Eurasian Journal of Agricultural Research 2025; Vol: 9, Issue: 1, pp: 32-47

Evaluation of Physiological Parameters in Cotton Production (*Gossypium hirsutum* L.) under Water Stress Conditions

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Abstract

Influences of different irrigation rates on some physiological parameters of various cotton varieties were assessed in Diyarbakır conditions, located in the Southeast Anatolia region of Türkiye. Three different cotton varieties (FiberMax, Stoneville 468 and Kartanesi) were evaluated in the years 2017 and 2018 under three levels of drip irrigation. The data acquired from Class-A pan evaporation included the treatments of I_{50} (50% water stress), I_{75} (25% water stress), and the fully irrigated. In the study, the application of water stress resulted in decreased fiber yield, chlorophyll content, normalized difference vegetation index value (NDVI) photosynthesis rate, stomatal conductance, and transpiration rate. In contrast, canopy temperature values increased. In the two-year study, it was revealed that water stress adversely affected cotton fiber yield and many physiological parameters. In light of these findings, it was concluded that water stress should be avoided to achieve optimum efficiency in cotton production.

Keywords: Cotton, Physiological Parameters, Water stress

Research article
Received Date: 10 April 2025
Accepted Date: 01 June 2025

INTRODUCTION

Since water makes up 70–90% of the fresh mass of actively growing plants, the availability and the quality of water have an effect on the growth and physiological processes of all plants (Gardner and Gardner, 1984). Water stresses cause alterations to anatomic and morphological features as well as physiological and biochemical processes that impact plant functioning because of its major role in plant nutrition delivery, chemical and enzymatic reactions, cell expansion, and transpiration (Wahab et al., 2022). The world today faces water scarcity, food demand and climate change, all of which are intricately interconnected. Global warming due to the greenhouse effect creates an unpredictable situation in the mass distribution of water. This situation indicates that some regions will experience excessive rainfall, while precipitation levels in other regions will decrease significantly, leading to prolonged water scarcity in countries with limited water resources.

Mitigating the adverse effects of these wetness and drought possibilities on agricultural production is only possible by developing new solutions. Therefore, comprehensive information on plant water requirements, the efficient use of water and the correct scheduling of irrigation programs have become an essential priority (Li et al., 2024). With its extensive and mandatory use, the cotton plant holds great economic importance for humanity and for producer countries due to the added value and employment opportunities it generates. Cotton is an essential source of natural fiber; particularly in semi-arid regions, serving as a crucial income source for many farmers and also is considered as one of the plants with high water consumption. The consumption of the cotton plant is directly related to the water resources available in the countries where cotton is cultivated (Chapagain et al., 2006). Water waste and scarcity result from cotton's high-water consumption, which can be caused by improper management (Brar et al., 2022). To overcome this problem, many cotton growing countries are implementing drip irrigation and fertigation systems to cope with the challenges of improper water and fertilizer management. Farmers are adopting drip irrigation techniques progressively because of their benefits, which include possible water and fertilizer savings in addition to increased yield once properly designed, installed, and managed (Kang et al., 2012; Singhet al., 2018; Thompson et al., 2009). However, due to government supports in Türkiye, the utilize of drip irrigation and fertigation in cotton production has significantly increased. A major factor in sustainable cotton production is the accessibility of water, and deficiencies can negatively impact plant physiological and biochemical processes, which diminishes fiber yield (Khan et al., 2018). The severity of damage is determined by the intensity and duration of stresses as well as the growth stage in plant in which stresses appear. Stomatal transpiration (TRst) and reduced cuticular transpiration (TRcu) are among significant physiological indicators of water stress (Osmond et al., 1987). Under water scarcity circumstances TRst is regulated by stomatal conductance, while TRcu is influenced by morphological characteristics and the thickness of the leaf surface (Richards et al., 1986).

