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Agronomic Performance and Technological Attributes of Sugarcane Cultivars Under Split-Irrigation Management

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Abstract: In addition to being an important instrument in the search for increasingly greater productivity, agricultural production with adequate use of irrigation systems significantly minimizes the impact on water resources. To meet high productivity and yield, as well as industrial quality, a series of studies on sugarcane cultivation are necessary. Despite being able to adapt to drought, sugarcane is still a crop highly dependent on irrigation to guarantee the best quality standards. Our study aimed to analyze the agronomic performance and technological attributes of two sugarcane cultivars, evaluating the vegetative and productive pattern, as well as the industrial quality of the cultivars RB92579 and SP80–1816, which were cultivated under split-irrigation management in the Sugarcane Research Unit of IF Goiano—Campus Ceres, located in the state of Goiás in the Central-West region of Brazil. A self-propelled sprinkler irrigation system (IrrigaBrasil) was used, duly equipped with Twin 120 Komet sprinklers (Fremon, USA). The cultivars were propagated vegetatively and planted in 0.25 m deep furrows with 1.5 m between rows. The experiment was conducted in a completely randomized design (CRD), with a bifactorial split-plot scheme (5 × 2), with four replications, where the experimental plots were subjected to one of the following five split-irrigation management systems: 00 mm + 00 mm; 20 mm + 40 mm; 30 mm + 30 mm; 40 mm + 20 mm; or 60 mm + 00 mm. At 60 and 150 days after planting (DAP), the following respective irrigation management systems were applied: 00 mm + 00 mm and 20 mm + 40 mm. Biometric and technological attributes, such as plant height (PH) and stem diameter (SD), were evaluated in this case at 30-day intervals, starting at 180 DAP and ending at 420 DAP. Measurements of soluble solids content (°Brix), apparent sucrose content (POL), fiber content (Fiber), juice purity (PZA), broth POL (BP), reducing sugars (RS), and total recoverable sugars (TRS) were made by sampling stems at harvest at 420 DAP. RB92579 showed total recoverable sugar contents 11.89% and 8.86% higher than those recorded for SP80–1816 under split-irrigation with 40 mm + 20 mm and 60 mm + 00 mm, respectively. Shoot productivity of RB92579 reached 187.15 t ha^{-1} under split-irrigation with 60 mm + 00 mm, which was 42.16% higher than the shoot productivity observed for SP80–1816. Both cultivars showed higher qualitative and quantitative indices in treatments that applied higher volumes of water in the initial phase of the culture, coinciding with the dry season. Sugarcane cultivar RB92579 showed a better adaptation to the prevailing conditions in the study than the SP80–1816 cultivar.

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1. Introduction

Scenarios of climate change and high emissions of greenhouse gases, such as fossil carbon dioxide (CO_2), point to a global demand for renewable energy sources, such as bioenergy [1–3]. In this context, sugarcane cultivation stands out as one of the main bioenergy crops and assumes a prominent position among agricultural commodities due to its high commercialization [2,4,5].

In this scenario, Brazil has considerable bioenergy potential, standing out as an important producer of sugarcane [2,6–8]. Its production has more than doubled in recent decades [9], seeking to meet the growing global demands for bioenergy and aiming to reduce dependence on crude petroleum and mitigate the effects of climate change [10].

Sugarcane is recognized as one of the most crucial agricultural crops worldwide due to its contributions to sugar production, renewable energy, and biomaterials. It is cultivated in over 100 tropical and subtropical countries. By the year 2031, Brazil and India are anticipated to contribute significantly to the global sugar output, accounting for approximately 23 and 17%, respectively [11]. Brazil and India are responsible for 72% of global sugarcane production, with Brazil's largest producers reaching around 715 million tons and India producing 405 million tons [5].

The National Supply Company (CONAB), in its 2nd survey of the 2024/2025 harvest, highlights an estimate of sugarcane production for Brazil at around 689.8 million tons (3.3% lower than the 2023/2024 harvest) and productivity of 79,953 kg per hectare (6.6% lower than the 2023/2024 harvest) [12], which were mainly affected by climate conditions including high rainfall variability, drought, and water deficit [13–15]. However, it is also worth noting that both the Central-West region of Brazil (the second largest sugarcane producing region in the country), and the state of Goiás have expanded their cultivation areas, growing around 2.8% at the regional level and 2.1% at the state level, respectively, consequently obtaining higher production and productivity when compared to the 2023/2024 harvest [12]. However, limitations to biotechnological approaches and genetic improvement must be recognized, given that they can be strategic approaches to increasing sugarcane productivity in regions of Brazil.

The high performance of sugarcane cultivation involves various technological attributes for maximum production potential [16]. Genetic engineering techniques can be used for introducing commercially relevant characteristics, with tolerance to diseases and pests, tolerance to salt and drought [2,17,18], and in addition, a high sucrose content [8]. Studies have observed that the climate change scenario under the effects of drought affects the productivity and yield of sugarcane [17,19].

Sugarcane plants have a variety of important drought tolerance mechanisms; that is, to deal with this stress, a series of morphophysiological, biochemical, and molecular changes, adaptations, and reactions are stimulated [17–22]. More specifically, plant strategies stand out, such as delaying dehydration (maintaining turgor and cell volume and delaying the opening and closing of stomata) [20], as well as the mechanism of better use of roots (selecting plants with a greater number of deeper roots) [18] and plant genetic improvement (with characteristics resistant to pests and diseases, as well as increased productivity and tolerance to abiotic stresses) [22].

