' grapevines were more associated with Ir100 and Ir66 in comparison with Ir33. On the other hand, WUE_i and WUE_{inst} were more related to Ir66 and Ir33.

Discussion

Previous studies indicate that precipitation and temperature variation influence phenological stages in warmer climates (Ramos et al. 2018). In the current study, bud break (EL-05), flowering (EL-23) and fruit set (EL-27) stages were similar in both years. This may be explained by the fact that the main temperature values were close to each other in the 2019 and 2020 growing seasons. Martínez-Lüscher et al. (2016) reported that temperature significantly affects phenological periods and increasing temperatures might advance phenology. Therefore, there is no big difference between the development stages in years with similar temperature values. On the other hand, the harvest dates (EL-38) were different between the two experimental years and 12 days earlier ripening was observed in 2019 compared to the 2020 season. Moreover, the growing period in the 2019 season was 16 days shorter than in 2020. The amount of precipitation in 2019 was 40 mm less than in 2020 shows the harvest date was advanced in our study. It is known that ripening varies with temperature and rainfall or soil moisture content (Martínez-Lüscher et al. 2016). According to modelling studies evaluating the relationship between climate and viticulture, it has been reported that the vegetation period between bud break and harvest will be shorter and harvest will be earlier in the Mediterranean basin with the warming trend (Fraga et al. 2016; Santos et al. 2020). Increasing temperatures due to climate change accelerate sugar accumulation and negatively affect the phenolic maturity of wine grapes (Torres et al. 2022), whereas, in raisin production, earlier harvest with rapid ripening under high temperature reduces the risk of precipitation and accelerates the drying process of grapes.

Increasing water scarcity due to climate change negatively affects the sustainability of viticultural activities. Therefore, prior studies focused on monitoring soil water content and optimizing water use (Lanari et al. 2014; Çolak and Yazar 2017; Ma et al. 2019). In this trial, SWC was regularly monitored, and the total irrigation amount was between 188 and 713 mm in both experimental years. In addition, higher water use efficiency values were obtained in terms of fresh and dried grapes with the decrement of irrigation amount. Grapevine ET varied from 332 mm in Ir33 to 903 mm in Ir100 treatment parcels during the study. These findings are slightly higher than previous studies (Çolak and Yazar 2017; Soltekin and Altındisli 2022) because of ET is highly dependent on the variation of SWC, amount of irrigation water and effective rainfall in the growing season (Wilson et al. 2020). Moreover, SWC in the most restricted irrigation (Ir33) parcels remained below 50% available water in both experimental years and fell towards the WP at the end of both growing seasons. This situation might be explained by increasing evaporative demand at the end of the season (Cancela et al. 2016; Hochberg et al. 2017; Soltekin and Altındisli 2022).

There are different suggestions about measurements of vine water status and some researchers have successfully used the leaf (Ψ_L) water potential (Girona et al. 2006;

Williams et al. 2012; Sebastian et al. 2015), while other researchers stated that the stem (Ψ_S) water potential is a better indicator for determining water stress in the vine (Cancela et al. 2016; Intrigliolo et al. 2016; Munitz et al. 2017). Furthermore, some researchers have stated that since both methods used to monitor the vine water potential are highly correlated with each other, both techniques can be used to assess vine water status (Williams et al. 2012; Williams 2017). In the current study, leaf water potential measurements were conducted at noon during the different phenological stages. Regarding to the F–V and V–H stages, irrigation treatments had significant effects on Ψ_{md} values in both growing seasons. Lower Ψ_{md} values (more negative) were obtained under Ir33 for all phenological stages. Across all irrigation treatments, Ψ_{md} did not exceed negative values of –1.45 MPa in F–V and –1.64 MPa in V–H of 2019 season. Additionally, the lowest (most negative) Ψ_{md} was –1.41 MPa in F–V and –1.56 MPa in V–H of 2020 season. In both experimental years, 'Sultan 7' vines under increasing water deficit resulted in a progressive increment of water stress which was observed in prior studies (Romero et al. 2014; Intrigliolo et al. 2016; Shellie 2019). Moreover, our findings show that vine water stress was higher under all irrigation treatments in V–H of 2019 and 2020 seasons. Cancela et al. (2016) reported that increasing of evaporative demand along the season might increase water stress level because of higher temperature and depletion of SWC.

