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Pulses and intervals of subsurface drip irrigation on sugarcane gas exchange and yield

Pulsos e intervalos de irrigação por gotejamento subsuperficial nas trocas gasosas e produtividade da cana-de-açúcar

Igor Almir Silva Gonçalves[1]*; Gerônimo Ferreira da Silva[2]; Manassés Mesquita da Silva[3]; Mário Monteiro Rolim[3]; Ênio Farias de França e Silva[4]; Alexsandro Oliveira da Silva[4]; Djalma Eusébio Simões Neto[5]; Alexandre Nascimento dos Santos[6]; Ronaldo Alves de Oliveira Filho[7]

Highlights

The best production was obtained with the application of four irrigation pulses.
Irrigation application interval of 40 minutes was the best factor for gas exchange.
Pulse irrigation got the best results to the detriment of continuous irrigation.

Abstract

Pulsed irrigation is an alternative for irrigation management capable of reducing the harmful effects of stress. The objective of this work was to evaluate the effect of the number and intervals of irrigation pulses applied by pulsed subsurface drip on gas exchange in sugarcane. The experiment was conducted in the field at the Carpina Sugarcane Experimental Station (EECAC), from October 2022 to October 2023. The experimental design used was completely randomized, in a 4 x 2 + 1 factorial arrangement, the first factor consisting of 4 different numbers of pulses (2, 3, 4 and 5 pulses), the second factor consisting of 2 application intervals between pulses (20 and 40 minutes) and the third factor consisting of a control treatment (irrigation applied in a continuous), with 4 repetitions. The sugarcane cultivar evaluated

[1] Master Degree in Agricultural Engineering, Universidade Federal Rural de Pernambuco, UFRPE, Recife, PE, Brazil. E-mail: iasgon99@gmail.com
[2] Prof. Dr., Postgraduate Degree in Phytotechnics, UFRPE, Recife, PE, Brazil. E-mail: geronimo.silva@ufrpe.br
[3] Profs. Drs., Postgraduate Degree in Agricultural Engineering, UFRPE, Recife, PE, Brazil. E-mail: manasses.mesquita@ufrpe.com; mariorolim10@gmail.com
[4] Profs. Drs., Postgraduate Degree in Irrigation and Drainage and Postgraduate Degree in Agronomy, UFRPE, Recife, PE, Brazil. E-mail: enio.fsilva@ufrpe.com; alexsandro@ufc.com
[5] Prof. Dr., Postgraduate Degree in Soil Science, UFRPE, Carpina, PE, Brazil. E-mail: djalmasimoesneto@gmail.com
[6] Prof. Dr. Postgraduate Degree in Agricultural Engineering, Instituto Federal de Alagoas, IFAL, Alagoas, AL, Brazil. E-mail: alexandre.santos@ifal.edu.br
[7] Prof. Dr., Postgraduate Degree in Agricultural Engineering, Instituto Federal de Pernambuco, IFPE, Recife, PE, Brazil. E-mail: rcnaldoalvesfoto@hotmail.com
* Author for correspondence

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was RB 041443. The following variables were analyzed with an Infrared Gas Analyzer (IRGA LI-6400): Internal CO_2 concentration (Ci), Stomatal conductance (gs) mol, transpiration (E), net photosynthesis (A), instantaneous water use efficiency (A/E), intrinsic water use efficiency (A/gs) and instantaneous carboxylation efficiency (A/Ci). The best responses for net photosynthesis, stomatal conductance and intrinsic water use efficiency were obtained with the application of 4 irrigation pulses. The highest values of transpiration and instantaneous carboxylation efficiency were obtained with an interval of 40 minutes, the number and intervals of irrigation did not influence the internal carbon concentration and instantaneous efficiency of water use.
Key words: *Saccharum* spp. Irrigation management. RB041443.

Resumo

A irrigação pulsada é uma alternativa para o manejo da irrigação capaz de reduzir os efeitos deletérios do estresse. Objetivou-se com este trabalho avaliar o efeito do número e intervalos de pulsos de irrigação aplicados por gotejamento subsuperficial pulsada nas trocas gasosas da cana-de-açúcar. O experimento foi conduzido em campo na Estação Experimental do Cana-de-Açúcar do Carpina (EECAC), no período de outubro de 2022 a outubro de 2023. O delineamento experimental utilizado foi inteiramente casualizado, em arranjo fatorial 4 x 2 + 1, o primeiro fator constituído 4 diferentes números de pulsos (2, 3, 4 e 5 pulsos), o segundo fator por 2 intervalos de aplicação entre os pulsos (20 e 40 minutos) e o terceiro fator composto por um tratamento testemunha (irrigação aplicada de forma contínua), com 4 repetições. A cultivar de cana-de- açúcar avaliada foi a RB 041443. Foram analisados com Analisador de Gás Infravermelho (IRGA LI-6400), as seguintes variáveis: concentração Interna de CO_2 (Ci), condutância Estomática (gs) mol, transpiração (E), fotossíntese líquida (A), eficiência instantânea de uso da água (A/E), eficiência intrínseca do uso da água (A/gs) e eficiência instantânea de carboxilação (A/Ci). As melhores respostas para a fotossíntese líquida, condutância estomática e eficiência intrínseca do uso da água foram obtidas com a aplicação de 4 pulsos de irrigação. Os maiores valores de transpiração e eficiência instantânea de carboxilação foram obtidos com o intervalo de 40 minutos, o número e intervalos de irrigação não influenciaram na concentração interna de carbono e eficiência instantânea do uso da água.
Palavras-chave: *Saccharum* spp. Manejo de irrigação. RB041443.

Introduction

Sugarcane (*Saccharum* spp.) is considered one of the main agricultural commodities in terms of yield, with Brazil frequently being the largest producer, followed by India and China (Vandenberghe et al., 2022; Menezes et al., 2024). In 2023, the Brazilian production of the crop was 685.8 million tons, in a planted area of 8.6 million hectares, with the country producing 46 million tons of sugar and accounting for 26% of the world's bioethanol production (Companhia Nacional de Abastecimento [CONAB], 2024).