This tolerance to drought becomes fundamental, considering that, in Brazil, several changes in the climate have been occurring, mainly with the reduction of rainy days and precipitation [23]. The agronomic and technological characteristics of sugarcane varieties may vary according to climatic and environmental conditions [2,19]. Therefore, the practice of irrigation and management with regulated water deficit can influence the technological characteristics of the sugarcane, but they also have the potential to increase the productivity of the stalks and the sugar without significantly impacting the efficiency of water use [8,24].

Sugarcane passes through four distinct growth phases: germination, tillering, grand growth, and maturity [19]. With suitable conditions of adequate temperature and sunlight, cane grows in direct proportion to the amount of water available. The formative phase (tillering combined with early grand growth) has been identified as the most critical water demand period, and stress during this phase affects the final yield. Achieving maximum productivity requires an abundant supply of water from either rainfall or irrigation [25].

Good climate efficiency for sugarcane production in Brazil occurs in average annual temperatures between 28 and 38 °C and annual rainfall between 1000 and 1500 mm. Thus, the Central-West and Northeast regions have water restrictions for sugarcane crops, requiring alternatives such as irrigation systems to maintain the crops [26].

Agricultural production with the implementation of irrigation systems, adequate management, and the support of new monitoring and production technologies allows the increase of production yields in irrigated agriculture, efficiently and considerably containing the impact on water resources [27].

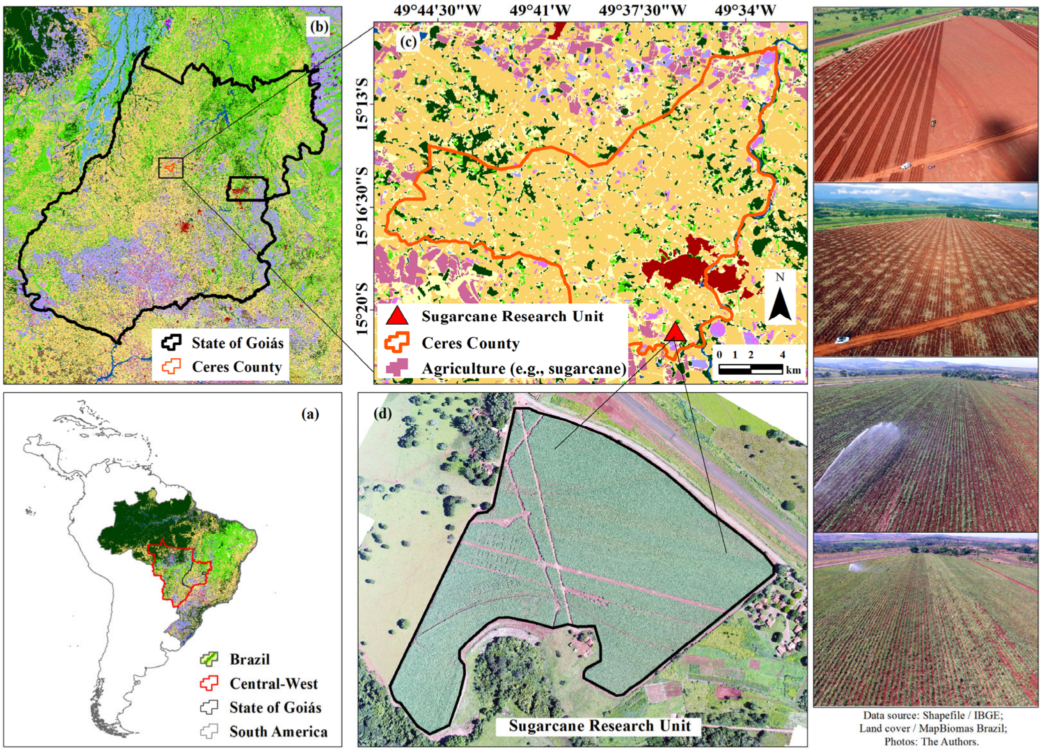
Sugarcane varieties need to be adapted to different environments. These varieties need to be tested for their suitability in various ecosystems, and research results provide valuable information on the performance of these varieties, including their yield components, physiological characteristics, and sugar content [28]. Increasing irrigation depths correlates positively with technological quality, improving parameters such as sucrose content and juice purity levels and their production yields, which are directly related to increased stalk production, with irrigation up to 125% of crop evapotranspiration [29] improving temporal stability—evaluated in three cycles—concerning quality in juice production and Brix content [30].

Some varieties in Brazil have demonstrated high acceptance, such as the RB92579 variety, which is present in more than 35% of the cultivation areas in Northeast Brazil [2], and the SP80–1816 variety, which has been widely cultivated in the continent of America and has drought tolerance characteristics. In this context, it is necessary to investigate the behavior of cultivars tolerant to water scarcity, considering regions with high temperature variations and, consequently, atmospheric demand, and test variations in the amount of water during phases of water scarcity to help producers achieve greater production. This study aimed to analyze the agronomic performance and technological attributes of sugarcane cultivars, evaluating the vegetative and productive pattern and the industrial quality of the RB92579 and SP80–1816 cultivars under split-irrigation management in an experimental area in the Central-West region of Brazil.

