Physiological performance of sugarcane genotypes under different irrigation levels

Comportamiento fisiológico de genotipos de caña de azúcar bajo diferentes niveles de riego

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Abstract

Developing and selecting genotypes that are responsive or tolerant to variations in water availability is essential for sugarcane production. The aim of this study was to evaluate the performance of 32 sugarcane genotypes under different water conditions. The responses of physiological variables as a function of different irrigation levels were evaluated. The experiment used a Randomized Complete Block Design (RCBD) in a split-plot arrangement. Four irrigation levels (20 %, 40 %, 60 %, and 100 % of crop evapotranspiration) were allocated to main plots, and the subplots were represented by 32 genotypes belonging to different genera and species. The evaluated physiological variables of the plants were photosynthesis rate (A), stomatal conductance (gs), quantum yield of CO_2 assimilation (PhiCO$_2$), and transpiration rate (E). Leaf vapor pressure deficit (VpdL) was estimated based on leaf temperature. The results revealed that genotypes 10, 26, and 29 consistently maintained high physiological performance across all irrigation levels, whereas genotype 7 showed notable resilience under water deficit. These genotypes are identified as promising candidates for cultivation under water-limited conditions and may support the selection of efficient, drought-tolerant material for semi-arid regions.

Keywords: Evapotranspiration, infrared gas analyzer, photosynthesis, *Saccharum* spp., water deficit.

Resumen

El desarrollo y la selección de genotipos sensibles o tolerantes a variaciones en la disponibilidad hídrica son esenciales para la producción de caña de azúcar. El objetivo de este estudio fue evaluar el rendimiento de 32 genotipos de caña de azúcar bajo distintas condiciones hídricas, buscando analizar el comportamiento de las variables fisiológicas en distintos niveles de riego. El diseño experimental fue de Bloques Completos al Azar, donde los tratamientos fueron distribuidos en parcelas subdivididas. Se asignaron cuatro niveles de riego (20 %, 40 %, 60 % y 100 % de la evapotranspiración del cultivo) a las parcelas principales, y las subparcelas estuvieron representadas por 32 genotipos pertenecientes a diferentes géneros y especies. Las variables fisiológicas de las plantas analizadas fueron tasa de fotosíntesis (A), conductancia estomática (gs), rendimiento cuántico calculado a partir de la asimilación de CO_2 (PhiCO2) y tasa de transpiración (E). El déficit de presión de vapor (VpdL) se estimó con base en la temperatura foliar. Los resultados revelaron que los genotipos 10, 26 y 29 mantuvieron un alto rendimiento fisiológico de forma consistente en todos los niveles de riego, mientras que el genotipo 7 mostró una resiliencia notable ante el déficit hídrico. Estos genotipos fueron identificados como candidatos prometedores para el cultivo en condiciones de escasez de agua, lo que respalda la selección de material más eficiente y tolerante a la sequía para regiones semiáridas.

Palabras clave: análisis de gases infrarrojos, déficit hídrico, evapotranspiración, fotosíntesis, *Saccharum* spp.

Introduction

The sugarcane production forecast for Brazil's 2024–2025 harvest estimates a total output of 678.67 million tons, representing a 4.8 % decrease compared with the previous harvest (Conab, 2024). Irrigation in sugarcane fields is an economically viable investment, as it increases productivity and helps secure yields under adverse weather conditions (Oliveira *et al.*, 2020).

Sugarcane (*Saccharum* spp.) is a crop of great economic interest worldwide due to its socially relevant by-products, including sugar and ethanol (Li *et al.*, 2021). Water limitation is one of the main constraints on achieving satisfactory crop yields in Brazil and globally, and producers often rely on irrigation to achieve their goals given the unstable rainfall conditions (Gomathi *et al.*, 2020).

Sugarcane is a C4 plant with a long growing cycle, remaining in the field for at least one year and therefore being exposed to a wide range of climatic conditions (Shrivastava *et al.*, 2016). Under water restriction, sugarcane increases the production of the hormone abscisic acid, which induces stomatal closure and reduces water loss through transpiration (Li *et al.*, 2016; Marcos *et al.*, 2018). As a result, photosynthesis decreases and, under severe water deficit, chlorophyll degradation may occur (Silva *et al.*, 2007). These physiological responses are linked to the genetic expression of each strain of the species (Garcia *et al.*, 2020).