According to CONAB (2024), the state of Pernambuco is the second largest producer of sugarcane in the Northeast region and the seventh in the country, with a production of 13.8 million tons harvested in an area of 233 thousand hectares, approximately 969.5 thousand tons of sugar and 331 million liters of ethanol, and most of this production results from the cultivation of the crop in coastal areas. In these areas, despite the high annual rainfall, the poor distribution of rainfall at summer entails the need for total irrigation o obtain satisfactory yields (Andrade et al., 2024).

In this context, the search for new technologies and the improvement of existing techniques in irrigated agricultural production systems of sugarcane are fundamental for the rational use of water resources, improvement of physiological efficiency and, consequently, increase of yield and improvement in the technological quality of the crop. In this regard, pulse irrigation emerges, a technique used within irrigation management, which promotes better use of the applied water, reducing water losses by percolation (Zamora et al., 2019).

This technique consists of applying the required daily depth fractionated into small amounts, with application periods called pulses, applied in short cyclical periods of wetting and resting, promoting lower losses due to percolation, as well as greater uniformity and application efficiency (Rank & Vishnu, 2021).

Some studies point to the use of pulse irrigation as a possible strategy to mitigate the harmful effects of water deficit, due to improvements in the distribution and maintenance of moisture in the soil profile throughout the day (Eid et al., 2013), and also to increments in water use efficiency and yield and improvements in crop quality (Zamora et al., 2019; Cormier et al., 2020; Menezes et al., 2024).

Although some promising results for this technique have been reported in the literature, there is a need for more studies evaluating the effects of pulse irrigation on sugarcane crop and especially improving the knowledge on the influence of irrigation with different numbers and intervals of application of these pulses on its yield and gas exchange.

According to Taiz et al. (2017), the decrease in gas exchange caused by water limitation negatively affects CO2 assimilation in chloroplasts, which limits the production of sucrose. In sugarcane, the reduction of the diffusive flux of CO2 to the mesophyll causes, as a consequence, the decline of the photosynthetic rate and the decrease in the yield of the crop.

In view of the above, the objective of this study was to evaluate the effect of the number and intervals of pulses of subsurface drip irrigation on the gas exchange and yield of sugarcane.

Material and Methods

The experiment was carried out in the fourth cycle of sugarcane production, conducted in the field at the Carpina Sugarcane Experimental Station (Estação Experimental de Cana-de-Açúcar do Carpina - EECAC), in the municipality of Carpina, PE, Brazil, located at the following geographic coordinates: 7º 51′ 24.31″ S and 35º 14′ 16.97″ W.

According to Köppen's classification, the climate of the region is classified as Tropical Megathermal (humid tropical) (Alvares et al., 2014). The average rainfall in the last 52 years is 1,149 mm, with the highest concentration occurring between autumn and winter, with an average of 199.6 mm in the wettest month (June). The maximum and minimum annual air temperatures are 29.1 and 21.8 °C, respectively, with average relative humidity of 79.8% and insolation 2550.7 hours.

The experiment was conducted in a randomized block design, in a 4x2+1 factorial arrangement, with the first factor consisting of 4 different numbers of pulses (2, 3, 4 and 5 pulses), the second factor of 2 application intervals between pulses (20 and 40 minutes) and the third factor of a control treatment (irrigation applied continuously), with irrigation equivalent to 100% ETc, with 4 replicates, totaling 36 experimental units.

All pulsed treatments were irrigated with 100% crop evapotranspiration depth. The duration of each pulse for the pulsed treatments was defined after the daily calculation of the irrigation depth required by the crop.

Each experimental plot consisted of four combined furrows (double row of plants) of 7 m in length, at spacing of 1.4 m between furrows and 0.6 m between rows of plants, resulting in 56 m^2 per experimental unit, and the two combined furrows of the center of each plot (20 m^2), disregarding 1 m from the ends of each row, were considered as a usable area for the analyses.

In order to ensure the uniformity of regrowth and the establishment of sugarcane plants after cutting, the treatments were differentiated only at 45 days after cutting of the third-cycle sugarcane. During this period, uniform irrigations were carried out in all treatments.

The experiment was carried out from October 2022 to October 2023. The planted sugarcane variety was RB041443, developed by the Interuniversity Network for the Development of the Sugarcane Sector (Rede Interuniversitária para o Desenvolvimento do Setor Sucroenergético - RIDESA) through the sugarcane breeding program of the Federal Rural University of Pernambuco (UFRPE).

Fertilizer recommendation was based on the chemical analysis of the soil (Table 1) considering the nutritional requirement of the crop. 200 kg ha^{-1} of nitrogen using urea as a source and 110 kg ha^{-1} of potassium using potassium chloride as a source were applied through fertigation.

Table 1
Chemical characterization of the soil in the experimental area, Carpina 2023

Layer	CHEMICAL CHARACTERIZATION OF THE SOIL												
	pH	P	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	Al^{+3}	$H^{+}+Al^{+3}$	SB	CTC	m	V	M.O
m	H_2O	mg dm^{-3}	------------------------ cmol$_c$ dm^{-3} ------------------------								--- %---		g kg^{-1}
0,0 - 0,2	5,86	21	2,58	1,34	0,23	0,11	0	4,14	4,27	8,41	0	50,76	23,8
0,2 -0,4	5,93	20	2,53	1,34	0,22	0,08	0	3,98	4,16	8,14	0	51,09	21,9

SB: Sum of Bases; CTC: Cation borrow capacity; m: alumunium saturarion; V: Base saturation; M.O: Organic Matter.

The fertilizers were applied via irrigation water between March and August 2023, in a split manner, with one application per month. A nutritional supply was made with the mixed mineral fertilizer of the manufacturer BIOGROW with the trade name BIOSTIM COMPLEX, which claims to contain magnesium (Mg) (23.1 g L^{-1}), boron (B) (2.8 g L^{-1}), copper (Cu) (2.5 g L^{-1}), iron (Fe) (25 g L^{-1}), manganese (Mn) (21.8 g L^{-1}), molybdenum (Mb) (0.5 g L^{-1}) and zinc (Zn) (21.8 g L^{-1}). Foliar application was performed at 230 DAC, at a dose of 2 L ha^{-1}, according to the manufacturer's recommendation.

