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Article

Impact of Photosynthetic Efficiency on Watermelon Cultivation in the Face of Drought

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Abstract: Water availability is a limiting factor for plant production, especially in Brazilian semi-arid regions. The main aim of the study was to investigate the physiological effects of drought during the fruiting stage of watermelon cultivation. A completely randomized block design with four replications and six treatments varied by the number of lateral drip tapes (1 or 2) and the duration of drought stress (0, 4, and 8 days) was used. The following parameters were evaluated: relative chlorophyll content, relative leaf water content, electrolyte leakage, CO_2 assimilation (A), stomatal conductance (g_s), internal CO_2 concentration, leaf temperature, transpiration (E), water use efficiency (WUE), carboxylation efficiency (CE), yield, thickness, diameter, length, and fruit °brix, at 4 and 8 days of drought. Drought negatively affected photosynthesis, particularly in treatments with a single dripper and 4 days of drought, resulting in reductions of up to 60% in A, 68% in g_s, 44% in E, 58% in WUE, and 59% in CE, but did not have a significant effect on watermelon yield after 4 or 8 days of irrigation. It was concluded that drought influences the physiological responses of watermelon plants, mainly in reducing photosynthesis, but does not drastically affect fruit productivity in short periods of stress.

Keywords: *Citrulus lanatus* Thumb. Mansf.; photosynthesis; water deficiency; yield

1. Introduction

Watermelon (*Citrulus lanatus* Thumb. Mansf.) is a demanding vegetable in terms of edaphoclimatic conditions; nevertheless, it is one of the most produced fruits in Brazil [1], generating employment and income in the countryside, highlighting its socioeconomic importance. In the 2022 harvest, Brazil produced 1.91 million tons of watermelon, with an average yield of 22.3 t ha^{-1}. Among Brazilian regions, the northeast is the largest national producer, holding 36% of the production and an average yield of 18.7 t ha^{-1} [2].

The Brazilian semi-arid, located in the northeast of the country, is characterized by irregular rainfall distribution, which affects rainfed crops like watermelon, justifying the adoption of irrigation in the region [3]. Therefore, combining economic and agronomic aspects becomes essential for the success of irrigated agriculture in the region, as water significantly burdens agricultural activities carried out by mainly small and medium-sized local producers. Thus, proper irrigation management becomes even more critical to meet the demand for crops like watermelon, favoring the attainment of potential agricultural productivity [4].

In this regard, the adoption of irrigation methods such as localized drip systems, which form irrigated strips and ensure a large wetted area near crop plants, is recommended in regions with water scarcity and high evapotranspiration demand [5]. However, researchers have observed that this premise is not always valid, as watermelon plants grown in areas with lower water availability may exhibit agricultural productivity levels comparable to those cultivated in areas with higher soil moisture [6]. This demonstrates that watermelon can tolerate reduced water availability.

However, it is a fact that phenological phases such as flowering and fruiting are sensitive to water scarcity, as flower abortion and fruit drop are commonly observed under water stress during this period [7]. This likely occurs in plants under water scarcity due to physiological alterations, such as reduced stomatal conductance, which impacts CO_2 assimilation and water and nutrient absorption and limits photosynthetic efficiency [3,8].

These changes result in reduced accumulation and distribution of photoassimilates [9] and can compromise fruit yield and quality [10]. On the other hand, excess soil moisture can cause problems such as oxygen deficiency and increased disease incidence, leading to reduced productivity [11]. In this context, evaluating the physiological characteristics of watermelon crops under water restriction is important to understand the factors influencing the production of this vegetable under adverse conditions, especially in the Alagoas region, in which studies on this topic are still incipient. Therefore, this research hypothesizes that drought stress reduces the photosynthetic efficiency of watermelon crops and decreases their yield. To respond to the hypothesis raised, two drought conditions were simulated by suspending irrigation for 4 and 8 days, as the study region is susceptible to irregular periods of rainfall. Thus, this study was carried out with the objective of evaluating the physiological responses of watermelon crops to drought during the fruiting phase in the state of Alagoas, Northeast Brazil.