Yang et al. (2021) suggested that plants are able to prevent drought by closing their stomata. Besides stomatal behavior, initial water content (IWC) and the rate of excised leaf water loss have been suggested as a common accurate measure of drought tolerance in cotton (Quisenberry et al., 1982). Furthermore, canopy temperature, and retaining higher water content under water scarcity conditions have been recommended as selection criteria for drought resistance in cotton (Conaty et al., 2015). The severity of damage is determined by the intensity and duration of stresses as well as the growth stage in which stresses appear. Krieg (1997) suggested that water stress slowed crop growth by reducing the size and quantity of leaves generated as well as photosynthesis. Further research on plant responses following stress alleviation is necessary, as the ability of plants to recover and regenerate after the removal of abiotic stresses is just as critical as their initial tolerance to these stress factors (Fang and Xiong, 2015). Although significant increases in yield potential have been achieved by plant breeding through previous studies, future success will be determined by the cooperation of plant breeders and plant physiologists and the support of physiological criteria (Jackson et al., 1996). The current research aimed to assess the impact of various irrigation levels on yield and some physiological parameters for three different cotton varieties. The goal was to identify the most productive and adaptable cultivar under water stress conditions, considering the importance of efficient water usage due to the decreasing availability of water resources. The results of the study also can serve as a guide for cotton breeders, physiologists and decision makers related to water management within the framework of a multidisciplinary approach.

MATERIAL and METHOD

Experimental area

The study was carried out throughout 2017-2018 years in the experimental area of GAP International Agricultural Research and Training Center (GAPUTAEM) Diyarbakır, Türkiye. Deep craks (up to 80-90 cm) arises on the soil surface in summer as a consequence of clay- based feature of soil (Gürsoy et al., 2006). The soil was sampled from 0-30 cm depth through a drill and analyzed at GAPUTAEM laboratory and the findings is given in Table 1. The soil of experimental area was clay-loam, low in organic matter, high in obtainable potassium and low in phosphorus with no salinity problems. The mean bulk density of the soil in 2017 and 2018 growing season is 1.30 and 1.20 g cm^{-3} is respectively. With the assistance of a pressure plate, field capacity (FC) and permanent wilting point (PWP) values were determined, and the available water capacity (AWC) was calculated as subtraction from FC to PWP values (Tüzüner et al., 1990).

Climate Data

Diyarbakır is one of the provinces in the Southeastern Anatolia Region where continental climate prevails. The climatic data for the years in which the study was conducted (2017-2018) and for long years. In light of this data, it is evident that the monthly average precipitation in May 2018 (157.6 mm) and October 2018 (76.6 mm) significantly exceeds the long-term average precipitation values while the average relative humidity in July, August and September in both years of the experiment are below the long years' average relative humidity values.

Plant Materials, Experimental Design and Irrigation Treatments

In the experiment, ST 468 (Fig.1) cotton variety, which is widely planted in the Southeastern Anatolia Region, FiberMax 832 (Fig.2) an okra-leaved cotton variety and Kartanesi (Fig.3) cotton variety developed and registered by GAP UTAEM for drought tolerance were used as plant materials. The experiment was carried out according to the split plots experimental design in randomized blocks with 4 replications. The main plots consisted of irrigation treatments and the sub-plots formed the cultivars. All data obtained from the experiment were analyzed according to the experimental design used, with the help of the JMP 7.0.1 statistical package program, and groupings were made based on $LSD_{(0.05)}$. A homogeneity test was conducted without combining the years, and it was determined that the years were homogeneous.

Main Plots: Irrigation Applications

1-I_{100} (Full Irrigated)
2-I_{75} (25% Water Deficiency)
3-I_{50} (50% Water Deficiency)

Sub Plots: Cotton Varieties
1-ST 468
2-FM 832
3-Kartanesi

The irrigation system comprises the control unit (including hydrocyclone, gravel filter, disk filter, fertilizer tank, and water flow meters), main pipeline, manifold pipelines, lateral pipelines, and drippers. Irrigation water was provided using motor pump powered by electricity for distribution. An irrigation system with 32 mm PE main and manifold pipes and 16 mm diameter self-contained lateral pipes (in-line) with a pressure regulator was utilized to distribute water to the plots. Drippers spaced 25 cm apart have a capacity to irrigate at a rate of 2 L per hour. A single lateral has irrigated a row of cotton, so the lateral spacing is 70 cm. Following the analysis, the irrigation water's electrical conductivity (EC) was determined as 0.60 dS m^{-1} with a pH value of 7.6. Irrigation took place at 5- day intervals, utilizing the cumulative evaporation from a Class A pan as a basis (Cetin and Bilgel, 2002). In order to avoid animals drinking water, an evaporation pan shall be set up outside the rain shelter and fitted with a mesh. Pan evaporation data were carefully monitored before each irrigation and the pan was regularly cleaned and filled with fresh water to obtain accurate pan evaporation value (Avsar and Karademir, 2022). Primary irrigation was performed uniformly in all drip irrigation treatments, so that the soil moisture increased in the 0-60 cm soil layer up to the field capacity point. The following irrigations were applied with the formula mentioned below (Öktem, 2006).