The irrigation system used was subsurface drip, composed of drip tapes (DN 16 mm) with pressure-compensating and anti-drain inline emitters, spaced 0.50 m apart and with cylindrical outlet (PC/AS type, flow rate of 1 L/h), installed in the soil at 0.20 m depth. The system was also composed of a centrifugal electric pump with horizontal axis (3.5 CV), a filtration and backflushing system with two sand filters, a fertigation injection system consisting of a glycerin-filled manometer, Venturi-type injector nozzle (1.2") and a screen filter (1" basket of 200 mesh), and a set of 10 ball valves to control the flow of water for each treatment individually.

After setting up the irrigation system, a system flow uniformity test was carried out following the methodology proposed by Keller and Karmelli (1974), obtaining a coefficient of 97,5%. Flow measurements were carried out with the aid of a graduated cylinder and a stopwatch recording for 180 seconds, and the service pressure was determined with a glycerin-filled manometer.

The irrigation time for each treatment was determined daily, considering the gross irrigation depth (GID), calculated by the ratio between ETc and the application efficiency (94%) of the irrigation system, obtained by means of a water distribution uniformity test, carried out according to the methodology proposed by Keller and Karmeli (1974).

Irrigation was carried out daily according to the water requirement of the crop obtained based on crop evapotranspiration (ETc) and on the treatments evaluated, according to the equation: $ETc = ECA \times Kp \times Kc$, where: ETc = Crop evapotranspiration, mm day^{-1}; ECA = Evaporation from class A pan, mm day^{-1}; Kp = Class A pan coefficient, dimensionless, and Kc = Crop coefficient, dimensionless.

The Kp values were obtained from the data of wind speed, relative humidity and evaporation from the class A pan, installed near the experimental area, which has herbaceous vegetation with a 10 m border, according to the methodology proposed by Doorenbos and Pruitt (1977). The Kc values that were adopted in the experiment followed the recommendation of Doorenbos and Kassam (1994) for the development stages of the plant, aiming to determine crop evapotranspiration in each of them (Table 2).

Table 2
Crop coefficients (Kc) for sugarcane at different development stages

Development stages	
Days	*Kc*
1 – 61	*0.40*
62 – 153	*0.75*
154 – 244	*1.10*
245 – 334	*1.25*
335 – 360	*0.70*

Source: Adapted from Doorenbos and Kassam (1994).

At 330 days after cutting of the third-cycle sugarcane, gas exchange measurements were performed using a Portable Infrared Gas Analyzer (IRGA), model LI 6400 XT (LI COR) under photosynthetically active radiation maintained at 2500 μmol m^{-2} s^{-1}.

The measurements were carried out between 11 and 1 p.m., a time of intense sunlight and high evapotranspiration demand, in three plants per plot, chosen randomly, in the middle third of leaf +3, which corresponds to the third leaf of the stem or TVD (Top Visible Dewlap) leaf, which is classified as a diagnostic leaf of the crop (Malavolta et al., 1997).

At the time of the readings, net photosynthesis (A), μmol CO_2 m^{-2} s^{-1}, transpiration (E), mmol H_2O m^{-2} s^{-1}, stomatal conductance (gs), mol H_2O m^{-2} s^{-1}, internal CO_2 concentration (Ci), μmol mol^{-1}, instantaneous water use efficiency, μmol CO_2 m^{-2} s^{-1}/mmol H_2O m^{-2} s^{-1}, given by the ratio between net photosynthesis and transpiration (A/E), intrinsic water use efficiency, μmol CO_2 m^{-2} s^{-1}/mol H_2O m^{-2} s^{-1}, quantified by the ratio between net photosynthesis and stomatal conductance (A/gs), and instantaneous carboxylation efficiency, mol m^{-2} s^{-1}, obtained by the ratio between net photosynthesis and internal CO_2 concentration (A/Ci).

At the time of harvest, which was carried out at 350 days after the cutting of the third cycle, the stalks of the usable area of each experimental plot were weighed with a dynamometer, and the values were extrapolated to obtain stalk yield (ton ha^{-1}).

The data obtained were subjected to analysis of variance by the F test ($p<0.05$), using the statistical software SISVAR (Ferreira, 2011). When a significant effect was found for the F test, the data related to the different numbers of pulses were decomposed by means of regression analysis ($p<0.05$). The data related to irrigation application intervals were compared using the F test ($p<0.05$). The control treatment was compared with some treatments of interest by means of orthogonal contrasts.

The choice of the regression models that best fit the data was based on four criteria: non-significant effect of the regression deviation, significance of the parameters of the fitting equation ($p<0.05$), highest value of the coefficient of determination (R2) and biological explanation for each variable as a function of the treatments evaluated.

Results and Discussion

The summary of the analysis of variance (Table 3) showed that net photosynthesis (A), stomatal conductance (gs) and intrinsic water use efficiency (A/gs) were influenced individually by the pulses and application intervals. Transpiration (E) and instantaneous carboxylation efficiency (A/Ci) were influenced only by irrigation application intervals. On the other hand, the internal CO_2 concentration (Ci) and instantaneous water use efficiency (A/E) were not influenced by the factors studied.

Table 3

Summary of the analysis of variance for the variables: net photosynthesis (A), transpiration (E), stomatal conductance (gs), internal CO_2 concentration (Ci), instantaneous water use efficiency (A/E), intrinsic water use efficiency (A/gs) and instantaneous carboxylation efficiency (A/Ci) of sugarcane subjected to different irrigation pulses and application intervals, in Carpina, PE, Brazil, at 330 DAC

SV	DF	Mean Square							
		A	gs	E	Ci	A/E	A/gs	A/Ci	Yield
PULSES (PUL)	3	26.41*	0.001*	0.3067^{ns}	1612.1^{ns}	0.696^{ns}	3053.9**	0.015^{ns}	670.01**
INTERVALS (INT)	1	68.71**	0.019**	3.1187**	1739.0^{ns}	0.8172^{ns}	4038.6**	0.103*	611.8**
PUL x INT	3	1.79^{ns}	0.0008^{ns}	0.2473^{ns}	1952.8^{ns}	3.28^{ns}	792.2^{ns}	0.026^{ns}	285.02^{ns}
BLOCK	3	10.98	0.0004	0.3581	407.9	0.145	90.65	0.023	68.67
ERROR	21	7.65	0.0004	0.2191	743.8	0.519	324.8	0.015	111.03
CV	%	15.55	16.69	14.12	33.72	13.19	11.6	47.88	4.85

SV: Source of variation; DF: Degrees of freedom; ns not significant; ** and *, significant at 0.01 and 0.05 probability levels, respectively.