2. Materials and Methods

2.1. Experimental Conditions

The research was carried out in Arapiraca (9°46′07″ S; 36°33′41″ W; 324 m above sea level), state of Alagoas, Agreste of Northeast Brazil; the planting was carried out on 26 September 2023. According to the Köppen climate classification, the local climate is AS, tropical, with a rainy period from April to August and a dry period from September to March. Average annual rainfall and temperature are 800 mm and 25 °C, respectively [12].

The soil in the experimental area is classified as Red-Yellow Argisol [13]. The physical-hydric and chemical properties of the soil, from the layers of 0–0.20, 0.20–0.40, and 0.40–0.60 m, are shown in Table 1.

2.2. Agricultural Management

The watermelon cultivar used was "Crimpson Sweet" (3 × 1), characterized by an early cycle, intense red fruit, and high productivity. Soil preparation was carried out five days before planting. The foundation and cover fertilization were carried out according to Ribeiro et al. [14]. The fruit was hand-harvested 65 days after sowing (DAS).

The irrigation system adopted was drip irrigation. The emitters were spaced 0.2 m. The irrigation management was carried out by Barros et al. [6], by the ETo estimated daily by Hargreaves and Samani [15] (Equation (1)). The crop evapotranspiration was estimated by Equation (2) using the coefficients proposed by Ferreira et al. [16], as shown in Table 2.

Table 1. Chemical and physical-hydric properties of the soil in the research area.

Physical-Hydric Properties	**Unit**	**Soil Layers (m)**		
		0–0.2	**0.2–0.4**	**0.4–0.6**
Sand	g kg^{-1}	70.35	62.30	58.24
Silt	g kg^{-1}	11.71	26.80	30.85
Clay	g kg^{-1}	17.94	10.90	10.91
Soil Density (g cm^3)	g cm^3	1.29	1.43	1.31
Particle Density (g/cm^3)	g cm^3	2.68	2.68	2.71
Porosity (%)	%	51.86	46.64	51.66
θS	m^3 m^{-3}	0.518	0.466	0.516
θR	m^3 m^{-3}	0.077	0.070	0.083
a	-	0.371	0.313	0.271
n	-	1.542	1.523	1.627
m	-	0.351	0.343	0.385
Chemical properties	Unit	Soil Layers (cm)		
		0–20	20–40	
pH	-	6.05	5.74	
Calcium + Magnesium	cmolc dm^3	2.70	2.11	
Calcium	cmolc dm^3	1.94	1.54	
Aluminum	cmolc dm^3	<0.08	<0.08	
Sodium	mg dm^3	47.9	73.0	
Potassium	mg dm^3	80.0	116.0	
Phosphor	mg dm^3	29.4	28.9	
SB	cmol dm^3	3.12	2.73	
CTC	cmol dm^3	4.36	4.16	
V	%	71.60	65.60	

Table 2. Crop coefficient (K_C) and coefficient of wetted area reduction (K_R) for the watermelon crop.

Stadiums	**Intervals (Days)**	K_C	K_R
Emergence and growth	0–20	0.39	0.39
Flowering	21–35	0.80	0.53
Fructification	36–56	1.14	0.69
Fruit ripening	56–70	0.59	0.89

$$\text{ETo} = \text{a} \times \frac{\text{Ra}}{2.45} \times \left(\text{Tmáx} - \text{Tmín}\right)^{\text{b}} \times (\text{Tméd} + \text{c}) \quad (1)$$

$$\text{ET}_\text{C} = \text{ET}_0 \cdot \text{K}_\text{C} \cdot \text{K}_\text{R} \quad (2)$$

The adopted statistical design was in randomized blocks, with four replications and six treatments, which totaled 24 experimental plots. Each plot consisted of three watermelon plants.

The treatments were based on the number of lateral drip lines (1 or 2) and the number of days of water stress (0, 4, and 8 days), totaling 6 treatments: T1—Single line, 0 stress days; T2—Single line, 4 stress days; T3—Single line, 8 stress days; T4—Double line, 0 stress days; T5—Double line, 4 stress days; T6—Double line, 8 stress days.

The drip lines referred to the percentage of water applied. Thus, the double drip lines received twice the irrigation volume.

The stress was applied during the peak water demand phase of the fruiting stage (36 DAS) through the total suspension of irrigation, depending on the treatments under analysis, 4 or 8 days of water deprivation.

