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CROP WATER STRESS INDEX OF COWPEA UNDER DIFFERENT WATER AVAILABILITY LEVELS IN CASTANHAL-PA[1]

ERIKA DE OLIVEIRA TEIXEIRA DE CARVALHO[2]*, DEBORAH LUCIANY PIRES COSTA[2], IGOR CRISTIAN DE OLIVEIRA VIEIRA[2], BRUNO GAMA FERREIRA[2], HILDO GIUSEPPE GARCIA CALDAS NUNES[2], PAULO JORGE DE OLIVEIRA PONTE DE SOUZA[2]

ABSTRACT – Cowpea is a crop of great socioeconomic relevance for the populations of the North and Northeast of the country, and its low yield is commonly related to environmental stresses, especially water. The objective of this study was to evaluate the water stress index of cowpea, cultivar BR3 - Tracuateua, subjected to different irrigation levels (100, 50, 25 and 0% of ETc) in three reproductive phenological stages (R7, R8 and R9) in Castanhal-PA, Brazil. The experimental design was in randomized blocks, with six replications and four treatments corresponding to 100, 50, 25 and 0% of daily replacement of crop evapotranspiration, during the reproductive period, through an irrigation system. The surface temperature readings were made with infrared thermometer, during the reproductive stage. The smallest absolute temperature differences between canopy and air occurred in stages R7 and R8. The highest values of water stress index (CWSI) were verified when the plant was under water deficit, regardless of phenological stages. The effect of water deficit caused reductions in stomatal conductance of 58.82% (R7), 83.57% (R8) and 84.87% (R9), in leaf transpiration of 45.97% (R7), 64.21% (R8) and 65.90% (R9) and in the net photosynthetic rate of 40.75% (R7), 66.92% (R8) and 74% (R9). The CWSI varied with the availability of water, showing the highest value (0.75) in the treatment without irrigation, in the R8 stage. The CWSI proved to be a good indicator of the water status of the plant.

Keywords: Water deficit. Canopy temperature. *Vigna unguiculate.*

ÍNDICE DE ESTRESSE HÍDRICO DO FEIJÃO-CAUPI EM DIFERENTES DISPONIBILIDADES HÍDRICAS EM CASTANHAL-PA

RESUMO – O feijão-caupi é uma cultura de grande relevância socioeconômica para as populações do Norte e Nordeste do país, e seu baixo rendimento está comumente relacionado a estresses ambientais, em especial ao hídrico. O objetivo deste estudo foi avaliar o índice de estresse hídrico do feijão-caupi da cultivar BR3 - Tracuateua, submetido a diferentes níveis de irrigação (100, 50, 25 e 0% da ETc) em três estádios fenológicos reprodutivos (R7, R8 e R9), em Castanhal-PA, Brasil. O desenho experimental foi em blocos casualizados, com seis repetições e quatro tratamentos correspondentes a 100, 50, 25 e 0% de reposição diária da evapotranspiração da cultura, durante o período reprodutivo, por meio de um sistema de irrigação. As leituras de temperatura da superfície foram feitas com termômetro infravermelho, durante a fase reprodutiva. As menores diferenças absolutas de temperatura entre o dossel e o ar ocorreram nas fases R7 e R8. Os maiores valores de índice de estresse hídrico (IEHD) foram verificados quando a planta estava sob déficit hídrico, independente dos estádios fenológicos. O efeito do déficit hídrico proporcionou redução na condutância estomática de 58,82% (R7), 83,57% (R8) e 84,87% (R9), transpiração foliar de 45,97% (R7), 64,21% (R8) e 65,90% (R9) e na taxa fotossintética líquida de 40,75% (R7), 66,92% (R8) e 74% (R9). O IEHD variou com a disponibilidade de água, apresentando o maior valor (0,75) no tratamento sem irrigação, no estádio R8. O IEHD se mostrou como bom indicador do status hídrico da planta.

Palavras-chave: Deficiência hídrica. Temperatura do dossel. *Vigna unguiculata.*

*Corresponding author
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[2]Socio-environmental and Water Resources Institute, Universidade Federal Rural da Amazônia, Belém, PA, Brazil; eriikateixeira@hotmail.com - ORCID: 0000-0002-8413-7615, deborahpires.agro@gmail.com - ORCID: 0000-0002-3513-0759, cristianigor67@gmail.com - ORCID: 0000-0002-0488-5008, bruno12014ferreira@gmail.com - ORCID: 0000-0001-5782-819X, garibalde13@gmail.com - ORCID: 0000-0003-4072-003X, paulojorge_oliveira@globomail.com - ORCID: 0000-0003-4748-1502.

INTRODUCTION

In Brazil, cowpea (*Vigna unguiculata* (L.) Walp.) is widely found in the North and Northeast regions and commonly produced by family farmers, and its importance is linked to the composition of the food base of these populations and the contribution to the generation of employment and income (FERREIRA et al., 2021).

In the 3rd harvest of 2018/2019, the State of Pará had an average yield of cowpea around 821 kg ha^{-1} (RODRIGUES et al., 2020). This yield, below the production potential of the crop, which is 1,435.60 kg ha^{-1} (FREIRE FILHO et al., 2005), may be due to several factors including high temperatures and water stress conditions (SOUZA et al., 2017).