$$I = A.\ Ep.\ Kpc.\ P \quad (1)$$

Where; I is the quantity of water (mm); A is the parcel area (m^2); Ep is the Class A pan's total water depth depending on irrigation interval (mm); Kcp is the crop pan coefficient appointed as 100% of total Class A Pan (I_{100}), 75 % of total Class A Pan (I_{75}), 50% of total Class A Pan (I_{50}), P is the wetted area ratio which was admitted as 1. Utilizing the water balance equation and soil water measurements, plant water consumption was estimated. The formula for calculating plant water consumption includes irrigation, precipitation, water leakage, and soil water content changes during the season. The formula for calculating plant water consumption includes irrigation, precipitation, water leakage, and soil water content changes during the season as shown:

$$ET = I + P \pm DS - D \quad (2)$$

Where: ET is evapotranspiration (mm), I irrigation (mm), P precipitation (mm), D deep percolation (mm) and DS is change of soil water storage. Assuming negligible deep percolation losses below the root zone, the study implemented irrigation based on field capacity. Soil water content was measured every 15 days at 0-90 cm soil layer during both growing seasons using the gravimetric method (oven dry basis).

During the 2017 growing season, irrigation water was applied at 437.44 mm for I_{100}, 344.33 mm for I_{75}, and 251 mm for I_{50}. Similarly, in 2018, the irrigation amounts were 450 mm for I_{100}, 347 mm for I_{75}, and 243 mm for I_{50}. In accordance with the soil analysis conducted during the two years, each plot was treated with 80 kg ha^{-1} of total phosphorus (P2O5) and 1/4 of 160 kg pure nitrogen, while the remaining 3/4 nitrogen was applied for flowering and released until peak flowering time via fertigation system. Harvesting was performed manually; the first-hand harvest was done when 60% of the bolls opened and the remaining product was collected in the second-hand harvest. In 2017, first-hand and second-hand harvesting was performed on 10 October and 27 November, respectively, while in 2018, it was made on 1 October and 2 November.

Physiological observation and measurement methods
All the physiological measurements were recorded during the peak flowering period from the center rows of each parcel and observations were taken between 12.00 a.m and 14.00 p.m. during the day (cloudless and bright day).

Canopy Temperature was measured by using a Spectrum Brand 2956 Model Infrared Thermometer.

Chlorophyll content (SPAD value): Leaf chlorophyll contents were measured by Minolta SPAD-502 Plus chlorophyll meter. The measurements taken from ten randomly selected plants on the fifth fully expanded leaf below the terminal with one reading per leaf of the plant according to Johnson and Saunders (2002).

Normalized Difference Vegetation Index (NDVI), were measured at a height of 60 cm above the plant using a GreenSeeker Handheld Crop Sensor.

Photosynthesis, stomatal conductance and transpiration rate values; were measured by utilizing the LI-6400 XT Portable Photosynthesis System in ten plants from each parcel.

RESULTS and DISCUSSION

Fiber Yield

Mean values of fiber yield for each irrigation treatment during the period of measurements in 2017/18 were illustrated in Table 1. As shown in Table 1, year, treatment, year x treatment, variety and year x treatment x variety interactions were found significant. The treatments are significant at the P $\leq$0.01 level when examining the two-year combined variance analysis. Moreover, a reduction in cotton fiber yield is observed as a result of applying water stress. The highest fiber yield was obtained from full irrigation application (1,826 kg ha^{-1}), when 25% water stress applied, a 22.62 % decrease in fiber yield was observed (1,413 kg ha^{-1}), and when 50% water stress was applied, a 51.90 % decrease in fiber yield was observed (873 kg ha^{-1}).

Üzen et al. (2019) in a study on drought stress in cotton; informed that fiber yield increased as irrigation water increased in cotton plants utilizing different drip irrigation systems and irrigation rates. In the study conducted by Detar (2008) in California, USA, where Acala Maxxa and Acala Phytogel-72 (*Gossypium hirsutum* L.) cotton varieties were planted in sandy soil, the average mid-season critical water application level was determined to be above 95% based on the class A evaporation container. Furthermore, applying water below the threshold, caused a decrease in yield, while reducing water application by 5% below the critical level led to a 4.6% decrease in yield. The study's findings were in line with the existing literature. In terms of mean values of varieties, the highest fiber yield (1,536 kg ha^{-1}) was achieved from ST 468, while the lowest fiber yield was obtained from FM 832 (1,142 kg ha^{-1}). The variance analysis revealed significant statistical differences in the interactions between year, application, and variety. The significant variety x application interaction indicates that the responses of varieties to water stress may vary. The highest fiber yield of 2,290 kg ha^{-1} was obtained in 2017 with I_{100} full irrigation and the Kartanesi variety, while the lowest yield of 620 kg ha^{-1} was recorded in 2018 with I_{50} water stress and the FM 832 variety (Table 1).