Selecting genotypes with efficient physiological performance under water deficit (i.e., drought-tolerant types) is a key goal of plant breeding programs (Khalili *et al.*, 2012). To identify genotypes better adapted to drought, it is essential to assess photosynthetic rate (A), transpiration rate (E), and changes in stomatal conductance (gs) under different irrigation regimes (Zhang *et al.*, 2020). Sugarcane genotypes exhibit distinct physiological and biochemical responses to water availability (Kumar *et al.*, 2021), suggesting that no single trait can fully explain a genotype's stress tolerance.

Physiological changes in sugarcane under water-deficit conditions affect the carbon balance of photosynthesis, reducing starch and sucrose contents and an increasing leaf reducing sugars, which ultimately lowers sucrose concentration (Garcia *et al.*, 2020). Thus, developing and selecting genotypes that are responsive or tolerant to variation in water availability is essential for sugarcane production, as it enables more efficient management of limiting resources such as water while minimizing impacts on plant physiological processes (Gomathi *et al.*, 2020).

It is hypothesized that some genotypes can maintain higher physiological efficiency under water deficit by sustaining superior photosynthetic performance, stomatal regulation, and transpiration control compared with other genotypes. The aim of this study was to evaluate the performance of 32 sugarcane genotypes under different water conditions, seeking to examine physiological responses across different irrigation levels.

Materials and methods

A field experiment was conducted at the Bebedouro Experimental Field of the Brazilian Agricultural Research Corporation (Embrapa), Semiárido Unit, located in Petrolina, State of Pernambuco, Brazil (9º09' S, 40º22' W; 365.5 m a.s.l.). The soil is classified as Abruptic Red-yellow Argisol (Argissolo), with a medium-textured profile and a fragipan layer. Native vegetation is typical hyperxerophilic Caatinga with flat relief.

According to the Köppen classification, the climate of the region is BSWh, semi-arid tropical, with rainfall concentrated between November and April, and an irregular mean annual precipitation of 540 mm. Mean annual temperature is 26.5 ºC, fluctuating between 21 ºC and 32 ºC. Mean annual evaporation rate is approximately 2000 mm, while mean annual relative humidity is 67.8 %. Average wind speed is 2.3 m/s, and the region receives approximately 3000 hours of sunshine per year.

Experimental setup and irrigation treatments

The study evaluated sugarcane genotypes grown in a well-established experimental area. Given the perennial nature of sugarcane cultivation and its multiple harvest cycles, the experiment was conducted during a defined dry-season period (2022–2023) to ensure controlled water conditions. Irrigation treatments were initiated 90 days prior to physiological measurements and were maintained consistently throughout the evaluation period.

The experiment followed a Randomized Complete Block Design (RCBD) in a split-plot arrangement. Four irrigation levels (20 % = severe deficit, 40 % = moderate deficit, 60 % = mild deficit, and 100 % = full irrigation of crop evapotranspiration) were applied to the plot and the subplots.

Irrigation management and calculation

Water consumption was converted to crop evapotranspiration (ETc) based on the vegetated area of each experimental unit. Reference evapotranspiration (ETo) was estimated using the FAO Penman-Monteith method (FAO-56), according to Allen *et al.* (1998). Crop evapotranspiration (ETc) was calculated as ETc = ETo × Kc, where Kc is the sugarcane crop coefficient. Irrigation was applied using a drip system to ensure precise water delivery. Irrigation volumes for each treatment were adjusted

weekly according to ETc to maintain the defined percentage levels.

Experimental design and genotypes

The experiment followed a Randomized Complete Block Design (RCBD) in a split-plot arrangement, with three replications. The four irrigation levels were assigned to the main plots, and the subplots consisted of 32 genotypes from different genera and species: 18 genotypes of *Saccharum officinarum*, two genotypes of *Saccharum* spp., one genotype of *Saccharum hybrid*, two genotypes of *Saccharum robustum*, five genotypes of *Erianthus arundinaceus*, and two genotypes of *Miscanthus* spp.