According to Souza et al. (2020), water deficits in the reproductive stage greater than 47 mm cause yield drops greater than 20% in cowpea grown in northeastern Pará, because the crop (cultivar BR3 - Tracuateua) has high sensitivity to water stress, with a water stress coefficient (Ky) of 1.48 (MOURA et al, 2021).

Environmental conditions have great interference in plant development (FARIAS et al., 2017; SOUZA et al., 2019), and water deficit is one of the main factors that limit crop yield, since the stomata are the main route for CO_2 assimilation and water loss through transpiration (TAIZ; ZEIGER, 2017).

The absence of adequate amount of water in the soil affects the physiological activities of the plant, varying according to frequency, intensity and genotype (SOUZA et al., 2019), and to avoid water loss to the atmosphere, crops use strategies such as leaf area reduction, leaf abscission and stomatal closure (FREITAS et al., 2017). These strategies reduce photosynthesis and transpiration, compromising the production of photoassimilates and decreasing the dissipation of plant heat to the atmosphere, thus causing a thermal stress in the plant (JAGADISH et al., 2021).

Non-destructive methods have been used to determine water stress in plants and thus allow a more efficient planning for their water supply (KING; SHELLIE, 2018). The use of infrared thermometers has been one of these methods, since the water deficit experienced by the crop tends to decrease its transpiration and consequently heat dissipation, increasing the temperature of the leaves, allowing the measurement of the flow of thermal radiation on the crop surface in a practical and accurate way (RU et al., 2020).

The canopy water stress index (CWSI) was adopted by several researchers to monitor the thermal/water stress of crops such as tomato (SILVA et al., 2018) and grape (RU et al., 2020) either for the purpose of aiding irrigation management or due to its close relationship with crop yield (ÇOLAK et al., 2015)

The objective of this work was to evaluate the CWSI of cowpea under different levels of water availability as an indicator of water stress in three reproductive phenological stages, in the municipality of Castanhal-PA.

MATERIALS AND METHODS

The experiment was carried out at the Experimental Farm of the Federal Rural University of the Amazon, in Castanhal, northeastern Pará (1°19'24.48"S and 47°57'38.20"W), between September and November 2016. The climate of the region is type Am, humid tropical and with an average annual temperature of 26 ºC, according to the Köppen's classification (ALVARES et al., 2013).

The soil is a *Latossolo Amarelo Distrófico* (Oxisol), with sandy loam texture. For soil fertilization, 195 kg ha^{-1} of N-P-K chemical fertilizer formulation 6-18-15 was used and soil correction was performed, as recommended by Embrapa Eastern Amazon (Table 1).

Table 1. Chemical and physical characterization of soil, Castanhal, PA, Brazil.

Soil chemical characteristics (0-20 cm)						
pH	P	K^+	Na^{2+}	Ca^{2+}	Ca^{2+}+Mg^{2+}	Al^{3+}
H_2O	------- mg dm^{-3} -------			------- $cmol_c$ dm^{-3} -------		
3.7	20.0	30.0	2.0	1.0	1.2	0.6
Soil physical characteristics (0-20 cm)						
BD	FC	PWP	Sand	Silt	Clay	
g cm^{-3}	------- m^3 m^{-3} -------		-------------- g kg^{-1} --------------			
1.56	0.20	0.11	835	125	40	

BD - Bulk density; FC - Field capacity; PWP - Permanent wilting point.

The cultivar used was BR3 - Tracuateua, with sowing performed on September 17, 2016, in an area of 0.3 ha, after conventional soil preparation. The spacing used was 0.5 m between rows and 0.1 m between plants, totaling 200,000 plants ha^{-1}.

In the center of the area, a three-meter high micrometeorological tower was installed, instrumented with sensors of incident global solar radiation (Rg), temperature (Tair) and relative air humidity (RH), rainfall (P) and soil water volumetric content (SM). The sensors were connected to a datalogger (Model CR10X *Campbell Scientific)* and a multiplexer (model AM416, *Campbell Scientific*) with readings made every 10 seconds and averages recorded every 10 minutes. The average daily vapor pressure deficit (DPV) was calculated using the methodology described by Costa et al. (2019).

The experimental design used was in randomized blocks, containing six blocks of 22 x 24 m, separated by a 1 m border, and four treatments (T100, T50, T25 and T0), which correspond to the replacement of 100, 50, 25 and 0% of the crop evapotranspiration. These treatments were only applied from the reproductive stage, corresponding to the period from 36 to 65 days after sowing (DAS), lasting 29 days.

The irrigation system adopted was drip, with a hose diameter of 16 mm and a flow rate of 0.94 L h^{-1}. The reference evapotranspiration (ET0) was estimated using the Penman-Monteith equation (ALLEN et al., 1998) with data from the meteorological station of the National Institute of Meteorology (INMET) located 3 km away, and the crop coefficient was obtained by Bastos et al. (2008), in order to determine crop evapotranspiration (ETc) for the correct irrigation management.