Canopy Temperature

Canopy temperature is one of the indicators utilized in irrigation programs, suggesting that plants are suffering from water stress (Baker et al., 2007). The results of canopy temperature presented in Table 2. As seen in table the canopy temperature was affected by water stress and significant statistical differences were obtained between years and treatments ($p<0.01$). The results of statistical analysis indicated that there were non-significant associations among varieties in terms of year x treatment, year x variety, treatment x variety, and year x treatment x variety interactions. As stated in Table 2 the highest value was obtained from I_{50} (29.13 ^{o}C) water stress treatment, while the lowest value was acquired from I_{100} (26.25 ^{o}C) full irrigation treatment for an average of two years which means that non-stressed cotton plants maintained cooler leaves. In the study canopy temperature values increased gradually as water stress increased. Canopy temperature can be considered as a determinant of water stress related to transpiration, and an increase in canopy temperature above 28 ˚C leads to a decline in yield according to Conaty et al. (2015). Gonzalez-Dugo et al. (2006) stated that canopy temperature is highly sensitive to water stress and can be utilized as an indicator for irrigation programs, while Mahan et al. (2016) emphasized that canopy temperature values are related to environmental factors. Wiegand and Namken (1996) pointed that the variations in plant water stress significantly alter leaf temperature and accordingly, lower canopy temperature values are associated with better self-cooling mechanisms of plants.

Chlorophyll content

Statistical analysis of chlorophyll content showed significant differences ($p<0.01$) between irrigation treatments, variety and year x variety interactions effects. In the present study water stress caused a decrease in leaf chlorophyll content as shown in table 5 which has been reported similar results by several researchers' (Kırnak and Demirtaş, 2002). When the study examined in terms of varieties, the chlorophyll content value of FM 832 variety (50.40) with okra leaf was higher than ST 468 (47.18) and Kartanesi (46.82) varieties. However, according to the PATH analysis results in the drought stress study conducted by Karademir et al. 2009 with twenty cotton genotypes; the results revealed that chlorophyll content had a direct effect on yield. Leaf chlorophyll value differs not depending on the leaf shape but rather on its own genetic structure stated by Ekinci (2008). The previous researchers reported that chlorophyll content value changes significantly due to water stress however leaf water content (LWC) and chlorophyll values can be utilized for the instant determination of water stress (Çamoğlu et al. 2011).

Normalized Difference Vegetation Index

A statistically significant differences ($p<0.01$) were observed between years and irrigation treatments in terms of NDVI values (Table 4). Considering the result of the two-year combined analysis of variance, the plots with the I_{100} irrigation treatment had the highest NDVI value (0.80) while I_{50} had the lowest (0.74). The results are in agreement with Espinoza et al. (2017) who reported that NDVI and GNDVI correlated with yield. The variability in climatic conditions between the two years led to statistically significant differences. In 2018, the NDVI value was 0.79, which was greater than the NDVI value of 0.76 in 2017. No significant differences were observed in terms of year x treatment interaction, variety, year x variety, treatment x variety and year x treatment x variety interactions.

NDVI is a measure of the density and vigour of the vegetation at the surface of the plants and the incidence of NDVI is correlated with rate of photosynthetic activity. However, NDVI is a good argument of leaf area index, green biomass, and vegetation pattern (Bhutada et al., 2019).

Photosynthesis Rate

Water stress directly affects photosynthesis (P), P which is a key factor in determining crop yield in all plants as well as in cotton. The ratio of the water amount and potential water content of leaves declines with a decrease in photosynthetic rates (Lawlor and Cornic, 2002). Water stress has several complex consequences on P, some of which involve stomatal closure (Cornic and Massacci1996). P values significantly affected by the water stress as mentioned in Table 5. As shown in Table 5 photosynthesis rate was decreased while water stress increased. Years, irrigation treatments, year x treatment, year x variety and year x treatment x variety interactions had also significant effects on P. Highest P values, averaging 22.2 were obtained in 2017 from I_{100} treatment and Kartanesi variety while the lowest P values was attained averaging 11.2 in 2018 from I_{50} treatment and ST 468 variety. Comparison of two years revealed that, the P values of 2017 (18.66) is higher than the year of 2018 (16.95).