2.3. Relative Chlorophyll Content

The relative chlorophyll content was measured using a portable leaf greenness meter (SPAD-502, Minolta, Konica Minolta Sensing, Inc., Osaka, Japan).

2.4. Relative Leaf Water Content (RWC)

RWC was obtained by determining the mass of fresh, turgid, and dry matter of six leaf discs with an area of 0.5662 cm^2, taken from the mid-third leaf of the corn plants. The mass values were calculated based on the equation proposed by Barrs [17].

$$RWC = (MF - MS)/(MT - MS) \times 100 \quad (3)$$

where:

RWC = relative leaf water content (%);
MF = mass of fresh matter of leaf discs (g);
MS = mass of dry matter of leaf discs (g);
MT = mass of turgid matter of leaf discs (g).

2.5. Electrolyte Leakage (EL)

The integrity of cell membranes was analyzed by removing 10 discs with an area of 0.5662 cm^2 from the watermelon plants' leaves, which were kept for 24 h in 10 mL of deionized water. Electrical conductivity was measured 24 h after incubation, considered as initial conductivity. Then, the discs were placed in a water bath at 60 °C for three h, followed by a new measurement of the electrical conductivity of the solution, considered as final conductivity. EL was expressed as the percentage of initial conductivity relative to the final conductivity after heating for 3 h at 60 °C, according to the equation described by Campos and Thi [18].

$$EL = (C_i/C_f) \times 100 \quad (4)$$

where:

EL = electrolyte leakage (%);
C_i = initial electrical conductivity (µS cm^{-1});
C_f = final electrical conductivity (µS cm^{-1}).

2.6. Gas Exchange Parameters

Leaf gas exchange was evaluated by obtaining the net assimilation rate of CO_2 (A), stomatal conductance (g_s), transpiration rate (E), intercellular CO_2 concentration (C_i), and leaf temperature (T_{LEAF}) using an infrared gas analyzer (IRGA) (LI-COR Biosciences Inc., Li-6400xt, Lincoln, NE, USA). Measurements were taken between 08:00 and 11:30 a.m., using atmospheric CO_2 concentration, ambient temperature and humidity, and constant photosynthetically active radiation (PAR) of 1600 µmol m^{-2} s^{-1}. Water use efficiency (WUE) was calculated by the ratio A/E, in addition to carboxylation efficiency (CE) by the ratio A/C_i.

2.7. Production Components

The plant productivity analyses included the following: fruit production, thickness, diameter, length of fruit, and brix (°Bx) of fruit. Fruit mass was obtained by weighing on a precision scale with a sensitivity of 0.001 kg (Todelo, Prix 3 Plus, São Bernardo do Campo, Brazil). The °Bx content was determined using a refractometer (Vodex, VX0-90).

2.8. Statistical Analysis

The collected data were subjected to the Shapiro–Wilk normality test ($p \geq 0.05$). After confirming normality, they underwent analysis of variance (ANOVA), and when significant according to the F test ($p \leq 0.05$), their means were compared using the Scott–Knott test ($p \leq 0.05$) with the assistance of the statistical software SISVAR® version 5.8 Build 92 [19]. Pearson correlation analysis was conducted with normalized data from the treatments adopted to verify the relationship between the analyzed variables. The Pearson correlation heat map was generated using RStudio® software 4.2.0 (R Software, Central Development Team, Vienna, Austria).

3. Results

The average temperature during the planting phase was 25.2 °C, with a maximum reaching 34.7 °C and a minimum of 18.06 °C. The average reference evapotranspiration estimated during the cycle was 5.34 mm, and the cumulative crop evapotranspiration was 163.85 mm.

During the first 20 days of irrigation, the irrigation time was set at 20 min. There were 12 precipitation events, with a total accumulated rainfall of 17.5 mm, the highest being 4.3 mm. No precipitation occurred during the stress period (Figure 1).

