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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Assessment of Crop Water Stress Index (CWSI) of Sorghum Irrigated by Surface and Subsurface Drip Irrigation Methods under Mediterranean Conditions

Akdeniz Koşullarında Yüzeyüstü ve Yüzeyaltı Damla Sulama Yöntemleriyle Sulanan Sorgumun Bitki Su Stresi İndeksinin Değerlendirilmesi

Begüm POLAT[1*], Köksal AYDİNŞAKİR[2], Dursun BÜYÜKTAŞ[3]

Abstract

In recent years, subsurface drip irrigation has become increasingly important in view of the increasing drought. As it is a newly developed method, the effects of subsurface drip irrigation (SSDI) and surface drip irrigation (SDI) need to be compared in terms of plant growth and yield parameters as well as water savings. The CWSI is an important index that indicates the water status in the plant and is closely related to yield and plant development parameters. The aim of the study is to compare the CWSI calculated with the SDI and SSDI methods in sorghum. The relationship between CWSI and physiological parameters (leaf number (LN), leaf area index (LAI), chlorophyll content (CC)), as well as bioethanol and juice yield are also evaluated in the study. The study was designed in a randomized complete block design to include two drip irrigation methods (SDI and SSDI) and five different irrigation treatments (I_0, I_{25}, I_{50}, I_{75}, and I_{100}) in three replications in Antalya in 2017. The full irrigation treatment was applied when 40% of the available soil water capacity in the soil profile of 0-90 cm was depleted, while the deficit irrigation treatments were applied at 75%, 50% and 25% of the full irrigation treatment. Consequently, the upper limit value was calculated as 5.5°C and the lower limit equation was determined as T_c-T_a = -1.96*VPD-0.08 under Mediterranean conditions for the sorghum plant. Compared to the SDI treatments, lower CWSI values were calculated for the SSDI treatments. Additionally, it was determined that as the CWSI increased in sorghum, leaf number, leaf area index, and chlorophyll content values decreased and as a result, juice and bioethanol yield decreased. It was determined that there was a high level of exponential relationship and a strong negative correlation between CWSI-irrigation, CWSI-ET, CWSI-leaf number, CWSI-LAI, CWSI-CC, CWSI-Juice yield, CWSI-bioethanol yield, and CWSI-IWP for both irrigation methods in sorghum. Considering the lower CWSI and higher bioethanol yield, it was concluded that the SSDI method is more suitable for sorghum.

Keywords: Bioethanol yield, Juice yield, Leaf number, Leaf area index, Chlorophyll content

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Öz

Son yıllarda artan kuraklığın olumsuz etkilerinden dolayı, yüzey altı damla sulama yöntemi önem kazanmıştır. Yeni geliştirilen bir yöntem olduğu için yüzey altı ve yüzey üstü damla sulama yöntemlerinin etkisinin hem bitki gelişimi ve verim parametreleri hem de su tasarrufu açısından karşılaştırılması gerekmektedir. Bitki su stresi indeksi (CWSI), bitkideki su durumunu gösteren önemli bir indeks olup, verim ve bitki gelişim parametreleri ile yakından ilişkili olduğu belirlenmiştir. Sorgumun biyoetanol üretim amacı ile yetiştirildiği düşünüldüğünde, su kaynaklarını verimli kullanan ve su kullanım etkinliğini arttıran bir sulama yöntemi üretiminin sürdürülebilir olmasını sağlayacak en önemli uygulama olarak görülmektedir. Bu çalışmanın amacı, sorgumda yüzey (SDI) ve yüzeyaltı (SSDI) damla sulama yöntemlerinde hesaplanan bitki su stres indeksinin (CWSI) karşılaştırılmasıdır. Çalışmada CWSI ile bazı fizyolojik parametreler (yaprak sayısı, yaprak alanı indeksi, klorofil içeriği) ve biyoetanol, özsu verimi arasındaki ilişkiler değerlendirilmiştir. Çalışma, Antalya bölgesinde 2017 yılında tesadüf bloklarında bölünmüş parseller deneme desenine göre üç yinelemeli olarak yürütülmüştür. Deneme konuları, kullanılabilir su tutma kapasitesinin farklı oranları olacak şekilde beş farklı (%100, %75, %50, %25 ve %0) su uygulama düzeyi yüzey (SDI) ve yüzeyaltı (SSDI) damla sulama yöntemlerinde oluşturularak belirlenmiştir. Sonuç olarak sorgum bitkisi için Akdeniz koşullarında üst sınır değeri 5.5°C, alt sınır denklemi ise T_c-T_a = -1.96*VPD-0.08 olarak hesaplanmıştır. Deneme süresince, SDI yöntemi ile karşılaştırıldığında SSDI yönteminde hesaplanan CWSI değerlerinin daha düşük olduğu gözlemlendi. Ayrıca sorgumda CWSI arttıkça yaprak sayısı, yaprak alan indeksi ve klorofil içeriği değerlerinin azaldığı ve bunun sonucunda özsu ve biyoetanol veriminin azaldığı saptanmıştır. Bu çalışmada, sorgumda sulama suyu seviyesi (I)-CWSI, bitki su tüketimi (ET)-CWSI, bitkinin fizyolojik özellikleri (yaprak sayısı, yaprak alan indeksi, klorofil içeriği)-CWSI arasında, özsu verimi-CWSI, biyoethanol verimi-CWSI arasında yüksek düzeyde üstel ilişki ve negatif korelasyon olduğu belirlenmiştir. Düşük CWSI ve yüksek biyoetanol verimi dikkate alındığında, sorgum bitkisi için SSDI yönteminin daha uygun olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Biyoetanol verimi, Özsu verimi, Yaprak sayısı, Yaprak alan indeksi, Klorifil içeriği

1. Introduction

In recent years, the use of bioethanol among renewable energy sources has increased (Azadi et al., 2012; Sarkar et al., 2012; Aksoy et al., 2023). In 2030, it is estimated that bioethanol production will increase by 132 billion liters under current conditions in the world (OECD-FAO, 2021). The most important feature of bioethanol is that plants reuse the CO_2 released during its use and consumption and thus do not cause global warming (Kadam et al., 2002; Lal, 2008). Irrigation is the most important input limiting the environmental sustainability of bioethanol. Energy crops to be grown for this purpose will increase the pressure on water resources during cultivation, as they will constitute a separate area in the agricultural sector that continues to feed people in agriculture. Sorghum is considered the energy plant of the future (Reddy et al., 2005; Almodares et al., 2007; Davila-Gomez et al., 2011; Zegada-Lizarazu and Monti, 2012; Mullet et al., 2014) because it has been determined in many studies that it is a more drought-resistant plant than wheat, corn, and sugar cane used for bioethanol production. Additionally, compared to these plants, the cultivation time is shorter and the production cost is lower (Lueschen et al., 1991; Hunter, 1994; Assefa et al., 2010; Davila-Gomez et al., 2011; Fracassoa et al., 2016). As irrigation water is limited, especially in arid and semi-arid countries, sorghum's drought-tolerant characteristics make its bioethanol cultivation sustainable.

