Determination of drought stress indices, yield and water productivity in sorghum genotypes under full and deficit irrigation conditions

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Abstract

The aim of this research was to study yield and drought tolerant indices of four commercial sorghum genotypes (Uzun, Erdurmuş, Beydarı and Öğretmenoğlu) under full (FI) and deficit irrigation (DI) conditions at the Batı Akdeniz Agricultural Research Institute (BATEM), Antalya, Türkiye. Stress sensitivity index, stress tolerance index, harmonic mean, yield index, drought resistance index, yield stability index, geometric mean productivity, abiotic tolerance index, stress tolerance, mean productivity, and sensitivity drought index, were evaluated in the research. The highest evapotranspiration was calculated in FI treatment as 488.3 mm for Uzun genotype, while the lowest was calculated in DI treatment as 307.0 mm for Beydarı genotype. The highest water productivity was determined in FI as 3.97 kg m^{-3} for Uzun genotype. The results showed that deficit irrigation application significantly affected hay yield and yield parameters except for chlorophyll content. The highest hay yield (19.4 t ha^{-1}) was obtained from Uzun genotype under FI treatment. Mean productivity, stress tolerance index, harmonic mean, and geometric mean productivity were more informative classification of drought tolerant or sensitive sorghum genotypes in the study. It is concluded that Uzun genotype was more suitable for cultivation under water stress conditions according to the principal components analysis and correlation coefficient.

Abbreviations

AWC: Available soil water content
BATEM: Batı Akdeniz Agricultural Research Institute
DI: Deficit irrigation
EC: Electrical conductivity
ET: Evapotranspiration
FC: Field capacity
FI: Full irrigation
IWP: Irrigation water productivity
PWP: Permanent wilting point
SAR: Sodium adsorption ratio
WP: Water productivity

Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is a plant species within the C_4 group that has a remarkable ability to grow in dry and semi-dry climates. Among cereal crops, it holds the distinction of being the fifth most widely cultivated crop worldwide, displaying tolerance to extreme heat, drought, salinity (Assefa *et al.* 2010; Aydinsakir *et al.* 2021). Therefore, sorghum is grown in approximately 100 countries globally. The majority of these countries, which make up 90% of the total production area, are situated in the developing world. Sorghum is cultivated to meet silage and roughage needs of livestock in areas with less precipitation and insufficient fresh water resources within the scope of adaptation of climate change (Deb *et al.* 2004).

Despite its ability to withstand drought, irrigation is crucial in enhancing the yield of sorghum crops. Research has revealed that water stress can result in reductions in various growth and development factors, including plant height, dry matter content, chlorophyll levels, leaf area index, stomatal conductivity, grain number per panicle, and 1000 - grain weight (Solaimalai *et al.* 2001; Assefa *et al.* 2010; Devnarain *et al.* 2016; Jabereldar *et* *al.* 2017). Mastrorilli *et al.* (1999) stated that the decrease in hay yield under temporary water deficit conditions was related to the phenological stage and that the yield decreased by about 20% in early phenological periods because of water deficit. Mastrorilli *et al.* (2011) evaluated the influence of full evapotranspiration (100% ET) and deficit evapotranspiration (50% ET) irrigation levels on hay yield and irrigation water productivity of different sorghum genotypes and determined that 100% ET had the highest yield and 50% ET improved the water productivity by 13.5%.

Zhang *et al.* (2018) stated that drought stress is a significant challenge for plants in semi-arid and arid regions, causing limited growth and reduced yield. Anwaar *et al.* (2019) argued that selection of genotypes with tolerant or resistant genes is difficult because drought tolerance is a calculable feature with complex heritability and there is a lack of information on drought tolerance mechanisms. On the other hand, selection and cultivation of different genotypes under dry and semi-dry areas is one of the main goal of plant breeders and growers for increasing stress tolerance, yield and quality. Therefore, some researchers suggested the use of some indices to identify drought tolerant genotypes by comparing genotypes with each other (El-Hashash *et al.* 2018; Pour-Aboughadareh *et al.* 2019; Nazari *et al.* 2021). The correlation between yield and some drought indices on different drought conditions was investigated in rice (Chunthaburee *et al.* 2016), wheat (Pour-Aboughadareh *et al.* 2019), cotton (Ullah *et al.* 2019, 2022), sorghum (Nazari *et al.* 2021) and maize (Shojaei *et al.* 2022). Kharrazi and Rad (2011), Menezes *et al.* (2014) and Nazari *et al.* (2021) indicated that the yield index, mean productivity, stress tolerance index, yield stability index, harmonic mean, and geometric mean productivity indices were powerfully associated with sorghum yield, and these drought indices help growers and breeders in farming and breeding programs, respectively.

Gitore *et al.* (2021) argued that since different drought indices describe variant genotypes as water stress tolerant, classifying water stress tolerant genotypes based on a single principle does not give strong marks. For this reason, the mean and standard deviation of the ranks in all indices are used to identify the more drought resistant genotypes (Pour-Aboughadareh *et al.* 2019, Gitore *et al.* 2021). Moreover, Principal Component Analysis (PCA) was used for genotype selection under different stress conditions (Ullah *et al.* 2022). The aim of this research was to: (i) define the influence of FI and DI levels on hay yield of four sorghum genotypes and water productivity in the West Mediterranean Region of Türkiye, (ii) evaluate selection principles for classifying sorghum genotypes as drought tolerance, so that right sorghum genotypes can be suggested for growers and breeders in the arid and semi-arid region.

Materials and methods

Site description

The experiment was conducted in the Batı Akdeniz Agricultural Research Institute (BATEM) in Antalya, Türkiye (36° 56′ N latitude, 30° 53′ E longitude; 28 m a.s.l). The climatic conditions of this location is categorized by the Mediterranean type, hot and dry conditions in the summer and featuring mild and rainy conditions in the winter. Some climatic parameters (Table 1) related to the long-term (between 1954-2019 years) were acquired from Antalya Meteorological Regional Directorate Station. Furthermore, during the investigation period (from May, 24 to September, 16), climatic data were obtained from an automated weather station (iMETOS 3.3, Pessl Instrument, Austria) situated in the research area.