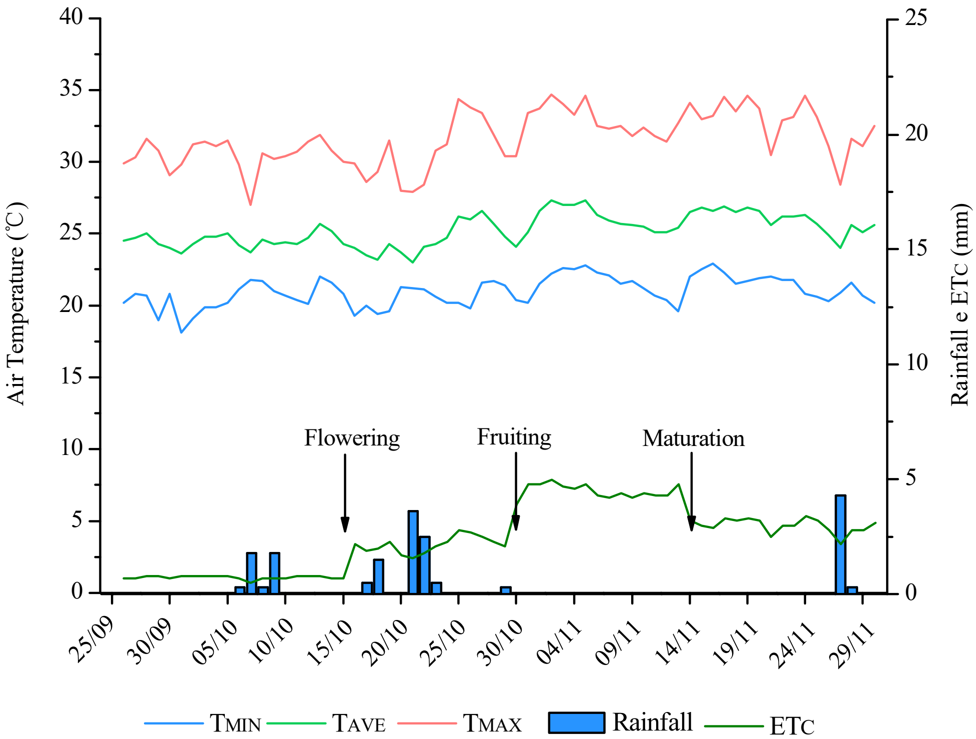

Figure 1. Climatic conditions during the execution of the experiment: minimum (MIN), average (AVE), and maximum (MAX) air temperature, rainfall, and crop evapotranspiration (ETc) of watermelon during the experimental phase.

3.1. Physiological Parameters

Through analysis of variance on the treatments tested in watermelon plants, a significant effect of the interaction between treatments and evaluation period was observed on the physiological variables A, g_s, E, WUE, and CE. The other physiological and production variables were not influenced by any of the treatments analyzed (Table 3).

CO_2 assimilation was higher after 8 days of water deficit, with superiority observed in the control treatments: no water restriction and one drip line (T1), four days of water restriction and one drip line (T2), no water restriction and two drip lines (T4), and four days of water restriction and two drip lines (T5), with approximate increases of 8%, 12%, 15%, and 12%, respectively, compared to plants under eight days of water restriction with one drip line (T3) and eight days of water restriction with two drip lines (T6). At 4 days of drought, T5 plants showed average reductions of 60% in A, 68% in g_s, 44% in E, 58% in WUE, and 59% in EC, regarding the control (Figure 2A).

Table 3. Summary of variance analysis of physiological variables of watermelon under different drip lines, water deficiency, and evaluation periods in Arapiraca, Alagoas. DF = degrees of freedom; A = CO_2 assimilation; g_s = stomatal conductance; C_i = internal carbon concentration; E = transpiration; T_{LEAF} = leaf temperature; WUE = water use efficiency; CE = carboxylation efficiency; SPAD = relative chlorophyll content; RWC = relative leaf water content; EL = electrolyte leakage.

Source of Variation	D.F.	Medium Squares				
		A	g_s	C_i	E	T_{LEAF}
Treatments (T)	5	50.380 *	0.015 *	1266.521 NS	1.574 *	4.040 NS
Periods (P)	1	679.589 *	0.034 *	239.2718 NS	7.181 *	3.379 NS
T × P	5	24.558 *	0.015 *	1005.808 NS	1.742 *	4.186 NS
Blocks	3	4.435 NS	0.011 *	792.825 NS	2.431 *	11.540 *
Residue	33	2.574	0.003	510.6970	0.578	1.932
C.V. (%)		10.12	25.33	9.56	20.37	4.45
		WUE	**CE**	**SPAD**	**RWC**	**EL**
Treatments (T)	5	1.193 NS	0.001 *	32.169 NS	403.623 NS	43.264 NS
Periods (P)	1	16.548 *	0.014 *	60.077 NS	6.106 NS	1.527 NS
T × P	5	1.939 *	0.000 *	24.198 NS	121.831 NS	103.042 NS
Blocks	3	2.976 *	0.000 NS	29.793 NS	43.028 NS	214.080 NS
Residue	33	0.575	0.000	32.170	175.753	124.983 NS
C.V. (%)		17.58	11.17	12.05	22.46	15.91

* Significant at the 5% level by the F-test ($p \leq 0.05$); NS—not significant.