The findings are in line with Jaleel et al. (2009) reporting that water stress is one of the abiotic stresses that negatively affect plant growth and productivity, Luo et al. (2016) indicating that water stress decreases photosynthesis, Deeba et al. (2012) stating that the detrimental effect of drought was mainly observed on photosynthesis rate in which physiology and biochemistry alterations under drought stress were analyzed and net photosynthesis (A) rate decreased with increasing drought severity.

Stomatal Conductance

Significant differences ($p<0.01$) were attained between years, irrigation treatments, year x treatment, year x variety, treatment x variety, year x treatment x variety interactions in terms of stomatal conductance (Table 6). Limiting water to 25% did not have a significant impact on stomatal conductance, but when it was reduced to 50%, the effect was much more severe. There are ongoing studies and debates on the varying contributions of stomatal opening and metabolic processes to reduced photosynthesis in plants during drought periods. Stomatal closure, reduced mesophyll conductance, or a combination of these factors has been identified as causing a decrease in CO_2 diffusion (Flexas et al., 2002).

In addition to reducing water loss, stomatal closure also slows down CO_2 uptake by the plant. There have been contradictory findings for cotton, but important correlations between stomatal conductance and leaf water potential have been documented in water-deficit stress situations (Dubey et al., 2023). Drought stress inhibits stomatal development to improve water use efficiency in cotton. The findings of Ullah et al. (2017), were in accordance with this study indicating that the plants close their stomata to prevent water loss under water stress conditions. However, Kıran et al. (2014) reported that stomatal conductance and leaf temperature are among the important parameters in determining tolerance to drought stress.

Transpiration Rate

Considering the two-year combined variance analysis findings the water stress affected transpiration rate significantly and I_{100} treatments resulted as 6.85 mmol H_2O $m^{-2}s^{-1}$ value in the first group while I_{50} water stress application placed in the third group with the value of 4.86 mmol H_2O $m^{-2}s^{-1}$. Statistically significant differences determined in terms of year x variety interactions and the highest transpiration rate recorded from Kartanesi variety in 2017 with 7.28 mmol H_2O $m^{-2}s^{-1}$ while the lowest value was obtained also from Kartanesi in 2018 with 3.94 mmol H_2O $m^{-2}s^{-1}$, however transpiration rates in stressed plants declined during the stress cycle for three cultivars. The results of this study were in agreement with Çamoğlu (2010) who reported that plant water stress caused by moisture deficiency in the soil causes a decrease in plant transpiration which leads to an increase in leaf temperature. Zakhidov et al. (2016) also reported that water stress caused a decrease in transpiration value. Devi and Reddy (2018) reported differences in the transpiration rate in arid and humid conditions and that transpiration increased in arid conditions. This may be due to the difference in relative humidity, temperature, light or measurement time in the environment at the time of transpiration measurement. The same researchers also reported significant differences between cultivars.

Table 1. Soil properties of the research area

Years	2017	2018
Texture	Clay-Loam(C-L)	Clay-Loam(C-L)
EC (dS m^{-1})	1,27	1,40
pH	8,10	8,20
$CaC0_3$ (%)	11,00	11,46
P_2O_5 (kg ha^{-1})	3,21	4,02
K_2O (kg ha^{-1})	243	250
Organic Matter (%)	0,98	1,15
Bulk Density (g/cm^3)	1,30	1,20
Field Capacity (%)	44,05	44,03
Permanent Wilting Point (%)	30,04	31,08

Table 2. Monthly climate data during the growth period of cotton in 2017-2018 and long-term averages in Diyarbakır

Months	Avg. temp. (°C)			Avg. max.temp. (°C)			Monthly avg. precipitation (mm)			Avg. relative humidity (%)		
	2017	2018	Long term avg.	2017	2018	Long term avg.	2017	2018	Long term avg.	2017	2018	Long term avg.
April	12.8	15.9	13.8	19.5	24	20.2	98.8	48.6	68.7	68.5	52.9	63
May	18.8	19.4	19.3	26.3	26.5	26.5	30.6	157.6	42.8	57.6	67.3	56
June	26.9	26.6	26.3	35	34.5	33.7	2.6	14.4	8	30	37.4	31
July	32.3	31.2	31.2	40.7	39.3	38.4	0	0	0.7	19.4	24.1	27
August	31.1	31.4	30.3	39.9	39.1	38.1	0	0.8	0.4	22.8	24.1	28
September	26.8	26.1	24.8	36.4	34.6	33.2	0	6.2	3.9	22.3	29.3	32
October	17.2	18.7	17.2	24.8	25.8	25.2	22	76.6	31.7	39.2	52.3	48