Some properties of the experimental soil are presented in Table 2. The soil of the experimental area is silty-clay, unsalted and rich in calcium carbonate and alkali. The water content in the soil, maintained at a pressure of 1.5 MPa at permanent wilting point (PWP), was

Table 1 - The long-term and experimental years average climatic data of the research area

Years	Months	Average temperature (°C)	Min. temperature (°C)	Max. temperature (°C)	Wind speed (m s^{-1})	Relative humidity (%)	Total rainfall (mm)	Evaporation (mm)
Long-term (1954-2019)	May	20.5	15.2	25.5	2.6	66.6	32.1	172.9
	June	25.3	19.6	30.7	2.9	59.3	10.9	243.2
	July	28.4	22.7	34.0	2.8	57.1	4.5	280.3
	Aug	28.3	22.7	34.0	2.7	59.3	4.6	253.5
	Sep	25.1	19.4	31.1	2.8	59.1	18.1	203.4
2020	May	21.9	18.6	26.4	4.0	60.3	10.6	229.8
	June	24.0	20.8	27.7	3.4	61.9	0.0	226.8
	July	29.5	25.8	33.8	3.3	61.3	0.2	309.5
	Aug	29.8	26.2	34.1	3.4	54.1	1.2	354.5
	Sep	28.4	25.4	32.8	3.2	58.3	1.4	293.5

Table 2 - Physical and chemical properties of the experimental soil

Soil depth (cm)	Sand (%)	Clay (%)	Silt (%)	Texture	Lime (%)	Electrical conductivity (dS m^{-1})	pH	$CaCO_3$ (%)	Field capacity (m^3 m^{-3})	Permanent wilting point (m^3 m^{-3})	Bulk density (g cm^{-3})
0-30	13	44	43	Silty clay	25.6	0.103	8.3	24.0	0.24	0.13	1.31
30-60	13	40	47	Silty clay	24.8	0.108	8.3	29.7	0.24	0.11	1.38
60-90	13	39	48	Silty clay	23.7	0.156	8.4	30.1	0.22	0.12	1.43

determined to be 0.13 m^3 m^{-3} in the 0-30 cm depth, 0.11 m^3 m^{-3} in the 30-60 cm depth, and 0.12 m^3 m^{-3} in the 60-90 cm depth. Meanwhile, at field capacity (FC), held at a pressure of 0.03 MPa, the soil water content was found to be 0.24 m^3 m^{-3} in the same respective soil depths. Some quality parameters of water used in the study are presented in Table 3. The sodium adsorption ratio (SAR) and the electrical conductivity (EC) of the irrigation water was determined to be 0.34 and 0.46 dS m^{-1}, respectively, which is considered safe for cultivating sorghum plants and does not pose any risk. The quality of irrigation was determined as C_2S_1 (Zaman *et al.* 2018).

Crop material, fertilization and sowing

Four sorghum (*Sorghum bicolor* L. Moench) genotypes widely cultivated in the Mediterranean and Southeast Anatolia Region of Türkiye, named Uzun, Erdurmuş, Beydarı, and Öğretmenoğlu were used in the study. These genotypes were developed and recorded by the BATEM. Fertilizer was applied uniformly and on the basis of soil analysis to all test plots. Before sowing, the experimental soil was fertilized with a recommended dose of 75 kg ha^{-1} of pure Nitrogen-Phosphorus-Potassium (15-15-15 composite), and when the plants reached a height of 0.3 to 0.5 meters, an extra 115 kilograms per hectare of nitrogen in the form of ammonium nitrate (equaling 50% of the total nitrogen requirement) was added. The sorghum seeds were sown at a depth of approximately 4-5 cm using a seed-sowing machine, with 0.70 × 0.10 m spacing on May 24, 2020.

Irrigation treatments, evapotranspiration and water productivity

Two irrigation levels (FI: full irrigation, which involved no water-stress and DI: deficit irrigation, which induced mild water stress) were applied as irrigation treatments in the study. FI involved applying enough water to refill the top 90 cm of soil to FC, whereas DI received 50% of the water applied to the FI.

The experimental plots' available soil water content (AWC) was measured weekly at depths of 0-30, 30-60, 60-90 cm. To determine AWC, soil samples were taken from within the wetted area of each replication and analyzed using the gravimetric method. In the FI treatment, irrigation was performed when the AWC in the upper 90 cm soil depth reached the allowable depletion rate (40%). The net amount of irrigation water required for the FI treatment was determined using Equation 1 (Doorenbos and Pruitt 1977).

$$d_n = \frac{(FC - AWC)\,\gamma_s}{100}\, D \times P_c \tag{1}$$

where d_n is the net irrigation water (mm), AWC is the available water content (m^3 m^{-3}), FC is the field capacity (m^3 m^{-3}), γ_s is the bulk density (g cm^{-3}), D is the soil depth (mm) and P_c is the canopy cover (%).

Experimental plots were irrigated by surface drip irrigation method, utilizing polyethylene drip lines with in-line drippers at 0.20 m intervals and 16 mm diameter. Each crop row was provided with one drip line, with drippers having an average discharge of 2 L h^{-1} at 0.1 MPa. The water balance method given in Equation 2 was used in the calculation of evapotranspiration (James 1988).

$$\mathrm{ET_a} = \mathrm{I} + \mathrm{P} - \mathrm{D_p} - \mathrm{R}_f \pm \Delta\mathrm{SW} \tag{2}$$

where $\mathrm{ET_a}$ is the actual crop evapotranspiration (mm), I is the total irrigation water applied to the plots (mm); P is the rainfall (mm); $\mathrm{D_p}$ is the deep percolation (mm); R_f is the runoff (mm) and ΔSW is the change in soil water storage between sowing and harvest (mm). Deep percolation and runoff values were assumed to be negligible because of the fact that the amount of irrigation water was controlled (Aydinsakir *et al.* 2021).