Although sorghum has been identified as a drought-tolerant plant, its response to water stress is unclear in the literature. In studies of deficit irrigation in sorghum, it has been found in some studies that up to a certain level of water deficiency there is no change in yield (Smith and Buxton, 1993; Howell et al., 2007; Miller and Ottman, 2012; Xie and Su, 2012; Campi et al., 2014) while in other studies there is a reduction in yield due to water stress (Sakellariou–Makrantonaki et al., 2006; Sakellariou-Makrantonaki et al., 2007; Dercas and Liakatas, 2007; Mygdakos et al., 2009; Mastrorilli et al., 2011; Vasilakoglou et al., 2011; Klocke et al., 2012; Wani, 2012; Tolk et al., 2013; Jahansouz et al., 2014; Jabereldar et al., 2017; Bell et al., 2018; Polat, 2022). In addition, although bioethanol yield is evaluated in some of the studies (Smith and Buxton, 1993; Sakellariou-Makrantonaki et al., 2007; Vasilakoglou et al., 2011; Miller and Ottman, 2012), there are more studies in which biomass yield is evaluated. More studies are needed to examine the effect of water stress on bioethanol yield in sorghum varieties grown for bioethanol production.

Accurately monitoring the water status of the plant and understanding the plant's response to water stress is very important for optimizing irrigation systems and saving water (Yazar et al., 1999; Gu et al., 2021). The water status of plants can be measured by methods based on plants, soil, and climate indicators, or a combination of these (Jones, 2014; Alves and Pereira, 2000). Direct measurement of the plant's water status is a more useful method because it can directly determine the plant's response to stress, and more accurate information can be obtained since plants can respond to both soil and climatic factors. (Jones, 1990; Khorsandi et al., 2018; Simbeye et al., 2023). Methods such as stomatal conductance, photosynthetic rate, leaf water potential, and stem water potential are commonly used to determine plant water status. However, these methods take a long time and require high labor. Additionally, leaf water potential and stem water potential measurements may cause damage to plants (Ballester, 2013; Khorsandi et al., 2018; Gu et al., 2021). For this reason, water status should be measured with a method that does not harm the plant, is not laborious, and is continuous.

Canopy temperature (T_c), measured via infrared thermometers or thermal cameras, is an ideal physiological indicator for monitoring plant water status (Moller et al., 2006; Ballester et al., 2013; Kullberg et al., 2017). With this method, the plant's water stress can be monitored for a long time without damaging the plant (Jones, 2004; Leinonen and Jones, 2004; Gu et al., 2021). When there is a water deficiency in the root zone of plants, the water potential gradient in the stem decreases. This change reduces stomatal conductance in leaves, causing a decrease in transpiration and consequently an increase in leaf temperature (Hsiao, 1973; Idso, 1982; Jones, 1999; Leinonen and Jones, 2004; Jones, 2004). Therefore, infrared radiation emitted by the canopy can be used as an indicator of plant water stress (Idso et al., 1981; Jackson, 1982; Jones, 1999; Alves and Pereira, 2000; Irmak et al., 2000; Payero et al., 2005; Payero and Irmak, 2006; O'Shaughnessy et al., 2011; Taghvaeian et al., 2012; Ballester, 2013; Bozkurt Çolak et al., 2015). However, canopy temperature is not only affected by water deficiency in the soil, but can also vary depending on meteorological conditions such as air temperature and wind, and morphological characteristics of the plant such as leaf shape and size (Maes et al., 2012). Therefore, canopy temperature needs to be standardized so that it can be used as an indicator of water stress (Gu et al., 2021). Idso et al. (1981) and Jackson et al. (1981) proposed the CWSI and developed empirical and theoretical models to calculate it.

Among CWSI calculation methods, the empirical model has gained importance because it can be calculated using fewer parameters and is more practical. Empirical method has been used to determine water status and schedule irrigation in many plants and consistent results have been obtained O'Shaughnessy et al. (2012) in sorghum, Veysi et al. (2017) in sugarcane, Yuan et al. (2004) in wheat, Payero and Irmak (2006) in corn and soybean, Taghvaeian et al. (2012) in corn. The basic graph on which the non-water stress baseline (NWSB) (lower limit) and non-transpiring baseline (upper limit) are constructed is the key to forming an empirical CWSI model (Idso, 1982). Defining the NWSB is the most important and distinctive stage in constructing the basic graph (Gardner et al., 1992). Studies in the literature have determined that NWSB varies in growth stages and may vary depending on the plant and climate (Idso, 1982; Taghvaeian et al., 2014; De Jonge et al., 2015). However, once reliable NWSB was determined, it was determined that CWSI could be accurately predicted in similar climatic conditions and the same plant, moreover, in the same growth periods (Gu et al., 2021). In many studies conducted under different plant and climate conditions, it has been determined that CWSI is strongly associated with plant physiological characteristics such as leaf water potential, stomatal conductance, and photosynthesis (Xu et al., 2016; Erdem et al., 2010; Sezen et al., 2014; Lena et al., 2020; King et al., 2020; Gonzalez-Dugo et al., 2020; Gu et al., 2021) and with yield (Yazar et al., 1999; Irmak et al., 2000; Wanjura et al., 2000). However, in sorghum, it is not yet clear whether CWSI can predict physiological and yield parameters in the plant or the relationships between them. In sorghum, there are very few studies on the possibilities of using CWSI in irrigation programming and its relationship with plant physical parameters. O'Shaughnessy et al. (2012) theoretically calculated the CWSI values in grain sorghum irrigated with the furrow irrigation method and reported that irrigation in sorghum could be programmed with the CWSI time threshold (CWSI-TT) method. They evaluated the yield as dry grain yield-biomass yield. Olufayo et al. (1996) calculated CWSI values (empirical method) in grain sorghum irrigated with the sprinkler irrigation method. They explained that grain yield can be estimated from average CWSI values. Wanjura et al. (1990) calculated CWSI values in grain sorghum irrigated with furrow irrigation with a theoretical method and determined a linear relationship between mean CWSI and grain yield. Ajayi and Olufayo (2004) explained that grain sorghum yield and ET values can be estimated from canopy temperature data and this can be used in optimum irrigation strategies on a local scale. Karataylı (2021) calculated CWSI values in grain sorghum according to the experimental method. The author determined a linear inverse relationship between the hay yield obtained from different irrigation levels and CWSI and concluded that the CWSI value could be used in irrigation scheduling. Keten (2020) obtained the lower limit and upper limit equations using the experimental method for silage sorghum irrigated with the drip irrigation method.