In the first assessment, at four days of water deficiency, treatments T1, T4, and T5 showed superior stomatal conductance (g_s) compared to the other treatments. However, by the eighth day of irrigation restriction, higher g_s was observed in plants under treatments T1, T2, T4, T5, and T6 compared to T3, with a 30% increase between T1 and T3 (Figure 2B).

The transpiration (E) of watermelon plants was not influenced by any of the treatments tested in the second assessment. However, higher E was observed under treatments T2 and T6 at eight days of irrigation restriction compared to four days of water restriction, with increases of 33% and 50%, respectively (Figure 2C).

Greater water use efficiency (WUE) was observed under treatments T3 and T6 at eight days of water restriction, with increases of 46% and 37%, respectively, compared to four days of water restriction (Figure 2D).

In the first assessment, greater carboxylation efficiency (CE) of plants was observed under treatments T1, T4, and T5, while in the second assessment, there was no difference between treatments for CE. However, when comparing the two assessment times, all treatments showed superiority of CE at eight days of water restriction, with increases of 20%, 51%, 24%, 34%, and 64% in T1, T2, T3, T4, T5, and T6, respectively, compared to the fourth day of stress (Figure 2E).

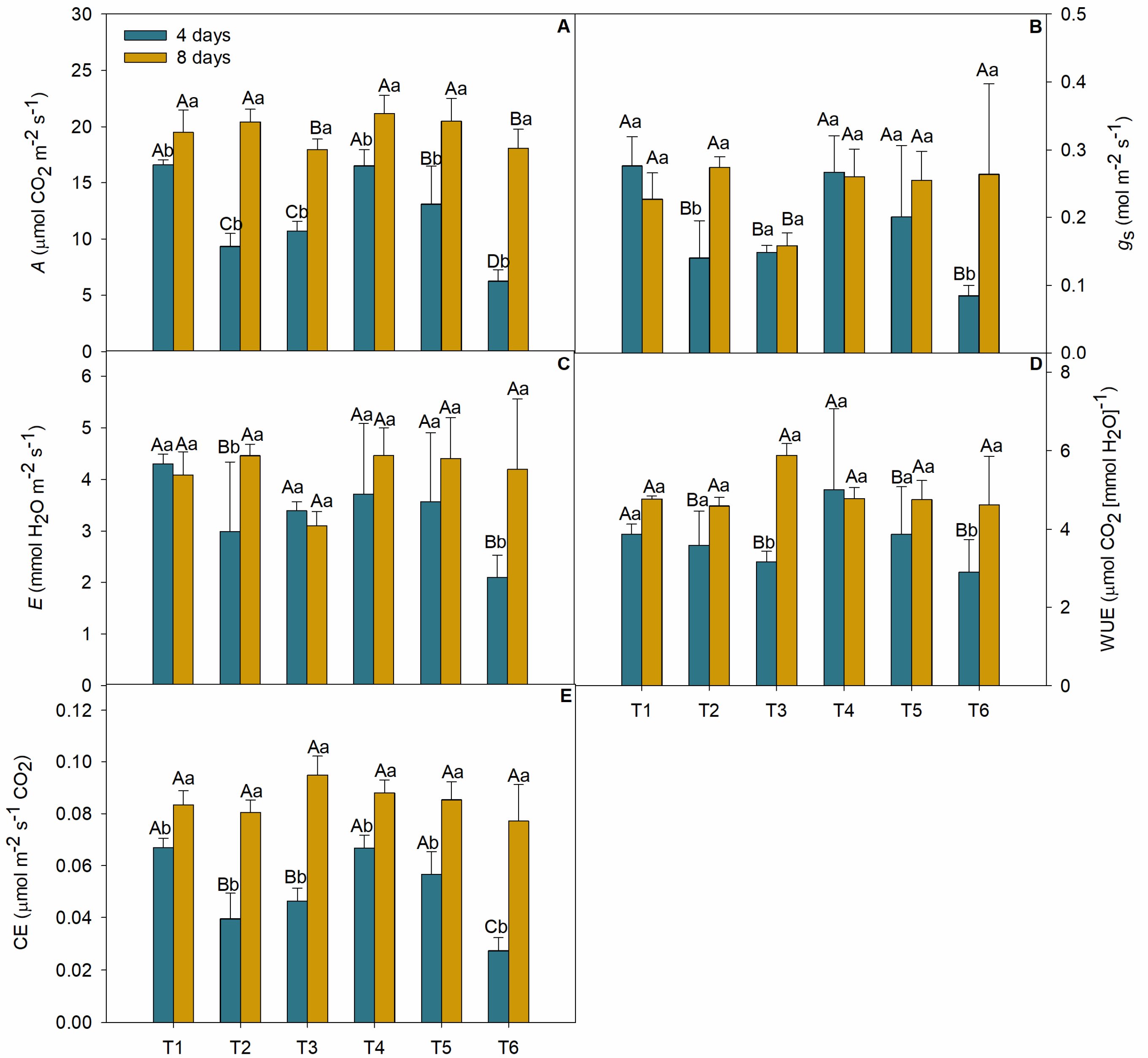

Figure 2. Gas exchange in watermelon plants under drought: CO_2 assimilation—*A* (**A**); stomatal conductance—g_s (**B**); transpiration—*E* (**C**); water use efficiency—WUE (**D**); and carboxylation efficiency—CE (**E**) of watermelon under water restriction during the flowering stage in Arapiraca, Alagoas. T1 = control under one drip line, T2 = 4-day irrigation restriction under one drip tape, T3 = 8-day irrigation restriction under one drip tape, T4 = control under two drip lines, T5 = 4-day irrigation restriction under two drip tapes, and T6 = 8-day irrigation restriction under two drip tapes. Blue