Table 3. Mean values of fiber yield (kg ha^{-1})

Varieties	Fiber Yield (kg ha^{-1})											
	2017				2018				Combined Analysis			
	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Ort.
Kartanesi	2290 a	1580 cd	750 h	1540	1610 c	1260 ef	930 gh	1266	1950	1420	840	**1403 b**
ST 468	2000 ab	1610 c	1190 fg	1600	1970 b	1530 c-e	910 gh	1470	1990	1570	1050	**1536 a**
FM 832	1840 bc	1210 fg	850 h	1300	1250 ef	1290 d-f	620 h	1053	1540	1250	730	**1173 c**
Mean	2043 a	1470 bc	930 d		1610 b	1360 c	820 d		**1826 a**	**1413 b**	**873 c**	
GM		**1480 a**				**1260 b**				**1370**		
CV (%)						16.08						
LSD$_{(0.05)}$												
Y.						11.9**						
T.						14.6**						
Y x T						20.7*						
V.						12.9**						
Y x V						N.S.						
T x V						N.S.						
Y x T x V						31.6**						

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; N.S = Not significant, Y: Year, T: Treatment, V: Variety, GM: General Mean, I_{100}: Full irrigated, I_{75}: %25 Water stress, I_{50}: %50 Water stress, Cv: Coefficient of Variation, $LSD_{(0.05)}$: Least Significant Difference

Table 4. Mean values of canopy temperature (° C)

Varieties	Canopy Temperature (° C)											
	2017				2018				Combined Analysis			
	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean
Kartanesi	24.2	25.4	27.1	25.6	28.6	30.0	31.6	30.1	26.4	27.70	29.36	**27.83**
ST 468	23.3	25.6	26.5	25.1	28.3	29.1	31.6	29.1	25.8	27.70	29.08	**27.53**
FM 832	24.1	25.8	26.8	25.5	28.1	30.1	31.1	29.7	26.5	27.95	28..5	**27.80**
Mean	23.8	25.6	26.8		28.6	29.9	31.4		26.3 c	27.78 b	29.13 a	
GM		**25.41 b**				**30.03 a**				**27.72**		
CV (%)							3.9					
LSD (0.05)												
Y.							0.51**					
T.							0.62**					
Y x T							N.S.					
V.							N.S.					
Y x V							N.S.					
T x V							N.S.					
Y x T x V							N.S.					

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; N.S = Not significant, Y: Year, T: Treatment, V: Variety, GM: General Mean, I_{100}: Full irrigated, I_{75}: %25 Water stress, I_{50}: %50 Water stress, Cv: Coefficient of Variation, $LSD_{(0.05)}$: Least Significant Difference

Table 5. Mean values of chlorophyll content (%)

Varieties	Chlorophyll Content (%)											
	2017				2018				Combined Analysis			
	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean
Kartanesi	46.77	46.53	46.30	46.53 d	49.27	46.40	45.63	47.10 cd	48.02	46.47	45.96	**46.82 b**
ST 468	47.60	46.60	44.37	46.19 d	50.18	47.75	46.55	48.16 bc	48.89	47.18	45.46	**47.18 b**
FM 832	53.80	51.07	49.70	51.52 a	51.70	48.85	47.28	49.28 b	52.75	49.96	48.49	**50.40 a**
Mean	49.39	48.07	46.79		50.38	47.67	46.48		**49.89 a**	**47.87 b**	**46.64 c**	
GM		**48.08**				**48.18**				**48.13**		
CV (%)							3.74					
LSD (0.05)												
Y.							N.S.					
T.							1.17**					
Y x T							N.S.					
V.							1.05**					
Y x V							1.49**					
Tx V							N.S.					
Y x Tx V							N.S.					