When the studies on sorghum are examined, it is seen that the studies examining the CWSI change in drip irrigation method are quite limited. While it has been determined that drip irrigation in sorghum both increases yield and saves water, studies comparing surface and subsurface drip irrigation methods have reported that more yields are achieved in SSDI and that this method increases water saving (Sakellariou-Makrantonaki et al., 2006; Sakellariou-Makrantonaki et al., 2007; Mygdakos et al., 2009; Aydinsakir et al., 2021). However, there is no study comparing CWSI obtained from SDI and SSDI methods. In addition, in these studies, the relationship between CWSI and biomass and hay yield values were examined. More studies are needed to examine the relationship between bioethanol yield and CWSI.

The aim of this study is, 1- to calculate the lower and upper limit equations for sorghum under Antalya conditions, 2- to assess mean CWSI values calculated by using experimental methods in SDI and SSDI drip irrigation methods for sorghum, 3- to use a non-linear exponential relationship to describe the relationships between CWSI and irrigation, evapotranspiration (ET), physical characteristics of the plant (leaf number, leaf area index, chlorophyll content), bioethanol and juice yield and irrigation water productivity (IWP).

2. Materials and Methods

2.1. Research area, soil, irrigation water and meteorological parameters

This research was conducted at the Batı Akdeniz Agricultural Research Institute (BATEM), Antalya, between July and September 2017. The physical and chemical properties of the soil are shown in *Table 1*. Na, K, Ca, Mg, HCO_3, SO_4, pH, and EC_w values of the irrigation water used in the study were determined as 0.49, 4.23, 1.85, 5.03, 0.53, 1.06 me L^{-1}, 7.3, and 0.56 dS m^{-1}, respectively. The Monthly average values of meteorological data and long-term measurements in Antalya during the experimental period are given in Table 2. During the research, all meteorological data belonging to the experimental area were taken from the 07.01 coded meteorological station of the Agricultural Monitoring and Information System (TARBIL), which is located at longitudes 36.9411°N, 30.891°E, 250 m away from the experiment side. Detailed information about fertilizer applications and crop protection measures in the research area is also given in Aydinsakir et al. (2021).

Table 1. Physical and chemical characteristics of the soil

Depth (cm)	Sand (%)	Clay (%)	Silt (%)	Texture	$CaCO_3$ (%)	ECw (dS m^{-1})	pH	Field Capacity (%, g g^{-1})	Permanent Wilting Point (%, g g^{-1})	Bulk Density (g cm^{-3})
0-30	29.18	21.2	49.6	Loam	24.0	0.63	7.50	24.04	12.78	1.35
30-60	32.65	17.3	50.1	Loam	29.7	0.44	7.70	23.52	12.81	1.30
60-90	36.59	15.3	48.2	Loam	30.1	0.38	7.80	21.67	11.30	1.32

Table 2. Monthly mean climatic data throughout the growing season of the sorghum at the experimental site for the long-term and the experimental year.

Years	Months	Temperature (°C)	Rainfall (mm)	Evaporation (mm)	Wind (m s^{-1})	Relative humidity (%)
1954-2016	May	20.4	30.0	143.2	2.0	66.2
	June	25.5	7.6	177.5	1.9	55.2
	July	28.3	3.4	195.5	1.9	54.3
	Aug.	28.2	1.8	172.4	1.7	56.7
	Sep.	24.4	12.3	134.4	1.8	58.8
	Oct.	20.0	80.1	150.6	2.0	61.0
2017	May	21.3	59.6	108.2	1.9	67.7
	June	26.3	-	125.6	1.8	63.1
	July	30.5	-	161.1	1.9	57.4
	Aug.	29.0	-	155.2	1.9	64.4
	Sep.	26.9	-	137.3	1.8	62.8
	Oct.	22.2	12.6	111.5	1.7	53.2

2.2. Plant material, planting, irrigation systems and statistical design

The plant material used was the Sorghum variety (*Sorghum bicolor* L.), which is widespread under 5 Mediterranean conditions. The sorghum seeds were planted in May 2017 with a row spacing of 45 cm and a row depth of 3-5 cm. As a result of the infiltration tests in the field, the average infiltration rate of 12 mm h^{-1} was determined. Accordingly, the distance between the drippers in the rows was 45 cm and the flow rate was determined to be 2.1 L h^{-1}. For SSDI irrigation, laterals were placed at a depth of 45 cm below the soil surface.

Table 3. Irrigation methods and treatments used in the study

Irrigation methods		Irrigation treatments
Irrigated	Surface drip irrigation (SDI)	SDI_{25} SDI_{50} SDI_{75} SDI_{100}
	Subsurface drip irrigation (SSDI)	$SSDI_{25}$ $SSDI_{50}$ $SSDI_{75}$ $SSDI_{100}$
Rainfed		I_0

The study was designed in randomized complete block design to include two irrigation methods (SDI and SSDI) and five different irrigation treatments (I_0, I_{25}, I_{50}, I_{75}, and I_{100}) in three replications. The full irrigation treatment was performed when 40% of the available water capacity in the 0-90 cm soil profile was depleted. In comparison, the deficit irrigation treatments were applied at 75%, 50%, and 25% of the full irrigation treatment. Irrigation methods and treatments are shown in *Table 3*. Details regarding the experimental design of the study can be found in Aydınsakir et al. (2021) article.

2.3. Measurements

The method used to calculate evapotranspiration (ET), leaf number (LN), leaf area index (LAI), chlorophyll content (CC), bioethanol, juice yield, and irrigation water productivity (IWP) values is explained in detail in Aydinsakir et al., (2021). The statistical method used is also detailed in this article. Therefore, information on measuring the parameters required to determine CWSI is given here.

