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Response of maize and black gram yield and water productivity to variations in canopy temperature and crop water stress index**

Afshin Khorsand[1], *Vahid Rezaverdinejad*[1]*, *Hossein Asgarzadeh*[2], *Abolfazl Majnooni Heris*[3], *Amir Rahimi*[4], *and Sina Besharat*[1]

[1]Department of Water Engineering, [2]Department of Soil Science, [4]Department of Agronomy, Urmia University, Urmia, Iran
[3]Department of Water Engineering, University of Tabriz, Tabriz, Iran

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A b s t r a c t. In order to evaluate the ability of the crop water stress index to estimate grain yield and water productivity of maize and black gram in the climatic conditions of Urmia (Iran), research was conducted under the conditions of single-row drip irrigation. This study was conducted in a randomized complete block design with four irrigation levels including 50 (I_1), 75 (I_2), 100 (I_3) and 125 (I_4) percent of the water requirements of the plants with three replications. The mean crop water stress index values for the I_1, I_2 and I_3 treatments were 0.53, 0.44, and 0.28, respectively during the growth period of maize, and 0.37, 0.23, and 0.15 for black gram, respectively. In the present study, the correlation between the crop water stress index and the grain yield and also the water productivity of maize and black gram was high. According to the results, the highest grain yield for maize and black gram was obtained at crop water stress index values of 0.28 and 0.15, respectively. Therefore, these values are recommended for the irrigation scheduling of the plants. It should be noted that the maximum water productivity index for maize and black gram was obtained at crop water stress index values of 0.44 (I_2) and 0.37 (I_1), respectively, which are the values recommended for irrigation scheduling under restricted access to water.

K e y w o r d s: canopy temperature, crop yield, *CWSI*, phenolic and flavonoid compounds, water stress

INTRODUCTION

Water shortages in arid and semiarid regions threaten the food security of millions of people. Since most parts of Iran are located in the arid and semi-arid belt, crop production is not possible without irrigation. In areas where crops are irrigated, proper management and planning for the optimal use of water may be necessary. Iran is in dire straits with regard to water resources; therefore, it is necessary to help conserve limited water resources by optimally using, maintaining and even increasing irrigation efficiency. In a situation where irrigation water shortage prevents the development of a cultivation area, the optimum and economical use of water can increase the profit per unit area (Ahmadi *et al*., 2018). Water productivity actually represents the amount of product or benefit gained from water consumption and includes various aspects of water management (Ahmadi *et al*., 2018). The issue of irrigation management and scheduling is very important because if the irrigation scheduling methods and tools (plant and soil indices) are properly used, a significant increase in water use efficiency may be achieved (Khorsand *et al*., 2019).

One of the established methods of irrigation scheduling is to measure the canopy temperature, which indicates the water status of plants and is the basis of the crop water stress index (*CWSI*) calculation which is one of the most effective non-destructive methods (Fitzgerald *et al*., 2006). *CWSI* is a valuable indicator for quantifying water stress and predicting crop yields, using *CWSI* for irrigation management under water stress conditions is very important (Edalat *et al*., 2010). *CWSI* is also used to estimate grain yield (GY), plant evapotranspiration and water productivity (*WP*).

*Corresponding author e-mail: v.verdinejad@urmia.ac.ir

In North America, two *CWSI* values of 0.2 and 0.4 were used for maize irrigation. Due to the use of irrigation scheduling based on a *CWSI* of 0.4, the *WP* of this crop increased from 2.3 to 2.5 kg m^{-3} (Stegman, 1986). Soybean irrigation scheduling with different *CWSI* values (0.2, 0.3, 0.4 and 0.5) for the initiation of irrigation in a semi-arid climate was investigated and a value of 0.2 was reported as the benchmark for irrigation scheduling to achieve maximum crop yield (Nielsen, 1990). Another study in North America used 0.2, 0.4, and 0.6 water stress indices for maize, which reduced water use by 28, 43, and 54%, respectively, and at a *CWSI* value of 0.2, crop yield does not experience a significant decrease (Steele *et al*., 1994).

For the irrigation scheduling of cowpea, the relationships between *CWSI* with evapotranspiration and crop yield were used in research. The irrigation time of the plant between 13 and 14 hours was estimated using *CWSI* at 0.11 (Sepaskhah and Ilampour, 1996). In another study, the efficiency of *CWSI* in watermelon irrigation scheduling was investigated. Five drip irrigation levels including 100, 75, 50, 25 and 0% soil moisture reduction were considered. Finally, the relationship between *CWSI* and crop performance was presented (Orta *et al*., 2003). The canopy temperature in different moisture conditions is affected by changes in nitrogen status, because nitrogen significantly affects the correlation between *CWSI* and crop yield (Meijer, 2005; Chen *et al*., 2010).

Researchers in Bursa (Turkey) conducted a study on soybean with five treatments of 100, 75, 50, 25 and zero percent of water requirement and a seven-day irrigation period for both 2005 and 2006 crop years and concluded that *CWSI* may be used to determine soybean irrigation time in humid climates. They determined a *CWSI* limit of 0.22. They also obtained statistical relationships between *CWSI*, grain yield and evapotranspiration (Candogan *et al*., 2013). In a study on olive trees, they set a value of 0.39 for *CWSI* to achieve maximum *WP* (Akkuzu *et al*., 2013). Also, the results showed that in order to achieve a maximum yield of grapes, irrigation should be implemented when *CWSI* is about 0.2 (Colak and Yazar, 2017).