Physiological measurements

After 90 days of water-deficit treatment, fully-expanded leaves were selected from each plant based on uniformity of color, maturity, size, and health status. Leaf gas exchange was measured using a portable infrared gas analyzer (IRGA), model Li-6400 LI-COR®, under artificial light set at 2000 µmol m^{-2} s^{-1}. The evaluated physiological variables of the plants were photosynthetic rate (A), stomatal conductance (gs), quantum yield of CO_2 assimilation (PhiCO$_2$), and transpiration rate (E). Leaf vapor pressure deficit (VpdL) was estimated from leaf temperature. Measurements were conducted between 8:00 and 11:00 h.

Statistical analysis

Data were subjected to analysis of variance (ANOVA). When there was a significant interaction between varieties and irrigation levels, the variables were split within each factor. When no significant interaction was detected, only the independent effects of the factors were considered. The Scott Knott-test (Scott and Knott, 1974) at the 5 % significance level was used to cluster the means of varieties, while the quantitative factor (irrigation levels) was analyzed using a linear regression at the 5 % significance level. Analysis of canonical variables was performed to assess the relationships between physiological variables and irrigation levels (Bhering, 2017). In addition, quadratic polynomial regression models were fitted using the treatment means (average of replicates) for each genotype across irrigation levels.

Results

Leaf vapor pressure deficit estimated from leaf temperature (VpdL) was significant only for irrigation levels, with no significant genotypes x irrigation level interaction. In contrast, net photosynthesis (A), stomatal conductance (gs), quantum yield of CO_2 assimilation (PhiCO$_2$), and transpiration rate

(E) showed significant effects for irrigation level, genotype, and their interaction (Table 1).

VpdL refers to the effect of leaf temperature on the vapor pressure inside the leaf. For example, low leaf temperatures reduce the rate of water evaporation by lowering the water vapor concentration in the leaf's internal atmosphere, thereby decreasing vapor pressure. In this study, this variable was significant only for the irrigation level factor (Figure 1), and increased linearly as irrigation levels increased (R^2 = 0.7145). Mean photosynthetic rates of sugarcane genotypes under different irrigation levels are presented in Table 2.

Genotypes 26 and 29 consistently showed the highest mean A values across all irrigation levels, indicating that they maintain superior photosynthetic performance regardless of the irrigation regime. In contrast, genotypes 1 and 31 reached the highest mean A only at 20 % ETc. Genotypes 2, 6, 19, and 23 achieved the highest means at all irrigation levels except 40 % ETc.

For most genotypes, A was best described by a quadratic regression model, indicating a non-linear response across irrigation levels. The fitted quadratic models achieved coefficients of determination (R2) above 0.7 for most genotypes. At 40 % ETc, A values were similar to or lower than those observed at 20 % ETc for most genotypes.

Stomatal conductance (gs) is related to the ability of the stomata to carry out gas exchange. At 20 % ETc, genotypes 1, 2, 5, 7, 8, 9, 10, 19, 22, 23, 24, and 25 showed higher mean gs values (Table 3). This condition represents water stress, and these genotypes showed high stomatal conductance, which may lead to excessive water loss through transpiration.

Table 1. Analysis of variance (ANOVA) mean squares for physiological variables in sugarcane across irrigation levels and genotypes

SV	DF	VpdL	A	gs	PhiCO$_2$	E
Irrigation (W)	3	0.26*	3676.00*	0.07*	< 0.001*	22.5*
Genotype (G)	31	0.02	270.00*	0.02*	< 0.001*	6.72*
W x G	93	0.03	80.48*	< 0.001*	< 0.001*	1.45*
Residual	254	0.04	37.47	< 0.001	< 0.001	0.99
CV (%)		9.01	21.17	23.71	21.84	25.24

