Anadolu Tarım Bilimleri Dergisi,
Anadolu Journal of Agricultural Sciences

e-ISSN: 1308-8769, ANAJAS Haziran 2024, 39 (2): 247-267

Effect of Drought Stress on Yield and Some Morphological Characteristics in Wheat

Kuraklık Stresinin Buğdayda Verim ve Bazı Morfolojik Özellikler Üzerine Etkisi

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Makale Bilgisi/Article Information

Makale Türü/Article Types: Araştırma Makalesi/Research Article
Geliş Tarihi/Received: 12 Eylül/September 2023
Kabul Tarihi/Accepted: 26 Nisan/April 2024
Yıl/Year: 2024 | **Cilt-Volume:** 39 | **Sayı-Issue:** 2 | **Sayfa/Pages:** 247-267

Atıf/Cite as: Gültekin, R., Yeter, T., Görgişen, C. "Effect of Drought Stress on Yield and Some Morphological Characteristics in Wheat" Anadolu Journal of Agricultural Sciences, 39(2), Haziran 2024: 247-267.

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https://doi.org/10.7161/omuanajas.1358800

EFFECT OF DROUGHT STRESS ON YIELD AND SOME MORPHOLOGICAL CHARACTERISTICS IN WHEAT

ABSTRACT

This study aimed to determine the impact of different irrigation levels as a drought factor on the water productivity and yield of Tosunbey variety wheat. Conducted between 2018 and 2020 at the Sarayköy Research and Application Station in Ankara Province, the experiment employed a randomized block design with three irrigation levels and three replications. Significant effects of irrigation levels on the yield and various morphological parameters of wheat plants were observed. The I100 treatment, which was irrigated up to field capacity, achieved the highest yield with an average of 6.55 tons ha-1 over the two growing seasons. In contrast, the rainfed treatment (I0) showed a yield reduction of approximately 80.99% and 77.77% compared to the I100 treatment across the two years, respectively. Water productivity analyses (IWP) revealed average values of 1.74 kg m-3 and 1.55 kg m-3 for the I100 and I50 treatments, respectively. The highest outcomes, both in terms of yield and water productivity, were obtained under the I100 irrigation management where irrigation was applied up to field capacity. Correlation analyses conducted during the study identified significant relationships between different drought stress applications and morphological parameters in wheat. These findings are expected to contribute to the understanding of optimal irrigation strategies to maximize water efficiency and enhance crop performance in wheat cultivation.

Keywords: Drip Irrigation, Drought Stress, Wheat, Deficit Irrigation.

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KURAKLIK STRESİNİN BUĞDAYDA VERİM VE BAZI MORFOLOJİK ÖZELLİKLER ÜZERİNE ETKİSİ

ÖZ

Bu çalışma, kuraklık faktörü olarak farklı sulama düzeylerinin Tosunbey çeşidi buğdayın su üretkenliğine ve verimine etkisi belirlemek amacıyla 2018-2020 yıllarında Ankara İlinde, Sarayköy Araştırma ve Uygulama İstasyonu'nda yürütülmüştür. Üç sulama seviyesi ve üç tekerrürlü olarak tesadüf blokları desenine göre yürütülen çalışmada, sulama düzeylerinin buğday bitkisinin verim ve bazı morfolojik parametreleri üzerinde önemli etkileri gözlemlendmiştir. Tarla kapasitesi düzeyinde sulamanın yapıldığı I100 konusunda, her iki yetişme sezonunda ortalama 6.55 ton ha-1 ile en yüksek verim elde edildi. Buna karşılık, yağışa dayalı konu (I0), I100 konusu ile karşılaştırıldığında her iki yılda sırasıyla yaklaşık

%80.99 ve %77.77 oranında verimde düşüş göstermiştir. Su üretkenliği analizlerinde (IWP) I100 ve I50 konularında sırasıyla ortalama 1.74 ve 1.55 kg m-3 değerleri elde edildi. En yüksek bulgular, hem verim hem de su üretkenliği açısından, tarla kapasitesine kadar sulamanın uygulandığı (I100) sulama yönetiminde elde edilmiştir. Yapılan korelasyon analizlerinde farklı kuraklık stresi uygulamaları altında buğdayda morfolojik parametreler arasında önemli düzeyde ilişki belirlenmiştir. Bu bulgular, buğday yetiştiriciliğinde su verimliliğini en üst düzeye çıkarmak ve ürün performansını artırmak için optimal sulama stratejilerini anlama konusuna katkı sağlayacağı düşünülmektedir.

Anahtar Kelimeler: Damla Sulama, Kuraklık Stresi, Buğday, Kısıntılı Sulama.

INTRODUCTION

Climate change is one of the largest environmental challenges facing the world. This has led to significant changes in weather patterns and increased the frequency and severity of droughts. Drought is a major problem in agriculture and significantly affects crop productivity, quality, and yield. Wheat, which is one of the most important cereal crops worldwide, is highly sensitive to drought stress, and its productivity is significantly reduced during drought periods (Hammad and Ali, 2014; Kizilgeçi et al., 2017; Zia et al., 2021).

Wheat production is of great importance for global food security because wheat is one of the most widely cultivated and consumed crops worldwide. According to the Food and Agriculture Organization of the United Nations (FAO), wheat is the second most important cereal crop globally after maize. In 2020, the world produced more than 763 million tons of wheat, with the largest producers being China, India, and Russia (FAO, 2020).