Maize with the scientific name of *Zea mays* L. is a monocotyledonous, annual plant from the *Geramineae* and *Poaceae* family which has a high degree phenotypic variability. Black gram is also a plant with the scientific name *Vigna mungo* L. from the Fabaceae family. The black gram used in this study was grown in a vast area in the south of the West Azerbaijan province to meet the nutritional needs of the local people. The objectives of the present study are to: (i) calculate the *CWSI* threshold under different drip irrigation regimes, (ii) evaluate the potential of *CWSI* to estimate the *GY* and *WP* levels of maize and black gram in the climatic conditions of Iran (Urmia city), and (iii) determine the relationship between the *WP* index and antioxidant compounds including phenol and flavonoid.

MATERIALS AND METHODS

This research was carried out on two maize crops (cultivar SC704) and black gram at Urmia (Iran) in the crop year 2017. The location of this field has been specified at 37° 39’ north latitude, 44° 58’ east longitude and 1365 m a.s.l. (Khorsand *et al*., 2019). The climate of Iran is semi-arid. The dimensions of the plots for the two maize and black gram crops were 4 × 3 and 3 × 2 (m × m), respectively, and the plots have a spacing of 2 m. Soil samples were also taken to determine the physical properties of the soil (Table 1).

In this study, the effects of different irrigation treatments on two maize and black gram crops were investigated. The experimental design was a randomized complete block design with four water treatments of maize and black gram in three replications (Fig. 1). The water treatments were as follows: I_1 – 50%, I_2 – 75%, I_3 – 100% and I_4 – supplying 125% of crop water requirements, respectively. Daily meteorological parameters were obtained from a meteorological station to determine water requirements (Khorsand *et al*., 2019). The meteorological parameters including maximum, minimum and average temperature, maximum and minimum relative humidity, hours of sunshine, wind speed and rainfall were obtained (Table 2). Then, the reference evapotranspiration (ET_o) value was calculated using the ET_o Calculator (Raes, 2009). Finally, the ET_o obtained by multiplying the crop coefficient (K_c) (Farshi *et al*., 1997) was generalized for the potential evapotranspiration (ET_c) values of maize and black gram.

Table 1. Physical properties of the experimental soil

Soil depth (cm)	Clay	Silt	Sand	Texture class	Maize			Black gram		
	(%)				FC	PWP	BD	FC	PWP	BD
					(cm^3 cm^{-3})		(g cm^{-3})	(cm^3 cm^{-3})		(g cm^{-3})
0-30	44	50	6	Silt Clay Loam	0.349	0.241	1.328	0.353	0.241	1.370
30-60	39	33	28	Clay Loam	0.366	0.279	1.530	0.360	0.249	1.473

FC – field capacity, PWP – permanent wilting point, BD – bulk density.

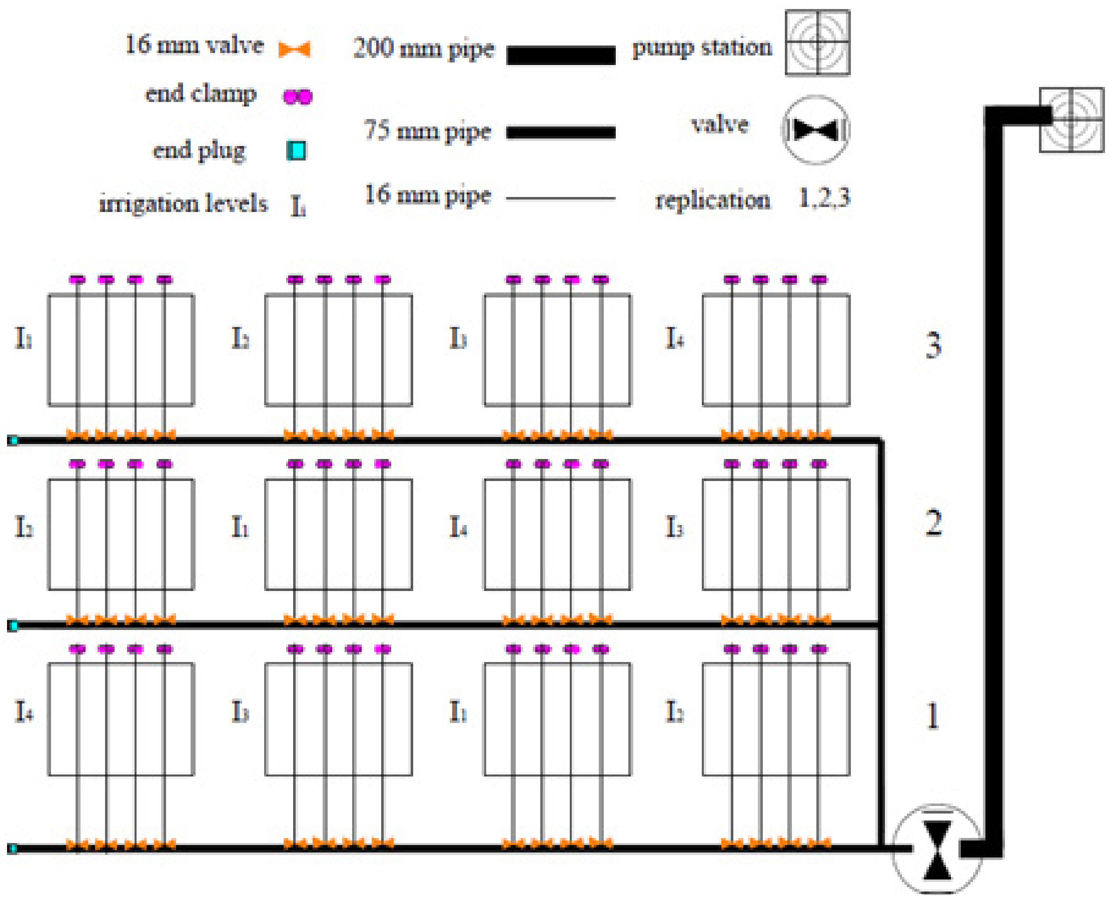

Fig. 1. Plot layout of field experiment for plants.