2. Materials and Methods

2.1. Study Area

The experiment was performed from April 2018 to June 2019 at the Sugarcane Research Unit at Usina CRV Industrial (15°20′44.6″ S, 49°36′24.4″ W, elevation of 561 m) located in the state of Goiás in the Central-West region of Brazil. More specifically, the research was carried out in Ceres County, between the parallels 15°13′0.0″ S and 15°20′0.0″ S and between the meridians 49°34′0.0″ W and 49°44′30″ W—Geographic Coordinate System, DATUM: UTM—Zone 22 South (Figure 1). According to Koppen–Geiger, the weather in the study area is classified as tropical savannah (Aw) [31], characterized as dry with mild winters, hot with rainy summers, with a well-defined water stress season from May to September, an average annual rainfall of approximately 1570 mm and an average temperature of 25 °C, and a maximum temperature of 30 °C and a minimum temperature of 19 °C. The photos on the right-hand side of Figure 1 represent the planning and systematization of sugarcane planting and sugarcane management during the experiment.



Data source: Shapefile / IBGE;
Land cover / MapBiomas Brazil;
Photos: The Authors.

Figure 1. Spatial location of the Sugarcane Research Unit (**d**) in Ceres County (**c**) in the state of Goiás (**b**), Central-West region of Brazil (**a**).

Temperature, relative humidity, and rain data were collected using a Vantage Pro2 weather station (Davis; Hayward, CA, USA) and showed a high amplitude throughout the experimental period, ranging from 9.1 to 43.8 °C and from 10 to 99%, respectively (Figure 2a,b).

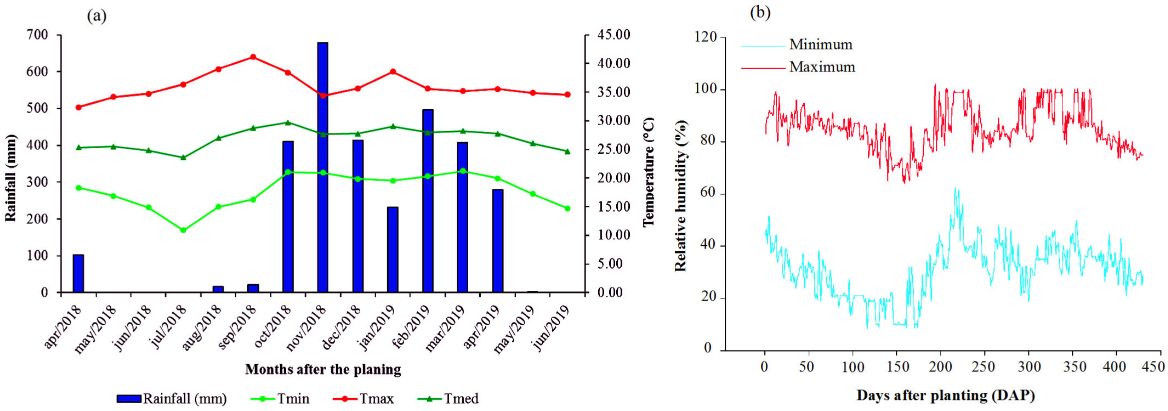


Figure 2. Meteorological data on air temperature: minimum (Tmin, °C), maximum (Tmax, °C), and average (Tmed, °C); rainfall (**a**); and relative air humidity: minimum and maximum (**b**) throughout the experimental period from the Sugarcane Research Unit.

Rainfall during the experimental period amounted to 1713 mm, with 95% concentrating mainly between October 2018 and April 2019 (Figure 2a). This rainfall was higher than expected according to the Koppen–Geiger classification. However, the period from May to September is considered dry. The soils in the experimental area are classified as eutrophic Red Latosol [32]. Table 1 presents the characterization of the chemical and physical properties of the soil in the study area.

Table 1. Chemical and physical properties of soil from the Sugarcane Research Unit.

Chemical properties

Soil (layers)	pH $_{CaCl2}$	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	T	Zn	V	OM
		mg dm^{-3}		cmol dm^{-3}				mg dm^{-3}	%	g dm^{-3}
0–20 cm	5.8	3.0	41.22	3.9	1.6	0.0	7.4	2.3	45.71	18.0
20–40 cm	5.8	2.1	27.8	3.1	1.3	0.0	5.9	6.3	74.87	15.0

Physical properties

Soil (layers)	Sand (%)	Silt (%)	Clay (%)
0–20 cm	34.63	17.52	47.85
20–40 cm	31.81	16.94	51.25

2.2. Experimental Split-Irrigation Management

The experimental treatments were defined according to the practices already adopted by Usina CRV Industrial, whereby a total of 60 mm of irrigation water and the sugarcane cultivars SP80–1816 (Copersucar, SP, (CTC)) and RB92579 (Planalsucar, AL, Ridesa (RB)) were studied. The experiment was laid as a split-plot bifactorial trial (5 × 2) in a completely randomized design with four replicates. Split-irrigation management systems were assigned to plots and cultivars to subplots. Thus, the experimental plots were subjected to one of the following five split-irrigation management systems: 00 mm + 00 mm; 20 mm + 40 mm; 30 mm + 30 mm; 40 mm + 20 mm; or 60 mm + 00 mm. The first and second irrigation management system were applied at 60 and 150 days after planting (DAP), respectively, using a self-propelled sprinkler irrigation system (GSV/350, Irriga-Brasil, Pinhais, Paraná, Brazil) equipped with Komet Twin 120 sprinklers (Komet Irrigation Corporate, Fremon, USA) operating with 32.5 mm nozzles under 5.0 kgf cm^{-2} for a flow of 93.2 m^3 h^{-1}. The sprinkler carriers were spaced 60 m apart. The five irrigation management systems applied at 60 and 150 days after planting are essential to verify the productive and industrial response of sugarcane in response to climate variations, with emphasis on a reduction in temperature during the initial days and an increase during the end period (Figure 2).