However, the production of wheat and other crops is increasingly threatened by water scarcity, which is a major challenge for agricultural production in many parts of the world. Water scarcity refers to a situation in which the demand for water exceeds the available supply, either because of physical scarcity or the poor management of water resources. Climate change, population growth, and increased water consumption in other sectors exacerbate water scarcity. Wheat is a water-intensive crop and its production requires large amounts of water (Kehl, 2020; Li et al., 2022; Tribouillois et al., 2022). In many parts of the world, water scarcity has led to reduced yields and productivity of wheat crops. Furthermore, competition for water resources between agriculture, industry, and households is likely to intensify in the coming years, putting further pressure on wheat production and food security. To address the challenge of water scarcity and ensure sustainable wheat production, it is important to adopt more efficient water management practices such as drip irrigation, deficit irrigation, and rainwater harvesting. These practices can help reduce water use in wheat production while maintaining or even increasing yields. Additionally, there is a need to invest in research and development to develop drought-tolerant and water-efficient wheat varieties that can withstand the challenges of water scarcity and climate change.

One of the strategies used to mitigate the effects of drought on crop productivity is deficit irrigation, which involves reducing the amount of water applied to the crop to a level below the full crop water requirements (Singh et al., 2019; Ahmadian et al., 2021; Abdelrasheed et al., 2021). This approach helps conserve water resources while ensuring that crops receive the minimum amount of water needed for their survival. Drip irrigation is an efficient technique widely used in deficit irrigation to directly apply water to the crop root zone (Si et al., 2020; Wang et al., 2021; Mattar et al., 2021). This technique ensures that water is used efficiently and reduces water loss due to evaporation and runoff. Recent studies have shown that deficit drip irrigation can be an effective strategy for increasing crop productivity and water-use efficiency in wheat under drought conditions (Abd El-Mageed et al., 2019; Tunc et al., 2019; El-Mageed et al., 2022; Lu et al., 2022). However, the effects of different levels of drought stress and the application of deficit drip irrigation on wheat productivity and morphological characteristics have not been fully explored. Understanding the effects of these factors on wheat productivity and morphological characteristics can help optimize the use of water resources and improve wheat productivity under drought stress.

In conclusion, world wheat production is essential for global food security, but is threatened by water scarcity. Addressing this challenge will require concerted efforts by governments, farmers, and the private sector to adopt more efficient water management practices and invest in the research and development of new technologies and varieties that can ensure sustainable wheat production in a water-scarce world.

Therefore, the aim of this study was to investigate the effects of different levels of water limitation as drought stress factors on yield and morphological parameters in wheat. The impact of the stress mechanism on wheat was examined by revealing the relationships among the physiological parameters of wheat. The findings from this research will enhance comprehension regarding the effects of drought stress on wheat and aid in the formulation of sustainable irrigation strategies to enhance wheat productivity in drought conditions.

MATERIAL AND METHODS

2.1. Experimental site

The information regarding the location where the research was conducted is reported in Gultekin et al. (2023). In this study, the test crop used was the Tosunbey wheat variety. Some soil properties from the field experiment conducted for two years are given in Table 1.

Table 1. Physical and chemical properties of soil in the experimental field

Depth (m)	Sand (%)	Loam (%)	Clay (%)	Texture	Bulk ($g\ cm^{-3}$)	Field		Wilting		Available Water
						%	mm	%	mm	mm
0.0-0.3	16.90	31.20	51.90	C	1.18	40.0	142	22.3	79	63
0.3-0.6	12.80	32.00	55.20	C	1.15	40.3	138	23.7	81	57
0.6-0.9	11.70	34.30	54.00	C	1.19	42.2	150	24.0	87	63

Depth (m)	EC ($dS\ m^{-1}$)	pH (Sat.Mud)	Organic Matter (%)	Phosphorus P_2O_5 ($kg\ da^{-1}$)	Potassium K_2O ($kg\ da^{-1}$)
0.0-0.3	0.77	7.99	1.23	5.40	182.0
0.3-0.6	0.80	7.98	1.18	4.0	168.0
0.6-0.9	0.90	7.96	1.15	1.50	157.0

Table 1 provides information regarding the physical properties of the soil in the experimental field. At a depth of 0.0-0.3 meters, the soil contained 16.90% sand, 31.20% loam, and 51.90% clay, indicating a predominantly clay texture. The bulk density of the soil was 1.18 g cm^{-3}. The field capacity (Tüzüner, 1990) was 40.0%, suggesting that the soil could hold the highest amount of water. The wilting point was 142 mm, which represents the moisture level at which plants start to experience water stress. The available water content was 22.3% or 79 mm, indicating the amount of water available to plants between field capacity and wilting point. The soil also had an EC of 0.91 dS m^{-1}, pH of 7.9, organic matter percentage of 0.26%, phosphorus content of 6.7 kg da^{-1}, potassium content of 179.0 kg da^{-1}, total nitrogen percentage of 0.06%, and calcium carbonate percentage of 12.8%. Similarly, at depths of 0.3-0.6 meters and 0.6-0.9 meters, the soil composition and properties are provided. These depths show slightly different percentages of sand, loam, and clay but still exhibit a clay texture.

Within this investigation, the utilized irrigation water fell under the classification of C_3S_2 (USSL, 1954). Consequently, the irrigation water was deemed satisfactory concerning its salinity levels and moderately basic properties (Table 2).

Table 2. Some characteristics of the irrigation water used in the study.

EC (dSm^{-1})	pH	Exchangeable Cations (meL^{-})					Soluble Anions (meL^{-})					SAR	Class
		Ca++	Mg++	Na+	K+	Top	CO_3	HCO_3	Cl^-	SO_4	Top		
2.05	8.51	1.27	6.2	10.9	0.2	18.6	0.69	5.38	7.27	5.25	18.6	5.63	C_3S_2

The seasonal precipitation and temperature values for the years 2019-2020, during which the experiment was conducted, are presented in Figures 1 and 2.