Table 2. Average and sum monthly weather parameters, during the 2017 growing seasons (Khorsand *et al*., 2019)

Month	Parameter							
	Air_{temp} (°C)			RH (%)		HBS (h d^{-1})	WS (m s^{-1})	P (mm)
	Mean	Min	Max	Min	Max			
May	18.7	12.5	24.9	26	65	309.8	7	15.1
June	24.0	16.7	31.3	24	54	341.9	5	0
July	27.4	20.2	34.5	25	50	344.4	4	0
August	26.9	19.6	34.2	29	52	349.0	3	2.2
September	22.2	15.1	29.4	35	57	296.5	4	0
October	14.4	7.9	21.0	35	63	255.4	5	3.3

Air_{temp} – air temperature, RH – relative humidity, HBS – hours of bright sunshine, WS – wind speed, P – precipitation.

During the vegetation season of maize and black gram, irrigation was applied using a 16 mm adipose drip pipe located next to each row of crops. The 16 mm pipes had a constant pressure and a thickness of 1.15 mm. In-line emitter intervals were 20 cm and the emitter discharge was 4 l h^{-1}. At the start of each 16 mm pipe, a 16 x 16 mm valve was used to control the stress over time (Khorsand *et al*., 2019).

In the present study, a handheld infrared device was used to measure the canopy temperature (T_c). In this study, T_c was not measured from treatments of maize and black gram from the time of planting until 10 July due to the small size of the shrubs. Canopy temperature was measured after the complete establishment and formation of the plants and when the sky was clear and sunny in four different directions (Erdem *et al*., 2005) for each water treatment with three replications. Measurements were taken from different maize and black gram leaves at an angle of 30 to 45 degrees relative to the horizon because different plant leaves were likely to have different temperatures; therefore, the average T_c was obtained by averaging these values (12 readings) (Sezen *et al*., 2014). Generally, 84 T_c readings were performed in 7 h for each treatment in one day for the maize and black gram separately.

To obtain the lower baseline equation, the T_c values of maize and black gram were measured between the hours of 8:50 and 14:50 for 100% water requirement (I_3) on the days after irrigation (Taghvaeian *et al*., 2013). Also, in order to determine *CWSI* and calculate $(T_c - T_a)_m$, the T_c of maize and black gram were measured hourly from 11:50 to 14:50 in the days before irrigation for all three treatments (I_1, I_2 and I_3):

$$(T_c - T_a)_{L.L} = a - b(AVPD) = a - b\left\{10 \times e^{\left[\frac{16.78T_a - 116.9}{T_a + 237.3}\right]} \times \left(1 - \frac{RH}{100}\right)\right\}, \quad (1)$$

where: T_c is the canopy temperature (˚C), T_a represents the air temperature (˚C), *AVPD* is the air vapour pressure deficit (mbar), *RH* denotes the relative humidity (%), *a* and *b* are the constant coefficients which are different for different products (crop and garden). The upper baseline also represents the maximum value that can be expected for $(T_c - T_a)$ (Idso *et al*., 1981). *CWSI* is one of the indices that express the water status of the plant based on $(T_c - T_a)$ and is calculated from the following formula (Idso *et al*., 1981):

$$CWSI = \frac{dT_m - dT_{L.L}}{dT_{U.L} - dT_{L.L}} = \frac{(T_c - T_a)_m - (T_c - T_a)_{L.L}}{(T_c - T_a)_{U.L} - (T_c - T_a)_{L.L}}, \quad (2)$$

where: dT_m is the difference between the canopy temperature and air temperature at the measurement time (˚C), $dT_{L.L}$ represents the difference between the canopy temperature and air temperature obtained from the lower baseline equation for the measured *AVPD*, and $dT_{U.L}$ is a constant number for the upper baseline.

Crop harvesting was implemented at the physiological maturity stage for black gram on 09/13/2017 and maize on 03/10/2017 by eliminating the marginal effects of each plot surface area. In order to obtain the grain yield, pods were harvested from black gram and corn from maize and samples from the harvest were transferred to the laboratory for drying. The samples were dried in an oven conditioned at 70°C for 48 h, the samples were then weighed to obtain grain yield using a digital scale (0.01 precision). Finally, the plant yield numbers were generalized to one hectare.

The water productivity (*WP*) index is one of the important indicators in the evaluation and optimal management of water consumption in irrigation projects. According to the measurement of yield and water consumption for each treatment, the *WP* index for different treatments of black gram and maize was calculated from the following relationship (Molden *et al*., 2003):

$$WP = \frac{GY}{V_I}, \quad (3)$$

where: *WP* is the water productivity index (kg m^{-3}), *GY* is the grain yield (kg ha^{-1}) and V_I is the volume of irrigation water (m^3 ha^{-1}).

RESULTS

The first step for estimating *CWSI* is the development of lower and upper baselines for maize and black gram plants. In order to calculate the lower baseline of the experimental method of Idso *et al*. (1981), the T_c of maize and black gram were measured from 8:50 a.m. to 02:50 p.m. The lower baseline equations from the results of this experimental method for the three growth stages of maize (vegetative phase-floral initiation, flowering-pollination and seed seating-seed filling) and the four growth stages of black gram (floral induction-flowering, pod formation, seed and pod filling and physiological maturity) are presented for different days after irrigation in Figs 2 and 3. The correlation between $(T_c - T_a)$ and *AVPD* is also shown in Figs 2 and 3.