The highest value of net photosynthesis (A) (Figure 1) found for sugarcane plants was 19.66 μmol CO_2 m^{-2} s^{-1} obtained with the application of 3.53 irrigation pulses. Regarding the application intervals evaluated, it was verified that the 40-minute interval promoted the highest value for this variable, with a maximum of 19.26 μmol CO_2 m^{-2} s^{-1} and an increase of 17.94% when compared to the 20-minute application interval.

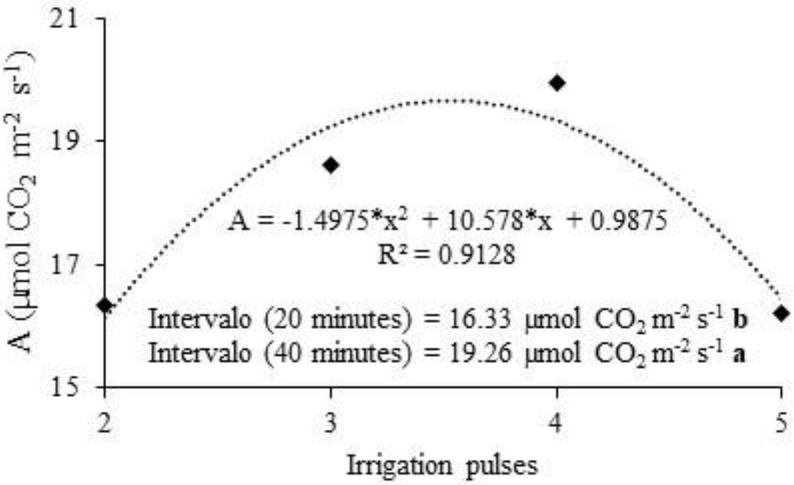

Figure 1. Net photosynthesis (A) of sugarcane subjected to different irrigation pulses and application intervals, in Carpina, PE, Brazil, at 330 DAP. *, significant at 0.05 probability level. Different letters indicate significant differences ($p \leq 0.05$) by the F Test between the irrigation application intervals (20 and 40 minutes).

The highest value of net photosynthesis, obtained with 3.53 irrigation pulses, highlights the greater efficiency of this type of irrigation management in keeping the soil moist for longer throughout the day and the better efficiency of water absorption by sugarcane plants. For photosynthesis, water is important in the photochemical phase due to the release of protons and electrons; in addition, in case of water stress, one of the immediate responses of plants is the reduction of water potential in their tissues, resulting in stomatal closure (Taiz et al., 2017), causing decreased transpiration and diffusion of CO_2 to the interior of the leaf, essential for photosynthesis (Klein et al., 2016).

The best result for net photosynthesis found in this study with the application of 3.53 pulses (19.66 μmol CO_2 m^{-2} s^{-1}) is consistent with those reported by Gonçalves et al. (2010) in sugarcane plants irrigated without water limitation, with values ranging from 19 to 24 μmol m^{-2} s^{-1}.

Regarding the irrigation application intervals, the 40-minute interval promoted better results for net photosynthesis (Figure 1). The lowest value of net photosynthesis verified with the 20-minute interval shows the need for a longer pause, which in the present study was 40 minutes between pulsed applications so that the absorption of water and nutrients by the plant is more efficient, because provides a longer period of time for water absorption by the plant.

In general, when subjected to less efficient water conditions, plants adopt conservative mechanisms, reducing stomatal conductance, transpiration (Soares et al., 2012) and, consequently, net photosynthesis. According to Hoang et al. (2019), when the availability of water in the soil is reduced, plants close their stomata to reduce water loss to the atmosphere; however, this process also limits the absorption of CO_2, which results in a reduction in the photosynthetic rate due to the scarcity of substrate to support photosynthetic activity.

The behavior of the variables stomatal conductance (gs) and transpiration (E) of sugarcane plants subjected to different irrigation pulses and application intervals is presented in Figure 2.

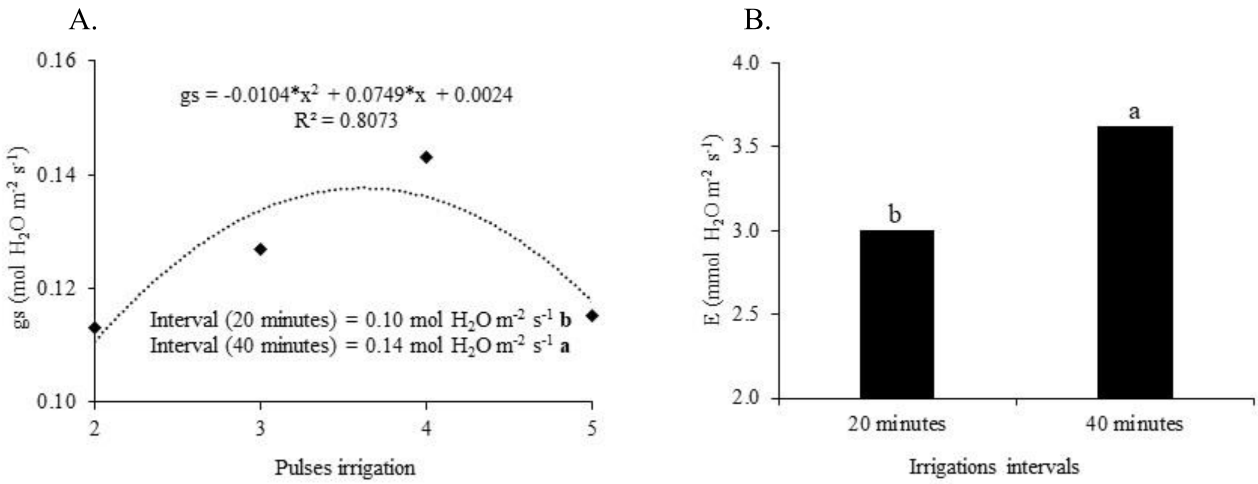

Figure 2. Stomatal conductance (gs) of sugarcane subjected to different irrigation pulses and application intervals (A) and transpiration of plants as a function of irrigation application intervals (B), in Carpina, PE, Brazil, at 330 DAP. *, significant at 0.05 probability level. Different letters indicate significant differences ($p \leq 0.05$) by the F Test between the irrigation application intervals (20 and 40 minutes).