CWSI was calculated according to Idso et al. (1981) by using measured crop canopy temperature (T_c) – air temperature (T_a) and vapor pressure deficit (VPD). Empirical CWSI was calculated using Equation 1.

$$CWSI = \frac{(T_c-T_a)_m-(T_c-T_a)_{ll}}{(T_c-T_a)_{ul}-(T_c-T_a)_{ll}} \qquad \text{(Eq. 1)}$$

Where $(T_c\text{-}T_a)_m$ is the measured difference between crop canopy temperature and air temperature, $(T_c - T_a)_{ll}$ is the lower limit representing the temperature difference for a fully irrigated crop, and $(T_c - T_a)_{ul}$ is the upper limit representing the temperature difference between the crop canopy and ambient air when the plants are severely stressed. Canopy temperatures were measured with an infrared thermometer (Spectrum Technologies Inc., Aurora, IL 60504, USA) held in a 90° angle to the soil surface between 12:00 and 15:00 hours, from four directions in each plot. The average of canopy temperatures measured every hour between 12:00 and 15:00 was used to calculate CWSI. To obtain the lower bound, canopy temperatures were measured hourly between 07:00 and 19:00 on August 20, 2017 and September 6, 2017 at full irrigation (I_{100}) in both methods, and their averages were used in the base graph. To increase water stress, three replicate plants were randomly selected from the rainfed treatment (I_0), and one day before the measurement, these plants were separated from their roots and tied with a stick (Sammis, 1988). Canopy temperatures were measured hourly between 12:00 and 15:00 and these values were used to establish a lower limit line. Measurements were taken on August 26 and 27 and on September 6, 7, and 11, 2017 to determine the lower limit.

Vapor pressure deficit (VPD) was calculated using the following equations depending on air temperature and RH values (Allen et al., 1998):

$$e_s = 0.6108 \times exp\left[\frac{17.27T}{T+237.3}\right] \qquad \text{(Eq. 2)}$$

$$e_a = e_s \times \left(\frac{RH}{100}\right) \qquad \text{(Eq. 3)}$$

$$VPD = e_s - e_a \qquad \text{(Eq. 4)}$$

Where, es is the saturation vapor pressure (kPa), T is the mean air temperature (°C), RH is the relative humidity of the air (%), and, VPD is the vapor pressure deficit (kPa). T and RH values were taken from the meteorological station.

To calculate the CWSI values obtained in this study, the average of canopy temperatures measured every hour between 12:00 and 15:00 was used. Canopy temperatures were measured on July 16, 17, 19, and on August 15, 20, 22, 26, and September 4,6, 7, 11 in 2017.

3. Results and Discussion

3.1. Soil water storage

Soil water storage values during the 2017 growing periods for each treatment (SDI and SSDI) are given in *Figure 1*.

Different irrigation water applications were started on June 10, 2017, and a total of 18 and 16 irrigations were conducted on the SDI and SSDI respectively, depending on soil moisture. With the exception of the rainfall treatment (I_0), soil moisture storage was between the field capacity and wilting point for all treatments in both SDI and SSDI methods. Soil moisture storage decreased below the wilting point from the 60th day after sowing in rainfed treatment (I0). With both irrigation methods, it can be is seen that soil water storage increases with decreasing water deficit (SDI-SSDI). Soil moisture storage flucted near the wilting point throughout the growing season in the SDI_{25} and $SSDI_{25}$ treatments. While soil moisture storage decreased from the 70^{th} day after sowing to the end of the growing period in SDI_{25}, it showed a decreasing change before irrigation and a decrease after irrigation in $SSDI_{25}$. The reason for this is probably that the plant benefits more from the irrigation water supplied to the plant in the SDI method and some of the irrigation water applied in the SDI method evaporates from the soil surface. On the other hand, the SDI_{50} treatment showed a change in soil moisture storage compared to the $SSDI_{50}$ treatment, which was closer to I_0 throughout the growing season. Soil moisture storage changed closer to 50% of available water, especially after the irrigation days in the $SSDI_{50}$ treatment. On the other hand, soil moisture storage decreased below 50% of available water, especially before the irrigation days in SDI_{75}, while the soil moisture storage was generally above 50% of available water throughout the growing season. In addition, soil moisture storage changed between field capacity and 50% of available water in SDI_{100} and $SSDI_{100}$ treatments throughout the growing period, but while the soil moisture storage did not decrease and showed a more stable change in $SSDI_{100}$ treatment, it decreased to 50% available water before irrigation in SDI_{100}.

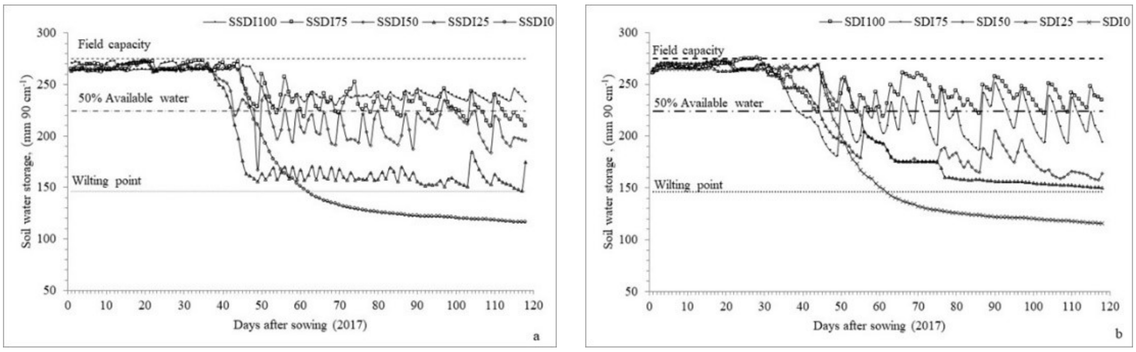

Figure 1. Soil water storage (mm) in 0–90 cm depth in the experiment (a: Subsurface drip irrigation, SSDI; b: Surface drip irrigation, SDI)

3.1. Upper and lower limit baselines

As explained in the material method section, T_c values were measured between 07:00 and 19:00 from I100 for the lower limit, and between 12:00 and 15:00 from the I0 for the upper limit. T_c-T_a values are plotted against VPD and when deriving the regression equation, it is assumed that the plant is not exposed to any environmental stress other than water stress Idso et al. (1981). The basic graph is given in *Figure 2*.