According to both sampling and field and laboratory measurements, the *GY* of the plants was calculated in kg per hectare and also through dividing the grain yield by the irrigation water, the *WP* of maize and black gram in kg m^{-3} was determined for each replicate of the tested treatments (Table 3). According to Table 3, crop yields decreased with the application of irrigation treatments and the stress applied to the plants and showed a greater decrease with increasing stress. The maximum average grain yield in the I_3 treatment (100% water requirement) for maize and black gram were 10.02 and 1.87 t ha^{-1}, respectively and the minimum average grain yield for the I_1 treatment (50% water requirement) for maize and black gram, respectively was found to be 5.28 and 1.47 t ha^{-1}, respectively.

The lower baseline equation for the experimental method Idso *et al*. (1981) was based on the non-stress treatment. In this study, the non-stress treatment is the I_3 treatment, which is the same as the lower baseline equation for the under-stress treatments (I_1 and I_2). In this experimental method, the basis of the calculations for the lower baseline equation of all treatments is the non-stress treatment. It should be noted that sometimes the measurement of canopy temperature is conducted after irrigation, this does not mean non-stress conditions exist and then the treatment data that received the most water can be used for the rest of the treatments. By examining the data and calculating the *CWSI* for the I_3 treatment, we found that the treatment had non-stress conditions; therefore, the *CWSI* calculation for treatment I_4 was not performed.

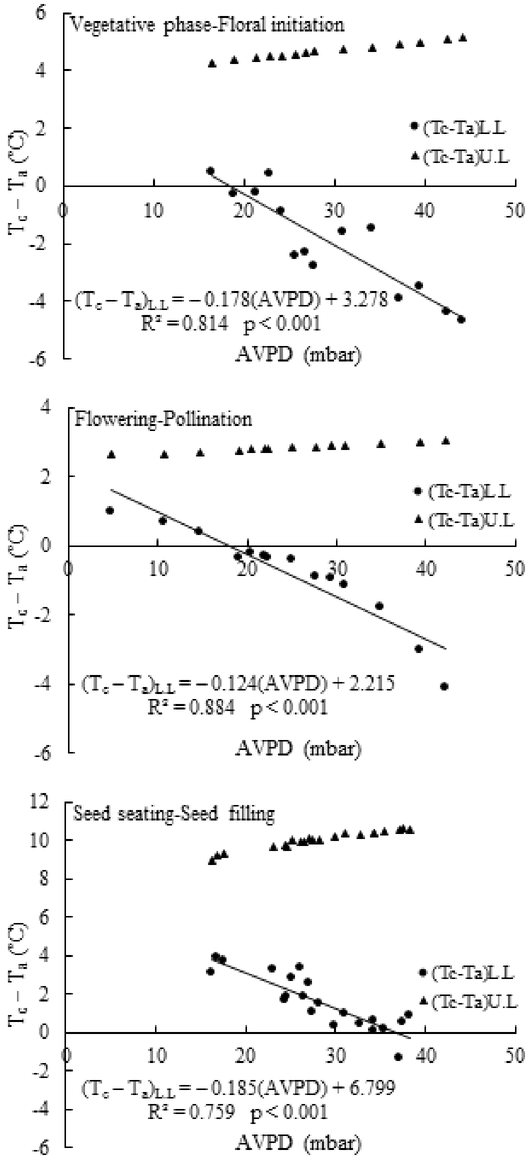

Fig. 2. Lower and upper baselines for the three stages of maize growth (Khorsand *et al.*, 2019).

The *GY* relationship of maize and black gram with *CWSI* may be observed from the results obtained in Fig. 4. According to these figures, the relationship between *GY* and *CWSI* is inverse, that is, the lower *CWSI* leads to the more favourable water conditions of the plant and higher *GY*; therefore, *CWSI* can be used to estimate *GY* under water stress conditions (Ahmadi *et al.*, 2018). The regression relationship between the *GY* of maize and black gram with *CWSI* may be determined as follows (Fig. 4):

$$GY_{maize} = - 17.53\ (CWSI) + 15.39 \quad R^2 = 0.79, \qquad (5)$$

$$GY_{black\ gram} = - 1.824\ (CWSI) + 2.144 \quad R^2 = 0.99, \qquad (6)$$

According to Fig. 4a, the maximum *GY* of maize for the I_3 treatment (100% water requirement) with an average water stress index of 0.28 is equal to 10.02 t ha^{-1} and the minimum *GY* for the I_1 treatment (50% water requirement) with an average water stress index of 0.53 was 5.28 t ha^{-1}. Also, according to Fig. 4b, the maximum *GY* of black gram for I_3 or the control treatment with an average water stress index of 0.15 is 1.88 t ha^{-1} and the minimum *GY* for the I_1 treatment with an average water stress index of 0.37 was found to be 1.47 t ha^{-1}. The higher degree of water stress in the plant causes the lower *GY* value of the crop.

According to the results, the highest *GY* values of maize and black gram were obtained at a water stress level of 0.28 and 0.15, respectively. These values are recommended for the irrigation scheduling of maize and black gram in Iran (Urmia). Given the high degree of accuracy of the regression models obtained between the *GY* values of the crops and *CWSI*, one can predict the *GY* value of crops through these relationships by calculating *CWSI* and the aforementioned models can also be used for better water management on the farm.

An examination of the relationship between *WP* and the *CWSI* index for maize and black gram showed that there is a respectively nonlinear (uni-variate) and linear (uni-variate) relationship between them, as presented in Fig. 5. According to Fig. 5, the *WP* range for maize is between 1.5 and 1.9 kg m^{-3} and for black gram it is between 0.3 and 0.6 kg m^{-3}. The highest *WP* value in maize was related to the I_2 treatment (75% water requirement) with a value of 1.88 kg m^{-3} and at a *CWSI* value of 0.44 (Fig. 5a). Also, the highest *WP* value in black gram was related to the I_1 treatment (50% water requirement) with a value of 0.53 kg m^{-3} and at a *CWSI* value of 0.37 (Fig. 5b).