In the F–V and V–H periods of experimental years, the physiological attributes of the 'Sultan 7' vines were strongly influenced by irrigation treatments. In general, Ψ_{md}, A, *gsw*, and E were positively correlated with the irrigation amount of water applied, meaning that Ir33 had the lowest values and Ir100 the highest. During the study, gas exchange parameters resembled the general trend of Ψ_{md}, where the 'Sultan 7' vines differed significantly in their physiological parameters according to their phenological stages. Gas exchange values under all irrigation regimes were typical for deficit-irrigated grapevines in Mediterranean regions (Romero et al. 2010; Munitz et al. 2017). According to previously established grapevine stress levels based on midday leaf water potential values (Sibille et al. 2007), 'Sultan 7' vines are in the severe stress group for all treatments, particularly in V–H period. However, this situation differed depending on the *gsw* values in the current study. Since the first response under deficit irrigation is the closure of stomata, *gsw* is generally an important non-destructive indicator to detect water stress (Romero et al. 2010). Benyahia et al. (2023) reported that factors such as genotype (isohydric and anisohydric varieties), climatic conditions at the time of measurement (i.e., temperature, SWC, VPD) and measurement type (leaf or stem) directly affect the vine water status. Therefore, determining water stress threshold values based on water potential is more challenging than stomatal conductance (*gsw*). According to the previous studies, the water stress level was classified into three groups based on *gsw* values. The first level is mild water stress defined by *gsw* between 150 and 500 mmol H_2O m^{-2} s^{-1}; the second level is moderate water stress with *gsw* between 50 and 150 mmol H_2O m^{-2} s^{-1}; and the third level is severe water stress defined by *gsw* <50 mmol H_2O m^{-2} s^{-1} (Cifre et al. 2005). Regarding to this classification, mild water stress was experienced in both F–V and V–H periods under all irrigation treatments. Although higher stress levels were observed with midday leaf water potential values (Table 3), gas exchange parameters, particularly *gsw* values of grapevines, are believed to be more promising in detecting the vine stress level (Cifre et al. 2005). Throughout the study, *gsw* decreased due to the decrement in the amount of applied water in all periods. As a consequence of decreasing stomatal conductivity, lower A values were obtained under all irrigation treatments. Similar results were described by previous studies (Romero et al. 2010; Munitz et al. 2017; Weiler et al. 2019).

As a result of stomatal closure and lower *gsw* values, WUE_i increased with severity of water stress in the current study. This is in accordance with results reported by Medrano et al. (2015), who reviewed the different cultivars had higher WUE_i values under drought conditions. Also, our findings reveal better stomatal control allows increasing WUE_i which is similar to the findings of Bota et al. (2016). Moreover, V–H period had higher WUE_i values than F–V during the experimental years. On the other hand, Romero et al. (2014) described similar WUE_i values in before and after veraison periods under morning measurements. Furthermore, Conesa et al. (2018) stated that irrigation treatments had no significant effect on WUE_i and pre-/post-veraison periods had much more effects on gas exchange parameters regardless of irrigation. In the Mediterranean basin, which is sensitive to the effects of climate change, the decrease in the amount of rainfall and irrigation water limits stomatal conductance and reduces photosynthetic activities (Gambetta 2016; Bahar et al. 2017). Particularly due to the increase in water stress level, vegetative development (Lanari et al. 2014; Buesa et al. 2017; Korkutal et al. 2019) and berry composition (Van Leeuwen and Darriet 2016; Zufferey et al. 2018; Caruso et al. 2023) of vines are restricted. Therefore, developing modern irrigation practices for effective use of water resources and investigating the performance and behavior of local varieties are important for sustainable viticulture (Candar et al. 2020; Soltekin and Altındisli 2022).