Water productivity (WP) is described as hay yield (Y_a, kg

Table 3 - Quality parameters of irrigation water

pH	EC_w dS m^{-1}	Cations (me l^{-1})				Anions (me l^{-1})				SAR
		Na	K	Ca	Mg	CO_3	HCO_3	Cl	SO_4	
7.7	0.46	0.60	0.18	4.18	1.81	-	4.24	0.30	2.23	0.34

Where Na^{+1} is the sodium, K^{+1} is the potassium, Ca^{+2} is the calcium, Mg^{+2} is the magnesium, CO_3^{2-} is the carbonate, HCO_3^- is the bicarbonate, Cl- is the chlorine, SO_4^{2-} is the sulphate, SAR is the sodium absorption rate and EC is the electrical conductivity.

Table 4 - The components of water balance and water productivity in the experiment

Sorghum genotypes	Treatments	Hay yield (t ha^{-1})**	Irrigation (mm)	Rainfall (mm)	Soil water depletion (mm)	ET_a (mm)	WP (kg m^{-3})**	IWP (kg m^{-3})**	Relative yield decrease (%)
Beydarı	FI	14.2 b	386.3	13.4	31.1	430.8	3.29 ab	3.68 c	-
	DI	11.9 c	210.6	13.4	82.9	307.0	3.88 a	5.65 a	17.0
Erdurmuş	FI	15.8 ab	422.1	13.4	36.5	472.1	3.35 ab	3.74 c	-
	DI	7.4 d	228.6	13.4	87.0	329.0	3.24 ab	2.25 d	54.0
Öğretmenoğlu	FI	11.7 c	398.3	13.4	39.0	450.7	2.60 b	2.94 d	-
	DI	8.3 d	216.6	13.4	83.9	314.0	2.64 b	3.83 c	30.0
Uzun	FI	19.4 a	430.9	13.4	44.0	488.3	3.97 a	4.50 b	-
	DI	13.0 b	233.0	13.4	87.0	333.4	3.90 a	5.58 a	33.0

ET_a: Actual evapotranspiration, WP: Water productivity, IWP: Irrigation water productivity**, significant at the $p < 0.01$ level. The means indicated with the same small letter in the same column are not significantly different.

ha^{-1}) divided by the actual evapotranspiration (ET_a, m^3 ha^{-1}). Irrigation water productivity (IWP) is described as the ratio of hay yield (Y_a, kg ha^{-1}) to the irrigation water (I_s, m^3 ha^{-1}). Equations 3 and 4 reported by Pereira *et al.* (2012) were used to calculated WP and IWP.

$$WP = \frac{Y_a}{ET_a} \tag{3}$$

$$IWP = \frac{Y_a}{I_s} \tag{4}$$

Plant growth parameters

Plant height, chlorophyll content index and stomatal conductance were measured every fifteen days on 30 carefully chosen plants in the middle six rows of each treatments in each replication. SPAD 502 (Minolta Camera Co. Ltd., Japan) was used to measure the chlorophyll content. Stomatal conductance was measured using a handheld SC-1 Leaf Porometer instrument (Leaf Porometer-Decagon Devices-Pullman, USA) between 12:00 and 14:00 (Pietragalla and Pask 2011).

Drought indices

Drought indices were computed based on the equations suggested by Fischer and Maurer (1978) for stress susceptibility index (SSI); Rosielle and Hamblin (1981) for stress tolerance (TOL) and mean productivity index (MP); Fernandez (1992) for geometric mean productivity (GMP) and stress tolerance index (STI); Gavuzzi *et al.* (1997) for yield index (YI), Bouslama and Schapaugh (1984) for yield stability index (YSI); Lan (1998) for drought resistance index (DRI); Khalili *et al.* (2012) for sensitivity drought index (SDI); Moosavi *et al.* (2008) for abiotic tolerance index (ATI); Hossain *et al.* (1990) for harmonic mean (HM). These indices are usually classified as yield (YI and YSI), tolerance (TOL and ATI), productivity (MP and GMP), and stress (STI, DRI, and SDI) indices.

Stress Susceptibility Index (SSI)

$$SSI = \left[\frac{1-\left(\frac{Y_s}{Y_p}\right)}{1-\left(\frac{\bar{Y}_s}{\bar{Y}_p}\right)} \right] \tag{5}$$

Stress Tolerance (TOL)

$$TOL = Y_p\text{-}Y_s \tag{6}$$

Mean Productivity (MP)

$$MP = \frac{Y_p + Y_s}{2} \tag{7}$$

Geometric Mean Productivity (GMP)

$$GMP=\sqrt{(Y_p{*}Y_s)} \tag{8}$$

Stress Tolerance Index (STI)

$$STI = \frac{Y_s * Y_p}{\bar{Y}^2{}_p} \tag{9}$$

Yield Index (YI)

$$YI = \frac{Y_s}{\bar{Y}s} \tag{10}$$

Yield Stability Index (YSI)

$$YSI = \frac{Y_s}{Y_p} \tag{11}$$

Drought Resistance Index (DRI)

$$DRI = \frac{Y_s * \left(\frac{Y_s}{Y_p}\right)}{\bar{Y}_s} \tag{12}$$

Sensitivity Drought Index (SDI)

$$SDI = \frac{Y_p - Y_s}{Y_p} \tag{13}$$

Abiotic Tolerance Index (ATI)

$$ATI = \left[\frac{Y_p - Y_s}{\bar{Y}_p - \bar{Y}_s}\right] \times \left[\sqrt{Y_p \times Y_s}\right] \quad (14)$$

Harmonic Mean (HM)

$$HM = \frac{2(Y_p \times Y_s)}{Y_p + Y_s} \quad (15)$$

where Ys is the yield under DI conditions, Yp is the yield under FI conditions, $\bar{Ys}$ is the mean yields of all sorghum under DI treatment, and $\bar{Yp}$ is the mean yields of all sorghum under FI treatment.