The water deficit accumulated throughout the cycle up to the three stages considered (R7, R8 and R9) was obtained by sequential water balance similar to the method used by Carvalho et al. (2011). For this, an available water capacity (AWC) of 34.24 mm was considered, through the physical-hydraulic characteristics of the soil and for an effective depth of the root system of 0.38 m. The adopted AWC was variable throughout the cycle. However, in the reproductive stage, this AWC was already established, due to the few effects related to the final stage of the cowpea cycle, which allowed considering a specific value. The water inflows and outflows occurred as a function of irrigation (I), precipitation (P) and crop evapotranspiration (ETc) data estimated as described above.

Phenology monitoring was performed using the scale recommended by Gepts and Fernández, adjusted for cowpea by Farias et al. (2017), establishing that the beginning of the phenological stage occurred when 50% of the plants, plus one, reached the observed stage.

An infrared thermometer (model 8601, TASI, Inc.) with 12:1 field of view and accuracy of ±1.5% was used to measure canopy temperature. These measurements were performed daily, between 8:00 am and 11:00 am, only in the reproductive stage, considering three repetitions per treatment.

The canopy water stress index (CWSI) was evaluated in the period from 45 to 64 DAS, corresponding to phenological stages R7 (45 to 48 DAS), R8 (50 to 57 DAS) and R9 (59 to 64 DAS), respectively. The CWSI was calculated by the empirical method employed by Idson et al. (1981), using the Equation 1 proposed by Jackson et al. (1988).

$$CWSI=\frac{(T_c-T_{air})-(T_c-T_{air})_{LBL}}{(T_c-T_{air})_{UBL}-(T_c-T_{air})_{LBL}} \quad (1)$$

Where, $(T_c - T_{air})$ - Difference between canopy temperature and air temperature of each treatment; $(T_c - T_{air})_{LBL}$ – is the lower base line and $(T_c - T_{air})_{UBL}$ – is the upper base line.

The minimum and maximum differences between the temperature of the cowpea canopy (Tc) and the air temperature (Tair) were used to replace the lower (LBL) and upper (UBL) base lines, respectively, due to simplicity and similarity with the theoretical method (SILVA et al., 2018), which corresponded to the mean values of -5.41 °C for LBL and 2.32 °C for UBL. The CWSI varies from zero, when the plant is well supplied with water, to one, characterizing a severe water stress.

After the beginning of the treatments, three ecophysiological data were collected from cowpea at 14, 21 and 28 days after the beginning of the treatments, corresponding to the phenological stages R7, R8 and R9, respectively. Two readings were performed per treatment in the six blocks, totaling 48 plants per collection. The measurements were performed between 8 and 11 h, in the central leaflet of the third or fourth leaf, counted from the apex, with good phytosanitary condition and fully expanded.

The rates of net photosynthesis (*A*), stomatal conductance (*gs*) and leaf transpiration (E_{leaf}) were determined by means of a portable infrared gas analyzer (IRGA), open system (model LI-6400 XT, LI-COR Biosci. Inc., Nebraska, USA), configured to work with constant photon flux density value of 1,500 μmol m^{-2} s^{-1} and with CO_2 flow of 400 μmol mol^{-1}. The temperature and relative humidity of the air followed the environmental conditions.

For yield analysis, pods/grains were collected from three linear two-meter central rows, from each treatment defined from the beginning of the experiment. A precision scale was used to obtain fresh weight and, after drying in an oven for 72 h at 70 ºC, the dry weight.

Data on grain yield, accumulated water deficit, stomatal conductance, net photosynthesis rate, leaf transpiration and CWSI were subjected to analysis of variance, and the means were compared by the Tukey test (5% probability).

When there was a significant effect of the treatments on CWSI, regression analysis ($p < 0.05$) was used and its relationship was compared with physiological parameters by linear correlation.

RESULTS AND DISCUSSION

Figure 1 shows the variability of meteorological conditions during the reproductive stage of cowpea, corresponding to phenological stages R7, R8 and R9. During the reproductive cycle, solar radiation (Rg) showed a daily average of 20.60 MJ m^{-2} day^{-1} (± 3.52) and the average daily vapor pressure deficit (VPD) was 1.08 (± 0.11) (Figure 1a). The air temperature (Tair) followed the trend of variation observed in Rg, due to its direct effect on it, showing a daily average of 27.30 ºC (± 0.42) with a minimum value of 26.70 ºC and a maximum of 27.82 ºC, both occurring in the R8 stage (Figure 1a).