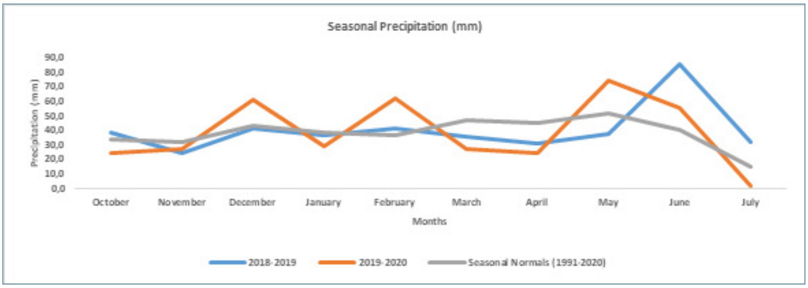

Figure 1. The precipitation values for the years of the experiment and the long-term average

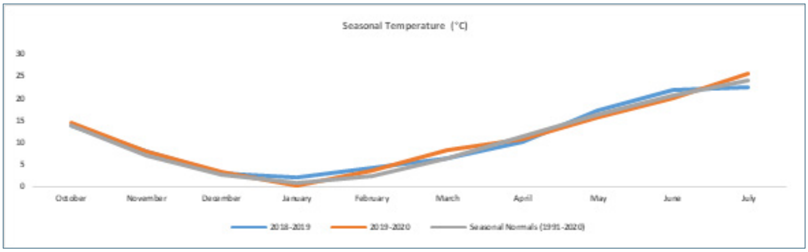

Figure 2. The temperature values for the years of the experiment and the long-term average

Accordingly, the annual precipitation (382.0 mm) for the first year was the same as the average seasonal normal (381.1 mm). The annual precipitation (384 mm) for the second year was also nearly the same as the average seasonal normal. According to these comparisons, precipitation was relatively at the same level as the long-term average seasonal normals in both the 2018-2019 and 2019-2020 periods.

2.2. Design of the Experiment and Cultivation Techniques

The experimental setup involved a randomized block design, which included four different irrigation regimes and was replicated three times. The dimensions of each plot were set at 3.0 meters in width and 5.0 meters in length. To mitigate the effects of lateral water movement, non-irrigated buffer zones of 2.0 meters were established between adjacent plots, and a distance of 3.0 meters was maintained between blocks (Arıtürk and Erdem, 2011). Site preparation for the experiment was conducted in the autumn prior to the spring planting, involving plowing and raking. In the first year of the study, wheat planting was done on 24.10.2018 and harvest was done on 23.07.2019. In the second year, wheat planting was carried out on 29.10.2019 and harvesting was carried out on 18.07.2020 The variety of wheat used for testing was Tosunbey, which was sown at a row spacing of 0.15 meters. The fertilization protocol included an application of 25 kg per hectare of diammonium phosphate (DAP) as a base fertilizer, complemented by 15 kg per hectare of ammonium sulfate (AS) delivered through a drip irrigation system subsequent to the initial watering. Neutron metering was utilized to monitor soil water content prior to each irrigation. The experimental field was segmented into 12 plots arranged according to the randomized block design, with each treatment replicated three times.

2.3. Irrigation

For the experiment, a drip irrigation system was employed, drawing water from a well situated within the research area. Typically, existing literature primarily focuses on supplemental irrigation concerning wheat water requirements. However, in this particular study, a comprehensive approach was adopted by implementing both full and deficit irrigation strategies throughout the entire growth cycle of the plants in response to soil moisture depletion. To ensure optimal pressure, the irrigation system utilized lateral pipes with a diameter of 16 mm and dripper spacing set at 0.33 m. The emitter flow rate was 2.0 L/h. These lateral pipes were installed at intervals of 0.40 m. The irrigation treatments used in this study were as follows:

I_0- Rainfed treatment.

I_{50}- Applying 50% of the water given for I100

I_{100}- Irrigation up to field capacity.

Irrigation was applied when 50% of the available water capacity in the topsoil layer (0-60 cm depth) was depleted.

Soil water content was determined using a neutron meter. Prior to irrigation, neutron-meter readings were recorded at soil depths of 0-30 cm, 30-60 cm, and 60-90 cm for calibration purposes. These values were then plotted alongside the soil water values obtained through the gravimetric method at the corresponding depths. Based on this data, a calibration equation was established (Figure 3).

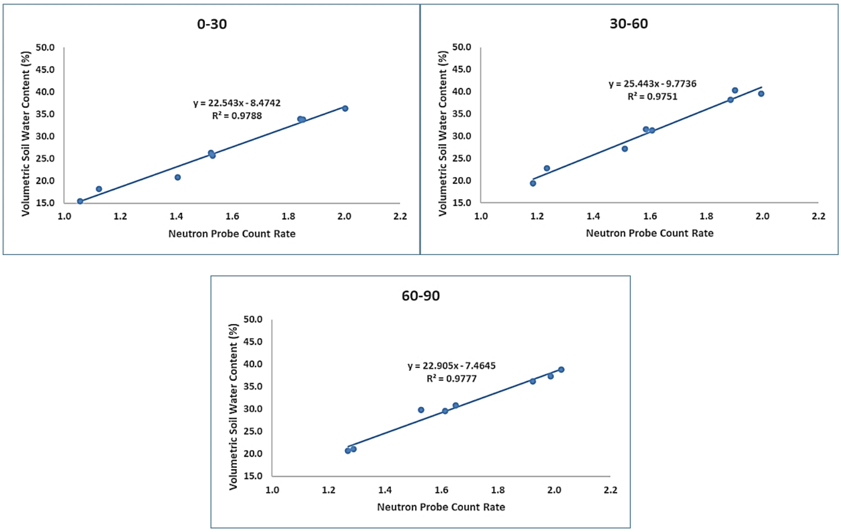

Figure 3. Neutronmeter calibration charts

To calculate the amount of irrigation water applied to the plots, the volumetric soil water content was assessed using a neutron meter, as described by Tüzüner (1981).

$$\theta_h = a + b\,(SO) \tag{1}$$

where θh represents the volumetric soil water content (%), a is the calibration curve constant, b is the slope of the calibration line, SO is the count ratio (SO = S/SS), S is the neutron-meter count reading value, and SS is the standard count value.

$$AW = \theta_h \times ɣt \times D/100 \tag{2}$$

where AW represents the current soil moisture (mm), ɣt represents the bulk density of the soil (g cm^{-3}), and D represents the depth of the soil to be irrigated (mm).