Data referring to stomatal conductance (Figure 2A) were described by an increasing quadratic model, with the highest value (0.137 mol H_2O m^{-2} s^{-1}) obtained with the application of 3.6 irrigation pulses. A significant difference was also observed between irrigation with 20-minute intervals and irrigation with 40-minute intervals, and the 40-minute irrigation interval promoted a higher value of stomatal conductance, with an increase of 40% compared to irrigation performed with 20-minute intervals. The stomatal conductance is important because the plant that has been irrigated for longer will have greater control over its stomatal and directly influence photosynthesis.

Figure 2B shows that transpiration was significantly influenced, individually, by the irrigation application intervals evaluated, and the highest value for the variable (3.62 H_2O m^{-2} s^{-1}) was obtained with the application of the 40-minute irrigation interval.

Irrigation with 3.6 pulses (Figure 2A) contributed to the maintenance of satisfactory results of stomatal conductance in sugarcane, highlighting the benefits of this number of irrigation pulses on this variable. In this regard, Stallmann et al. (2020) state that the frequency of irrigation events modifies plant growth and can contribute to higher yields.

The highest value of stomatal conductance (0.137 mol H_2O m^{-2} s^{-1}) obtained in the present study with the application of 3.6 irrigation pulses (Figure 2A) is similar to the highest value obtained by Lira et al. (2018), who evaluated the sugarcane crop, cultivar RB92579, subjected to optimal water supply, and found a value of 0.130 mol H_2O m^{-2} s^{-1}, at 320 days after planting.

The higher values of stomatal conductance observed for irrigation applied with a 40-minute interval to the detriment of the 20-minute interval (Figure 2B) are possibly due to the maintenance of a more constant soil moisture promoted by the longer interval of irrigation application, resulting in a greater stability of the soil solution and, consequently, a more balanced and constant water absorption, with direct effects on these higher values found for the variable. According to Dlamini (2021), water availability to plants is one of the fundamental factors responsible for the process of regulating stomatal opening or closing.

Closure of stomatal pathways compromises photosynthetic carbon assimilation, thus leading to a limitation of stomatal conductance, which results in a decrease in intracellular CO_2 concentration (Zivcak et al., 2013).

According to Taiz et al. (2017), stomatal conductance is affected by water stress, even when it is moderate, as the stomata tend to close in the early stages of stress, resulting in other consequences for plants, such as reduced CO_2 availability

In this context, it is highlighted that water and CO_2 are limiting factors of photosynthesis, and greater diffusive resistance of the stomata reduces photosynthesis, mainly by restricting gas conduction in the leaf, so water stress may cause inhibition in photosynthesis due to stomatal limitation. Ribeiro et al. (2014), when evaluating the effect of partial rootzone drying on the gas exchange, growth and water use efficiency of sugarcane, observed that there was no reduction in net photosynthesis, stomatal conductance and transpiration.

The trend of plant transpiration is similar to that observed for net photosynthesis and stomatal conductance, as reductions in the irrigation interval and, consequently, in water availability over time, reduced transpiration in sugarcane plants.

According to Inman-Bamber and Smith (2005), the reduction of stomatal conductance is an important strategy of sugarcane to avoid leaf dehydration. According to the results obtained for net photosynthesis (Figure 1), stomatal conductance (Figure 2A) and transpiration (Figure 2B), a close relationship between them is observed when water availability in the soil decrease over time, which is probably related to stomatal closure and the limitation of these variables. Taiz et al. (2017) report that higher rates of stomatal conductance, transpiration, and photosynthesis lead to a significant increase in crop yield.

Initially, stomatal closure can be a good alternative for the plant because it responds quickly against excessive water loss, avoiding leaf dehydration, but when it is prolonged, it becomes inefficient, as it ends up interfering with the diffusive flux of CO_2, which then interrupts the processes of cell division and elongation, compromising the growth and development of plants (Inman-bamber & Smith, 2005).

Transpiration is the main mechanism involved in leaf temperature regulation. When transpiration is reduced, the leaf loses its cooling capacity and its temperature increases since it continues to receive light. Loss of water vapor during transpiration contributes to heat dissipation, controlling the thermal conditions of the plant, which can cause irreversible damage to the plant under high temperatures in the environment or under water deficit (Araújo et al., 2010).

Figure 3 shows the effect of the number of irrigation pulses and irrigation intervals on the intrinsic water use efficiency (A/gs). The highest value found for the variable was 173.5 μmol CO_2 mol H_2O^{-1}, when irrigated with 3.98 pulses. Regarding the irrigation intervals evaluated, it was found that irrigation with 40 minutes of rest promoted better performance of the plants, increasing the intrinsic water use efficiency by 15.33% compared to the value obtained with the 20-minute interval.

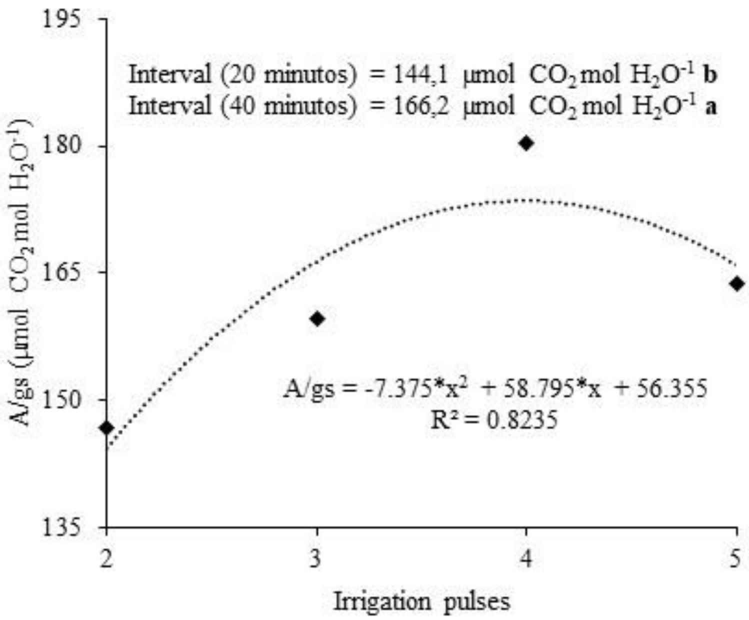

Figure 3. Intrinsic water use efficiency (A/gs) of sugarcane subjected to different irrigation pulses and application intervals, in Carpina, PE, Brazil, at 330 DAP. *, significant at 0.05 probability level. Different letters indicate significant differences ($p \leq 0.05$) by the F test between the irrigation application intervals (20 and 40 minutes).