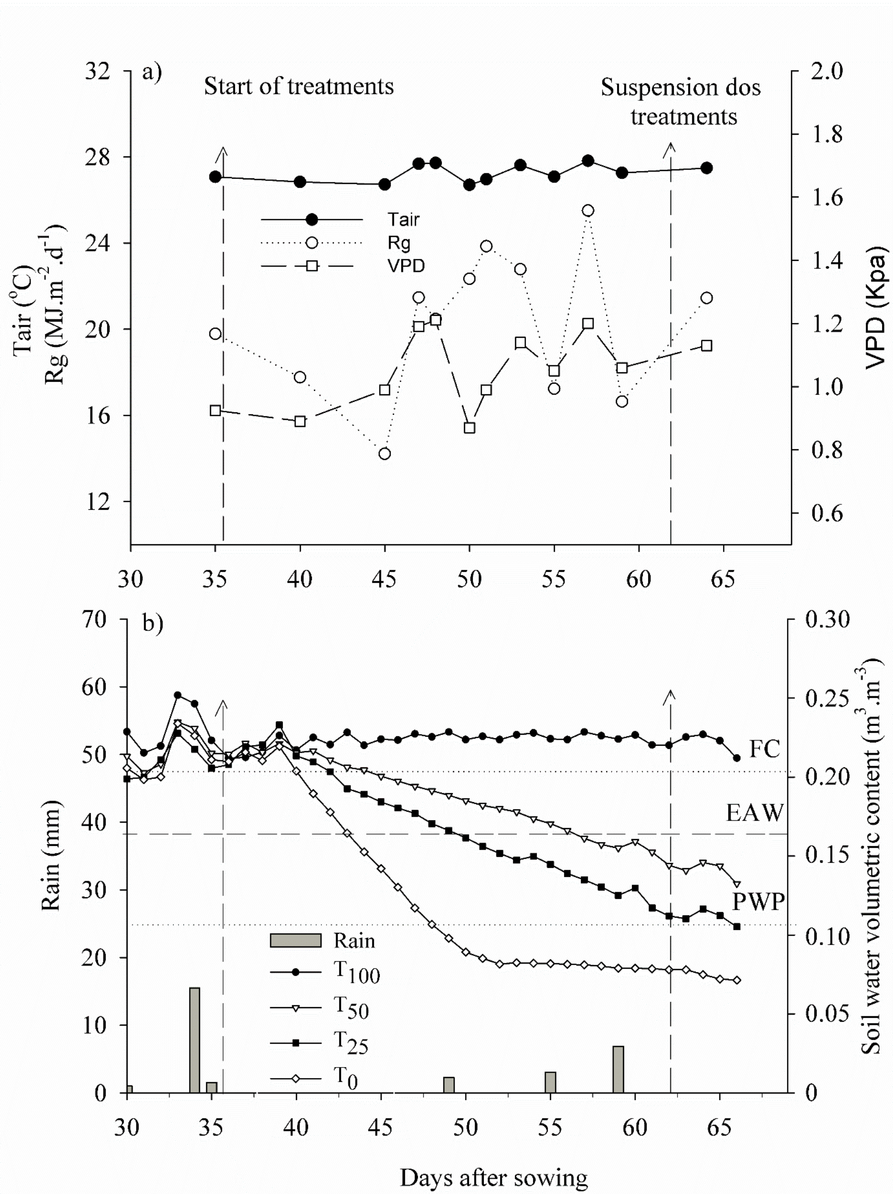

Figure 1. (a) Solar radiation (Rg), Temperatura do ar (Tar) and Vapor pressure deficit (VPD) and (b) Rain and Soil water volumetric contente during the period from 45 to 64 DAS.

The meteorological elements evaluated (Rg, Tair, VPD) showed little variation along the evaluated stages, suggesting that possible differences observed in canopy temperatures and CWSI may not be explained by these variables, but by water availability and the phenological evolution itself.

The water content in the soil varied between treatments, with the highest content in the T100 treatment with an average of 0.22 m^3 m^{-3} throughout the reproductive stage, while in the other treatments these values were reduced over the period of application of the treatments (Figure 1b). It was verified that treatments with reduced water availability consumed easily available water (EAW) quickly compared to the 100% irrigated condition, reaching the EAW limit at 43 DAS (T0), 49 DAS (T25) and 56 DAS (T50), reinforcing the occurrence of severe water deficit in some treatments (T25 and T0).

Irrigation was suspended from stage R9, where the water content available for treatments at the end of the cycle corresponded to 122% (T100), 47% (T50), 8% (T25) and 0%(T0) of storage. At 47 DAS, the T0 treatment promoted the consumption of soil water whose volumetric content monitored reached 0.117 m^3 m^{-3}, close to the wilting point for the type of soil studied. Ferreira et al. (2021) report, however, that each species differs in response to soil moisture and that PWP alone is not an adequate criterion to establish water availability for the plant.

According to Ferreira et al. (2021), this same cultivar when subjected only to the rainfed condition in the study region (0% irrigation) in the reproductive stage showed an increase in its leaf temperature of up to 4 °C throughout the stage, while when 100% irrigated was maintained they noticed a variation of only 2 °C in leaf temperature. According to the authors, stomatal closure to prevent water loss due to transpiration is the main responsible for the increase in leaf temperature, which also contributed to the reduction in photosynthetic capacity as the decrease in CO_2 influx suggests serious consequences due to water stress (FERREIRA et al., 2021).

The smallest differences between canopy and air temperatures (Tc-Tair) occurred in stages R7 and R8, with negative values, indicating that the air temperature (Tair), in almost every day evaluated, was higher than the canopy temperature (Tc) in the four treatments (Figure 2a), which suggests that cowpea was not under harmful water stress, even under water limitation, because the leaf temperature near or below the ambient temperature allows the plant to perform the transpiration process normally and continue dissipating heat into the atmosphere (SOUZA et al., 2020).