Experimental design and statistical analysis

The research was carried out using a randomized complete block design (RCBD), where the primary treatments were crop materials consisting of four sorghum genotypes (Uzun, Erdurmuş, Beydarı, and Öğretmenoğlu), and the sub-treatments were two irrigation water levels (FI: full irrigation without water stress and DI: mild water stress), with three repetitions. The experimental plots were designed to comprise 8 rows of plants that were 5.60 meters in width and 40 meters in length, with a 2-meter separation between plots that were exposed to different irrigation treatments.

In this study, seeds were planted on May 24, 2020 and harvested on September 16, 2020. The data collected on yield, plant height, water productivity at the end of the study, as well as the average seasonal SPAD and stomatal conductivity, were subjected to analysis of variance (ANOVA) using SPSS Statistics Base v23 (SPSS Inc., Chicago, IL, USA), and significant differences between means were compared through LSD test ($p<0.05$) (Dean *et al.* 2017). The correlations among drought indices were determined using the Pearson correlation test, while genotypic comparisons were conducted using principal component analysis (PCA) based on various drought indices under different drought conditions. These statistical analyses and graphical representations were performed using OriginPro v2023a (OriginLab Corporation, Northampton, MA, USA).

Results and discussion

Soil water storage variation

The soil water storage variation of the soil profile (0.90 m) before irrigation for two different water treatments of each genotype were given in Figure 1. Soil water storage variation in FI and DI irrigation treatments fluctuated differently between the FC and PWP. In the FI treatment, the soil water storage before irrigation remained within the limits of the allowable depletion rate (40%), representing that FI was continued throughout the growing season.

Irrigation water, evapotranspiration and water productivity

Table 4 shows the data for the parameters of water balance equation and water productivity in the experiment. For germination, 35.0 mm of irrigation water was applied equally to all plots among 24 May-20 June 2020. The first and final irrigation application was applied on June 20, and on September 6, 2020, respectively. The amount of applied irrigation water ranged from 210.6 to 386.3 mm for Beydarı genotype, 228.6 to 422.1 mm for Erdurmuş genotype, 216.6 to 398.3 mm for Öğretmenoğlu genotype and 233.0 to 430.9 mm for Uzun genotype among the FI and DI treatments. In relation to the applied irrigation water, ET ranged from 307.0 to 430.8 mm for Beydarı, 329.0 to 472.1 mm for Erdurmuş, 314.0 to 450.7 mm for Öğretmenoğlu and 333.4 to 488.3 mm for Uzun in the FI and DI treatments. Due to the low amount of rainfall occurred during the study (13.4 mm), ET was largely dependent on applied water and change in soil water storage.

Hay yields ranged from 11.9 to 14.2 t ha^{-1}, 7.4 to 15.8 t ha^{-1}, 8.3 to 11.7 t ha^{-1}, and 13.0 to 19.4 t ha^{-1} for Beydarı, Erdurmuş, Öğretmenoğlu, and Uzun genotype, respectively. Decreasing the water led to a relatively lower yield. The greatest hay yields were obtained from FI treatments and the lowest hay yields were obtained from DI treatments. Sorghum yields under FI and DI (50% of FI) were reported 27.1 and 21.1 t ha^{-1} by Cosentino *et al.* (2012), 10.0 and 40.0 t ha^{-1} by Campi *et al.* (2014), 9.8 and 6.1 t ha^{-1} by Bell *et al.* (2018), and 26.4 and 18.7 t ha^{-1} by Aydinsakir *et al.* (2021), respectively. The variation in yield values across previous studies could be associate with differences in cultivar, climate, and growing conditions. Full irrigation treatment of Uzun and Erdurmuş genotypes had the highest yield ($p<0.01$) (Table 4).

For the Beydarı, Erdurmuş, Öğretmenoğlu, and Uzun genotypes, the yield reductions in DI treatments were 17.0%, 54.0%, 30.0%, and 33.0%, respectively, compared to the FI treatment. Hay yield reductions in the FI and DI treatments was determined 46.3% by Jahansouz *et al.* (2014), 20.1% by Uzun *et al.* (2017), and 43.6% by Aydinsakir *et al.* (2021) under different climatic conditions.

The WP and IWP obtained in the study are given in Table 4. Water productivity values were considerably affected by the FI and DI and ranged from 3.29 to 3.88 kg

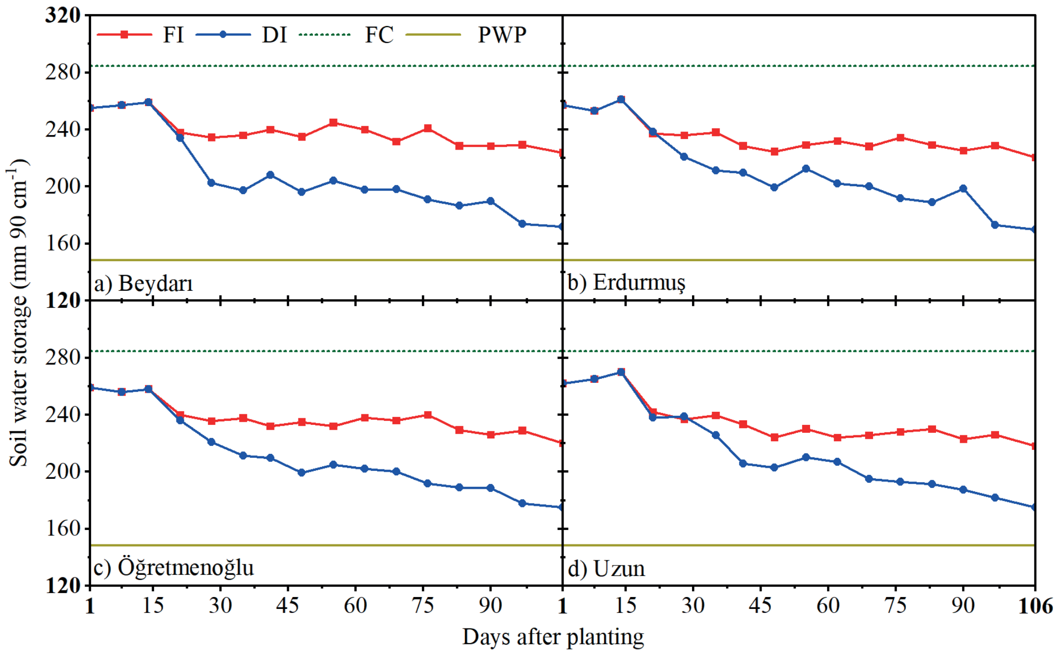

Fig. 1 Soil water content in the soil profile (FI is the full irrigation treatment, DI is the deficit irrigation treatment, 50% of FI, FC: Field capacity, PWP: Permanent wilting point)