The lower intrinsic water use efficiency found for irrigation with a shorter application interval shows that during the photosynthetic process the plants subjected to this irrigation interval fixed a lower amount of carbon per unit of transpired water compared to plants subjected to the 40-minute irrigation interval. In addition, the behavior of the data related to the number of pulses that promoted the highest value for intrinsic water use efficiency (3.98 pulses) (Figure 3) was similar to that (3.6 pulses) that allowed plants to have a higher stomatal conductance (Figure 2A).

Figure 4 shows that the highest instantaneous carboxylation efficiency (A/Ci) (0.316 mol m^{-2} s^{-1}) was obtained with the application of irrigation at 40-minute interval, indicating that this irrigation interval promoted a greater assimilation of photosynthetic carbon, which, associated with the increase in stomatal conductance, increased this value compared to that obtained with irrigation at 20-minute interval.

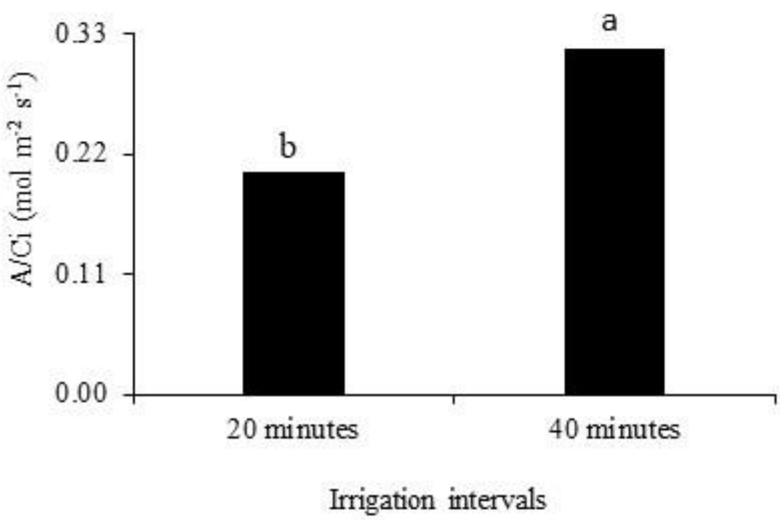

Figure 4. Instantaneous carboxylation efficiency (A/Ci) of sugarcane as a function of irrigation application intervals (20 and 40 minutes), in Carpina, PE, Brazil, at 330 DAP. Different letters indicate significant differences ($p \leq 0.05$) by the F test between the irrigation application intervals (20 and 40 minutes).

These results are of great importance considering that the improvement of photosynthetic carbon assimilation promoted by irrigation management strategies may help increase crop yield in places where abiotic conditions become limiting.

Figure 5 shows that the highest yield of sugarcane (228.38 ton ha^{-1}) was obtained with the application of 3.84 irrigation pulses. As for the application intervals evaluated, it was verified that crop yield was increased by 9.75% under the 40-minute application interval compared to the 20-minute interval.

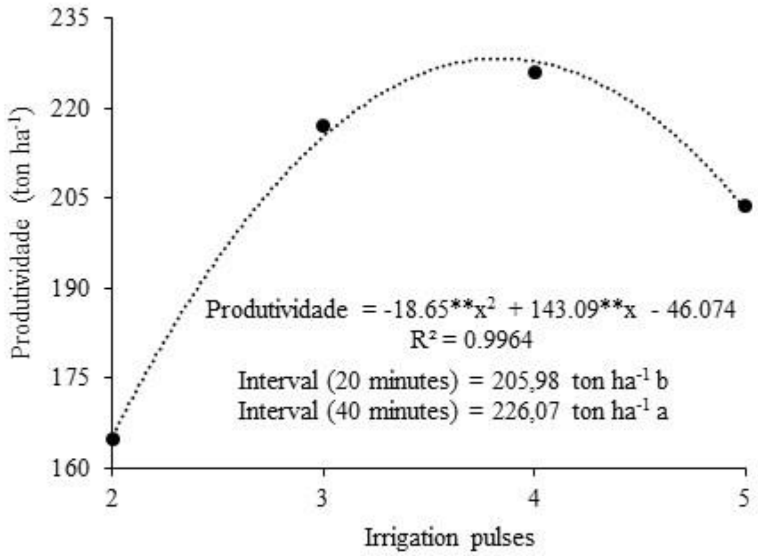

Figure 5. Yield of sugarcane subjected to different irrigation pulses and application intervals in Carpina, PE, Brazil. *, significant at 0.01 probability level. Different letters indicate significant differences ($p \leq 0.05$) by the F test between the irrigation application intervals (20 and 40 minutes).

In view of the results obtained (Figure 5), it is worth highlighting that the benefits of pulse irrigation on the increase in sugarcane yield are mainly associated with a better distribution of moisture in the rhizospheric zone of the plants and, when combined with an adequate number and interval of pulse application, the benefits led to even more significant increases in crop yield. According to Zamora et al. (2021), with the use of pulse irrigation and its intervals, the wet bulb remains constant for longer, due to better water availability conditions and reduction of losses due to evaporation or deep percolation.

The maximum sugarcane yield obtained in the present study, both with the use of 3.84 pulses (228.38 ton ha^{-1}) and with the use of the 40-minute interval (226.07 ton ha^{-1}) (Figure 5), was considerably higher than the national average, in the 2023/2024 season, which was 85.58 ton ha^{-1}, and the average for the state of Pernambuco, which was 58.16 ton ha^{-1}, according to CONAB (2024).