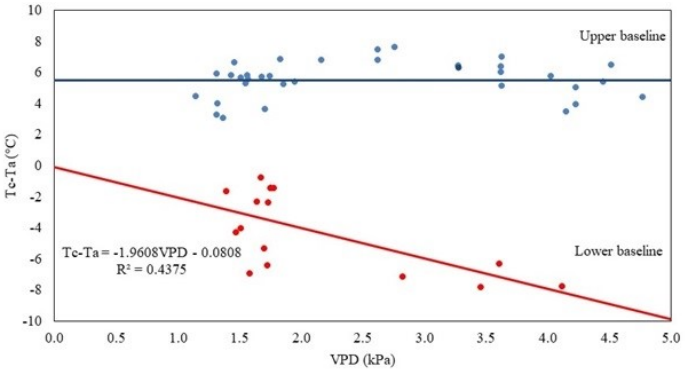

Figure 2. Relationships between canopy temperature and air temperature (T_c-T_a) and vapor pressure deficit (VPD) of sorghum at Antalya

When examining the graph, it becomes clear that the VPD range for the lower limit is between 1.0 and 4.5. Gardner and Shock (1989) suggested that the VPD range should be between 1 and 6, for better use in other studies. In our study, measurements were taken in a wider VPD than in other studies, even though it was not between 1 and 6. As can be seen in Figure 2, the lower baseline changes as a function of VPD, while the upper baselines does not depend on VPD. The resulting lower baseline (No Water Stress Baseline: NWSB) was defined by the linear equation T_c-T_a =-1.96 VPD-0.08 (R^2=0.44). Significant differences were found between the baselines we developed for sorghum and the previously developed baselines. Olufayo et al. (1996) found this baseline for grain sorghum as T_c-T_a=-2.51VPD+3.76 in France, while Keten (2020) determined the lower limit baseline for silage sorghum as T_c-T_a=-1.44VPD+0.4095 in 2018 and T_c-T_a=-1.51VPD-1.18 in 2019 in Kahramanmaraş, Karataylı et al. (2021) determined the lower baseline equation of sweet sorghum plant as $T_c - T_a = -1.7763\ VPD + 3.3395$ under Adana conditions. The slope and intercept of a linear relationship in these studies and our study are different. Many researchers have emphasized that slope and intercept may vary according to plant type and different climatic conditions (Idso, 1982; Taghvaeian, 2014; De Jonge et al., 2015). When we compare Karatayli et al. (2021) and Keten (2020), we think that this difference is due to the plant variety. It is known that sweet sorghum, grain sorghum, and silage sorghum show different morphological and biochemical responses to water stress (Massacci et al., 1996; Zegada-Lizarazu and Monti, 2012). Slope and intercept values may vary depending on the plant species or even different genotypes of the same plant (Gu et al., 2021; Godson-Amamoo et al., 2022). For example, Candogan et al. (2013) suggested that the reason for the difference between the slopes and intervals obtained by Nielsen (1990) in soya plants is due to the plant variety and climate conditions. This difference may also be due to the difference in leaf areas between varieties. Kanbar et al. (2020) explained that under the same conditions, there is a difference between the leaf areas (green) obtained from sweet, grain, and forage sorghum genotypes. Since leaf size affects leaf temperature (Smith, 1978), it may have caused the lower limit values obtained from different genotypes to differ. Moreover, the lower limit is also differentiated by the fact that the study was not carried out under similar climatic conditions, irrigation practices, and soil types (Erdem et al., 2012). On the other hand, Olufayo et al. (1996) obtained grain yield in his study. When sorghum is grown for bioethanol, it is harvested immediately after the flowering period, while it is harvested after grain filling for grain yield. Taking measurements during different growth periods may change the NWSB. Although there have been previous studies in which the same NWSB was used successfully in different plants in different growing seasons and did not change according to the growth period (Grimes and Williams, 1990; Candogan et al., 2013; Bellvert et al., 2014; De Jonge et al., 2015; Bozkurt Çolak and Yazar, 2017; Zhang et al., 2023), there are also studies in which it was determined that NWSB varies considerably according to the growth periods and cannot be used (Nielsen et al., 1994; Orta et al., 2003; Cui et al., 2005; Gontia and Tiwari., 2008; Taghvaeian et al., 2014; Veysi et al., 2017; Alghory and Yazar, 2019; Khorsand et al., 2019; Ru et al., 2020; Gu et al., 2021). When these studies are examined, it is a remarkable result that this change occurs mostly in corn plants according to growth periods. For example, Khorsand et al. (2019) determined that the slopes and intercept of the lower limit values obtained in different growth periods of the corn are different. Gu et al. (2021) reported that the slope and intercept values of the lower line change severely as the growth period changes in both corn varieties. Taghvaeian et al. (2013) and De Jonge et al. (2015) obtained different slope values in the same country and city. Although there is no study comparing growth periods in sorghum, we think that similar findings can be obtained with corn plants. Since the sorghum plant is harvested in different growing periods depending on the yield to be calculated, it should be specifically stated in which period the measurements were taken when establishing the lower limit. Since the lower limit values in our study were taken towards the end of the flowering period and the leaf morphology differs during the growth periods of sorghum, we thought that T_c values might also be different.

When we compare the upper limit, Olufayo et al. (1996) calculated it as 0.5-4.5, Keten (2020) calculated it as 0.34-1.13, and Karataylı (2021) calculated it as 3.48. When these studies are examined, it is seen that our upper limit (5.5) is closer to the value found by Olufayo et al. (1996). Since the upper limit line does not depend on the VPD, plant type is more important than the same climate and region. Since the upper limit value was determined in the generative period in this study, this difference may also be due to the difference in the growth period. For instance, Khorsand et al. (2019) determined the upper limit value for corn as 4.69 in vegetative phase-floral initiation, 2.83 in flowering-pollination, and 10.01 in seed seating-seed filling.

For sorghum, in particular studies are required in which both the lower and upper limits are determined and compared separately in different growing seasons as, otherwise the accuracy of the use of the base graphs determined decreases. Idso (1982) stated that taking canopy development into account when developing baselines helps to reduce errors associated with the natural spatial variability of field crops. Furthermore, the use of the graph is limited when the climate changes, even in the same region (Jackson et al., 1981; Jackson, 1982; Payero et al., 2005; De Jonge et al., 2015). Taking measurements under the same climatic conditions, on the same plant species, and during the same growing seasons increases the accuracy of the graph. In addition, the high measurement frequency also has an effect. Payero and Irmak (2006) compared the lower and upper limit lines of corn and soybean by calculating them every 10 minutes. They explained that the baselines varied throughout day and from day to day, and observed a daily variation of about 5 degrees.

3.2. Relationships between mean CWSI and crop growth and yield parameters

The effects of the interaction between the drip irrigation methods and irrigation levels on sorghum parameters are shown in *Table 4*. The relationships among between mean bioethanol yield, juice yield, leaf number, LAI, CC, irrigation, ET, IWP, and mean CWSI for different irrigation treatments in SDI and SSDI methods are given in Figure 3. The correlation coefficients indicating the direction and strength of the relationship between bioethanol yield, juice yield, leaf number, LAI, CC, irrigation, ET, IWP, and mean CWSI are given in *Table 5*. Since this article aims to compare the CWSI values obtained by different methods, we have not discussed the effect of the interaction of irrigation methods and irrigation levels on physiological parameters and yield parameters. More detailed information can be found available in Aydinsakir et al. (2021).