Both sugarcane cultivars SP80–1816 and RB92579 were propagated vegetatively and planted in April 2018 in 0.25 m deep furrows with 1.5 m between rows. The experimental plots had rows 60 m long of sugarcane plants. Morphological and technological characteristics were evaluated in the four central lines according to the methodology adapted from Molin et al. [33].

2.3. Biometric and Technological Attributes

Both plant height (PH) and stem diameter (SD) were measured based on ten randomly selected plants along ten meters of the central furrow of each plot and evaluated at 30-day intervals, from 180 to 420 DAP. PH was determined based on the distance from the ground to the last visible auricular region of the leaf +1 (the first leaf from the top down, which is inserted with the auricle visible), based on the methodology suggested by Costa et al. [34]. A digital caliper (King Tools, Pompeia, São Paulo, Brazil) was used to measure the SD at the median height of the stalk between the 1st and 2nd thirds of the stalk, based on the methodology suggested by Oliveira et al. [35].

Technological attributes were evaluated, such as the following: (i) soluble solids content (°Brix)—measured from digital refractometer (Brix/RI-Chek; Reichert Technologies, Unterschleissheim, Munich, Germany); (ii) apparent sucrose content (POL); (iii) fiber content (Fiber); (iv) juice purity (PZA); (v) broth POL (BP); (vi) reducing sugars (RS); and (vii) total recoverable sugars (TRS), using the official methodology by Consecana [36].

Measurements were made by stalk sampling at harvesting at 420 DAP. To determine the quality of the juice extracted from the sugarcane stalks, technological attributes were used.

2.4. Crop Yield

Crop yield was estimated by harvesting 10 linear meters per plot, separating stem and pointer, based on the methodology suggested by Pires et al. [37]. The fresh stem mass, plant weight, shoot productivity (stalks, leaves, and pointers), and sugarcane production per hectare were evaluated. Based on the productivity and averages of the sucrose percentages in the samples of each experimental unit, the sucrose yield was determined from the crop yield by the corresponding percentage of sucrose.

2.5. Statistical Analysis

The effect of split-irrigation on productivity and technological quality was evaluated between sugarcane cultivars RB92579 and SP80–1816. The data were evaluated using analysis of variance (ANOVA) statistics and the F test at 5% and 1% probability, where the treatment means were compared using the Tukey test at 5% and 1% probability. Statistical analyses were performed using R software, version 4.0.3 [38].

3. Results and Discussion

3.1. Biometric Attributes

PH varied significantly among split-irrigation management combinations at 210 and 360 DAP ($p < 0.01$) and 300 DAP ($p < 0.05$). Furthermore, there was a significant effect ($p < 0.01$) on all sampling time points among cultivars for the PH (Table 2). At 300 and 420 DAP, there was a significant interaction between split-irrigation management and cultivars of ($p < 0.01$) and ($p < 0.05$), respectively. In turn, split-irrigation management showed a significant effect on SD at 180, 390, and 420 DAP ($p < 0.01$), and with the cultivars, differed statistically from each other at 270 DAP ($p < 0.01$) and 180 and 240 DAP ($p < 0.05$). Finally, a significant interaction between split-irrigation water amount and cultivars was observed at 180 and 390 DAP ($p < 0.05$) and 420 DAP ($p < 0.01$) (Table 2).

Table 2. Biometric attributes (PH and SD) of sugarcane cultivars RB92579 and SP80–1816 in response to the irrigation depth split at 180, 210, 240, 270, 300, 330, 360, 390, and 420 DAP.

Split-irrigation water (mm)	DAP								
	180	210	240	270	300	330	360	390	420
	Plant height—PH (cm)								
00 + 00	36.09 a	70.32 b*	138.32 a	177.70 a	Table 3	271.20 a	305.28 b*	350.67 a	Table 3
20 + 40	38.28 a	92.10 a*	161.86 a	191.00 a		290.42 a	323.50 a*	357.10 a	
30 + 30	35.76 a	81.37 ab*	160.78 a	198.52 a		283.52 a	317.20 ab*	355.35 a	
40 + 20	36.52 a	82.67 ab*	157.18 a	194.67 a		277.10 a	329.15 a*	357.55 a	
60 + 00	41.56 a	86.32 a*	155.17 a	194.82 a		286.85 a	312.75 ab*	356.42 a	
Standard error	1.95	3.41	5.31	5.70		7.96	3.70	6.74	
	Stalk diameter—SD (mm)								
00 + 00	Table 3	29.81 a	30.75 a	29.03 a	27.41 a	29.04 a	28.99 a	Table 3	Table 3
20 + 40		30.67 a	32.56 a	29.22 a	28.39 a	27.41 a	28.18 a		
30 + 30		30.31 a	30.28 a	28.49 a	28.55 a	27.37 a	29.14 a		
40 + 20		32.46 a	30.90 a	29.13 a	29.70 a	27.86 a	28.77 a		
60 + 00		29.97 a	30.90 a	28.39 a	27.07 a	27.32 a	28.61 a		
Standard error		0.94	0.84	0.56	0.63	0.59	0.38		

Table 2. *Cont.*

Cultivars	Plant height—PH (cm)								
RB92579	33.61 b*	69.88 b*	140.67 b*	177.68 b*	Table 3	273.78 b*	300.79 b*	347.42 b*	Table 3
SP80–1816	41.67 a*	95.24 a*	168.66 a*	205.01 a*		289.85 a*	334.36 a*	363.42 a*	
Standard error	1.26	2.78	2.47	2.57		3.60	3.05	3.67	
	Stalk diameter—SD (mm)								
RB92579	Table 3	31.36 a	31.90 a	29.79 a	28.63 a	27.61 a	28.46 a	Table 3	Table 3
SP80–1816		29.93 a	30.25 b	27.71 b	27.81 a	27.99 a	29.02 a		
Standard error		0.87	0.42	0.33	0.32	0.44	0.31		

Means followed by the same lowercase letters within columns did not differ statistically by the Tukey test ($p < 0.01$ *).