According to the above, the highest *WP* value for maize and black gram were obtained respectively at a water stress index of 0.44 (I_2 treatment) and 0.37 (I_1 treatment), which are the values recommended for irrigation scheduling under access restriction conditions with high water prices. The *WP* vs. *CWSI* relationship for maize and black gram includes Eqs (11) and (12), respectively:

$$WP_{maize} = - 17.17\ (CWSI)^2 + 14.25\ (CWSI) - 1.067 \quad R^2 = 1.0, \qquad (7)$$

$$WP_{black\ gram} = - 0.868\ (CWSI) + 0.207 \quad R^2 = 0.99. \qquad (8)$$

In the present study, antioxidant activity was determined using the total phenol and flavonoid content in four water treatments w ith three replications for black gram and maize. According to the results obtained for black gram, the highest total phenol content (22.6 mg of gallic acid per 100 g of seed dry matter) was observed for the I_1 treatment and the lowest amount (17.82 mg of gallic acid per 100 g of seed dry matter) was observed for the I_4 treatment (Fig. 6a). Also, according to Fig. 6b for maize, the maximum total phenolic content (7.68 mg of gallic acid per 100 g

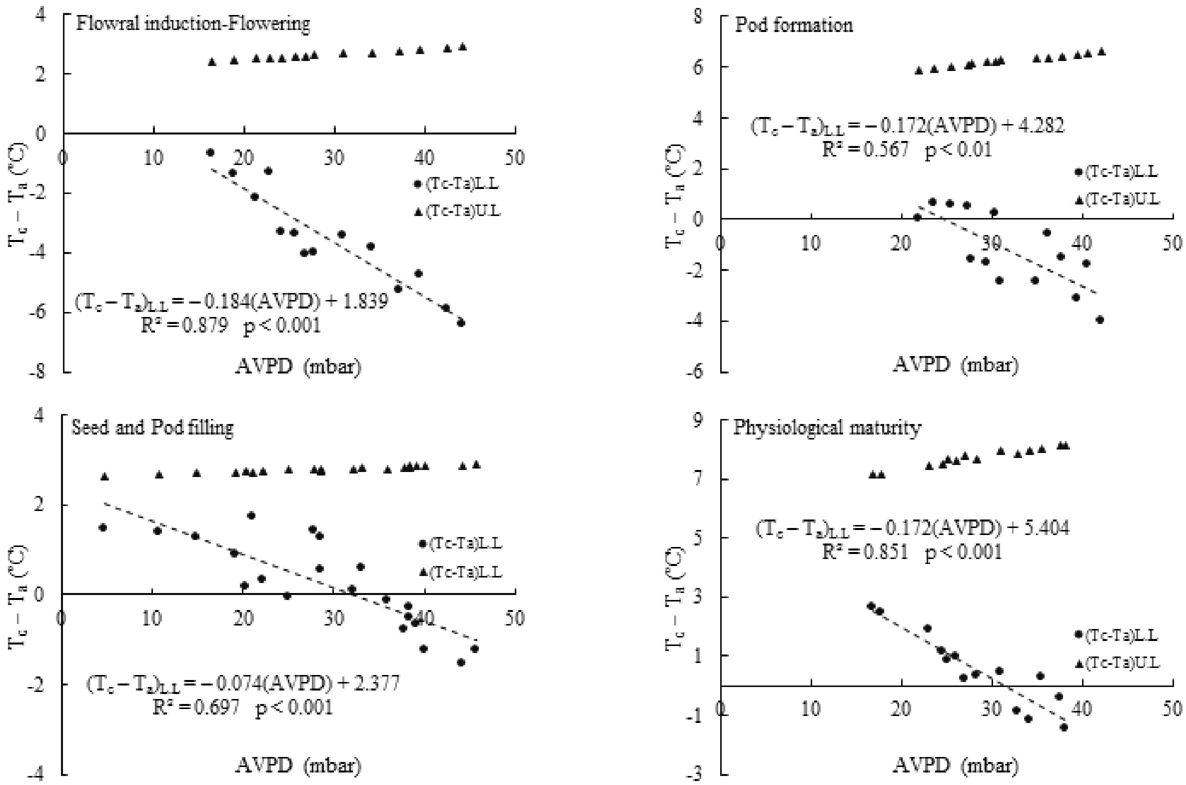

Fig. 3. Lower and upper baselines for the four stages of black gram growth.

Table 3. Quantities of irrigation volume, grain yield and water productivity of crops for different irrigation treatments

Treatment	Plant					
	Maize			Black gram		
	I_1	I_2	I_3	I_1	I_2	I_3
CWSI (-)	0.53	0.44	0.28	0.37	0.23	0.15
V_I (m^3 ha^{-1})	3177.80	4766.60	6355.50	2794.10	4191.20	5588.20
GY (kg ha^{-1})	5281.11	8954.07	10021.33	1473.73	1710.33	1878.69
WP (kg m^{-3})	1.66	1.88	1.58	0.53	0.41	0.34

CWSI – crop water stress index, V_I – irrigation volume, *GY* – grain yield, *WP* – water productivity.

of seed dry matter) was observed for the I_2 treatment and its minimum amount (5.47 mg of gallic acid per 100 g of seed dry matter) was observed for treatment I_4.