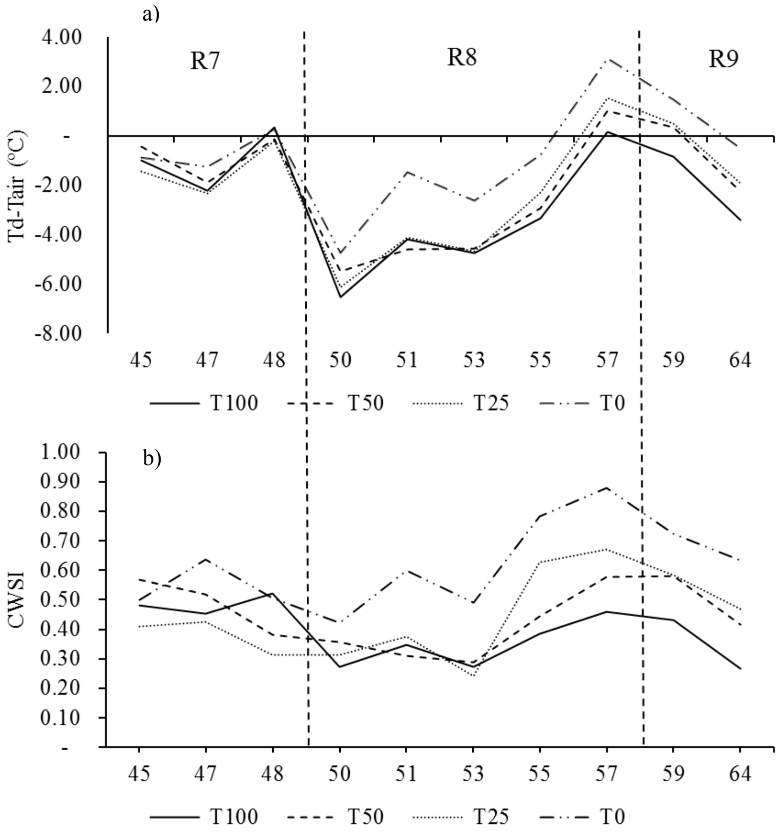

Figure 2. (a) Differences between canopy and air temperatures (Tc-Tair) and (b) Canopy water stress index (CWSI) during the period from 45 to 64 DAS.

In the transition from stage R8 to R9, all treatments, except T100, showed, however, Tc above Tair, with greatest difference (3.14 ºC) in the treatment not irrigated at 57 DAS (Figure 2a). Similar results were found by Nascimento et al. (2011), who observed canopy temperature values 3.5 ºC above air temperature for different cowpea genotypes under water deficit.

According to Mendes et al. (2007), under dry conditions, leaf temperature is usually higher than air temperature, resulting in an increase in leaf/ environment temperature ratio. The rise in leaf temperature in response to water stress can be explained by the reduction of latent heat through transpiration, which typically decreases under these conditions, increasing the sensitive heat in the air (GRAAMANS et al., 2017).

According to Lin et al. (2017), transpiration exerts important effects on tropical plants, such as leaf cooling, since to evaporate in the leaf, water removes its thermal energy, reducing leaf temperature by 2 to 3 °C.

The highest CWSI values were observed when the plant was under water deficit, regardless of phenological stages (Figure 2b). This result is due to the low availability of water in the soil (Figure 1b), which affects the stomatal opening and transpiration of the plant, favoring the increase in leaf temperature due to lower heat dissipation (LIU et al., 2020; FERREIRA et al., 2021). High CWSI values for plants under water deficit conditions were also found by Silva et al. (2018) in tomato (1 <CWSI <0.75) and by Alghory and Yazar (2019) in wheat (CWSI = 0.90).

The plant reached the highest accumulated deficit (79.64 mm) in stage R9, being higher in the treatment without irrigation, due to the low availability of water in the soil (Table 2), different from that observed in the other treatments, which obtained water replacement, promoting less deficit (Figure 1b).

Table 2. Accumulated water deficit (AWD), soil water volumetric content (SM), canopy water stress index (CWSI), stomatal conductance (gs), transpiration (E), photosynthesis rate (A) and statistical analysis, Tukey test, probability level of 5%.