The specific periods of water deficit observed in this study were between April and September 2018 and from May to June 2019 in the latter period, equivalent to 390 and 420 DAP, respectively. Coincidentally, at 180 DAP (October 2018), when data collection and analysis to determine the variables began, the rainy season in the region also began, extending until 360 DAP (April 2019) and the beginning of 390 DAP (May 2019) of the experiment. Regarding the phenological phases in the analysis period of the experiment, vegetative growth of the stems was observed, which occurred between 180 and 270 DAP, that is, from October 2018 to January 2019, respectively. And the maturation phase occurred after 270 DAP and between 300 and 420 DAP, from February to June 2019.

The study region, located in the savannah of the Central region of Brazil, has a period of prolonged water deficiency that runs from May to September (Figure 2). The occurrence of this water deficit is one of the main limiting factors for sugarcane production. Therefore, sugarcane requires considerable application of irrigation water during periods of water deficit, making split-irrigation a crucial management system for supplying water to the crop in a more sustainable way, considering that sugarcane develops and grows directly proportional to the amount of water available [11,25].

Water scarcity is one of the main factors contributing to reduced productivity in sugarcane, affecting the leaf area index, meaning the plant does not respond adequately in terms of production [3,4]. Therefore, irrigation is necessary to meet the high water demand for sugarcane in several countries [24]. Furthermore, in Brazil, it is recommended that irrigation management based on crop coefficient (Kc) should use the average evapotranspiration of the previous 3 days before irrigation to save water and energy while maintaining high yield levels [39].

Plots with no irrigation showed statistically lower mean values for PH at 210 and 360 DAP. Interestingly, plants at 210 DAP under split-irrigation with 20 mm + 40 mm have shown height statistically similar to plants under split-irrigation with 60 mm + 00 mm, being, respectively, 30.97 and 22.75% taller than unirrigated plants. This confirms that the total handling of 60 mm is the most efficient for greater results (Table 2). The sugarcane cultivar SP80–1816 showed a higher mean PH than the RB92579 cultivar, but the difference gradually decreased over the experimental period. The absolute growth rate of the RB92579 cultivar was more uniform throughout the growing period. Thus, in the end, the differences between cultivars were smaller, as one cultivar showed a greater growth rate early in the season, while the other grew at a lower but constant rate throughout the crop cycle.

In the final evaluation at 420 DAP, SP80–1816 showed a mean PH 4.23% higher than RB92579 (Table 2), consistent with a study in the Brazilian semiarid region where this cultivar differed statistically from the others tested, showing the largest mean values for PH [40].

Saccharum officinarum (a tropical plant) has as its predominant characteristics low tillering and large-diameter stems, also presenting a low fiber content, being succulent and with broad, short leaves [41,42]. However, it is worth noting that the profitability of the crop depends mainly on the tillers produced, with tillering being a fundamental characteristic of sugarcane, where its growth forms the stalk, which in turn plays a fundamental role in the photosynthesis process [43].

RB92579 showed mean SDs that were 5.45 and 7.51% higher than those of SP80–1816 at 240 and 270 DAP, respectively (Table 2). Modern sugarcane feedstock production worldwide is based on high-performing adapted cultivars [44]. Over the decades, strategic research has focused on genetic improvement to combat the various stresses of sugarcane to improve yield, sucrose content, disease resistance, and drought adaptation around the world [41,45–47].

The interaction analysis (Table 3) showed that there was no statistical difference in PH among split-irrigation management systems in the RB92579 cultivar at 300 nor at 420 DAP. For the SP80–1816 cultivar, only the plots without irrigation obtained lower averages than the other treatments at 300 DAP. Similarly, SP80–1816 showed the highest average PH at 300 DAP in all evaluated plots, while at 420 DAP, this cultivar had a mean PH 10.31% greater than RB92579 under split-irrigation with 40 mm + 20 mm.

Table 3. PH at 300 and 420 DAP and SD at 180, 390, and 420 DAP of sugarcane cultivars RB92579 and SP80–1816 in response to the splitting of irrigation water amount.