SV: source of variation; DF: degrees of freedom; CV: coefficient of variation; VpdL: leaf temperature; A: net photosynthesis; gs: stomatal conductance; PhiCO$_2$: quantum yield of CO_2 assimilation; and E: transpiration rate. * significant at the 5 % probability level by the F test ($p \leq 0.05$).
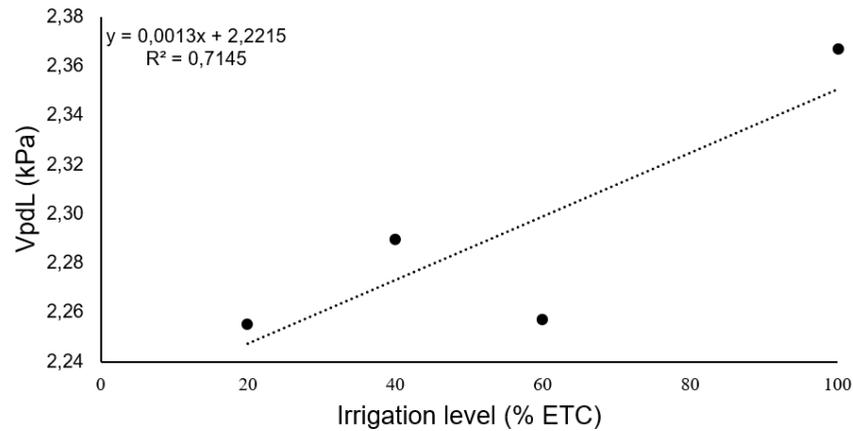
Figure 1. Linear regression of leaf vapor pressure deficit estimated from leaf temperature (VpdL, kPa) as a function of irrigation level (%ETc).

Table 2. Mean photosynthetic values (A; $\mu mol\ m^{-2}s^{-1}$) of sugarcane genotypes across different irrigation levels (% of ETc) and their respective quadratic regression models

Geno-type	20 %	40 %	60 %	100 %	Model	R^2
1	27.64 a	16.20 c	32.80 b	30.89 b	$= 0.0012x^2 - 0.047x + 24.856$	0.22
2	23.38 a	26.92 b	34.85 a	35.38 a	$= -0.0026x^2 + 0.4761x + 14.1272$	0.92
3	15.86 b	22.35 c	28.30 b	30.32 b	$= -0.0030x^2 + 0.5473x + 5.8917$	0.99
4	18.82 b	26.09 c	36.13 a	24.12 b	$= -0.0080x^2 + 1.0463x - 0.0033$	0.91
5	28.53 a	32.40 b	19.22 b	36.14 a	$= -0.005x^2 - 0.6095x + 41.0929$	0.49
6	22.26 a	24.04 c	35.53 a	36.26 a	$= -0.0025x^2 + 0.4935x + 11.9774$	0.85
7	18.33 b	38.16 a	40.16a	37.12 a	$= -0.0091x^2 + 1.3049x - 2.8661$	0.93
8	24.31 a	30.99 b	45.36 a	46.75 a	$= -0.0047x^2 + 0.8682x - 7.4576$	0.94
9	24.90 a	37.70 a	33.04 b	36.77 a	$= -0.0032x^2 + 0.5072x + 17.8344$	0.62
10	27.74 a	36.61 a	45.43 a	41.30 a	$= -0.0062x^2 + 0.9234x + 11.1704$	0.98
11	15.56 b	14.33 c	27.47 b	22.26 b	$= -0.0032x^2 + 0.5054x + 4.7067$	0.55
12	20.29 b	31.61 b	37.14 a	35.40 a	$= -0.0059x^2 + 0.8995x + 4.8042$	0.99
13	13.72 b	21.49 c	30.76 b	31.23 b	$= -0.0045x^2 + 0.7734x - 0.5518$	0.97
14	17.72 b	17.65 c	42.75 a	41.14 a	$= -0.0047x^2 + 0.9156x - 2.1844$	0.75
15	14.91 b	18.62 c	22.82 b	32.23 b	$= 0.0005x^2 + 0.1594x + 11.5150$	0.99
16	13.77 b	22.35 c	25.05 b	39.37 a	$= 0.0002x^2 + 0.2846x + 8.7221$	0.98
17	13.87 b	15.04 c	27.50 b	30.12 b	$= -0.0018x^2 + 0.4503x + 4.0685$	0.86
18	18.14 b	17.71 c	34.36 a	44.21 a	$= 0.0001x^2 + 0.3438x + 9.1757$	0.90
19	30.59 a	25.24 c	34.68 a	34.89 a	No fitted	
20	12.68 b	30.15 b	32.49 b	28.39 b	$= -0.0085x^2 + 1.2012x - 6.9426$	0.95
21	15.32 b	30.53 b	32.31 b	29.73 b	$= -0.0071x^2 + 1.0150x - 1.2121$	0.94
22	27.92 a	29.95 b	31.25 b	35.28 a	No fitted	
23	28.46 a	27.77 b	34.93 a	41.09 a	$= -0.0071x^2 + 1.0150x - 1.2121$	0.92
24	34.76 a	37.04 a	41.16 a	29.92 b	No fitted	
25	19.92 b	27.10 b	28.28 b	36.78 a	$= -0.0006x^2 + 0.2768x + 15.2979$	0.96
26	24.82 a	40.16 a	37.42 a	41.03 a	$= -0.0046x^2 + 0.7270x + 13.8473$	0.78
27	16.39 b	18.53 c	33.60 a	29.76 b	$= -0.0045x^2 + 0.7417x + 1.3729$	0.77
28	16.46 b	21.99 c	30.87 b	22.82 b	$= -0.0060x^2 + 0.8155x + 1.5772$	0.89
29	32.42 a	38.54 a	34.90 a	41.92 a	No fitted	
30	21.23 b	27.56 b	27.70 b	37.81 a	$= -0.0003x^2 + 0.1546x + 18.7793$	0.95
31	27.63 a	18.20 c	28.76 b	30.67 b	No fitted	
32	16.63 b	19.57 c	41.40 a	34.63 a	$= -0.0068x^2 + 1.0913x - 5.3906$	0.75