column = assessment after 4 days of drought; yellow column = assessment after 8 days of drought. Lowercase letters within treatments and uppercase letters between treatments do not differ from each other by the Scott–Knott test ($p \leq 0.05$). The bar in each column indicates the sample standard deviation.

3.2. Production Components

Productive parameters were not influenced by any of the tested treatments (Table 4).

Table 4. Summary of the analysis of variance of yield, peel thickness, diameter, length, and brix degree of watermelon fruit under different drip line setups, water deficiency, and evaluation periods in Arapiraca, Alagoas. DF = degrees of freedom.

Source of Variation	D.F.	Medium Squares				
		Yield ($kg\ ha^{-1}$)	Thickness (mm)	Diameter (cm)	Length (mm)	Brix (°)
Treatment	5	3.120 ^{NS}	24.547 ^{NS}	1.953 ^{NS}	7.208 ^{NS}	0.720 ^{NS}
Blocks	4	1.787 ^{NS}	6.980 ^{NS}	3.822 ^{NS}	1.924 ^{NS}	0.377 ^{NS}
Residue	31	1.896	11.682	3.318	9.506	1.174
C.V. (%)		10.12	15.77	6.54	6.52	10.17

^{NS}—not significant.

Among the physiological parameters evaluated, CO_2 assimilation (A) and carboxylation efficiency showed a positive correlation with yield, with a significance of 5%. Additionally, stomatal conductance (g_s) exhibited a linear response to intercellular CO_2 concentration (C_i), indicating a positive correlation between them, where higher gs resulted in higher C_i, potentially influencing plant productivity, justifying the maintenance of production under stressful conditions as open stomata favored the entry of CO_2 into plant cells. Leaf temperature (T_{LEAF}) negatively correlated with A, gs, and C_i, demonstrating that high leaf temperature reduces A, g_s, and C_i. Furthermore, the strong negative correlation between T_{LEAF} and water use efficiency (WUE) supports the negative effect of water deficit, indicating that drought may induce thermal stress in plants due to water deprivation for leaf cooling and photosynthetic activities, resulting in low WUE (Figure 3).