Split-irrigation water (mm)	**Plant height—PH (cm)**			
	300 DAP *		420 DAP **	
	RB92579	SP80–1816	RB92579	SP80–1816
00 + 00	223.65 aB	236.95 bA	356.20 aA	366.20 aA
20 + 40	223.15 aB	275.95 aA	376.90 aA	382.85 aA
30 + 30	233.10 aB	268.45 aA	361.95 aA	369.07 aA
40 + 20	234.85 aB	267.25 aA	355.85 aB	392.50 aA
60 + 00	231.15 aB	263.20 aA	363.90 aA	379.00 aA
Standard error	5.06	5.06	8.24	8.24

Split-irrigation water (mm)	**Stalk diameter—SD (mm)**					
	180 DAP **		390 DAP **		420 DAP *	
	RB92579	SP80–1816	RB92579	SP80–1816	RB92579	SP80–1816
00 + 00	20.79 abB	24.48 aA	28.65 aA	29.71 aA	29.78 aA	31.15 aA
20 + 40	20.33 bB	25.81 aA	27.64 aA	27.37 aA	28.81 aA	27.59 aA
30 + 30	23.25 abA	22.66 aA	27.94 aA	24.67 bB	29.43 aA	27.37 aB
40 + 20	24.64 aA	24.06 aA	27.59 aA	29.02 aA	28.28 aB	32.63 aA
60 + 00	23.01 abA	25.08 aA	28.01 aA	27.33 aA	28.46 aA	28.91 aA
Standard error	1.02	1.07	1.63	1.83	0.59	1.83

Means followed by the same lowercase letters within columns did not differ statistically between the split-irrigation treatments. Means followed by the same uppercase letters within rows did not differ statistically between the cultivars by the Tukey test ($p < 0.01$ * and $p < 0.05$ **).

An interaction analysis for SD (Table 3) at 180 DAP showed that under split-irrigation with 40 mm + 20 mm, the sugarcane cultivar RB92579 yielded a mean 21.20% higher than that recorded under split-irrigation with 20 mm + 40 mm. Furthermore, at 390 DAP, SP80–1816 showed lower mean values under split-irrigation with 30 mm + 30 mm compared with the other split-irrigation management systems. Additionally, the sugarcane SP80–1816 cultivar showed higher mean SD values at 180 DAP in irrigation treatments with lower water volume in the first irrigation management (i.e., no irrigation and 20 mm of water), with mean SDs 17.75 and 24.15% higher compared with those observed for RB92579 in the same treatment, respectively. In turn, RB92579 had a mean SDs 13.38 and 7.53% higher at 390 and 420 DAP, respectively, than SP80–1816 under split-irrigation with

30 mm + 30 mm. Meanwhile, SP80–1816 showed a 15.38% higher mean SD than split-irrigation with 40 mm + 20 mm at 420 DAP (Table 3). Cunha et al. [48] showed higher plant height at field capacity water reposition levels above 93% for plant cane and 97% for ratoon cane. In general, our data showed higher PH and SD when 40 mm of water was supplied by the irrigation system at first, which means higher plant use and demand for water during initial growth.

SD is hardly affected by irrigation treatment, being more directly related to the genetic characteristics of the cultivars [49], highlighting the number of tillers and leaf area, as well as spacing and the environmental conditions themselves [35]. Our study indicated at the end of the cycle that the PH and DS results were not influenced by split-irrigation management.

In both the cane-plant cycle and the cane cycle, sugarcane cultivars commonly present larger diameters under water stress conditions because less water availability reduces growth in height, thus providing for an increase in SD due to there being a relationship between shorter sugarcane clones and larger stalk diameters [50]. However, it is worth noting that after the periods of split-irrigation, carried out at 60 and 150 DAP in this experiment, the rainy season set in from 180 to 360 DAP, favoring good development and production results. Only at 390 and 420 DAP, the final phase of this experiment, was a water deficit observed.

3.2. Technological Characteristics of Sugarcane

Irrigation treatments had a significant effect on °Brix, POL, and BP at a 1% level of significance. Further, there were statistical differences for fiber between cultivars ($p < 0.01$). Lastly, the interaction between irrigation and cultivars showed a significant effect on °Brix, POL, BP ($p < 0.05$), and fiber ($p < 0.01$) (Table 4). In contrast, PZA did not differ significantly between irrigation treatments or cultivars but reached important average values for the industry, being above 80% for both RB92579 and SP80–1816 (Table 4). It is worth highlighting that this technological variable may be rejected by the industrial unit when the PZA is <75%, as established by [36]. According to the high percentage of PZA, a high concentration of sucrose in the broth of the cultivars is also confirmed, which reflects in high yield in the industry, likely due to the amount of rain that occurred during the growing season, as observed in the rainfall graph in Figure 2. This likely led to an improvement in the quality of the juice by reducing the number of amino acids, starch, organic acids, and RS, in addition to color-forming agents and other precursors [51].

Table 4. Technological characteristics (°Brix, POL, fiber, and BP) of sugarcane cultivars RB92579 and SP80–1816 in response to split-irrigation treatments at 420 DAP.

Split-irrigation water (mm)	**Soluble Solids Content—°Brix (%)**		**Sucrose Content—POL (%)**	
	RB92579	SP80–1816	RB92579	SP80–1816
00 + 00	16.95 cA	18.10 bA	13.96 cA	14.85 bA
20 + 40	19.40 bcA	20.92 aA	16.03 bA	17.16 aA
30 + 30	20.57 abA	21.05 aA	16.76 abA	17.27 aA
40 + 20	22.02 aA	19.42 abB	18.01 aA	16.04 abB
60 + 00	20.62 abA	19.12 abA	16.89 abA	15.74 abA
	Fiber (%)		**Broth POL—BP (%)**	
	RB92579	SP80–1816	RB92579	SP80–1816
00 + 00	10.84 aB	12.46 aA	12.05 cA	12.46 cA
20 + 40	10.96 aB	11.98 aA	13.65 bA	14.53 abA
30 + 30	11.58 aA	10.91 bA	14.29 abA	14.89 aA
40 + 20	10.86 aA	11.68 abA	15.55 aA	13.65 abcB
60 + 00	10.78 aB	12.24 aA	14.60 abA	13.27 bcA

Table 4. *Cont.*

Split-irrigation water (mm)	Juice Purity—PZA (%)	
	RB92579	SP80–1816
00 + 00	82.38 aA	82.11 aA
20 + 40	82.62 aA	82.07 aA
30 + 30	81.53 aA	82.05 aA
40 + 20	81.82 aA	82.61 aA
60 + 00	81.96 aA	82.36 aA

Means followed by the same lowercase letters within columns did not differ statistically between the split-irrigation treatments. Means followed by the same uppercase letters within rows did not differ statistically between the cultivars by the Tukey test (significance level of 0.05).