The amount of irrigation water applied was calculated using the following equation.

$$I = \frac{TK - MN}{100} . ɣt . D . p \tag{3}$$

where I represents the net irrigation water amount (mm), TK represents the field capacity (%), ɣt represents the bulk density of the soil (g cm^{-3}), MN represents the current soil moisture (%), D represents the depth of irrigated soil (mm), and p represents the wetting ratio (strip width of the wetted area/lateral spacing).

Crop water consumption was calculated using Equation 4 based on the water budget, taking into account the measured soil moisture values before each irrigation application (Allen et al., 1998).

$$ETa = I + P + Cr \pm \Delta S - DP - RO \quad (4)$$

In the equation: ET: Crop water consumption, mm, I: Applied irrigation water, mm, P: Precipitation, mm, DP: Deep percolation, mm, ΔS: Change in soil moisture content in the profile, mm, RO: Surface runoff, mm, Cr: Capillary rise. In this study, irrigation applications were conducted based on the soil moisture deficit using drip irrigation, and because there were no groundwater issues in the field, the values of surface runoff and capillary rise were considered to be zero.

2.4. Water Productivity

Water productivity was assessed through the division of the crop yield by the amount of water employed. In order to ascertain water economic productivity (WEP), the net income per unit area was divided by the specific irrigation water utilized in that particular region, as elucidated in the investigations conducted by Paredes et al. (2014), and Cetin and Kara (2019).

The computation of water productivity was carried out using the equation put forth by Cetin and Kara (2019), Oweis and Hachum (2003), and Tavakol et al. (2012);

$$WP_R = \frac{Y}{R} \quad (5)$$

$$WP_{ETa} = \frac{Y}{ETa} \quad (6)$$

$$IWP = \frac{Y}{I} \quad (7)$$

$$WP_{I+R} = \frac{Y}{I+R} \quad (8)$$

$$WP_{I-R} = \frac{YI}{I} \quad (9)$$

Where; WP_R: Rainfall water productivity under combined rainfall and irrigation conditions, Y: Average yield achieved under rainfall and irrigation over a span of two experimental years, R: Amount of rainfall received during the growing season, WP_{ETa}: Water productivity for actual crop evapotranspiration (kg m^{-3}), ETa: Actual crop evapotranspiration (m^3 ha^{-1}), IWP: Irrigation water productivity for the quantity of irrigation water applied in the presence of rainfall, YI: Yield increment solely attributed to irrigation (kg ha^{-1}), I: Quantity of irrigation water applied (m^3 ha^{-1}), Y_{I+R}: Yield under rainfall and all treatments combined (kg ha^{-1}), R: Amount of rainfall (m^3 ha^{-1}), WP_{I+R}: Water productivity under combined rainfall (R) and irrigation (I) conditions (m^3 ha^{-1}), WP_{I-R}: Water productivity excluding rainfall, based on the yield increment solely attributed to irrigation.

2.5. Statistical Analysis

The data obtained in the study were subjected to analysis of variance using JMP v17 statistical software and were grouped according to the Tukey test at the $p \leq 0.05$ probability level. Three replicates were performed for each analysis, and the outcomes were presented as the average value accompanied by the standard deviation (Yurtsever, 2011).

3. RESULTS

3.1 Water Consumption

The plant water consumption values for both years of the research are given in Table 3. and Table 4 displays the data concerning water productivity, which is obtained from yield parameters and associated with the values of plant water consumption in a two-year study. In both years of the study, for the I_{50} and I_{100} treatments, soil water contents were brought up to field capacity (FC) level prior to the deficit irrigation treatments. Accordingly, in the first year of the study, 46.6 mm of irrigation water was applied to the I_{50} and I_{100} treatments for the FC level, and in the second year, 42.3 mm was applied. The first irrigation was conducted at the budding stage. Subsequently, irrigations were carried out according to the subjects when the available water amount in the 0-60 cm soil profile decreased by 50%. Irrigations were terminated when the wheat grains entered the dough stage. During this period, irrigation was conducted five times in each of the two years.

Table 3. Corp water consumption

Growing Seasons	Treatments	I (mm)	R (mm)	ƛS	ETa (mm)
	I_0	0		-58.4	440.4
2018-2019	I_{50}	216.7	382	-23.6	622.3
	I_{100}	386.7		9.1	759.6
	I_0	0		-48.5	432.5
2019-2020	I_{50}	203.7	384	-24.8	612.5
	I_{100}	365.1		-6.8	755.9

I: Irrigation; R: precipitation; ƛS: water exchange in soil; ETa: Actual evapotranspiration

Table 4. Water productivity according to the experimental treatments.