Menezes et al. (2024), when evaluating the growth, yield and industrial yield of sugarcane (cultivar RB041443) cultivated under continuous and pulse drip irrigation, found maximum yield of the crop (147.4 ton ha^{-1}) when the plants were irrigated with pulse drip compared to continuous drip irrigation, which promoted a yield of 135 ton ha^{-1}. These results show the importance of the pulse irrigation technique during irrigation management, as well as the positive impact of the correct definition of the number and interval of pulses to be employed during the application of the technique on the increase of crop yield.

According to the analysis of the orthogonal contrasts (Table 4), net photosynthesis (A), transpiration (E), stomatal conductance (gs) and yield of sugarcane were significantly influenced by the irrigation intervals applied, and it was found that any of the irrigation intervals applied promoted the best results for the variables compared to the control treatment (continuous application of 100% ETc).

Table 4

Summary of the analysis of variance of the orthogonal contrasts tested for net photosynthesis (A), transpiration (E), stomatal conductance (gs), internal CO_2 concentration (Ci), instantaneous water use efficiency (A/E), intrinsic water use efficiency (A/gs), instantaneous carboxylation efficiency (A/Ci) and yield of sugarcane subjected to different irrigation pulses and application intervals, and a control treatment in which irrigation management was carried out continuously and with the application of 100% ETc

SV	DF	Mean Square							
		A	E	gs	Ci	A/E	A/gs	A/Ci	Yield
INT 20 x CTRL	1	1.487*	0.047*	0.004*	792.4^{ns}	0.099^{ns}	5.95^{ns}	0.185^{ns}	932.3**
INT 40 x CTRL	1	8.736*	0.083*	0.0035*	1220.4^{ns}	0.031^{ns}	4.32^{ns}	0.054^{ns}	1447.2**
PUL x CTRL	1	1.419*	0.001*	0.007*	817.04*	0.054^{ns}	5.96^{ns}	0.105^{ns}	4488.9**
ERROR	12	40.2	2.42	0.005	302.4	2.67	10.5	0.45	218.6
CV	%	5.73	5.82	4.03	11.3	5.85	5.69	15.9	7.23

ns not significant; ** and *, significant at 0.01 and 0.05 probability levels, respectively. INT: intervals; CTRL: control; PUL: pulse; CV: coefficient of variation; DF - Degrees of freedom.

It can be seen (Table 3) that the variables internal CO_2 concentration, instantaneous water use efficiency, intrinsic water use efficiency and instantaneous carboxylation efficiency were not significantly influenced by the contrasts tested, highlighting that the values obtained with the control treatment do not differ from those obtained with any of the irrigation intervals evaluated (20 or 40 minutes).

Table 3 shows that the contrast between irrigation pulses (PUL) and control (CTRL) significantly affected net photosynthesis (A), transpiration (E), stomatal conductance (gs), internal CO_2 concentration (Ci) and yield of sugarcane. These results highlighted that any number of pulses among those evaluated in the present study has already promoted higher values for the aforementioned variables (A, E, gs, Ci and yield) than those obtained with the application of continuous irrigation and with 100% ETc depth.

According to the results obtained, through the orthogonal contrasts tested on gas exchange and yield of sugarcane in this study (Table 3), it can be emphasized that the conservation of soil moisture for a longer time throughout the day due to the application of irrigation pulses and the fixed intervals of 40 minutes between the applications of these pulses favored the photosynthetic activities of plants and contributed significantly to the signaling of stomatal control and their metabolic processes. In addition, through the orthogonal contrasts tested, it was possible to highlight the importance of defining not only the correct number of pulses but also the interval between them compared to the conventional irrigation management (100% ETc depth applied continuously).

Conclusions

In general, the best physiological responses for net photosynthesis, stomatal conductance, intrinsic water use efficiency and yield of sugarcane were obtained with the application of 4 irrigation pulses;

The highest values of net photosynthesis, stomatal conductance, transpiration, intrinsic water use efficiency, instantaneous carboxylation efficiency and yield were achieved with the 40-minute irrigation interval;

The number and intervals of irrigation pulses evaluated did not influence the internal CO_2 concentration and instantaneous water use efficiency;

Net photosynthesis, transpiration, stomatal conductance and yield showed better values when using any of the irrigation pulses and application intervals compared to irrigation applied continuously.

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References

Alvares, C. A., Stape, J. L., Sentelhas, P. C., & Gonçalves, J. L. M., & Sparovek, G. (2014). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift, 22*(6), 711-728. doi: 10.1127/0941-2948/2013/0507

Andrade, W. J. M., Silva, G. F., Menezes, S. M., Silva, M. M., Silva, A. O., Lopes, I. A. P., Oliveira, R. A., Fº., & Sousa, R. R. (2024). Características fisiológicas e rendimento da cana-de-açúcar sob lâminas de irrigação. *Observatorio de La Economía Latinoamericana, 22*(1), e03463. doi: 10.55905/oelv22n1-232

Araújo, S. A. C., Vasquez, H. M., Campostrini, E., Torres, A., Netto, Deminicis, B. B., & Lima, E. S. (2010). Características fotossintéticas de genótipos de capim-elefante anão (Pennisetum purpureum Schum.) em estresse hídrico. *Acta Scientiarum, 32*(1), 1-7. doi: 10.4025/actascianimsci.v32i1.8961

Companhia Nacional de Abastecimento (2024). *Acompanhamento da safra brasileira de cana-de-açúcar. Safra 2024/2025.* CONAB. https://www.conab.gov.br/info-agro/safras/cana/boletim-da-safra-de-cana-de-acucar

Cormier, J., Depardieu, C., Letourneau, G., Boily, C., Gallichand, J., & Caron, J. (2020). Tensiometer-based irrigation scheduling and water use efficiency of field-grown strawberries. *Agronomy Soils, & Environmental Quality, 112*(3), 2581-2597. doi: 10.1002/agj2.20205

Dlamini, P. J. (2021). Drought stress tolerance mechanisms and breeding effort in sugarcane: a review of progress and constraints in South Africa. *Plant Stress, 2*(13), 100027. doi: 10.1016/j.stress.2021.100027

Doorenbos, J., & Kassan, A. H. (1994). *Efeito da água no rendimento das culturas.* UFPB.