*Different lowercase letters within a row indicate significant differences among irrigation levels (Scott-Knott test, $p \leq 0.05$). Regression models were fitted only when the irrigation level effect was significant ($p \leq 0.05$); otherwise are indicated as "No fitted"

At an irrigation rate of 40 % ETc, genotypes 7, 10, 24, 26, and 29 showed higher gs, which under this condition may be beneficial as it favors photosynthesis. Combined with the fact that these genotypes also had high A, this suggests that higher gs improved photosynthesis in these genotypes. At 60 % ETc, genotypes 2, 6, 7, 8, 9, 14, 20, 22, 24, 26, 27, 29, and 32 had higher gs, and most of them also had higher A, supporting the idea that higher gs increases gas exchange and favors photosynthetic processes. At 100 % ETc, genotypes 8, 10, and 18 showed the highest gs and were also the genotypes that maintained the highest A.

Overall, high stomatal conductance favors photosynthesis. However, it is crucial that the plant be able to adjust stomatal opening to cope with environmental adversities, especially water stress.

If gs remains high under water-deficit conditions, excessive water loss through transpiration may occur, compromising proper plant development. Practically all genotypes that differed across irrigation levels were best fitted by a quadratic model. The coefficients of determination (R^2) were higher than 0.60 for most genotypes. As observed for A, gs decreased at 40 % ETc compared with 20 % ETc for most genotypes.

Quantum yield is the ratio between the amount of CO_2 fixed by the plant during the stomata opening process and the amount of light energy absorbed by pigments. This metric is an important measure of photosynthetic efficiency. Thus, at an irrigation level of 20 % ETc, genotypes 1, 2, 5, 6, 7, 8, 9, 10, 14, 19, 22, 23, 24, 25, 26, 29, and 31 showed higher $PhiCO_2$ values (Table 4), suggesting that they were able to maintain higher CO_2 assimilation and sustain photosynthesis under water deficit.