1	2	3	4	5	6	7	8	9	10	11	12
Growing Seasons	**Treatments**	**Y (t ha⁻¹)**	**I (mm)**	**R (mm)**	**ETa (mm)**	**YI (t ha⁻¹)**	**WP_R (kg m⁻³)**	**WP_{ETa} (kg m⁻³)**	**IWP (kg m⁻³)**	**WP_{I+R} (kg m⁻³)**	**WP_{I-R} (kg m⁻³)**
	I0	1.26 c	0		440.4	–	0.33	0.29	–	0.33	–
2018-2019	I50	3.08 b	216.7	382	622.3	1.82	0.81	0.49	1.42	0.51	0.84
	I100	6.67 a	386.7		759.6	5.41	1.75	0.88	1.72	0.87	1.40
	I0	1.43 c	0		432.5	–	0.37	0.33	–	0.37	–
2019-2020	I50	3.43 b	203.7	384	612.5	2	0.89	0.56	1.68	0.58	0.98
	I100	6.44 a	365.1		755.9	5.01	1.68	0.85	1.76	0.86	1.37

Where; $\mathbf{I_0}$: rainfed, $\mathbf{I_1}$: applying 50% of the water given for I100, **I100**: irrigation up to field capacity, **Y**: yield, **I**: irrigation amount, **R**: rain, **ETa**: actual evapotranspiration, **YI**: yield increased by only irrigation, $\mathbf{WP_R}$: rainfall water productivity under rainfall, $\mathbf{WP_{ETa}}$: actual crop evapotranspiration, **IWP**: irrigation water productivity, $\mathbf{WP_{I+R}}$: water productivity under rainfall, $\mathbf{WP_{I-R}}$: water productivity without rainfall

Statistical analysis of the experimental results provides valuable insights into the performance of different treatments during the growing seasons of 2018-2019 and 2019-2020. The results indicated significant variations in yield (Y), irrigation amount (I), rainfall (R), actual evapotranspiration (ETa), and yield increase per unit of irrigation (YI). These results indicate that compared to Treatment I_{100}, Treatment I50 shows a significant decrease in yield of approximately 53.81% in the 2018-2019 season and 46.76% in the 2019-2020 season. Similarly, Treatment I_0 exhibits the highest decrease in yield, with reductions of approximately 80.99% and 77.77% for the respective growing seasons. This suggests that as the treatment level decreases from I_{100} to I_0, there is a significant decline in yield during both growing seasons. These findings highlight the significance of proper irrigation management and the effectiveness of Treatment I_{100} in achieving higher yields, whereas

Treatment I_{50} has the potential to optimize water use efficiency and improve water productivity. The yield values obtained in the study were found to be lower than the values reported by Chen et al. (2015), Mostafa et al., (2018), and Eissa et al. (2018), and similar to the findings of Wang et al. (2013), and Dar et al. (2017). It is believed that the wheat variety used, differences in fertilizer and water levels, and the climatic conditions of the location where the experiment was conducted have an impact on the findings.

ETa values among the treatments, I_{100} consistently has the highest ETa value, while treatments I_O and I_{50} show percentage differences relative to the highest value. These differences highlight the disparities in evapotranspiration rates among the treatments, indicating potential variations in water use and crop performance. The values obtained in the study were found to be higher than the values reported by Umair et al. (2019), Bai et al. (2020), Shen et al. (2020), Yang et al. (2020). It can be said that the differences in wheat varieties, climate variations, and variations in agricultural practices have been influential in the differences observed in the literature findings.

In the 2018-2019 growing season, the WP_R values were recorded as 0.33 for treatment I_0, 0.81 for treatment I_{50}, and 1.75 for treatment I_{100}. Comparing these values, we can observe significant variations in water productivity among the treatments. Treatment I_{100} had the highest water productivity, which was approximately 116% higher than treatment I_{50}. In the 2019-2020 growing season, treatment I_0 had a WP_R value of 0.37, treatment I_{50} had a value of 0.89, and treatment I_{100} had a value of 1.68. Here, treatment I_{100} again displayed the highest water productivity, similar to the previous season. The differences among treatments can be seen as treatment I_{100} being approximately 88.8%% higher than treatment I_{50}. These percentage differences highlight the significant impact of the treatments on water productivity and suggest the importance of selecting the appropriate treatment for maximizing water efficiency in wheat production. The values obtained in the study were found to be higher than the values reported by Hagos G. L., (2005), Cetin and Akinci, (2022). For WP_{ETa} compared to treatment I_{100}, treatment I_{50} exhibited a decrease of approximately 56% in WP_{ETa}, while treatment I_0 showed a larger decrease of approximately 67% in WP_{ETa} during the 2018-2019 growing season. During the 2019-2020 growing season compared to treatment I_{100}, treatment I_{50} exhibited a decrease of approximately 34% in WP_{ETa}, while treatment I_0 showed a larger decrease of approximately 61% in WP_{ETa}. These percentage differences highlight the significant disparities in water productivity among the treatments, indicating potential variations in water use efficiency and crop performance. The obtained WP_{ETa} values were found to be higher than those reported by Cetin and Akinci, (2022). When the obtained IWP data is examined, in the first year of the study treatment I_{50} exhibited an IWP value of 1.42, while treatment I_{100} demonstrated a higher IWP value of 1.72. Moving on to the second year, the IWP values for treatments I_{50} and I_{100}

were 1.68 and 1.76, respectively. Consistent with the previous season, treatment I_{100} maintained its superiority in terms of irrigation water productivity. Collectively, these findings underscore the consistently superior performance of treatment I_{100} in terms of irrigation water productivity across both growing seasons. On the other hand, it can be said that in irrigation at I50 level, the decrease in water productivity has increased to acceptable levels. Irrigation at I50 level can be recommended, especially in conditions of insufficient water resources. The obtained IWP (Irrigation Water Productivity) values were found to be higher than the findings reported by Liu et al., (2007), Faramarzi et al., (2010,) and Cetin and Akinci, (2022), and were lower than Degirmenci et al. (2017). High IWP should be considered an important target in agricultural water management. It can be stated that the main reason for the differences between the findings obtained in the study and the literature findings is due to some variations in agricultural practices and climate conditions.