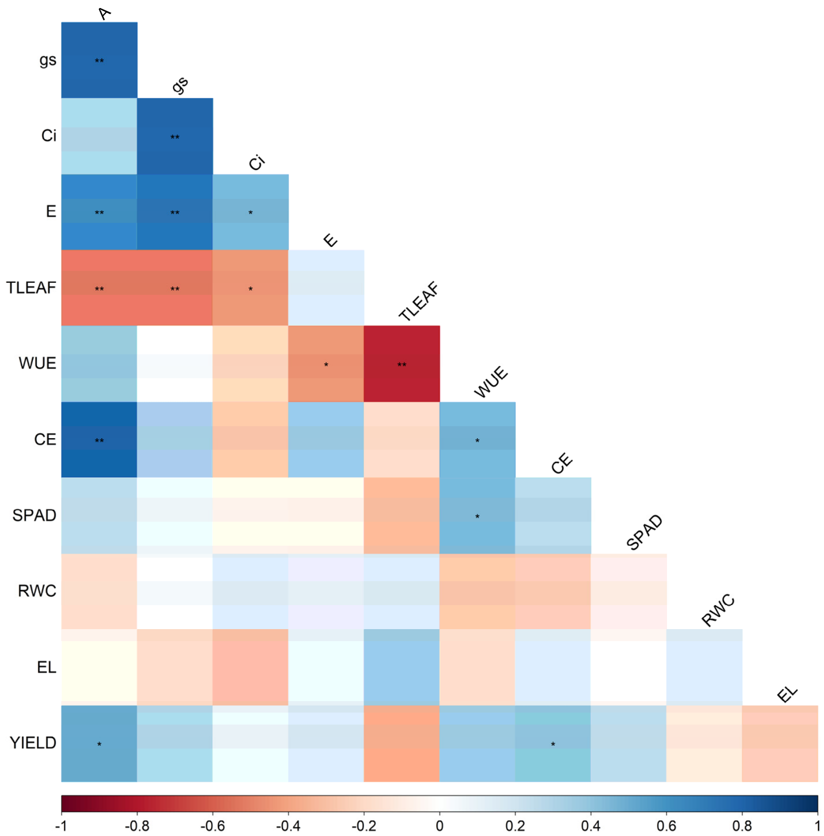

Figure 3. Pearson's correlation between yield: CO_2 assimilation (A), stomatal conductance (g_s), internal carbon concentration (C_i), transpiration (E), leaf temperature (T_{LEAF}), water use efficiency (WUE),

carboxylation efficiency (CE), relative chlorophyll content (SPAD), relative leaf water content (RWC), and electrolyte leakage (EL) in watermelon plants under different drip irrigation lines, water deficit, and evaluation periods in Arapiraca, Alagoas. * Significant at 5% significance; ** Significant at 1% and 5% significance.

4. Discussion

Water deficiency is recognized as one of the main abiotic challenges faced in watermelon cultivation, as the stress resulting from water shortage can significantly reduce fruit production and quality [20,21]. However, in the present study, even after eight days of water restriction, an impact on plant gas exchange was observed without it being reflected in production parameters. This may be related to the activation of compensatory physiological mechanisms in plants to mitigate the negative effects of water deficiency, ensuring fruit production.

Photosynthesis is closely influenced by stomatal conductance, plant transpiration rate, and ambient temperature. When the plant's water status is adequate, photosynthesis is enhanced [22,23]. Soil with adequate water content favors nutrient availability, stimulating plant leaf area growth and increasing photoassimilate production and crop yield [23,24]. The results of this research demonstrated that the abiotic conditions during the experiment justify the adoption of irrigation (Figure 1) and that two lines of drip irrigation favored increased photosynthesis in watermelon leaves at four days under water restriction, but not enough to provoke an increase in CO_2 assimilation (*A*) at eight days under water restriction.

When subjected to water deficiency and two lines of drip irrigation, watermelon plants showed lower photosynthetic rates. In fact, under conditions of low water availability, one of the plant's first adaptive responses is stomatal closure to reduce water loss through excessive transpiration, consequently leading to a reduction in *A* [8,25]. However, a reduction in stomatal conductance was observed only at four days of water restriction, indicating that two lines of drip irrigation increased water availability for plants, thus maintaining the regular functioning of the photosynthetic apparatus even under eight days of water restriction.