Doorenbos, J., & Pruitt, W. O. (1977). *Crop water requirements.* FAO.

Eid, A. R., Bakry, B. A., & Taha, M. H. (2013). Effect of pulse drip irrigation and mulching systems on yield, quality traits and irrigation water use efficiency of soybean under sandy soil conditions. *Agricultural Sciences, 4*(5), 249-261. doi: 10.4236/as.2013.45036

Ferreira, D. F. (2011). Sisvar: a computer statistical analysis system. *Ciência e Agrotecnologia, 35*(6), 1039-1042. doi: 10.1590/S1413-70542011000600001

Gonçalves, E. R., Ferreira, V. M., Silva. J. V., Laurício, E., Barbosa, T. P., & Duarte, W. G. (2010). Trocas gasosas e fluorescência da clorofila a em variedades de cana-de-açúcar submetidas à deficiência hídrica. *Revista Brasileira de Engenharia Agrícola e Ambiental, 14*(4), 378-396. doi: 10.1590/S1415-43662010000400006

Hoang, D. T., Hiroo, T., & Yoshinobu, K. (2019). Nitrogen use efficiency and drought tolerant ability of various sugarcane varieties under drought stress at early growth stage. *Plant Production Science, 22*(2), 250-261. doi: 10.1080/1343943X.2018.1540277

Inman-Bamber, N. G., & Smith, D. M. (2005). Water relations in sugarcane and response to water deficits. *Field Crops Research, 92*(2-3), 185-202. doi: 10.1016/j.fcr.2005.01.023

Keller, J., & Karmelli, D. (1974). Trickle irrigation design parameters. *Transactions of the ASAE, 17*(4), 678-684. doi: 10.13031/2013.36936

Klein, J., Rampim, L., Kestring, D., Guimarães, V. F., & Rodrigues, J. D. (2016). Influência de protetores físicos coloridos nas trocas gasosas em mudas de canafístula [Peltophorum dubium (Spreng.) Taub.] seedlings. *Ciência Florestal, 26*(3), 797-809. doi: 10.5902/1980509824208

Lira, R. M., Silva, E. F. F., Simões, D. E., Neto, Santos, J. A., Jr., Lima, B. L. C., & Silva, J. S. (2018). Growth and yield of sugarcane irrigated with brackish water and leaching fractions. *Revista Brasileira de Engenharia Agrícola e Ambiental, 22*(3), 170-175. doi: 10.1590/1807-1929/agriambi.v22n3p170-175

Malavolta, E., Vitti, G. C., & Oliveira, S. A. (1997). *Avaliação do estado nutricional das plantas: princípios e aplicações* (2a ed.). Potafos.

Menezes, S. M., Silva, G. F., Silva, M. M., Morais, J. E. F., Vasconcelos, M. C., Souza, C. S., Simões, D. E., Neto, & Rolim, M. M. (2024). Pulsed drip irrigation reduces sugarcane water consumption and improves growth, productivity, sugar and ethanol yield. *Bioenergy Research, 17*(15), 1413-1424. doi: 10.1007/s12155-024-10729-4

Rank, P. H., & Vishnu, B. (2021). Pulse drip irrigation: a review. *Journal of Pharmacognosy and Phytochemistry, 10*(1), 125-130. doi: 10.13031/s2021.36936

Ribeiro, M. S., Torres, A., Netto, Couto, T. R., Silva, J. R., Figueiredo, F. A. M. M. A., Nogueira, R. J. M. C., Glenn, D. M., & Campostrini, E. (2014). Partial rootzone drying in sugarcane (Saccharum officinarum L.): effects on gas exchange, growth and water use efficiency. *Theoretical and Experimental Plant Physiology, 26*(8), 251-262. doi: 10.1007/s40626-014-0024-0

Soares, L. A. A., Sousa, J. R. M., Brito, M. E. B., Andrade, E. M. G., Sá, F. V. S., & Silva, E. C. B. (2012). Influência de diferentes lâminas de irrigação nas trocas gasosas do tomateiro na fase vegetativa. *Revista Agropecuária Técnica no Semiárido, 8*(3), 118-122. doi: 10.30969/acsa.v8i3.425

Stallmann, J., Schweiger, R., Pons, C. A. A., & Müller, C. (2020). Wheat growth, applied water use efficiency and flag leaf metabolome under continuous and pulsed deficit irrigation. *Scientific Reports, 25*(10112), 1-13. doi: 10.1038/s41598-020-66812-1

Taiz, L., Zeiger, E., Moller, I., & Murphy, A. (2017). *Fisiologia e desenvolvimento vegetal* (6a ed.). Artmed.

Vandenberghe, L. P. S., Valladares-Diestra, K. K., Bittencourt, G. A., Zevallos Torres, L. A., Vieira, S., Karp, S. G., Sydney, E. B., Carvalho, J. C., Thomaz Soccol, V., & Soccol, C. R. (2022). Beyond sugar and ethanol: the future of sugarcane biorefineries in Brazil. *Renewable and Sustainable Energy Reviews, 167*(12), e112721. doi: 10.1016/j.rser.2022.112721

Zamora, V. R. O., Silva, M. M., Santos, J. A., Jr., Silva, G. F., Menezes, D., & Almeida, C. D. G. C. (2021). Assessing the productivity of coriander under different irrigation depths and fertilizers applied with continuous and pulsed drip systems. *Water Supply, 21*(5), 2099-2108. doi: 10.2166/ws.2021.008

Zamora, V. R. O., Silva, M. M., Silva, G. F., Santos, J. A., Jr., Menezes, D., & Menezes, S. M. (2019). Pulse drip irrigation and fertigation water depths in the water relations of coriander. *Horticultura Brasileira, 37*(1), 22-28. doi: 10.1590/S0102-053620190103

Zivcak, M., Brestic, M., Balatova, Z., Drevenakova, P., Olsovska, K., Kalaji, H. M., Yang, X., & Allakhverdiev, S. I. (2013). Photosynthetic electron transport and specific photoprotective responses in wheat leaves under drought stress. *Photosynthesis Research, 117*(7), 529-546. doi: 10.1007/s11120-013-9885-3