m^{-3} for Beydarı, from 3.24 to 3.35 kg m^{-3} for Erdurmuş, from 2.60 to 2.64 kg m^{-3} for Öğretmenoğlu, and from 3.90 to 3.97 kg m^{-3} for Uzun genotypes (Table 4). Howell (2006) and Pereira *et al.* (2012) reported that WP generally tends to increase with a decline in irrigation amount. In this study, although quantitatively similar results were obtained for Beydari and Oğretmenoğlu varieties, the application of deficit irrigation had effect on WP in each of the genotypes ($p<0.01$). The lowest WP was in the Öğretmenoğlu genotype (p<001). Indeed, some researchers (Mastrorilli *et al.* 1995; Hassanli *et al.* 2009; Hadebe *et al.* 2017) mentioned that WP of sorghum genotypes is influenced not only by the amount of irrigation but also by their physiological characteristics and exposure to abiotic stress conditions. The IWP value of the different treatments and genotypes ranged from 2.25 to 5.65 kg m^{-3} (Table 4). The highest IWP belonged to Uzun genotype among DI treatments, whereas it belonged to Uzun and Beydari genotypes among FI treatments ($p<0.05$). Unlike WP, the impact of deficit irrigation on IWP was significant across all genotypes. The WP of sorghum was found by Abd El-Mageed *et al.* (2018) to be 6.4 kg m^{-3} and 7.9 kg m^{-3} under FI and DI treatments, respective. Similarly, WP was determined as 4.4-5.5 kgm^{-3} by Steduto and Albrizio (2005), as 7.7-8.9 kg m^{-3} by Irmak *et al.* (2014) 5.8-13.7 kg m^{-3} by Aydinsakir *et al.* (2021) under well irrigated and rainfed conditions, respectively.

Plant growth parameters

In Table 5, the influence of deficit irrigation on end-of-season plant height, average seasonal SPAD, and stomatal conductance was presented. The impact of water stress on genotypes resulted in significant changes in plant height and stomatal conductivity ($p<0.01$), but no significant effect was observed on SPAD (Table 5). The highest plant height was in FI treatments of Erdurmuş and Uzun genotypes with 324.0 cm and 321.0 cm, respectively, while the lowest plant height was in DI treatments of Öğretmenoğlu and Beydarı genotypes with 128.7 cm and 131.3 cm, respectively. Plant height of DI treatments of Uzun and Erdurmuş genotypes were higher than FI treatments of Beydari and Öğretmenoğlu genotypes ($p<0.01$). In addition, plant height shortened with increasing water stress in Erdurmuş and Uzun genotypes, while there was no statistical effect in Beydarı and Öğretmenoğlu genotypes. According to Sun *et al.* (2015), water stress during each phenological stage can inhibit plant height, which is considered a reliable scaler for assessing the impact of water shortage on plants. When yield and plant height are evaluated together, it can be concluded that plant growth was better in Uzun and Erdurmuş varieties under the same growing conditions. Plant height was determined as 138.0 cm and 36.6 cm by Mahinda (2014), as 165.0 cm and 138.0 cm by Abd El-Mageed *et al.* (2018), as 294.8 cm and 254.7 cm by Aydinşakir *et al.* (2021) in full and deficit irrigation levels, respectively.

Table 5 - Effect of deficit irrigation on final plant height and seasonal average leaf chlorophyll content (SPAD) and stomatal conductance

Plant height (cm)

Genotypes (G)	Irrigation treatments (I)		Mean of genotypes
	DI	FI	
Beydarı	131.3 c	140.0 c	135.7 B
Erdurmuş	223.3 b	324.0 a	273.7 A
Öğretmenoğlu	128.7 c	134.3 c	131.5 B
Uzun	251.3 b	321.0 a	286.2 A
Mean of irrigation treatments	183.7 b	229.8 a	

Significance level, G: **, I: **, G×I: **
** Significant at P<0,01

SPAD

Genotypes (G)	Irrigation treatments (I)		Mean of genotypes
	DI	FI	
Beydarı	45.4	50.3	47.8
Erdurmuş	41.7	46.9	44.3
Öğretmenoğlu	48.6	52.9	50.8
Uzun	41.7	48.1	44.9
Mean of irrigation treatments	44.4	49.5	

Significance level, G: ns, I: ns, G×I: ns
Ns: not significant

Stomatal conductivity (mmol $m^{-2}s^{-1}$)

Genotypes (G)	Irrigation treatments (I)		Mean of genotypes
	DI	FI	
Beydarı	135.5	186.3	160.9 C
Erdurmuş	225.4	265.7	245.5 B
Öğretmenoğlu	118.4	176.2	147.3 D
Uzun	241.2	285.0	263.1 A
Mean of irrigation treatments	180.1 b	228.3 a	

Significance level, G: **, I: **, G×I: ns ns and **, not significant and significant at P<0,01, respectively.
FI is the full irrigation treatment, DI is the deficit irrigation treatment (50% of FI).
The capital letters showed the comparison of the averages given along the horizontal (along the row) and the small letters were given in vertical (along the column) at the 5% significance level according to the LSD test.