Table 3. Mean values of stomatal conductance (gs; mol m^{-2} s^{-1}) of sugarcane genotypes across different irrigation levels (% of ETc) and their respective quadratic regression models

Geno-type	20 %	40 %	60 %	100 %	Model	R^2
1	0.19 a	0.10 c	0.14 b	0.18 c	= 0.00004x² - 0.0045x + 0.2545	0.62
2	0.17 a	0.18 b	0.20 a	0.22 b	No fitted	
3	0.13 b	0.05 d	0.14 b	0.18 c	= 0.00003x2 - 0.0021x + 0.1423	0.55
4	0.13 b	0.16 b	0.15 b	0.17 c	No fitted	
5	0.18 a	0.15 b	0.08 b	0.21 b	= 0.0001x² - 0.0066x + 0.2965	0.85
6	0.14 b	0.17 b	0.21 a	0.24 b	= -00001x² + 0.0026x + 0.0882	0.99
7	0.19 a	0.23 a	0.23 a	0.23 b	No fitted	
8	0.16 a	0.19 b	0.24 a	0.31 a	= 0.0000x² + 0.0019x + 0.1210	0.99
9	0.17 a	0.18 b	0.19 a	0.21 b	No fitted	
10	0.19 a	0.25 a	0.18 b	0.29 a	= 0.00002x2 - 0.0015x + 0.2292	0.53
11	0.09 b	0.06 d	0.11 b	0.10 c	No fitted	
12	0.13 b	0.18 b	0.14 b	0.17 c	No fitted	
13	0.11 b	0.15 b	0.13 b	0.18 c	No fitted	
14	0.10 b	0.11 c	0.24 a	0.21 b	= -0.00003x² + 0.0056x - 0.0141	0.70
15	0.11 b	0.06 d	0.12 b	0.17 c	= 0.00002x2 - 0.0015x + 0.1190	0.79
16	0.10 b	0.12 c	0.14 b	0.19 c	= 0.000001x² + 0.0010x + 0.0806	0.99
17	0.09 b	0.08 d	0.16 b	0.15 c	= -0.00001x² + 0.0025x + 0.0347	0.59
18	0.11 b	0.08 d	0.14 b	0.27 a	= 0.0004x² - 0.0032x + 0.1526	0.96
19	0.15 a	0.14 c	0.17 b	0.13 c	No fitted	
20	0.09 b	0.19 b	0.21 a	0.13 c	= -0.0001x² + 0.0082x - 0.0446	0.96
21	0.11 b	0.17 b	0.18 b	0.12 c	= -0.00005x² + 0.0059x - 0.0092	0.98
22	0.18 a	0.19 b	0.20 a	0.23 b	No fitted	
23	0.18 a	0.13 c	0.18 b	0.24 b	= 0.00003x² + 0.0023x + 0.2005	0.82
24	0.24 a	0.23 a	0.26 a	0.23 b	No fitted	
25	0.19 a	0.17 b	0.18 b	0.14 c	No fitted	
26	0.13 b	0.24 a	0.28 a	0.23 b	= -0.0001x² + 0.0094x - 0.0316	0.99
27	0.12 b	0.10 c	0.22 a	0.15 c	= -0.00003x² + 0.0046x + 0.0252	0.41
28	0.12 b	0.12 c	0.18 b	0.13 c	No fitted	
29	0.22 a	0.23 a	0.26 a	0.24 b	No fitted	
30	0.02 b	0.14 c	0.18 b	0.24 b	= -0.00004x² + 0069x - 0.0972	0.98
31	0.14 b	0.09 d	0.14 b	0.22 b	= 0.00004x² - 0.0032x - 0.1846	0.87
32	0.09 b	0.11 c	0.23 a	0.15 c	= -0.0001x² + 0.0070x - 0.0431	0.68

*Different lowercase letters within a row indicate significant differences among irrigation levels (Scott-Knott test, $p \leq 0.05$). Regression models were fitted only when the irrigation level effect was significant ($p \leq 0.05$); otherwise are indicated as "No fitted".