		R7		
Treatments	T100	T50	T25	T0
AWD (mm)	0d	9.76c	18.67b	30.81a
SM ($m^3 m^{-3}$)	0.22a	0.20ab	0.18b	0.13c
CWSI^{ns}	0.48(±0.03)a	0.49(±0.10)a	0.52(±0.04)b	0.55(±0.08)b
gs (mmol H_2O $m^{-2} s^{-1}$)	631.7 (±17.8)a	550.8 (±9.6)b	470.6 (±18.7)c	260.1 (±14.3)d
E (mmol H_2O $m^{-2} s^{-1}$)	8.7 (±0.1)a	8.1 (±0.1)b	7.5 (±0.09)c	4.7 (±0.09)d
A (µmol CO_2 $m^{-2} s^{-1}$)	37.3 (±0.63)a	33.4 (±0.84)b	29.8 (±0.26)c	22.1 (±0.42)d
		R8		
Treatments	T100	T50	T25	T0
AWD (mm)	0d	20.25c	37.36b	58.79a
SM ($m^3 m^{-3}$)	0.22a	0.18b	0.15c	0.08d
CWSI**	0.35(±0.06)a	0.44(±0.13)ab	0.56(±0.16)b	0.75(±0.14)c
gs (mmol H_2O $m^{-2} s^{-1}$)	624.7 (±8.1)a	415.3 (±10.0)b	274.5 (±11.0)c	102.6 (±5.1)d
E (mmol H_2O $m^{-2} s^{-1}$)	9.5 (±0.09)a	7.6 (±0.15)b	5.9 (±0.11)c	3.4 (±0.15)d
A (µmol CO_2 $m^{-2} s^{-1}$)	38.4 (±0.51)a	31.7 (±0.69)b	25.1 (±0.71)c	12.7 (±0.57)d
		R9		
Treatments	T100	T50	T25	T0
AWD (mm)	0d	27.83c	50.23d	79.64a
SM ($m^3 m^{-3}$)	0.23a	0.16b	0.13c	0.08d
CWSI**	0.35(±0.12)a	0.50(±0.12)b	0.53(±0.08)b	0.68(±0.06)c
gs (mmol H_2O $m^{-2} s^{-1}$)	547.4 (±7.2)a	394.2 (±16.1)b	168.3 (±6.2)c	82.8 (±3.4)d
E (mmol H_2O $m^{-2} s^{-1}$)	8.8 (±0.17)a	7.2 (±0.15)b	4.8 (±0.17)c	3.0 (±0.12)d
A (µmol CO_2 $m^{-2} s^{-1}$)	32.7 (±0.28)a	22.2 (±0.34)b	14.2 (±0.37)c	8.5 (±0.26)d

Means followed by the same letter in the row do not differ statistically by the Tukey test at 5%.
ns - not significant ** - significant at the level of 1%.

In stage R7, CWSI showed no significant difference between treatments (p>0.05), despite the significant differences observed between treatments in the other variables that indicate water status (gs, E, A). On the other hand, in stages R8 and R9, there was already a difference between treatments with deficient water replacement (Table 2).

The highest mean values of CWSI per stage were found in R8, mainly in treatment T0 (Table 2), due to the effects of deficit irrigation observed between 53 and 57 DAS (Figure 2b). Studies conducted by Nascimento et al. (2011) prove that the reproductive stage is the one with greatest sensitivity to low water availability in the soil and that the most critical stage of the crop is R8, as this is characterized by the filling of the pods, requiring an ideal amount of water for the full productive development of the plant (SILVA et al., 2020).

During the R9 stage, despite the greatest deficiencies accumulated in all treatments compared to R8, these were not enough to cause an increase in CWSI (Table 2). Results from Moura et al. (2021) indicate stage R9 as the least sensitive to water stress considering the water stress response factor for biomass production (Ks = 0.87) compared to previous stages.

This pattern may be associated with lower levels of solar radiation incidence during the days monitored in stage R9 (Figure 1a) as well as the smaller leaf area of cowpea crop in this phenological stage (SOUZA et al., 2017). Slaterry and Ort (2021) report that the reduction in leaf area of plants causes a decrease in light interception and CO_2 absorption, as can be seen by the photosynthesis rates observed between R9 and the previous stages (Table 2).

Figure 3 shows the relationships between the water status indicators and the CWSI for cowpea (gs, E, A) from which it is observed that the relationships were significant (p<0.05) with a high coefficient of determination. Except for the one observed in conductance, the relationship observed between indicators E and A with CWSI was more significant in stage R8 (R^2 = 0.989 and 0.998, respectively) (Figure 3b and 3a), reinforcing the importance of the occurrence of water deficit in this stage. On the other hand, there is a strong correlation between CWSI and water status indicators also in the other stage of the plant, demonstrating that the CWSI index is a good indicator of the diagnosis of water status due to the reduction in water supply, as also observed in other species (GONZALES-DUGO et al., 2014; ÇOLAK et al., 2015; BLANCO-CIPOLLONE et al., 2017; RU et al., 2020).