°Brix, POL, and BP showed the lowest values in the treatment without irrigation, possibly due to the water stress experienced by plants in the initial growth stages, up to 180 DAP. For RB92579, plants irrigated with 40 mm + 20 mm showed average values for °Brix, POL, and BP that were 29.91, 29.01, and 29.04% higher, respectively, than plants with no irrigation. The average values recorded for the same technological characteristics in SP80–1816 cultivar under split-irrigation with 30 mm + 30 mm were 16.30, 16.30, and 19.50% higher, respectively, compared to the treatment with no irrigation (Table 4).

The analysis of the effect of split-irrigation management on both cultivars tested showed that for °Brix, POL, and BP, RB92579 showed average values that were 13.39, 12.28, and 13.92% statistically higher, respectively, than SP80–1816 under split-irrigation with 40 mm + 20 mm (Table 4). It suggests that the technological characteristics studied may differ significantly among cultivars [52]. Additionally, based on the methodology suggested by Endres et al. [53], faced with water deficit conditions, RB92579 presents an efficient water absorption system, indicating greater tolerance to drought, probably due to its robust root system. Oliveira et al. [35] found lower technological characteristics values (e.g., total solids content, BP, and PZA) working with sugarcane SP80–1816, independently of suppressing irrigation at some periods.

Irrigation helped achieve POL above 14%, presenting a quality suitable for industrialization [54]. The fiber was higher for SP80–1816 compared to RB92579, both without irrigation and for the treatment with the larger initial irrigation water amount (60 mm + 00 mm). In the first case, fiber was 14.94% higher, and in the second, fiber was about 13.54% higher (Table 4). Oliveira et al. [35] found lower levels of fiber in plants grown under full irrigation than under no irrigation. Percent fiber tends to decrease with increasing irrigation volume. This is likely due to a greater amount of broth with increasing water availability [48]. However, Mendoça et al. [29] catch a glimpse of fiber higher than 12% for both the plant cane and ratoon cane of RB92579, in addition to lower total sugar content when plants received a higher amount of water by irrigation, assuming those traits are more prone to be influenced by the variety and number of crop cycles than by irrigation itself.

In contrast, fiber and sugar have a negative relationship, and this is more pronounced in early varieties because they are rich in sucrose and have a lower fiber content [55]. Sugarcane fiber affects the extraction efficiency of the mill, and the higher it is, the lower the extraction efficiency [56]. Fiber should ideally be between 11 and 13%, according to the recommendation of Consecana [36], among other studies [49,57], for greater efficiency of juice extraction. Morais et al. [2] reinforced the fiber content in sugarcane, which both increases resistance to juice extraction by the industry when fiber content is high and reduces resistance to tipping when fiber content is low.

Several abiotic factors affect plant performance, including water deficit, which stands out as one of the limiting factors in crop development due to its harmful effects, particularly on cell expansion [58]. Thus, water availability has a decisive influence on the development of sugarcane plants and, consequently, on the production of sucrose [59].

Briefly, the results of the technological characteristics of sugarcane plants are influenced by genetics, water availability, and environmental conditions. Excess moisture during the sugarcane maturation stage affects sugar content, just as it is otherwise affected by water deficit conditions [60].

Furthermore, these findings support the suggestion that improving irrigation regularity positively influences an increase in soluble sugars, with an adequate supply of water [24]. Significant results were also found in pulsed drip irrigation systems, where studies confirmed the potential of irrigation for sugarcane, improving growth and productivity, as well as sugar and ethanol yields, in addition to improving physiological characteristics and water use efficiency [3,4]. Menezes et al. [3] observed that pulsed drip irrigation provided increases of 9% in stalk yield, 21% in sugar yield, and 17% in ethanol. In the same sense, Menezes et al. [4] observed increases of 21% in photosynthesis, 17% in water use efficiency, and 39% in leaf area.

3.3. Yield Characteristics

For total recoverable sugar, under split-irrigation with 40 mm + 20 mm, sugarcane cultivar RB92579 showed 27.68 and 12.20% higher values ($p < 0.05$) than plants with no irrigation and plants irrigated with 20 mm + 40 mm, respectively. For total recoverable sugar, RB92579 showed an average value 13.50 and 9.73% higher than SP80–1816 under split-irrigation with 40 mm + 20 mm and 60 mm + 00 mm, respectively (Table 5).

Table 5. Yield characteristics (fresh stalk mass, plant weight, productivity, ton of cane per hectare, total recoverable sugar, and RS) of sugarcane cultivars RB92579 and SP80–1816 in response to split-irrigation treatment at 420 DAP.