Table 4. Irrigation, evapotranspiration, leaf number, leaf area index, chlorophyll content, juice yield bioethanol yield, hay yield, irrigation water productivity, and crop water stress index in the experiment

Treatments	**I (mm)**	**ET (mm)**	**LN**	**LAI (m^2 m^{-2})**	**CC**	**Juice yield (L ha^{-1})**	**Bioethanol yield (L ha^{-1})**	**Hay yield (t ha^{-1})**	**IWP (kgm^{-3})**	**Seasonal average CWSI**
SDI_{100}	468.2	553.6	11.0	14.0 b	47.0	44890 a	1799 ab	20.52 b	2.7	0.32
SDI_{75}	346.6	495.8	10.7	11.0 e	38.1	37260 b	1603 bc	15.07 c	2.1	0.34
SDI_{50}	252.0	412.2	10.7	10.6 f	26.7	26260 c	1447 c	13.37 cd	2.3	0.40
SDI_{25}	140.0	312.9	9.7	9.8 h	14.2	24793 d	1412 c	9.15 f	1.2	0.49
I_0	30.5	206.0	9.3	9.0 i	5.8	1596.3 e	90.3 d	7.44 f	-	0.58
$SSDI_{100}$	429.0	526.4	11.0	15.0 a	51.4	51322 a	2085 a	23.67 a	3.1	0.27
$SSDI_{75}$	335.2	450.1	11.0	11.9 b	33.3	50462 a	2045 a	21.07 ab	3.3	0.29
$SSDI_{50}$	232.5	361.4	10.7	11.2 d	20.2	40903 b	1684 bc	15.96 c	2.5	0.35
$SSDI_{25}$	130.2	278.4	10.3	9.9 g	11.5	25574 b	1569 bc	12.11 de	1.6	0.41
			NS	**	NS	*	*	*		-

SDI: Surface drip irrigation, SSDI: Subsurface drip irrigation, I: Irrigation water applied, ET: Evapotranspiration, IWP: Irrigation water productivity, LN: Leaf number (number plant^{-1}) LAI: Leaf area index, CC: Chlorophyll content.
*, ** and N.S., Significant at the $p < 0.05$, $p < 0.01$ level and not significant, respectively.

The means indicated with the same small letter in the same column are not significantly different ($p < 0.05$).

Table 5. Correlation coefficients indicating the direction and power of the relationship between irrigation-CWSI, ET-CWSI, leaf number-CWSI, LAI-CWSI, CC-CWSI, Juice yield-CWSI, bioethanol yield-CWSI, IWP-CWSI of sorghum depending on the amount of irrigation water

Parameters	**Irrigation methods**	**Correlation coefficients (r)**
CWSI-Irrigation	SDI	-0.980
	SSDI	-0.945
CWSI-ET	SDI	-0.976
	SSDI	-0.956
CWSI-Leaf number	SDI	-0.972
	SSDI	-0.997
CWSI-LAI	SDI	-0.835
	SSDI	-0.836
CWSI-CC	SDI	-0.981
	SSDI	-0.853
CWSI-Juice yield	SDI	-0.938
	SSDI	-0.994
CWSI-Bioethanol yield	SDI	-0.937
	SSDI	-0.994
CWSI-IWP	SDI	-0.883
	SSDI	-0.976

(CWSI: Crop water stress index, ET: Evapotranspiration, LAI: Leaf area index, CC: Chlorophyll content, IWP: Irrigation water productivity, SDI: Surface drip irrigation, SSDI: Subsurface drip irrigation)