In the 2018-2019 growing season, the water productivity with irrigation + rainfall (WP_{I+R}) values were assessed for three treatments: I_0, I_{50}, and I_{100}, with values of 0.33, 0.51 and 0.87, respectively. The observed variations in water productivity among the treatments indicate significant differences in their performance. Treatment I_{100} exhibited the highest water productivity, surpassing treatment I_0 by approximately 163% and treatment I_{50} by approximately 89.1%. These findings highlight the substantial impact of treatment I_{100} in enhancing water productivity. In the second year of study, the W_{PI+R} values for treatments I_0, I_{50}, and I_{100} were 0.37, 0.58, and 0.86, respectively. Consistent with the previous season, treatment I_{100} showcased the highest water productivity with irrigation plus rainfall. The percentage differences among treatments revealed that treatment I_{100} outperformed treatment I_0 by approximately 132% and treatment I_{50} by approximately 48%. These results consistently indicate the superior performance of treatment I_{100} in terms of water productivity across both growing seasons. Treatment I_0 consistently exhibited lower water productivity, while treatment I_{50} demonstrated intermediate performance. These percentage differences underscore the significant influence of the treatments on water productivity and emphasize the importance of considering both irrigation and rainfall factors when assessing water use efficiency in wheat production. In the 2018-2019 growing season, treatment I_{50} demonstrated a water productivity index with a rainfall (WP_{I-R}) value of 0.84, while treatment I_{100} exhibited the highest value of 1.40. A comparative analysis of these values reveals substantial variations in water productivity among the treatments. Notably, treatment I_{100} showcased the highest water productivity index, surpassing treatment I_{50} by approximately 66%. Moving to the second year of the study, treatment I_{50} yielded a WP_{I-R} value of 0.98, whereas treatment I_{100} achieved a value of 1.37. Consistent with the previous season, treatment I_{100} maintained its superior performance in terms of the water productivity index. The percentage difference between treatments I_{100} and I_{50} can be calculated as approximately 40%. These collective findings highlight the consistent superiority of treatment I_{100} in terms of water productivity index with rainfall across both growing seasons. The water productivity index with irrigation plus rainfall (WP_{I+R}) and water productivity index with rainfall (WP_{I-R}) values obtained in our study was higher than the findings reported by Cetin (2022). Although precipitation has a relatively balancing effect on water productivity values, when considering irrigation water values alone, the importance of irrigation in reducing plant stress is quite significant depending on the applied treatments. The higher water productivity observed with respect to irrigation levels indicates a strong water-yield response of the crop. Additionally, it should be noted that the choice of wheat variety, as well as climate and soil characteristics, significantly influence water efficiency.

3.2. Yield and Yield Components

The results of the variance analysis for specific physiological parameters of wheat are presented in Table 5, while the Tukey groupings are detailed in Table 6.

Table 5. Variation table of same morphologic parameters of wheat

Variation Source	*sd*	*PH (cm)*	*NT*	*NPP*	*DTN (cm)*	*GPS*	*NS*	*SGW*	*TGW*	*YLD*	*PR*	*HI*
Irrigation level (I)	2	**	**	**	*	**	*	**	**	**	*	**
Year (Y)	1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y x I	2	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
Error	8	12.59	0.09	0.01	2.10	7.88	1954.2	0.02	100.97	251616	1.19	16.61
CV(%)		4.9	8.6	2.2	12.9	9.0	11.0	15.1	13.1	13.5	6.6	13.9

Where **PH**: plant height, **NT**: number of tillering, **NPP**: nodes per plant, **DTN**: distance from top node, **GPS**: number of grains per spike, **NS**: number of spikes, **SGW**: spike grain weight, **TGW**: thousand-grain weights, **YLD**: yield, **PR**: protein rate, **HI**: harvest index. Values in a column followed by the same letter are not significantly different at P<0.05. NS indicates no significant difference and * and ** indicated significance at P<0.05 and P<0.01

Regarding the irrigation level (I), statistically significant differences were observed for most of the parameters, with significance at the P<0.05 and P<0.01 levels. The parameters such as PH (cm), NT, NPP, DTN (cm), GPS, SGW, TGW, YLD, PR, and HI exhibited significant variations among different irrigation levels. Except for the NPP, the combination of year and irrigation level (Y x I) did not exert a notable influence on the measured parameters.

Table 6. Grouping results according to Tukey's test.

Irrigation level (I)	*PH (cm)*	*NT*	*NPP*	*DTN (cm)*	*GPS*	*NS ($sp.m^{-2}$)*	*SGW (g)*	*TGW (g)*	*YLD t ha^{-1}*	*PR (%)*	*HI (%)*
I_{100}	81.2a ± 3.9	4.4a ± 0.3	4.1a ± 0.1	13.7a ± 0.9	39.3a ± 2.9	460.0a ± 35.4	1.48a ± 0.1	37.2a ± 1.50	6.6a ± 0.06	17.7a ± 0.6	42.1a ± 3.0
I_{50}	71.4b ± 3.0	3.5b ± 0.3	3.9b ± 0.1	11.9b ± 1.0	33.4b ± 3.1	408.7b ± 46.0	0.88b ± 0.1	24.9b ± 3.4	3.3b ± 0.04	16.3b ± 1.2	28.1b ± 3.6
I_0	64.4c ± 2.4	2.80c ± 0.1	3.7c ± 0.1	8.1c ± 1.6	20.1c ± 2.6	334.7c ± 34.1	0.63c ± 0.1	19.1c ± 2.9	1.3c ± 0.02	15.2c ± 0.6	17.7c ± 2.6

Where I_0: rainfed, I_{50}: applying 50% of the water given for I_{100}, I_{100}: Irrigation up to field capacity, **PH**: plant height, **NT**: number of tillering, **NPP**: nodes per plant, **DTN**: distance from top node, **GPS**: number of grains per spike, **NS**: number of spikes, **SGW**: spike grain weight, **TGW**: thousand-grain weights, **YLD**: yield, **PR**: protein rate, **HI**: harvest index.