Table 5. Mean values of transpiration rate (E, mmol H_2O m^{-2} s^{-1}) of sugarcane genotypes across different irrigation levels (% of ETc) and their respective quadratic regression models

Genotype	20 %	40 %	60 %	100 %	Model	R^2
1	4.33 a	3.43 c	3.60 b	4.72 a	No fitted	
2	3.82 a	5.37 a	4.07 b	4.91 a	No fitted	
3	2.97 b	3.04 c	3.32 b	4.09 b	No fitted	
4	3.13 b	3.82 b	4.30 b	3.34 b	No fitted	
5	4.03 a	4.27 b	3.49 b	4.77 a	No fitted	
6	3.37 b	3.32 c	4.31 b	5.22 a	No fitted	
7	3.39 b	5.22 a	5.19 a	5.09 a	No fitted	
8	3.74 a	4.39 b	5.74 a	6.29 a	$= -0.0003x^2 + 0.0735x + 2.2902$	0.95
9	3.15 b	4.26 b	4.74 a	4.14 b	No fitted	
10	4.16 a	5.65 a	4.90 a	5.58 a	No fitted	
11	2.43 b	1.64 c	2.77 b	2.47 b	No fitted	
12	3.09 b	4.13 b	3.40 b	4.13 b	No fitted	
13	2.70 b	2.89 c	3.34 b	3.42 b	No fitted	
14	3.19 b	2.60 c	3.92 b	4.93 a	$= 0.0003x^2 - 0.0103x + 3.0760$	0.84
15	2.54 b	3.11 c	3.46 b	3.28 b	No fitted	
16	2.40 b	2.95 c	3.25 b	4.48 a	No fitted	
17	2.21 b	1.97 c	3.78 b	3.59 b	No fitted	
18	2.90 b	2.76 c	4.18 b	6.29 a	$= 0.0004x^2 - 0.0048x + 2.6810$	0.97
19	3.63 a	3.49 c	5.22 a	4.23 b	No fitted	
20	2.16 b	4.91 a	4.62 a	3.22 b	$= -0.0014x^2 + 0.1826x - 0.6861$	0.87
21	2.51 b	4.12 b	4.20 b	2.96 b	No fitted	
22	4.18 a	4.24 b	4.58 a	4.61 a	No fitted	
23	4.05 a	3.02 c	4.84 a	4.81 a	No fitted	
24	5.37 a	4.60 b	5.71 a	4.34 a	No fitted	
25	3.61 a	4.02 b	4.21 b	4.82 a	No fitted	
26	4.03 a	6.26 a	5.50 a	5.67 a	$= -0.0007x^2 + 0.1007x + 2.5929$	0.62
27	2.92 b	4.02 b	5.13 a	2.93 b	$= -0.0013x^2 + 0.1527x + 0.2424$	0.95
28	2.64 b	2.97 c	4.23 b	2.64 b	No fitted	
29	4.96 a	5.29 a	7.09 a	4.77 a	$= -0.0011x^2 + 0.1341x + 2.4386$	0.72
30	3.16 b	3.14 c	3.05 b	4.87 a	No fitted	
31	3.49 a	2.85 c	3.22 b	4.08 b	No fitted	
32	2.31 b	2.97 c	5.20 a	3.77 b	$= -0.0011x^2 + 0.1494x - 0.5496$	0.78

*Different lowercase letters within a row indicate significant differences among irrigation levels (Scott-Knott test, $p \leq 0.05$). Regression models were fitted only when the irrigation level effect was significant ($p \leq 0.05$); otherwise are indicated as "No fitted".

The genotypes that showed a significant difference for the quantitative factor were better fitted by the quadratic model, with coefficients of determination (R^2) above 0.8 for most genotypes. Genotypes 7, 8, 9, 10, 26, and 29 maintained the highest PhiCO$_2$ means at all irrigation levels compared with the other genotypes, indicating that, regardless of water availability, these genotypes are efficient at assimilating CO$_2$. It is worth noting that genotypes 5, 7, 9, 19, 22, 24, 25, 29, and 31 were not influenced by irrigation regime, showing statistically similar means across all regimes.

Transpiration rate (E) refers to the amount of water lost from the leaves to the atmosphere, mainly through the stomata. Genotypes 1, 2, 5, 8, 10, 19, 22, 23, 24, 25, 26, 29, and 31 showed higher E under 20 % ETc (Table 5). Under the same irrigation conditions, these genotypes also maintained the highest gs means. In other words, under conditions of water deficit, these genotypes keep their stomata more open, increasing stomata conductance and, consequently, transpiration. Genotypes 2, 7, 10, 20, 26, and 29 showed higher E rates under an irrigation regime of 40 % ETc.