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; N.S = Not significant, Y: Year, T: Treatment, V: Variety, GM: General Mean, I_{100}: Full irrigated, I_{75}: %25 Water stress, I_{50}: %50 Water stress, Cv: Coefficient of Variation, $LSD_{(0.05)}$: Least Significant Difference

Table 6. Mean values of Normalized Difference Vegetation Index

Varieties	Normalized Difference Vegetation Index (NDVI)											
	2017				2018				Combined Analysis			
	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean
Kartanesi	0.81	0.76	0.74	0.77	0.82	0.82	0.77	0.80	0.81	0.79	0.76	**0.79**
ST 468	0.77	0.77	0.74	0.76	0.81	0.78	0.76	0.78	0.79	0.77	0.75	**0.77**
FM 832	0.80	0.77	0.71	0.76	0.81	0.81	0.74	0.79	0.80	0.79	0.73	**0.77**
Mean	0.79	0.77	0.73		0.81	0.80	0.76		**0.80 a**	**0.78 a**	**0.74 b**	
GM		**0.76 b**				**0.79 a**				**0.77**		
CV (%)							4.55					
LSD (0.05)												
Y.							0.02**					
T.							0.02**					
Y x T							N.S.					
V.							N.S.					
Y x V							N.S.					
TxV							N.S.					
Y x T x V							N.S.					

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; N.S = Not significant, Y: Year, T: Treatment, V: Variety, GM: General Mean, I_{100}: Full irrigated, I_{75}: %25 Water stress, I_{50}: %50 Water stress, Cv: Coefficient of Variation, $LSD_{(0.05)}$: Least Significant Difference

Table 7. Mean values of Photosynthesis Rate ($\mu mol\ CO_2\ m^{-2}s^{-1}$)

Varieties	Photosynthesis Rate ($\mu mol\ CO_2\ m^{-2}s^{-1}$)											
	2017				2018				Combined Analysis			
	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean
Kartanesi	19.5a-d	22.2a	18.3b-e	19.9a	18.4b-e	17.1c-f	12.2gh	15.9c	18.9	19.7	15.3	**17.9**
ST 468	20.2a-c	17.6b-e	15.1e-g	17.7bc	22.1a	19.3a-d	11.2h	17.5bc	21.2	18.4	13.2	**17.6**
FM 832	20.7ab	20.5a-c	13.7f-h	18.4ab	19.9a-d	15.6e-g	16.6d-f	17.4bc	20.3	18.1	15.2	**17.8**
Mean	20.1 a	20.1 a	15.7 b		20.2 a	17.3 b	13.3 c		**20.1 a**	**18.7 b**	**14.5 c**	
GM		**18.66 a**				**16.95 b**				**17.81**		
CV (%)						13.60						
LSD (0.05)												
Y.						0.98**						
T.						1.22**						
Y x T						1.71*						
V.						N.S.						
Y x V						2**						
T x V						N.S.						
Y x T x V						3.45**						

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; N.S = Not significant, Y: Year, T: Treatment, V: Variety, GM: General Mean, I_{100}: Full irrigated, I_{75}: %25 Water stress, I_{50}: %50 Water stress, Cv: Coefficient of Variation, $LSD_{(0.05)}$: Least Significant Difference

Table 8. Mean values of Stomatal Conductance ($mol\ H_2O\ m^{-2}s^{-1}$)

Varieties	Stomatal Conductance ($mol\ H_2O\ m^{-2}s^{-1}$)											
	2017				2018				Combined Analysis			
	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean
Kartanesi	0.3b	0..4a	0.2e	0.3a	0.2ef	0.2de	0.1f	0..2d	0.2b	0.3a	0.2d	**0.23**
ST 468	0.3b	0.3b	0.2e	0.3b	0.3b	0.3bc	0.1f	0.2bc	0.3a	0.3a	0.2d	**0.26**
FM 832	0.3b-d	0.3b	0.1f	0.2bc	0.3b	0.2f	0.2c-e	0.2c	0.3a	0.2bc	0.2cd	**0.26**
Mean	0.3ab	0.3a	0.2cd		0.3b	0.2c	0.1d		**0.26 a**	**0.26 a**	**0.20 b**	
GM		**0.27 a**				**0.22 b**				**0.25**		
CV (%)							15.80					
LSD (0.05)												
Y.							0.02**					
T.							0.03**					
Y x T							0.04**					
V.							N.S.					
YxV							0.03**					
TxV							0.04**					
Y x T x V							0.05**					

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; N.S = Not significant, Y: Year, T: Treatment, V: Variety, GM: General Mean, I_{100}: Full irrigated, I_{75}: %25 Water stress, I_{50}: %50 Water stress, Cv: Coefficient of Variation, $LSD_{(0.05)}$: Least Significant Difference