Table 6 presents the results obtained from the analysis of different treatments using Tukey's test. Treatment I100, representing irrigation up to field capacity, demonstrated the highest values for most of the measured parameters. It had the highest plant height (81.2 cm), number of tillering (4.4 pieces/plant), nodes per plant (4.1), distance from the top node (13.7 cm), number of grains per spike (39.3), number of spikes (460.0), spike grain weight (1.48 g), thousand-grain weight (37.2 g), yield (6.6 t ha-1), protein rate (17.7%), and harvest index (42.1%). Comparatively, treatment I_1, which received 50% of the water given to I_{100}, exhibited lower values for these parameters, followed by treatment I_0 (rainfed), showing the lowest values. The percentage differences between treatments can be observed by comparing the values. Treatment I_{100} generally outperformed the other treatments, showing significant improvements in most of the measured parameters. For example, treatment I_{100} had approximately 14.4% higher plant height, 25.7% more tillering, 5.1% more nodes per plant, 41.2% greater distance from the top node, 17.6% more grains per spike, 12. 6% more spikes, 67.7% higher spike grain weight, 93.5% greater thousand-grain weight, 99.2% higher yield, 6.1% higher protein rate, and 50.7% higher harvest index compared to treatment I_{50}. The results indicate that irrigation up to field capacity (I_{100}) led to improved plant growth, grain production, and overall crop performance compared to the other treatments. These findings highlight the importance of adequate irrigation in achieving higher yields and better quality in wheat cultivation.

The obtained findings indicated that the plant height (PH) values were lower compared to the results reported by Li et al. (2015), and Memon et al. (2021), while they were similar to the findings of Wang et al. (2010), Sarwar et al. (2010), Gao et al. (2020). The plant height can be considered as a significant outcome of water stress, which is dependent on the variety. In the conducted study, the plant height under full irrigation conditions was found to be higher compared to reference values. The results of plant height (PH) generally showed compatibility with literature in similar conditions. NT values were found lower than the results reported by

Ye et al. (2015), Sun et al. (2023) and similar to the findings of Sarwar et al. (2010) and Shang et al. (2021). NT primarily depends on the plant variety used and can be considered an important indicator of stress for wheat under drought conditions. High drought stress can promote early maturation and inadequate tillering in wheat. The NPP values obtained in this study were found to be within acceptable ranges for the selected wheat variety under full irrigation, aligning with findings reported in similar research. Conversely, under conditions of drought stress, characterized by the promotion of early maturation in wheat, the NPP values were lower in deficit irrigation and rainfall treatments. In other words, the development of nodes and leaves in plants is influenced by the moisture content and water availability in the soil (Roberts and Mattoo, 2018). The observed NPP values demonstrated significant similarity to the findings of Maqbool (2015) and Aurangzaib et al. (2021), while surpassing the results reported by Onyemaobi (2017). These results highlight the sensitivity of NPP to irrigation conditions and emphasize the importance of appropriate water management strategies in optimizing wheat productivity. The parameter is known as DTN (distance from the top node) is defined as the distance between the spike node and the first node directly below it in wheat plants. It was observed that a higher DTN value was positively correlated with a higher wheat yield. These findings regarding DTN values are consistent with the results reported by Aurangzaib et al. (2021), while being lower compared to the studies conducted by Wang et al. (2015) and Yu et al. (2020). These results highlight the importance of considering the DTN parameter as a potential indicator for wheat yield and its potential implications in agricultural practices. The number of grains per spike (GPS) is a crucial parameter strongly correlated with wheat yield. Consequently, it is one of the key parameters closely monitored by producers. In our study, we observed a consistent parallel relationship between GPS values and yield across all irrigation levels. However, the obtained GPS values were lower compared to the findings reported by Wang et al. (2015), Aurangzaib et al. (2021), and Memon et al. (2021). It is important to note that GPS values can vary depending on factors such as wheat variety, climate conditions, and agricultural practices. The number of spikes per square meter is directly related to the germination power and tillering count. The obtained NS values in the research exhibited similarity to the findings of Li et al. (2015), Ebrahimnejad and Rameeh (2016), while they were higher than the results reported by Rahman et al. (2016), Rivera-Amado et al. (2019). The spike grain weight (SGW) is among the key factors directly influencing wheat yield. In particular, drought stress during the spike maturation process can significantly affect grain weight. Therefore, the correlation between grain weight and deficit irrigation practices serves as an important reference for irrigation management. The obtained SGW (spike grain weight) values in the research were found to be similar to the findings of Kutlu and Olgun (2015), but lower than the results reported by Ebrahimnejad and Rameeh (2016), Rajput (2019), Glenn et al., (2021), Memon et al. (2021). The thousand-grain weight (TGW) in wheat can be significantly affected by the level of drought stress during the milk ripening stage, similar to spike grain weight (SGW). Adequate irrigation fulfillment during this phenological stage plays a crucial role in determining TGW, leading to significant differences in grain weight. The present study investigates the impact of different irrigation levels on TGW, highlighting its importance in wheat production. The obtained results showed lower TGW compared to the findings of Xu et al. (2018) and Rivera-Amado et al. (2019), while demonstrating similarity to the results reported by Ye et al. (2015) and Feng et al. (2018). The morphological changes observed in wheat under different levels of drought stress have varying impacts on wheat yield (YLD). The conducted study revealed that the wheat yield was similar to the findings of Feng et al. (2018), Rivera-Amado et al. (2019), and Gao et al. (2020), but higher than the results reported by Memon et al. (2021). It should be noted that the choice of wheat variety and various agricultural practices can significantly influence yield outcomes. Protein ratio (PR) is an important quality parameter for wheat. It is crucial to meet the wheat's nutrient and water requirements adequately throughout its growth stages. Under drought stress, insufficient development often leads to lower protein content. In the conducted study, it was found that the protein content was inversely proportional to the severity of drought stress. The results obtained in the research were higher than the results reported by Zeleke and Nendel (2016), Rathore et al. (2017), and Zhang et al. (2017). These findings highlight the negative impact of drought stress on protein content and emphasize the importance of addressing water management strategies to optimize wheat quality. The harvest index (HI) is a measure that quantifies the proportion of grain yield in relation to the overall biomass of plants. Under drought stress, inadequate physiological development leads to a weak grain yield. Conversely, under non-stress conditions, the opposite occurs. The obtained HI values in the study were similar to the findings of Ebrahimnejad and Rameeh (2016), and Rathore et al. (2017), but lower than the results reported by Wang et al. (2015), Rivera-Amado et al. (2019). The conducted study revealed significant variations in the HI value under different drought levels, with an inverse relationship between HI and increasing water stress.