Current study demonstrates interesting results of irrigation regimes on PWW and RI (yield to pruning weight ratio) values which were not statistically influenced by the irrigation treatments (Fig. S2). Although higher *gsw* and A values were experienced due to the increment in the amount of irrigation water applied, treatments did not modify PWW and RI which were similar (non-significant) in the study. Conesa et al. (2018) indicated that irrigation treatments had no significant effect on PWW of field grown cv. 'Crimson Seedless' variety. The fact that PWW and RI in deficit irrigations did not differ from full irrigation suggests that the amount of water applied was enough to reach the optimum PWW and similar RI under mild water stress conditions. These findings exhibited that the stress level of grapevines concerned with *gsw* values is more reliable than the midday leaf water potential. In this regard, under all treatments, the vines were in mild stress levels, and this did not make any difference in vegetative growth patterns.

In the current study, PCA demonstrated that strong positive correlation between A, E and *gsw*. Additionally, A and *gsw* values of 'Sultan 7' vines were found more associated with Ir100 and Ir66 compared to the Ir33. This situation showed us how important the increment of vine water status is in terms of photosynthesis and stomatal conductivity. These two parameters showed a decrement with less irrigation amount depending on each other. Numerous studies have shown that reduced irrigation volumes in the growing season decreased the stomatal conductivity and gas exchange (Zufferey et al. 2018).

Study findings and observations in the field showed that vegetative growth patterns, particularly PWW and RI, were not affected significantly by irrigation treatments. Although midday leaf water potential (Ψ_{md}) values indicate high stress levels under deficit irrigations, 'Sultan 7' vines remained at mild stress class based on *gsw* results. Furthermore, 'Sultan 7' variety exhibited better stomatal control allows increasing WUE_i with the water stress conditions. Therefore, study results clearly showed *gsw* is a trustworthy parameter to detect the water stress level of 'Sultan 7' vines. Nevertheless, for the future sustainability of viticulture in semi-arid regions, it is necessary to define predawn water potential, stem water potential and drought tolerance under different irrigation courses. Thus, a more detailed evaluation of physiological parameters can be achieved in adverse climatic conditions.

Conclusions

This work presents the first study that allowed the assessment of field-grown 'Sultan 7' vines to different irrigation treatments in western Türkiye. During the study, irrigation treatments had clear influences on Ψ_{md} and gas exchange parameters in the F–V and V–H periods. During the V–H period, average Ψ_{md} values reached moderate to severe stress in all treatments. Furthermore, V–H period had higher stomatal closure and WUE_i comparison to F–V. On average, *gsw* varied within the range of mild stress threshold values although Ψ_{md} exhibited higher stress levels under deficit irrigations. Also, irrigation treatments had non-significant effects on vegetative growth parameters. In fact, this indicates that *gsw* is a more reliable parameter to determine the water stress level of the vine compared to Ψ_{md}. The results show that better stomatal control results in higher WUE_i for 'Sultan 7' vines. This type of water-saver behaviour is very important for sustainable production against climate change impacts in semi-arid conditions. It is also noteworthy that water savings can be achieved thanks to deficit irrigation strategies in growing the 'Sultan 7' variety, which is used in raisin production in regions with similar climate characteristics where viticulture is impossible without irrigation. Consequently, the results of this study are crucial since it is the first study that has been conducted on the 'Sultan 7' cultivar. In concern with the seedless raisin production potential and the water scarcity due to climate change, it is expected that the results obtained from this study will shed light on future studies. More research is needed in multi-year studies to evaluate how the 'Sultan 7' dried grape's quality attributes are affected by the vine water status.

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Data availability statement The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interest O. Soltekin and S. Karabat declare that they have no competing interests.

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