According to the results obtained for black gram, the highest flavonoid content (15.07 mg of quercetin per 100 g of seed dry matter) was observed for the I_1 treatment and the lowest amount (8.39 mg of quercetin per 100 g of seed dry matter) was associated with the I_4 treatment (Fig. 7a). Also according to Fig. 7b for maize, the maximum flavonoid content (3.08 mg of quercetin per 100 g of seed dry matter) was associated with the I_2 treatment and its minimum value (1.82 mg of quercetin per 100 g of seed dry matter) was observed for the treatment I_4.

DISCUSSION

Using the experimental method proposed by Idso *et al.* (1981), the values of (T_c – T_a) were plotted versus *AVPD* and, regression relationships were obtained for the growth stages of maize (three stages) and black gram (four stages) (Figs 2 and 3). In deriving regression relationships, it was assumed that the plants did not tolerate environmental stress other than water stress. According to Figs 2 and 3, the range of *AVPD* and (T_c – T_a) for the three stages of maize growth is 4 to 45 mbar and 4 to – 5°C, respectively, and for the four stages of black gram growth it is 4 to 46 mbar and 3 to – 7°C, respectively. The equations of the low base

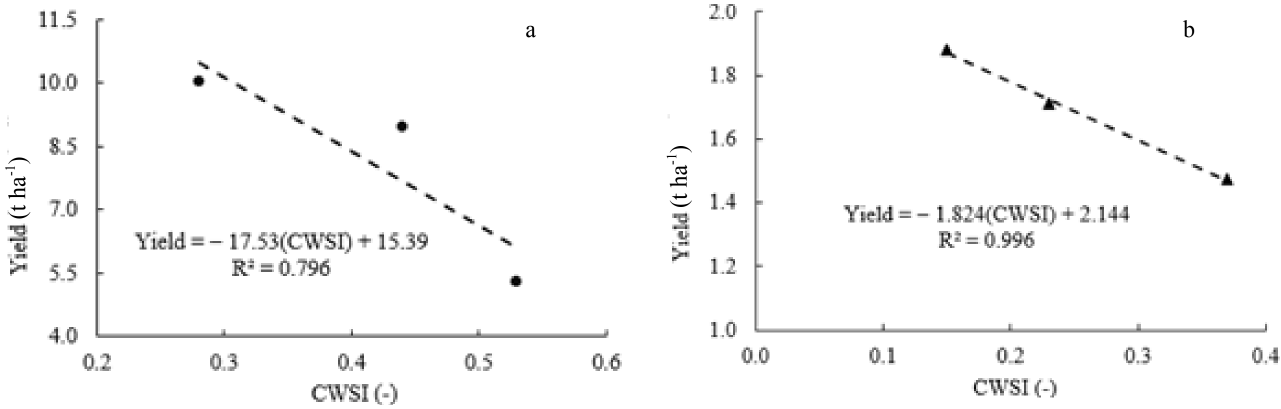

Fig. 4. Relationship between grain yield and crop water stress index of maize (a) and black gram (b).

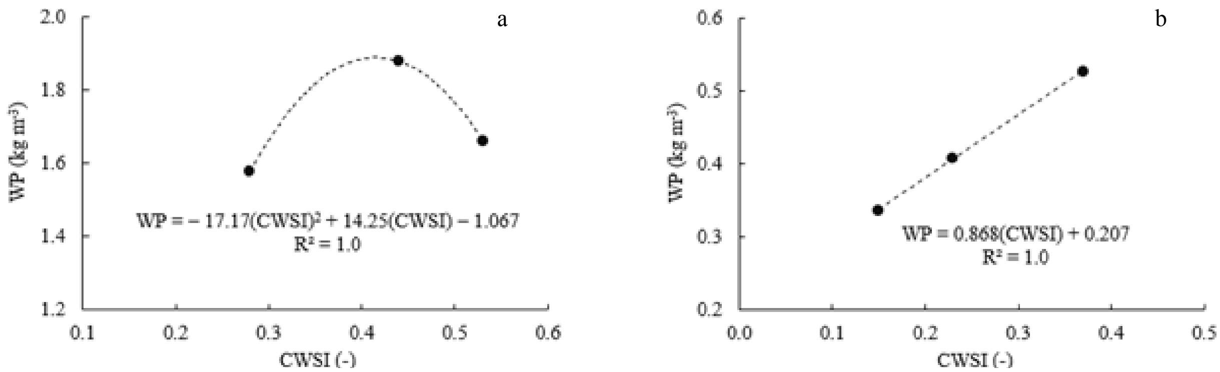

Fig. 5. Relationship between the water productivity index and crop water stress index of maize (a) and black gram (b)

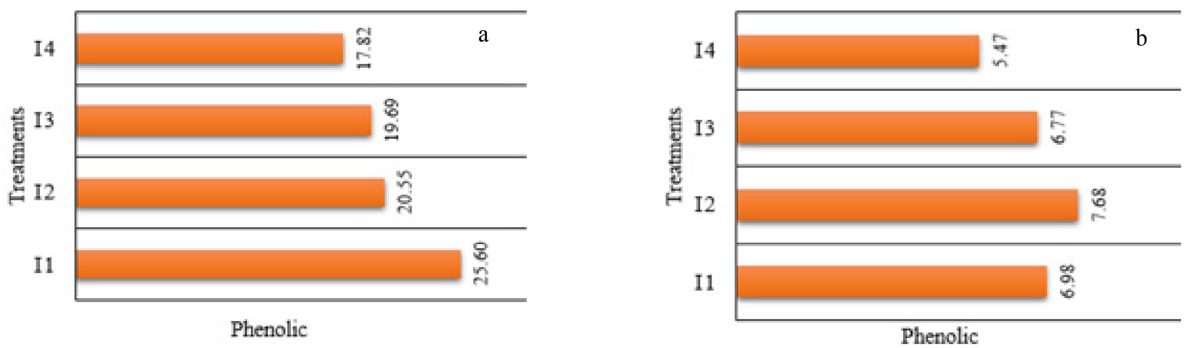

Fig. 6. Comparison of mean total phenolic content of black gram seeds (a) and maize (b) in the different irrigation treatments.