3.2 Multivariate Correlations

The correlation analysis conducted in the study to determine the level of interaction among various physiological parameters (crop height, number of tillering, nodes per plant, distance from top node, number of grains per spike, number of spikes, spike grain weight, thousand-grain weights, yield, protein rate, harvest index) in wheat plants is presented in Figure 4.

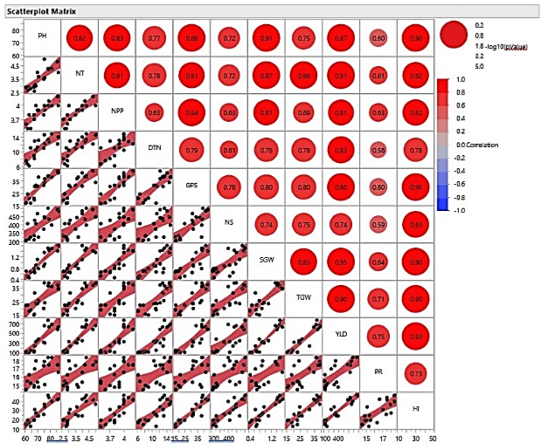

Figure 4. Correlation levels of some morphological parameters in wheat.

Where **PH**: plant height, **NT**: number of tillering, **NPP**: nodes per plant, **DTN**: distance from top node, **GPS**: number of grains per spike, **NS**: number of spikes, **SGW**: spike grain weight, **TGW**: thousand-grain weights, **YLD**: yield, **PR**: protein rate, **HI**: harvest index. The correlations were estimated using the pairwise method.

The correlation table presents the relationships between the various morphological parameters of wheat. The correlation coefficients, which ranged from -1 to 1, elucidated the strength and direction of the relationships. A value closer to 1 indicated a robust positive relationship, while a value nearer to -1 indicated a strong negative relationship. Values close to 0 suggested the absence of a relationship. The table displayed numerous robust positive correlations among the parameters. For instance, plant height (PH) showed strong positive correlations with the number of grains (NG; r = 0.8877) and the harvest index (HI; r = 0.8971). This suggests that taller plants tend to have more grains and higher harvest indices. Similarly, the number of tillers (NT) was strongly and positively correlated with thousand-grain weight (TGW; r = 0.8552) and yield (YLD; r = 0.9061). This indicates that plants with more tillers generally have higher thousand-grain weights and yields. The number of nodes per plant (NP) also showed a strong positive correlation with the number of grains (NG; r = 0.8400), suggesting that plants with more nodes tended to have more grains. The distance from the top node (DTN) had a strong positive correlation with the number of grains (NG; r = 0.7912), indicating that plants with greater distances between nodes tended to have more grains. The table also reveals strong positive correlations between yield (YLD) and other parameters, such as thousand-grain weight (TGW; r = 0.9046) and harvest index (HI; r = 0.9259). This suggests that higher yields are associated with higher thousand-grain weights and harvest index values. In conclusion, the strong positive correlations observed between several parameters, such as plant height, number of tillers, nodes per plant, distance from the top node, number of grains, thousand-grain weight, yield, and harvest index, highlight the interconnected nature of these traits and their potential influence on overall crop productivity. Understanding these relationships can help inform agricultural practices and optimize wheat production.

4. CONCLUSION

This research has demonstrated that irrigation treatments play a pivotal role in optimizing wheat yield and water productivity under drought conditions. The study's findings reveal that maintaining soil moisture up to field capacity (Treatment I_{100}) not only maximizes wheat yield but also enhances water productivity significantly compared to other treatments (I_{50} and I_0). The data showed that Treatment I_{100}, where irrigation was maintained at field capacity, consistently achieved the highest yield and water productivity across two consecutive growing seasons. It resulted in superior growth in terms of plant height, tillering, grain per spike, and other yield-contributing factors. On the other hand, the I_{50} treatment, which received 50% of the water provided to I_{100}, demonstrated a balance between reduced water use and crop yield, highlighting its potential as a water-efficient irrigation strategy. The rainfed treatment (I_0) displayed the lowest yield and water productivity, underscoring the critical need for adequate irrigation in wheat cultivation under drought conditions.

The results underline the importance of adopting strategic irrigation management to cope with water scarcity while maintaining crop performance. Future studies should explore the scalability of applying such differential irrigation levels in diverse agro-climatic scenarios to validate the robustness of these findings across various environmental conditions.

Acknowledgements

This study was supported by the Soil, Fertilizer, and Water Resources Central Research Institute, Ankara Turkey. The authors thank the institution for their support.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethics

This study does not require ethics committee approval.

Author Contribution Rates

Design of Study: RG(%50), TY(%25), CG(%25)

Data Acquisition: RG(%50), TY(%25), CG(%25)

Data Analysis: RG(%100)

Writing Up: RG(%100)

Submission and Revision: RG(%100)

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