Kapanigowda *et al.* (2013) argued that chlorophyll content is highly susceptible to water stress, and lower chlorophyll level can restrict the amount of photosynthesis. Additionally, Devnarain *et al.* (2016) and Aydinsakir *et al.* (2021) determined that deficit irrigation led to a decline in chlorophyll content. In this study, although there was a quantitative decrease in the SPAD of all genotypes due to water stress, this decrease was not statistically significant. The major reason for this situation is related to water stress treatments. Indeed, Devnarain *et al.* (2016) and Aydinsakir *et al.* (2021) had severe water stress treatment in their study. Therefore, SPAD was not significantly affected under moderate water stress conditions because sorghum is a drought tolerant plant species. To adapt to these drought conditions and reduce their effects, crops close their stomata and reduce water loss through transpiration (Liu *et al.* 2008). Furthermore, stomatal conductance of genotypes may vary in relation to their drought resistance.

The effect of deficit irrigation on stomatal conductivity of each genotype was found significant (P<0.01). Under full irrigation conditions, stomatal conductance was measured as 186.3, 265.7, 176.2, and 285.0 mmol m^{-2} s^{-1} in Beydarı, Erdurmuş, Öğretmenoğlu, and Uzun genotypes, respectively, while it was measured as 135.5, 225.4, 118.4, and 241.2 mmol m^{-2} s^{-1} under deficit irrigation conditions. It was determined a significant decrease in stomatal conductivity under deficit irrigation conditions (p<0.01). Since stomatal conductivity is an indicator of CO_2 assimilation and water loss (Messina *et al.* 2015), many studies on sorghum (Assefa *et al.* 2010; Vasilakoglou *et al.* 2011; Dahmardeh *et al.* 2015; Bhattarai *et al.* 2020; Gonulal 2022) reported significant decrease in stomatal conductivity under drought conditions.

Drought indices

Table 6 presents various indices of different sorghum genotypes related to hay yield per plot under FI and DI treatments. On the other hand, Table 7 shows the

Table 6 - Yield of sorghum genotypes and drought indices under full and deficit irrigation conditions

Genotypes	Yield		Drought indices										Mean
	FI	DI	Yield indices		Tolerance indices		Productivity indices		Stress indices				
	Yp	Ys	YI	YSI	TOL	ATI	MP	GMP	STI	SSI	DRI	SDI	HM
Beydarı	14.2	11.9	1.17	0.84	2.29	5.82	13.05	13.00	0.72	0.48	0.98	0.16	12.95
Erdurmuş	15.8	7.4	0.73	0.47	8.38	17.78	11.62	10.84	0.50	1.59	0.34	0.53	10.11
Öğretmenoğlu	11.7	8.3	0.82	0.71	3.38	6.54	10.02	9.88	0.42	0.86	0.58	0.29	9.74
Uzun	19.4	13.0	1.28	0.67	6.38	19.83	16.19	15.87	1.08	0.98	0.86	0.33	15.56

FI is the full irrigation treatment, DI is the deficit irrigation treatment (50% of FI), Y_p is the yield under full irrigation, Ys is the yield under stress, YI is the yield index, YSI is the yield stability index, TOL is the stress tolerance, ATI is the abiotic tolerance index, MP is the mean productivity, GMP is the geometric mean productivity, STI is the stress tolerance index, SSI is the stress susceptibility index, DRI is the drought resistance index, SDI is the sensitivity drought index and HM is the harmonic mean.

ranking for each index, average sum of ranks (ASR), standard deviation (SD), and total score of the genotypes. Bonea (2020) reported that the tolerance or susceptibility of genotypes determines drought-stress by comparing their SSI values. Based on YI, ATI, MP, GMP, STI, HM indices (1.28, 19.83, 16.19, 15.87, 1.08, 15.56, respectively), Uzun genotype was classified as drought tolerant compared to other genotypes. In addition, based on DRI and SDI indices, Uzun genotype is the genotype with the second highest drought tolerance. However, YSI, TOL and SSI indices showed that Uzun genotype was more sensitive than Beydari and Öğretmenoğlu genotypes. Regarding YSI, TOL and SSI (0.84 2.29, 0.48, respectively) the Beydari genotype was more drought tolerant. However, Beydari genotype is the most sensitive genotype in terms of ATI (5.82) and SDI (0.16) indices. Except for the SDI index, other drought indices showed that the Erdurmuş genotype was the most sensitive to water stress. Öğretmenoğlu genotype was another drought sensitive genotype based on drought index values. This was because the Öğretmenoğlu had worse drought resistance performance than Uzun and Beydarı genotypes except for YI and YSI index. The total score showed that the most drought resistant genotype was Uzun (2.5), followed by Beydarı (3.1), Öğretmenoğlu (4.0) and Erdurmuş (4.1) (Table 7). Under full irrigation conditions, Erdurmuş genotype had the highest yield together with Uzun genotype, (Table 4) but had poor performance in terms of adaptation to drought conditions. Both the yield values under different water conditions and the drought tolerance score calculated with drought indices showed that Uzun variety was the best genotype.

The correlation plot of hay yield and drought indices under FI and DI treatments is given in Figure 2. It was found a strong positive correlation between Yp and ATI, MP, STI, GMP, and HM (r>0.80), a modest positive correlation between YI and TOL (r>0.54), and no significant correlation between YSI, SSI, DRI and SDI. Therefore, ATI, HM, STI, GMP, and MP indices can be used to select the highest yielding genotypes for sorghum under drought conditions. Oppositely, YSI, SSI, DRI and SDI are not useful for the selection of high yielding genotypes under drought conditions. Moreover, in terms of both yield and drought index score, Uzun variety was not the best in the ranking of these indexes. It was determined a strong positive correlation between Yp and, YI, MP, STI, GMP, DRI, and HM (r > 0.80), a moderate negative correlation between SSI and SDI (r <- 0.55), and no significant correlation between YSI, TOL and ATI. There was no significant correlation between YSI and either Yp or Ys. Therefore, this index is not recommended for sorghum genotype selection. There was a perfect positive correlation (r = 1) between Ys and YI, SDI and SSI, STI and GMP, and a perfect negative correlation (r = -1) between SDI and YSI. It is related to