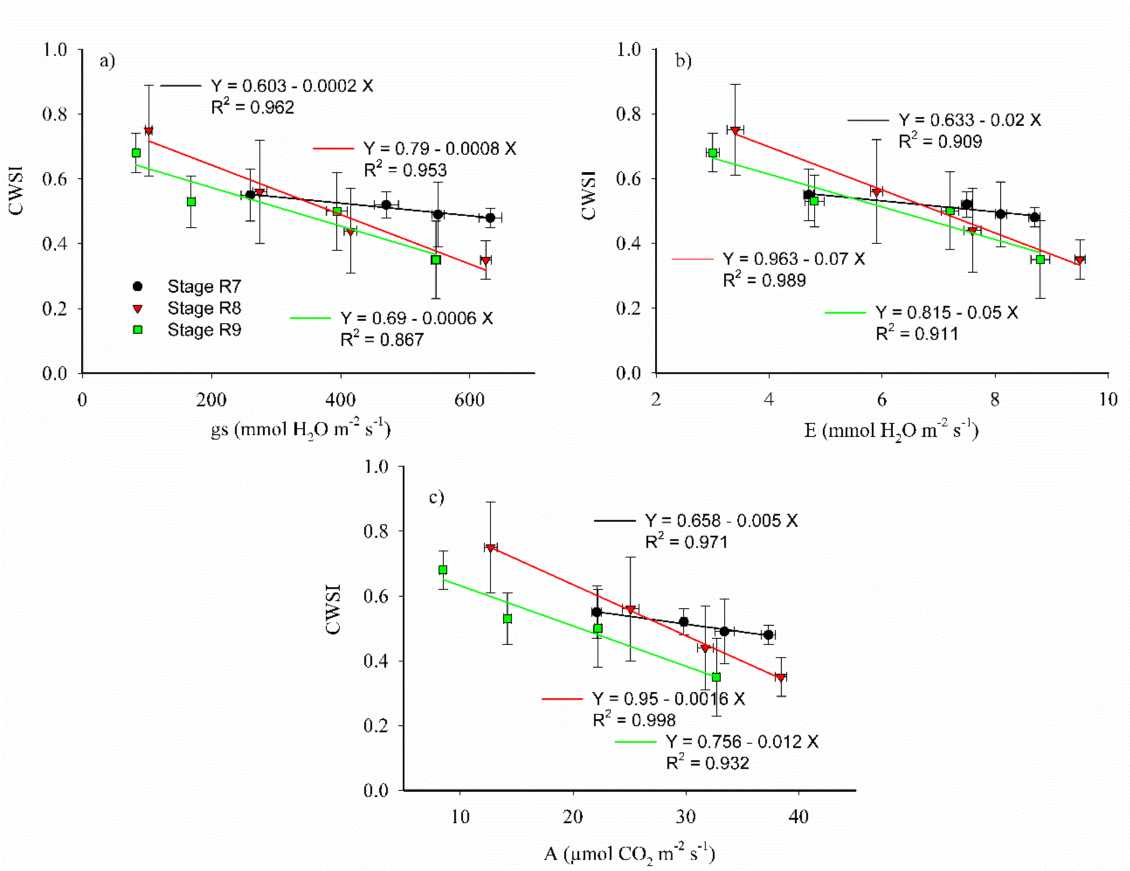

Figure 3. CWSI correlation with (a) Stomatal conductance (gs); (b) Transpiration (E) and (c) Photosynthesis rate (A) during the stage R7, R8 and R9.

Significant reductions in gas exchange ($p<0.05$) were observed from the decrease in water availability, regardless of phenological stage (Table 2, Figure 3). During the conduction of the experiment, gs ranged from 82.8 to 631.7 mmol H_2O m^{-2} s^{-1}, showing a minimum value in the R9 stage, in plants without irrigation. E_{leaf} and A ranged from 3.0 to 9.5 mmol H_2O m^{-2} s^{-1} and from 8.5 to 38.4 μmol CO_2 m^{-2} s^{-1}, respectively, where both minimums were found in plants under water deficit at stage R9.

The effect of water deficit caused reductions in all ecophysiological responses monitored in the three stages evaluated (Table 2, Figure 3). These reductions corresponded to 58.82% (R7), 83.57% (R8) and 84.87% (R9) for gs and 45.97% (R7), 64.21% (R8) and 65.90% (R9) for E_{leaf}, which contributed to reductions of 40.75% (R7), 66.92% (R8) and 74% (R9) in A when the plant leaves an ideal water condition (T100) for a stressful water condition (T0).

This response to the effect of water deficit was also observed by Costa et al. (2019) and Ferreira et al. (2021) in cowpea, since the low availability of water in the soil causes stomatal closure by the plant in order to reduce water losses by transpiration aiming at the maintenance of cellular turgor, which contributes to the decrease of CO_2 assimilation, as it is a common route to both (COSTA et al., 2019).

The stomatal control of transpiration is a mechanism used by many species to restrict water loss and overcome periods of drought (FERREIRA et al., 2021). Mendes et al. (2007) verified significant reductions in leaf transpiration in cowpea plants subjected to water deficit in the vegetative and reproductive stages.

In the present study, it is possible to observe that CWSI was different for stages R8 and R9, with R8 having the highest mean CWSI in treatments with water deficit, indicating that this stage is the one in which the crop expresses greatest sensitivity to low water availability, corroborating Moura et al. (2021) and confirmed by the ecophysiological responses between treatments during this stage (Table 2, Figure 3).

On the other hand, it is noted that the R7 stage was the least sensitive to the decrease in soil water content, since both gs and A remained high and close to each other (Figure 3) even when plants were subjected to water limitation of 25% of its demand, and due to this they were able to maintain their E_{leaf} in a similar way, dissipating heat.

The increase in CWSI is a consequence of the water stress to which the plant is subjected, which reduces its cooling and consequently increases leaf temperature due to the decrease in the stomatal opening (MENDES et al., 2007). This reduction in the opening of stomata will also compromise the influx of CO_2 into the substomatal chamber, limiting the photosynthetic process (COSTA et al., 2019), which can cause a reduction in the final yield of the plant (SLATERR; ORT, 2021).