Table 9. Mean values of Transpiration Rate (mmol H2O $m^{-2}s^{-1}$)

Varieties	Transpiration Rate (mmol H_2O $m^{-2}s^{-1}$)											
	2017				2018				Combined Analysis			
	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean	I_{100}	I_{75}	I_{50}	Mean
Kartanesi	8.03a	7.38ab	6.43bc	7.28a	4.16de	3.99de	3.69e	3.94e	6.09bc	5.68cd	5.06de	**5.61**
ST 468	7.56ab	6.85ab	5.01de	6.47b	7.94a	5.33cd	3.78e	5.68cd	7.75a	6.09bc	4.40e	**6.08**
FM 832	6.44bc	6.97ab	5.19cd	6.20bc	7.00ab	3.79e	5.03de	5.27d	6.72b	5.38cd	5.11de	**5.73**
Mean	7.34a	7.07ab	5.54c		6.37bc	4.37d	4.17d		**6.85 a**	**5.72 b**	**4.86 c**	
GM	**6.65 a**				**4.97 b**				**5.81**			
CV (%)	16.22											
LSD (0.05)												
Y.	0.50**											
T.	0.61**											
Y x T	0.87*											
V.	N.S.											
Y x V	0.77**											
T x V	0.95**											
Y x T x V	1.33*											

*, **, Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively; N.S = Not significant, Y: Year, T: Treatment, V: Variety, GM: General Mean, I_{100}: Full irrigated, I_{75}: %25 Water stress, I_{50}: %50 Water stress, Cv: Coefficient of Variation, $LSD_{(0.05)}$: Least Significant Difference

Table 10. Mean squares from analysis of variance

Source of Variation	Degrees of Freedom	Fiber Yield	Canopy Temperature	Chlorophyll Content	Normalized Difference Vegetation Index	Photosynthesis Rate	Stomatal Conductance	Transpiration Rate
Y	1	8584.13**	383.03 **	0.17	0.0130 **	52.94 **	0.05 **	51.03 **
Replication	6	41.81	16103	33359	0.0012	19937	0.00	29587
T	2	54841.20**	49.76 **	64.62 **	0.0212 **	203.29 **	0.07 **	45893 **
Y x T Int.	2	2114.16 *	0.31	23437	0.0003	13.65 *	0.01 **	32234 *
Error 1	12	549.60	1.00	17593	0.0010	28915	0.00	1.00
V	2	8047.77 **	0.64	93.43 **	0.0015	0.79	0.00	14611
Y x V Int.	2	313.21	0.16	27.67 **	0.0004	25.81 **	0.02 **	12754 **
T x V Int.	4	510.43	0.49	29252	0.0011	45943	0.01 **	45352 **
Y x T x V Int.	4	2091.33 **	0.26	23743	0.0010	26.45 **	0.01 **	31809 *
Error 2	36	489.38	42736	45717	0.0012	32264	0.001	0.89
Total	71							

Figure 1. The image of ST 468 variety

Figure 2. The image of FM 832 variety

Figure 3. The image of Kartanesi variety

CONCLUSION

The results of this study demonstrated that water stress had a significant impact on physiological properties in cotton. Under water-limited conditions, a notable reduction (54%) in yield was observed. This highlights the critical importance of avoiding irrigation restrictions during the plant's growth period to achieve optimal yield. The study further revealed that the negative effects of water stress were more pronounced at the 50% water deficit level, leading to substantially greater yield losses compared to well-irrigated conditions.

Under the experimental conditions of the study area, two varieties Kartanesi and ST 468 consistently outperformed then other variety, exhibiting higher yields and better stress adaptability. These varieties are therefore highly recommended for cultivation in similar environments where water stress may be a limiting factor.

For future researches on cotton physiology, special emphasis should be placed on ensuring that the full irrigation requirement of the plant is met. This approach would help mitigate yield losses and improve crop resilience under suboptimal water conditions. Additionally, investigating the physiological mechanisms behind the superior performance of Kartanesi and ST 468 could provide valuable insights for breeding more drought-tolerant cotton varieties.

ACKNOWLEDGMENT

That trial was financially supported by the Republic of Türkiye the Ministry of Agriculture and Forestry. TAGEM (General Directorate of Agricultural Research and Policies) with TAGEM/TBAD/A/18/A7/P5/192 project number and also funded by the Scientific Research Projects Coordination Unit of Siirt University with the project number 2017-SIUFEB-DR-25.

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