Table 7 - Ranking of different drought tolerance indices of genotypes

Genotypes	Yield		Drought indices											Score			
	FI	DI	Yield indices		Tolerance indices		Productivity indices		Stress indices				Mean	ASR	SD	Score	Final Rank
	Y_p	Y_s	YI	YSI	TOL	ATI	MP	GMP	STI	SSI	DRI	SDI	HM				
Beydarı	3	2	2	1	1	4	2	2	2	1	1	4	2	2.1	1.0	3.1	2
Erdurmuş	2	4	4	4	4	2	3	3	3	4	4	1	3	3.2	1.0	4.1	4
Öğretmenoğlu	4	3	3	2	2	3	4	4	4	2	3	3	4	3.2	0.8	4.0	3
Uzun	1	1	1	3	3	1	1	1	1	3	2	2	1	1.6	0.9	2.5	1

FI is the full irrigation treatment, DI is the deficit irrigation treatment (50% of FI), Y_p is the yield under full irrigation, Ys is the yield under stress, YI is the yield index, YSI is the yield stability index, TOL is the stress tolerance, ATI is the abiotic tolerance index, MP is the mean productivity, GMP is the geometric mean productivity, STI is the stress tolerance index, SSI is the stress susceptibility index, DRI is the drought resistance index, SDI is the sensitivity drought index, HM is the harmonic mean, ASR is the average sum of ranks and SD is the standard deviation.

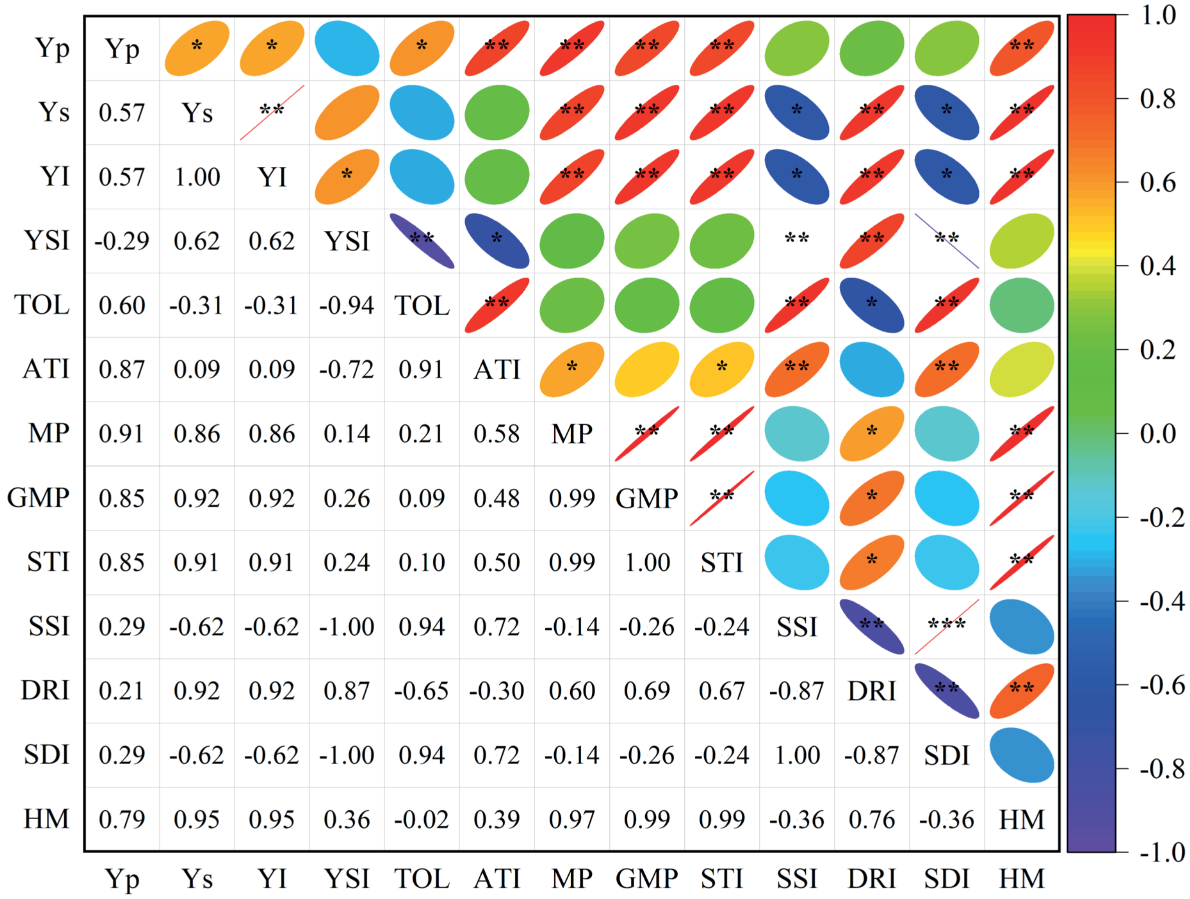

Fig. 2 Correlation plot of yield and drought tolerance indices under FI and DI conditions. Values close to +1 indicate a strong positive correlation, values close to -1 indicate a strong negative correlation, and a value close to zero indicates a weaker relationship between the two variables. Yp is the yield under full irrigation, Ys is the yield under stress, YI is the yield index, YSI is the yield stability index, TOL is the stress tolerance, ATI is the abiotic tolerance index, MP is the mean productivity, GMP is the geometric mean productivity, STI is the stress tolerance index, SSI is the stress susceptibility index, DRI is the drought resistance index, SDI is the sensitivity drought index, and HM is the harmonic mean. * and ** indicate moderate and strong relationship between the two variables.

the mathematical equation used in the calculation of drought indices and this has been reported in previous research (Mickky *et al.* 2019; Nazari *et al.* 2021). There was a positive and strong correlation between yield and MP, GMP, STI and HM in both FI and DI conditions. Some researchers (Farshadfar *et al.* 200;, Gitore *et al.* 2021), stated that drought indices with high correlations with both Ys and Yp are best for selecting stress-tolerant genotypes. Therefore, ATI, HM, STI, GMP, and MP drought indices were the most effective keys for the selection of drought-tolerant genotype in sorghum.