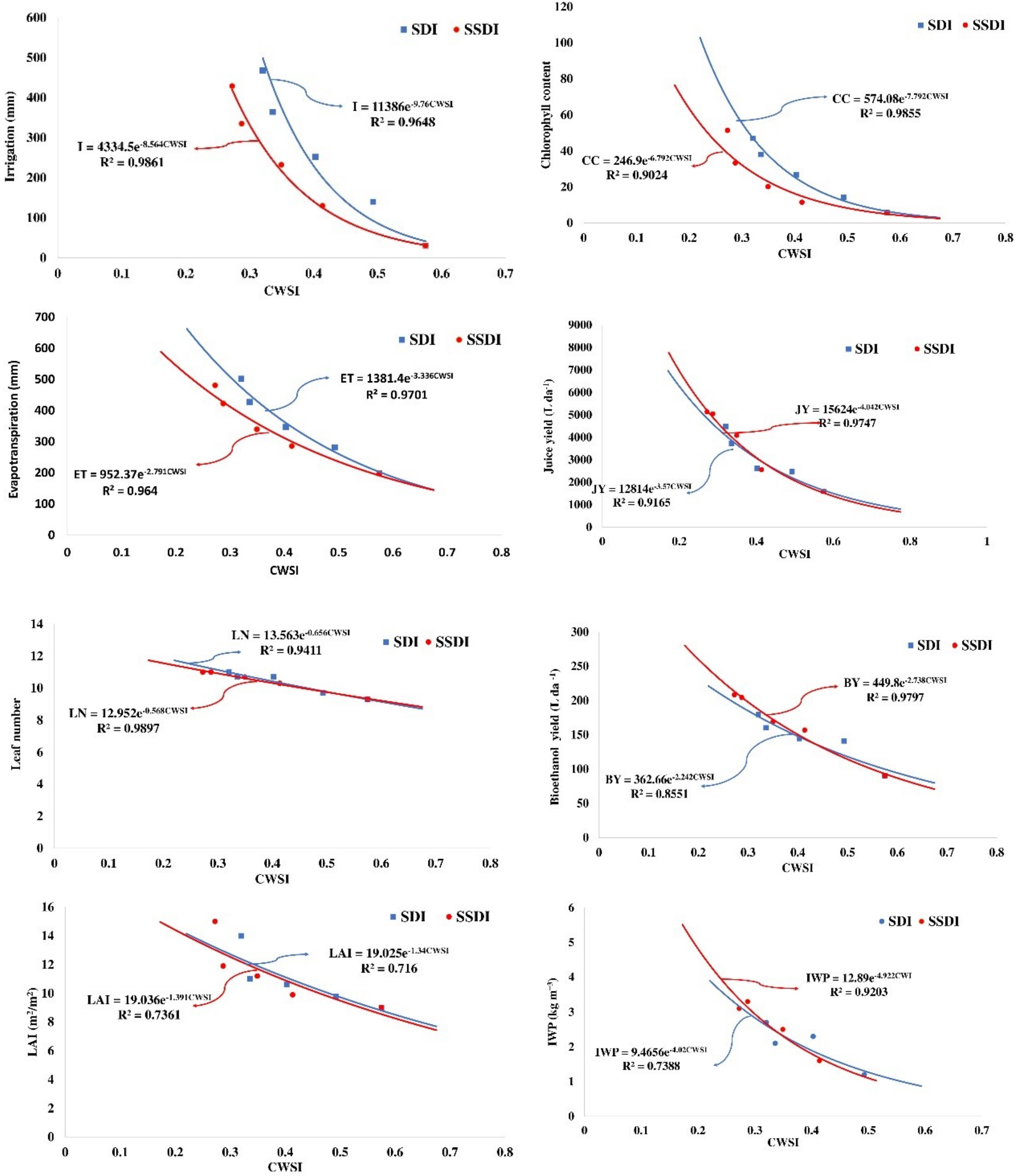

Figure 3. Relationships between CWSI and irrigation, CWSI and ET, CWSI and Leaf number, CWSI and LAI, CWSI and CC, CWSI and Juice yield, CWSI and bioethanol yield, CWSI and IWP (CWSI: Crop water stress index, ET: Evapotranspiration, LAI: Leaf area index, CC: Chlorophyll content, IWP: Irrigation water productivity, SDI: Surface drip irrigation, SSDI: Subsurface drip irrigation)

The seasonal average CWSI in treatments I100, I75, I50 and I25 is calculated as 0.32, 0.34, 0.40, and 0.49, respectively, in the SDI method, while it is calculated as 0.27, 0.29, 0.35 and 0.41, respectively in the SSDI method (*Table 4*). It is a noteworthy that a lower CWSI is calculated for the SSDI method in all treatments with the SSDI method same amount of irrigation. Although less irrigation water was applied at the same levels in the SSDI method, we thought that the lower CWSI value was obtained in all treatments as a result of the plant benefiting more from irrigation water in the root zone in this method. Although there is no statistical difference, the higher IWP values in the SSDI method with the same irrigation levels support this hypothesis. It can be assumed that, the plant uses the water more efficiently with the SSDI method and the amount of transpiration is higher than with the SDI method. It can be assumed that as the amount of transpiration increases, the canopy temperature decreases and, accordingly, CWSI values decrease.

There are only a few studies that compare the CWSI values determined using different methods. Similar to our study, Bozkurt Çolak et al. (2015) compared the SSDI and SDI methods in eggplant and found that the SDI method reduced CWSI values. Similarly, Sezen et al. (2014) reported that the CWSI value calculated by the drip irrigation method in red pepper (*Capsicum annuum L.*) was lower than the furrow irrigation method. On the other hand, Bozkurt Çolak et al. (2021) found that they could not detect any difference between the CWSI values determined by these two methods in the quinoa plant. For sorghum, there is no study in the literature that compares the CWSI values obtained with these methods. For sorghum production to be sustainable, the most appropriate irrigation method must be determined. In our study, the lower CWSI values of the SSDI method prove that this method is more advantageous. However, further studies are needed, especially to compare the CWSI values of the SDI and SSDI methods.

It can be seen that there is no statistical difference between the LN and CC values of the different treatments, but there is a difference between the LAI values (*Table 4*). Again, although higher LAI values were obtained with the SSDI method, lower CWSI values were calculated. The relationship between LAI and CWSI appears to be stronger than the relationship between LN and CC. Although there are studies in which the SSDI method increases LAI values in sorghum (Sakellariou et al., 2007) there is a need for studies investigating the relationship with CWSI.

The highest bioethanol yield values were obtained with $SSDI_{100}$, $SSDI_{75}$ and SDI_{100} and no statistical difference was found between these treatments. In addition, the CWSI value for these treatments was calculated to be 0.27, 0.29, and 0.32, respectively. The lower CWSI calculation for $SSDI_{75}$ than for SDI_{100} indicates that $SSDI_{75}$ is advantageous to achieve the highest bioethanol yield in sorghum while water savings. Also, Aydinsakir et al. (2021) suggested that in cases where water resources are limited, SSDI75 can be used to save water. CWSI values obtained in this study support this result.

When *Figure 3* and *Table 5* were considered together, it was found that there was a high degree of exponential relationship and a strong negative correlation between irrigation-CWSI, ET-CWSI, leaf number-CWSI, LAI-CWSI, CC-CWSI for both irrigation methods in sorghum. In both methods, as the amount of irrigation water applied increases, the water consumption of the plant also increases and thus the transpiration of the plant. Canopy temperature decreases and correspondingly CWSI values decrease. Similarly, Yazar et al. (1999) obtained a linear inverse relationship between applied irrigation (mm) and CWSI in corn. It has been determined that CWSI values increase as water deficit increases in different plants (Sezen et al., 2014; Bahmani et al., 2017; Bozkurt Çolak and Yazar, 2017; Yetik and Candogan, 2023).

Decreasing ET values reduce transpiration values, which increases causing the canopy temperature and thus the CWSI value. Our result is consistent with studies from the literature. Olufayo et al. (1996) observed common and strong relationships between baseline indices canopy surface temperature and relative ET in sorghum under different weather conditions. Furthermore, the researchers stated that ET can be predicted from crown temperature data obtained at different time points. Yazar et al. (1999) identified a linear inverse relationship between ET and CWSI in maize. Braunworth and Mack (1989) found a significant correlation between ET and CWSI (in sweet corn). Yetik and Candogan (2023) found the relationship between ET and CWSI significant in the sugar beet and calculated the determination coefficient of the relationship between ETc and CWSI as $R^2 = 0.9902$. Moreover, the researchers explained that regression equations obtained by graphing ET against CWSI can be used to predict ET. Gu et al. (2021) determined a significant linear correlation between ET and CWSI in corn. In our study, we determined that ET values can be estimated by using CWSI values and $ET = 1381.4e^{-3.336\,CWSI}$ (SDI), $ET = 952.37e^{-2.791CWSI}$ (SSDI) equations. Of course, more studies are needed to support this finding.

The decrease in the number of leaves is due to a lack of moisture in the soil (Sanchez et al., 2002). The decrease in soil moisture reduces carbon assimilation, stomatal conductance, and cell turgor, and leads to stomatal closure. As water stress increases, stomata closure causes leaves to wilt and leaf number to decrease (Prasad et al., 2021). Consequently, when the stomata close, the canopy temperature increases and the CWSI value of the plant increases. In sorghum, the decrease in soil moisture content has been found to reduce the number of leaves (Rostampour, 2013; Mahinda, 2014). In this study, the decrease in the number of leaves was found to increase the CWSI.