Furthermore, greater water availability obtained through irrigation with two lines of drip promoted higher transpiration (*E*) in the treatment with eight days of irrigation restriction. Higher *E* allows for the maintenance of leaf temperature and nutrient transport to the aerial part of the plant, as plants under drought conditions exhibit high vulnerability to embolism and cavitation, compromising their water and nutrient transport capacity [26,27].

This study demonstrated an increase in water use efficiency (WUE) and carboxylation efficiency (CE) even under eight days of drought. WUE is characterized as the amount of carbon assimilated as biomass or grain produced per unit of water used by the crop [23,28,29], and the response of WUE at the leaf level is directly associated with various physiological processes that control gradients of CO_2 and water, such as leaf vapor pressure deficits [29]. Higher CE suggests reduced CO_2 in the leaf mesophyll due to the integrity of the photosynthetic apparatus, followed by high regeneration of the RUBISCO enzyme, facilitating the carboxylation process [30,31]. Possibly, CE was decisive in preventing losses in watermelon production in plants stressed by drought (Figure 2).

Responses to gas exchange of watermelon plants under different water conditions have been documented in the literature. Kawasaki et al. [32] found a reduction in stomatal conductance, transpiration rate, and photosynthesis in wild watermelon plants. Akashi et al. [33], evaluating wild watermelons, observed a decrease in transpiration with increasing leaf temperature. Meanwhile, Ribeiro et al. [23] noted that responses of photosynthesis, stomatal conductance, transpiration, and leaf temperature were influenced by water availability. They found that applying 370 to 470 mm of water resulted in higher photosynthesis, stomatal conductance, and transpiration while reducing leaf temperature compared to a 100 mm water depth.

In this study, at 8 days of water restriction, an increase in photosynthetic parameters was observed compared to 4 days of restriction. The response mechanisms of watermelon plants to water deficiency may have been activated only after 8 days of stress through an increase in photosynthetic efficiency. This may be attributed to the possibility that, during this period, the root system may have deepened in search of water at greater depths in the soil. Consequently, the roots may not have noticed the lack of water, and the stomata may have remained open, facilitating the entry of CO_2 and increasing the efficiency of carboxylation (Figures 2 and 3). It is possible that the initial 4 days of stress were insufficient to activate the culture's response mechanisms to water scarcity conditions.

Gas exchange in citron watermelon (*Citrullus lanatus* var. citroides (L.H. Bailey) Mansf. ex Greb.) was negatively affected by water deficiency, with significant reductions in stomatal conductance, CO_2 assimilation, transpiration, and internal carbon concentration [34]. Dantas et al. [3] found that an irrigation deficit corresponding to 50% of the actual crop evapotranspiration resulted in inhibition of gas exchange, synthesis of photosynthetic pigments, growth, and fruit quality in 'Sugar Baby' mini watermelon. Indeed, photosynthetic efficiency determines the plant's ability to convert solar energy into compounds essential for fruit growth [35,36]. Thus, higher efficiency results in larger, more numerous, and better-quality fruit. Conversely, reduced efficiency may limit plant growth and produce lower and inferior quality.

Similar to the findings in this research, Rouen et al. [37] found that genotypes from dry areas in Iran performed better under severe drought, while those from wet regions experienced a significant reduction in yield. These authors suggested that watermelon varieties from dry areas perform better under unfavorable conditions, which may justify maintaining production under water deficiency in the watermelon variety tested under semi-arid Brazilian conditions. Certainly, the "Crimpson Sweet" watermelon variety tested in the present research is adapted to the northeast region, and the applied stress was insufficient to be reflected in productive losses (Figure 1, Table 4).

In a scenario similar to that of the present research, Barros et al. [6] found that a range of 12 to 22% of wetted areas did not result in physiological damage to watermelon or a reduction in agricultural productivity in Arapiraca, Alagoas. These findings again highlight the potential tolerance of watermelon varieties to water scarcity, as tested under local conditions.

5. Conclusions

(1) Water deficiency reduced the photosynthetic efficiency of watermelon plants after 4 days of drought.
(2) The suspension of irrigation for four and eight days was not sufficient to influence watermelon yield.
(3) The "Crimpson Sweet" variety of watermelon cultivated in the soil conditions of Arapiraca shows signs of adaptation and tolerance to water deficiency.

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