There was a statistical difference ($p<0.05$) between the yields of all treatments evaluated (Table 3). Among these, T100 had the highest yield associated with lower water stress index, due to higher stomatal opening and possibly greater absorption of nutrients which are responsible for crop growth and development (FERREIRA et al., 2021).

Table 3. Total available water and total deficit (mm), yield of treatments evaluated (kg ha^{-1}), mean CWSI and Tukey test, at probability level of 5%, for the four treatments (T100, T50, T25 and T0) at the end of harvest.

Treatments	Total available water (rain + irrigation) (mm)*	DEF Total (mm)	Yield (kg ha^{-1})	CWSI (medium)
T100	126	0	1597.13 a	0.37 (±0.09)a
T50	68	33	1295.32 b	0.44 (±0.11)b
T25	41	59	1068.84 c	0.44 (±0.14)b
T0	0	94	684.33 d	0.62 (±0.14)c

*Total available water during the reproductive stage from the differentiation of treatments.

The low availability of water in the soil compromised the yield of the pods, since water is indispensable for the proper functioning of plant metabolism and water stress in any stage of the crop causes negative impacts, which depending on the stage can result in greater yield losses, especially in more critical and stress-sensitive periods such as flowering and gametogenesis (JAGADISH et al., 2020).

It is noted that cowpea yield decreases significantly ($p<0.05$) as CWSI increases and as the amount of water available in the soil is reduced (Figure 4). CWSI values lower than 0.42 resulted in higher yield of cowpea grains (Figure 4 and Table 3). The results indicate that the final yield of cowpea decreases by 19, 33 and 57% when the mean CWSI in the reproductive stage exceeds 0.44, 0.44 and 0.62, respectively.

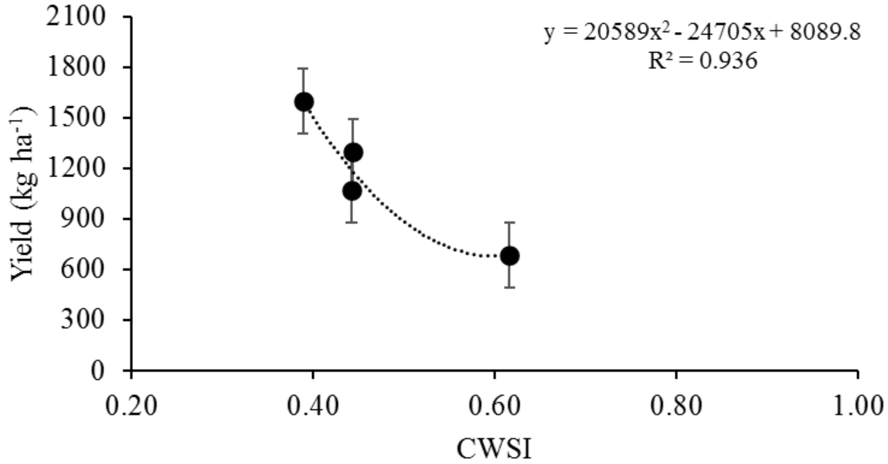

Figure 4. Yield (kg ha^{-1}) of cowpea as a function of canopy water stress index (CWSI).

Silva et al. (2018) in studies conducted with tomato also concluded that the increase in CWSI led to lower harvest yield. Candogan et al. (2013) obtained for soybean cultivated under sub-humid climatic conditions an average minimum CWSI value in the cycle of approximately 0.22 as indicative of beginning of irrigation and obtaining higher yield. For eggplant crop grown in Mediterranean climate region, average CWSI values between 0.18 and 0.20 can be used as irrigation indicators to obtain high yields and good quality (ÇOLAK et al., 2015).

In general, CWSI proved to be a good indicator of the water status of the plant, since its increase shows decreases in gs, E_{leaf} and A (Table 2, Figure 3), and can be adopted as an index to assist irrigation management, as also observed by Çolak et al. (2015). Considering that cowpea has average state yield around 821 kg ha^{-1}, it is noticed that environmental conditions that favor average CWSI below 0.5 would result in higher yields than that commonly obtained in the region. Therefore, mean CWSI values below 0.5 can be used as indicators for irrigation in order to obtain yields higher than the state average. To achieve higher yields, mean CWSI values equal to 0.4 can be used as indicators of irrigation start.

CONCLUSIONS

The water stress index varied due to water availability, with a higher value of 0.75 in the R8 stage when cowpea plants were subjected to treatment without irrigation.

CWSI is a good indicator of the water status of cowpea, as it clearly has a strong relationship with other variables that indicate water condition such as stomatal conductance, leaf transpiration and photosynthetic rate. In addition, it is a practical and efficient tool in monitoring the crop for its simplicity and easy management in the field.

Severe water deficit (T0) increases CWSI and reduces cowpea yield by 57% (912.8 kg ha^{-1}).

CWSI higher than 0.5 may indicate cowpea yields below the state average yield when subjected to the same environmental conditions as in the experiment.

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