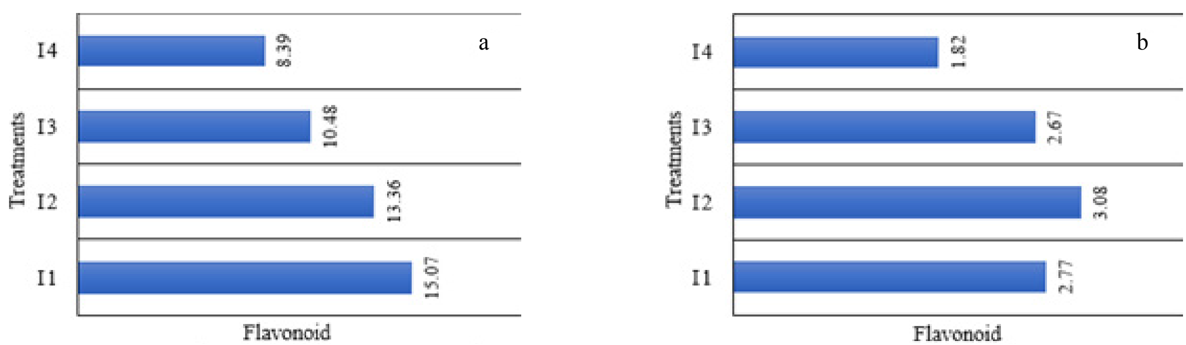

Fig. 7. Comparison of flavonoid content of black gram seeds (a) and maize (b) for the different irrigation treatments.

lines fitted in the plant growth stages may be used in different places for maize and black gram, provided that the range of *AVPD* is wide (Gardner and Shock, 1989). With increasing *AVPD* ($T_c - T_a$) (in terms of absolute magnitude) and also evaporation and transpiration increase, moreover the ($T_c - T_a$) increase rate decreases with time (Taghvaeian *et al*., 2013; Khorsand *et al*., 2019).

An examination of the relationships of the lower baselines showed that the values of coefficients a and b are different for the growth stages of the two plants. The negative slope of the line was obtained for all three stages of maize growth and the four stages of negative black gram growth (Figs 2 and 3). The reasons for the different values of coefficients a and b include the difference in water absorption potential as well as transpiration during the plant growth stages (Khorsand *et al*., 2019). Using the method of Idso *et al*. (1981) and according to Figs 2 and 3, the values of the upper baseline for the three stages of maize growth were found to be 4.69, 2.83 and 10.01°C (Fig. 2), respectively, and for the four stages of growth of black gram, they were found to be 2.63, 6.25, 2.79 and 7.73°C, respectively (Fig. 3).

In the present study, the values of coefficients a and b of the baseline for maize were different from the results of other studies conducted for this plant (Irmak *et al*., 2000; Taghvaeian *et al*., 2012; Taghvaeian *et al*., 2013). The coefficients a and b of the first and second stages of maize plant growth are similar to those obtained by Idso (1982) and Steele *et al*. (1994). Also, a study by DeJonge *et al*. (2015) in the United States reported coefficients a and b of 2.34 and − 0.179, respectively, which were close to the coefficients of the second stage of maize growth in this study. It should also be noted that as yet no research has been conducted on the equations of the black gram base lines to compare with the results of this study. According to the studies of researchers in the field of irrigation scheduling based on *CWSI*, it has been determined that the location of baselines depends on the plant type and cultivar, soil type, type of irrigation system, water vapour saturation, climatic conditions and the complete cessation of transpiration in the growth stages (Taghvaeian *et al*., 2013; Khorsand *et al*., 2019). The purpose of *CWSI* is to provide a simple method for measuring plant water stress and to serve as a valuable tool for the irrigation scheduling of crops and garden products that can predict irrigation time (Irmak *et al*., 2000; Chen *et al*., 2010) and its value is a variable between zero and one (DeJonge *et al*., 2015). The mean *CWSI* values during the growing periods of maize and black gram for the three treatments are presented in Table 3. The maximum *CWSI* of both plants is related to treatment I_1 (severe deficit irrigation). The factor that increased *CWSI* for the I_1 treatment was T_c; because the plant closed its stomas due to water stress and the T_c of the plant increased (Taghvaeian *et al*., 2013).

The *CWSI* method has been used in various studies to manage plant irrigation. The *CWSI* threshold values in this study for maize and black gram undergoing the non-stress treatment were 0.28 and 0.15, respectively, these values were the basis of irrigation scheduling. Stegman (1986) conducted a study in the United States concerning the timing of maize irrigation and used two *CWSI* values (0.2 and 0.4). Plant *WP* was increased to 2.5 kg m^{-3} using irrigation scheduling based on *CWSI* (with a threshold of 0.4). In the present study, the maximum maize *WP* (1.88 kg m^{-3}) was observed to have a *CWSI* value of 0.44. It is true that the *CWSI* of this study is close to the *CWSI* obtained by Stegman (1986), but the *WP* of maize in this study was approximately 0.62 kg m^{-3} (24.8% decrease in *WP*) less than the *WP* obtained by Stegman (1986). Steele *et al*. (1994) conducted a similar study with maize for three years in the region where Stegman (1986) conducted a study in the United States. In this study, *CWSI* values of 0.2, 0.4 and 0.6 were used, which reduced water consumption by 28, 43 and 54%, and no significant *GY* reduction occurred for the product at a *CWSI* threshold of 0.2. Irmak *et al*. (2000) conducted a study on maize in Turkey and concluded that the mean *CWSI* should be below 0.22 to prevent a reduction in maize *GY*. In the present study, the difference between the mean value of *CWSI* and the result produced by Irmak *et al*. (2000) is 0.06, which is about 21.4% higher, and the mean value of *CWSI* in this research with maize should be below 0.28 so that the *GY* of the plant does not decrease.