In both irrigation methods, LAI decreased when CWSI values increased. Decreasing the number of leaves over soil moisture also decreases LAI. In addition, the transpiration rate of the plant decreased with decreasing irrigation amount, which led to increased temperatures in the tree canopy and growth losses. While CWSI values increased, leaf area decreased due to the decrease in growth, and as a result, LAI values also decreased. An inverse relationship between CWSI and LAI has been identified in many different plants (Erdem et al., 2010; Sezen et al., 2014; Alghory and Yazar, 2019; Kirnak et al., 2019; Bozkurt Çolak et al., 2021; Gu et al., 2021). Although many studies have found that LAI values decrease with increasing irrigation water deficit or water stress in sorghum (Sakellariou-Makrantonaki et al., 2006; Sakellariou-Makrantonaki et al., 2007; Dercas and Liakatas, 2007; Zegada et al., 2012; Mahinda, 2014) no study investigating the relationship between CWSI and LAI was found.

Water stress reduces CC in sorghum (Xu et al., 2000). In both methods, an increase in CWSI leads to a significant decrease in CC and thus impairs efficiency. When plants are under stress, chlorophylls decrease during leaf senescence (Merzlyak et al., 1999). When the plant closes its stomata under stress, transpiration decreases, T_c increases and consequently CWSI increases. CC and CWSI are related to each other, but the correlation test is designed to strengthen the degree of this relationship. In addition, from the equations obtained in our study (*Figure 3*), it was determined that CWSI values can be estimated by measuring the CC value.

Juice yield and bioethanol yield are linked. In different sorghum varieties, bioethanol yield has been determined to be positively correlated with juice yield in various studies (Rono et al., 2018; Suwarti et al., 2018; Güden et al., 2021). Therefore, in this study, we evaluated the relationship of both yield parameters with CWSI. It was determined that there was a high level of exponential relationship (R^2=0.917 in SDI, R^2= 0.975 in SSDI) and a strong negative correlation (r = -0.938 in SDI, r =-0.994 in SSDI) between juice yield and CWSI. In addition, it was determined that there was a high level of exponential relationship (R^2=0.855 in SDI, R^2= 0.980 in SSDI) and a strong negative correlation (r = -0.937 in SDI, r =-0.994 in SSDI) between bioethanol yield and CWSI.

Additionally, by measuring CWSI values, juice yield was determined with the equations $y = 12814e^{-3.57CWSI}$ in the SDI method, $y = 15624e^{-4.042CWSI}$ in the SSDI method, bioethanol yield was determined with the equations $y = 362.66e^{-2.242CWSI}$ in the SDI method, $y = 449.8e^{-2.738CWSI}$ in the SSDI method. These equations can be used to determine the harvest time in sorghum plants grown for bioethanol purposes. When the bioethanol yield values are compared and confirmed by field studies with the help of these equations in all grown periods of sorghum, the harvest time can be decided at a certain threshold value.

It is seen that as CWSI values increase, both juice yield and bioethanol yield decrease. A strong inverse relationship between CWSI and yield has been determined in different plants (Abdul-Jabbar et al., 1985 for alfalfa; Braunworth and Mack, 1989 for sweet corn; Candogan et al. 2013 for soybean; Wang et al., 2005 and Alghory and Yazar, 2019 for wheat; Irmak et al., 2000 and Gu et al., 2021 for corn; Yetik and Candoğan, 2023 for sugar beet). There are studies that a negative linear relationship between grain yield and CWSI in sorghum. Researchers stated that as CWSI value increases in sorghum, grain yield decreases (Wanjura et al., 1990; Olufayo et al., 1996; Karataylı, 2021). Wanjura et al. (1990) emphasized that yield can be estimated using CWSI values in grain sorghum. In our study, we established the relationship between bioethanol yield and CWSI. More studies are needed to examine the relationship between CWSI and bioethanol yield in varieties grown for bioethanol yield.

Additionally, when *Figure 3* and *Table 4* are examined together, there is no statistical difference in terms of bioethanol yield between SDI_{100} (0.32) and SDI75 (0.34), also between $SSDI_{100}$ (0.27) and SSDI75 (0.29). The yield started to decrease after I_{50} (0.40) in the SDI method and after I50 (0.35) in the SSDI method. Here, the threshold CWSI value can be considered as 0.40 in the SDI method and 0.35 for SSDI. In other words, the yield decreases after the CWSI 0.40 in the SDI method, while 0.35 in the SSDI method.

It was determined that there was a high level of exponential relationship (R^2=0.739 in DI, R^2= 0.920 in SDI) and a strong negative correlation (r = -0.883 in SDI, r =-0.976 in SSDI) between IWP and CWSI. As CWSI values increased, IWP values decreased. In other words, we can say that the increase in water stress in the plant reduces the efficiency of the plant per unit of water. As CWSI increased, yield decreased and, as a result, IWP values decreased. Since one of the purposes of determining CWSI is to determine the water status in the plant, it is important to know the relationship between IWP and CWSI. The exponential relation developed between IWP and CWSI is obtained as $IWP= 9.4656e^{-4.02CWSI}$ in SDI, and $IWP = 12.89e^{-4.922CWSI}$ in SSDI.

4. Conclusion

In this study, the upper limit value was calculated as 5.5ºC and the lower limit equation was determined as T_c-T_a = - 1.96 VPD - 0.08 in Antalya conditions for the sorghum plant. Additionally, we thought that determining the lower limit values of sorghum in different growth periods could increase the accuracy of using the graph in more areas. In sorghum, we recommend that lower limit values be determined and compared in the same growth periods. In sorghum, we calculated lower CWSI in the subsurface drip irrigation method. More studies are needed to support our finding, comparing CWSI values obtained from surface and subsurface irrigation methods. It was determined that there was a high level of exponential relationship and a strong negative correlation between irrigation-CWSI, ET-CWSI, leaf number-CWSI, LAI-CWSI, CC-CWSI, Juice yield-CWSI, bioethanol yield-CWSI, IWP-CWSI for both irrigation methods in sorghum. More studies are needed to examine the variation between bioethanol yield and CWSI in sorghum, especially in varieties grown for bioethanol production.

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Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

We declare that there is no conflict of interest between us as the article authors.

Authorship Contribution Statement

Concept: Polat, B., Aydinşakir, K., Büyüktaş, D.; Design: Polat, B., Aydinşakir, K., Büyüktaş.; Data Collection or Processing: Polat, B., Aydinşakir, K., Büyüktaş.; Statistical Analyses: Polat, B., Aydinşakir, K., Büyüktaş.; Literature Search: Polat, B., Büyüktaş, D.; Writing, Review and Editing: Polat, B., Aydinşakir, K., Büyüktaş, D.

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