To identify the most appropriate representative of the system attributes, we considered the principal components that accounted for at least 10% of the variation and had higher eigenvalues (>1) (Ullah *et al.* 2019; Ullah *et al.* 2022). Eigenvalues and variance percentages calculated by principal component analysis are shown in Figure 3a. The PC1 as the yield potential and drought tolerance, and PC2 as total variability contributed 59.61% and 40.23%, respectively, for a total cumulative variability of 98.84%. Biplot analysis showed that there is a high correlation between Yp and Ys and MP, GMP, STI and HM indices and that the use of these indices will increase grain yield both under FI and DI conditions. DRI, YI and HM are the most appropriate indices to select in DI conditions. These findings are also supported by the results of correlation analysis. The Uzun genotype remained in between Ys, Yp, YI, MP, GMP, STI and HM indices. This showed that if these indices were selected, Uzun would have the highest rank. A similar situation occurred between the Beydarı genotype and the YSI and DRI indices and the SSI of the Erdurmuş genotype. The genotypes were categorized into four distinct groups based on their performance with respect to yield and drought resistance under water stress conditions; 1- high yield and drought tolerant (Uzun), 2- low yield and drought tolerant (Beydarı), 3-high yield and drought sensitive (Erdurmuş), 4- low yield and drought sensitive (Öğretmenoğlu) (Figure 3b).

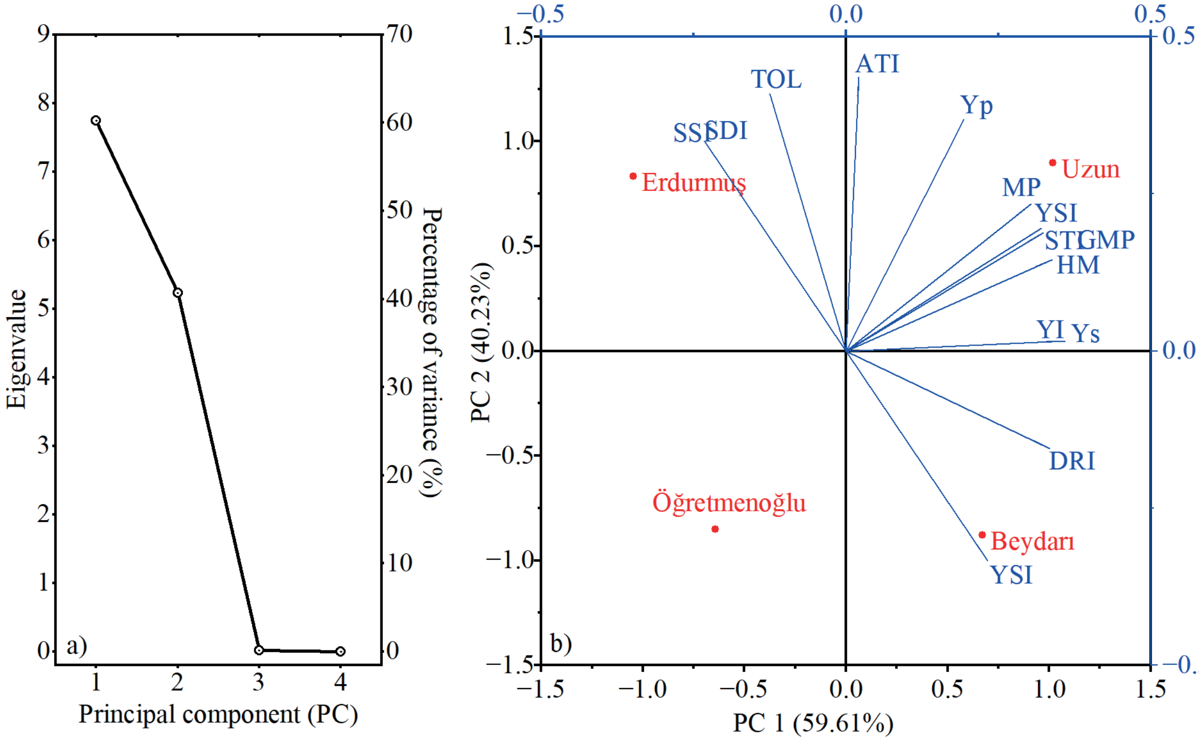

Fig. 3 Drought tolerance in different sorghum genotypes (a) line plot of principal components of eigenvalues and (b) biplot diagram of principal component analysis. Yp is the yield under full irrigation, PC1 is principal component one; PC2 is the principal component two; Ys is the yield under stress, YI is the yield index, YSI is the yield stability index, TOL is the stress tolerance, ATI is the abiotic tolerance index, MP is the mean productivity, GMP is the geometric mean productivity, STI is the stress tolerance index, SSI is the stress susceptibility index, DRI is the drought resistance index, SDI is the sensitivity drought index, and HM is the harmonic mean.

Conclusions

This work aimed to assess the effects of full and deficit irrigation conditions on hay yield and some drought indices of sorghum genotypes grown under Mediterranean conditions. The water shortage significantly affected the hay yield of genotypes causing a reduction of 17-54% compared to the full irrigation treatments. Although Uzun and Erdurmuş were the genotypes with the highest hay yields, the response of Erdurmuş genotype to drought stress was more sensitive. The MP, GMP, STI and HM indices can be used for drought resistance in combination with high yields. However, it is recommended to select ATI, STI, HM, MP and GMP as the most effective indices for drought conditions. Based on the rankings generated using various drought indices, as well as the results of PCA analysis, it was evident that the Uzun genotype had the highest yield under both FI and DI in comparison to the other genotypes. For this reason, Uzun genotype is recommended to the breeders for exploiting genetic variability to improve drought tolerant cultivars and to the farmers for obtaining high hay yield under water deficit conditions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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