In a study with different plants, the threshold value of *CWSI* for red pepper was 0.20 (Sezen *et al*., 2014), for eggplant it was 0.26 (Colak *et al*., 2015) and for soybean it was 0.18 (Ahmadi *et al*., 2018). The existence of a linear regression relationship between *GY* and *CWSI* and its use to predict performance has been confirmed by other researchers (Idso *et al*., 1981; Orta *et al*., 2003; Erdem *et al*., 2010; Sezen *et al*., 2014; Çolak *et al*., 2015). The following regression relationships were found between *GY* (kg ha^{-1}) and *CWSI* for red pepper under drip irrigation and furrow irrigation under different irrigation regimes in Turkey in 2010 and 2011 (Sezen *et al*., 2014):
drip irrigation:

$$GY_{2010} = -23.77\text{x}10^3\,(CWSI) + 48.84\text{x}10^3 \quad R^2 = 0.88, \tag{9}$$

$$GY_{2011} = -43.52\text{x}10^3\,(CWSI) + 60.61\text{x}10^3 \quad R^2 = 0.90, \tag{10}$$

furrow irrigation:

$$GY_{2010} = -94.80\text{x}10^2\,(CWSI) + 38.87\text{x}10^3 \quad R^2 = 0.75, \tag{11}$$

$$GY_{2011} = -35.07\text{x}10^3\,(CWSI) + 52.97\text{x}10^3 \quad R^2 = 0.66. \tag{12}$$

In another study carried out for eggplants under different irrigation regimes using surface and subsurface drip irrigation systems in Turkey in 2013, the following regression relationships were obtained between *GY* (kg ha^{-1}) and *CWSI* (Çolak *et al*., 2015):

surface drip irrigation:

$$GY = -79.71 \times 10^3 \,(CWSI) + 94.34 \times 10^3 \quad R^2 = 0.83, \tag{13}$$

subsurface drip irrigation:

$$GY = -78.16 \times 10^3 \,(CWSI) + 86.01 \times 10^3 \quad R^2 = 0.69. \tag{14}$$

In a study conducted with soybean under different irrigation regimes using a furrow irrigation system in the climatic conditions of Khorramabad, the *CWSI* values for irrigation scheduling to achieve maximum *WP* at the developmental, intermediate and final stages of plant growth were 0.42, 0.37 and 0.29, respectively (Ahmadi *et al*., 2018). It should be noted that the mean *CWSI* in this study for black gram should be below 0.15 so that *GY* does not decrease. Also, no research has been done to evaluate the *CWSI* of black gram to compare it with the results of the present study.

According to the results for phenol and flavonoid, the maximum values for black gram and maize where obtained for 50 and 75% water requirement treatments, respectively. We found that the maximum *WP* values for both plants were obtained for these treatments (I_1 and I_2) which were discussed in the previous section; therefore, a direct relationship between phenol and flavonoid and the *WP* of the plants may be considered. Phenolic compounds and flavonoids are the antioxidant compounds of plants (Lindsay and Astley, 2002) which are of great physiological and morphological importance in plants (Schijlen *et al*., 2004). The main reason for the high antioxidant activity of some extracts is due to the high content of phenolic compounds (Jiao *et al*., 2005). Various factors such as genotype, climate and weather conditions, soil type, plant growth season and storage conditions affect the antioxidant activity of plants (Asekun *et al*., 2006). Flavonoids have the ability to cleanse active oxygen species and prevent oxidative stress. An examination of the flavonoid content of canola under drought irrigation (water stress) showed that flavonoid content increases as a secondary metabolite in the plant (Sangtarash *et al*., 2009). In general, the results showed that by stimulating the factors promoting the formation of phenolic compounds and flavonoids, water stress increases its content in black gram seeds, which can also be a reason for reducing transpiration in this plant. Also, given the results for black gram, it may be concluded that this plant has a high tolerance for drought and may be used as a low water plant in arid and semi-arid climates. It should be noted that promoting the cultivation of low-water medicinal plants such as lavender, garden thyme, lemon balm among others is one of the plans for the Urmia Lake Restoration project, which aims to improve farmers' livelihoods (income generation) and reduce pressure on resources and soil (reduce water use) in the Urmia Lake basin; therefore black gram can also be cultivated as one of the medicinal plants in this basin.

CONCLUSIONS

The present study was conducted in order to investigate the relationship between the crop water stress index, grain yield, water productivity and antioxidant compounds (phenol and flavonoid) of two maize (cultivar SC704) and black gram (native bulk) plants in Urmia (Iran).

1. Based on the results, the highest grain yield values for maize and black gram were obtained at a crop water stress index of 0.28 and 0.15, respectively; therefore, these values are recommended for the irrigation scheduling of maize and black gram in Urmia (Iran). Given the high degree of accuracy of the regression models obtained between the grain yield of crops and the crop water stress index, one may predict the grain yield of the crops through the relationships between them by calculating the crop water stress index and this can also be used for better water management in the field.

2. The maximum water productivity for maize and black gram was obtained at a water stress index of 0.44 (I_2 treatment) and 0.37 (I_1 treatment), respectively, which are recommended for irrigation scheduling under water restriction conditions in Urmia (Iran).

3. In general, it may be stated that the crop water stress index is capable of assessing water stress and estimating the crop produced under water stress in plants.

4. It should be noted that the direct relationship between water productivity and the antioxidant compound content of the two plants was also obtained.

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