Discussion

Water regime is an important environmental factor that significantly affects crop development. Water deficit triggers different physiological responses, causing morpho-agronomic changes in sugarcane that particularly affect yield (Reyes *et al.*, 2020). Before yield losses occur, the crop often shows biochemical adjustments as it attempts to mitigate the effects of water stress (Kumar *et al.*, 2021).

VpdL was similar among the evaluated genotypes, differing only across irrigation levels. Higher vapor pressure deficit can promote stomatal closure during periods of water deficit, helping plants conserve water and maintain hydration (Chandiposha *et al.*, 2023). On days with high solar radiation, air temperature increases and relative humidity decreases, leading to higher VpdL, which can intensify transpiration demand and limit gas exchange when water is scarce (Dinh *et al.*, 2019).

Photosynthetic rates are significantly reduced under water stress, and this effect can be aggravated by decreases in stomatal conductance, which limit gas exchange and reduce CO_2 assimilation. (Leanasawat *et al.*, 2021). Genotypes subjected to 20 % ETc showed lower photosynthesis rates, and some had very similar or even lower values at 40 % ETc. This may be related to reduced light interception by the canopy due to leaf curling, which narrows leaves and reduces the photosynthetically active leaf area (Sajid *et al.*, 2023). Depending on the genotype, photosynthetic rates increased when irrigation was raised to 60 % ETc or 100 % ETc.

Higher transpiration rates under optimal watering conditions can be associated with adequate photosynthetic processes. Eight of the 32 genotypes showed significance responses to irrigation levels, and transpiration rate was best fitted by a quadratic model as ETc increased. The remaining genotypes showed no differences in transpiration rate across irrigation levels, maintaining a similar pattern as ETc increased.

Examining the performance of sugarcane genotypes under contrasting water conditions helps identify materials that are better adapted to specific environments. In this study, genotypes 10, 26, and 29 consistently stood out across multiple physiological variables, maintaining high photosynthetic rates (Table 2), stomatal conductance (Table 3), quantum yield of CO_2 assimilation (Table 4), and transpiration (Table 5) under different irrigation regimes. Additionally, genotype 7 also showed strong performance, particularly for stomatal conductance and quantum yield under deficit conditions. These genotypes are promising candidates for water-limited environments due to their ability to sustain physiological efficiency under stress. This approach also supports the identification of more water-efficient genotypes that maintain high photosynthetic rates (and potentially yield) with less water. Therefore, combining physiological assessments with agronomic traits can better guide genotype selection for specific water conditions in the region.

Genotypes 10, 26, and 29 stood out for their consistency in maintaining high photosynthesis and transpiration rates across all irrigation conditions in the Brazilian semi-arid region. Genotypes 1 and 31 were more sensitive to water stress, whereas

genotypes 2, 6, 9, 12, 14, 16, 19, 23, and 32 showed the best performance except at 40 % ETc, with high photosynthesis and quantum yield and lower stomatal conductance and transpiration, particularly under more adequate irrigation conditions.

This study relied on point-in-time gas exchange measurements. While informative, these measurements provide a snapshot and may not capture diurnal variations or acclimation over longer periods. In addition, using a single ETc estimate across genotypes standardized comparisons, but may not reflect differences in water consumption among different genetic materials. Future studies could benefit from continuous monitoring of plant water status (e.g., stem water potential) and soil moisture to more precisely relate irrigation application to plant-available water.

Conclusion

Studying the physiological traits of sugarcane genotypes under water deficit and adequate water supply provides essential information for selecting genotypes that are more resistant to water deficit. In this study, genotypes 10, 26, and 29 consistently performed well across all irrigation levels, maintaining high photosynthetic rates, efficient stomatal regulation, and favorable water use efficiency. Additionally, genotype 7 showed notable resilience under deficit conditions. These genotypes represent promising material for breeding programs aimed at improving drought tolerance in sugarcane and offer farmers viable options for cultivation under variable water availability in semi-arid regions.

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