Split-irrigation water (mm)	**Fresh stalk mass (kg m^{-1})**		**Plant weight (kg m^{-1})**	
	RB92579	SP80–1816	RB92579	SP80–1816
00 + 00	18.86 aA	19.49 aA	23.13 aA	22.95 aA
20 + 40	19.83 aA	18.23 aA	23.37 aA	20.49 aA
30 + 30	18.33 aA	15.88 aA	21.92 aA	18.43 aA
40 + 20	16.69 aA	16.77 aA	20.00 aA	20.75 aA
60 + 00	23.77 aA	13.45 aB	28.07 aA	16.23 aB
	Shoot productivity (t ha^{-1})		**Cane production (t ha^{-1})**	
	RB92579	SP80–1816	RB92579	SP80–1816
00 + 00	154.21 aA	153.00 aA	125.75 aA	129.93 aA
20 + 40	155.78 aA	136.57 aA	132.25 aA	121.56 aA
30 + 30	146.11 aA	122.86 aA	122.20 aA	105.90 aA
40 + 20	133.31 aA	138.35 aA	111.26 aA	111.83 aA
60 + 00	187.15 aA	108.23 aB	158.51 aA	89.68 aB
	Total recoverable sugar (kg ton^{-1})		**Reducing sugars—RS (%)**	
	RB92579	SP80–1816	RB92579	SP80–1816
00 + 00	122.57 cA	126.42 cA	0.70 bA	0.69 aA
20 + 40	139.48 bA	146.39 abA	0.80 aA	0.69 aB
30 + 30	144.25 abA	150.04 aA	0.84 aA	0.71 aB
40 + 20	156.50 aA	137.89 abcB	0.72 bA	0.69 aA
60 + 00	147.24 abA	134.18 bcB	0.71 bA	0.69 aA

Means followed by the same lowercase letters within columns did not differ statistically between the split-irrigation treatments. Means followed by the same uppercase letters within rows did not differ statistically between the cultivars by the Tukey test (significance level of 0.05).

As for total recoverable sugar, under split-irrigation with 40 mm + 20 mm, RB92579 showed 27.68 and 12.20% higher values ($p < 0.05$) than plants with no irrigation and those irrigated with 20 mm + 40 mm, respectively. RB92579 showed an average of 13.50 and

9.73% higher values for total recoverable sugar than SP80–1816 under split-irrigation with 40 mm + 20 mm and 60 mm + 00 mm, respectively (Table 5).

It is worth highlighting that the increase in sugarcane productivity varies depending on a series of factors, such as the planting season, water deficit conditions, irrigation water quality, as well as the phenological phase in which the plant is exposed to this stress [2,61]. Damage to sugarcane productivity is most severe when water stress occurs in the stalk growth stage, thereby affecting production more significantly at this point [62].

With split-irrigation, sugarcane production in tons per hectare varied from 89.68 (SP80–1816) to 158.51 (RB92579), these values being the sugarcane production presented in the split management of 60 mm + 00 mm, showing a statistically significant difference ($p < 0.05$) between the cultivars (Table 5).

Under the management systems 0 mm + 0 mm and 40 mm + 20 mm, the cultivar SP80–1816 presented a higher average productivity (129.93 and 111.83 t ha^{-1}) when compared to RB92579 (125.75 and 111.26 t ha^{-1}). On the other hand, under the management systems 20 mm + 40 mm, 30 mm + 30 mm, and 60 mm + 00 mm, RB92579 presented the higher productions of 132.25, 122.20, and 158.51 t ha^{-1}, respectively. However, statistically, no significant difference ($p < 0.05$) was observed between RB92579 and SP80–1816 for sugarcane production regarding the split-irrigation management systems (Table 5).

In the split management of 60 mm + 00 mm, shoot productivity presented the same conditions as the sugarcane production metrics, highlighting the higher productivity of 187.15 t ha^{-1} for the cultivar RB92579 compared to 108.23 t ha^{-1} for SP80–1816 (Table 5).

Still, regarding stress to culture, it is worth mentioning the quality of irrigation water. Morais et al. [2] evaluated the sugarcane cultivar RB92579 under saline stress and confirmed that an increase in salinity in irrigation water affects the variables of growth, productivity, technological quality, and industrial yield. However, the authors observed that sugarcane is moderately tolerant to salinity when the leaching fraction is 17% for the cane-plant and first ratoon cycles.

Silva et al. [51] obtained an average productivity of 133.88 t ha^{-1} for RB92579, in addition to high agronomic yields, which resulted in a high concentration of sucrose by dry biomass and, consequently, a high sugar and alcohol production, suggesting an excellent industrial performance of this cultivar in the edaphoclimatic conditions of the Brazilian semiarid region.

Studying the morphological changes in six sugarcane varieties under water deficit, Endres et al. [62] observed that RB92579 showed production of 128 t ha^{-1} for irrigation and of 98.2 t ha^{-1} for water stress conditions. Additionally, in the face of water stress, the authors observed high productivity due to the greater number of plants per linear meter. In addition to maintaining the height of the stem, the greater number of tillers allowed a certain balance in productivity rates.

TRS content differed between cultivars under split-irrigation management with 40 mm + 20 mm and 60 mm+ 00 mm, with RB92579 producing approximately 88.10% and 91.13% more than SP80–1816, respectively (Table 5). RB92579 showed its highest TRS value under split-irrigation with 40 mm + 20 mm, which was approximately 78.31 and 89.12% higher than the treatments with no irrigation and those under split-irrigation with 20 mm + 40 mm, respectively. The highest TRS value for SP80–1816 was observed under split-irrigation with 30 mm + 30 mm, which was approximately 84.25 and 89.42% higher than the treatments with no irrigation and those with split-irrigation with 60 mm + 00 mm, respectively (Table 5).

When sugarcane plants are subjected to water stress during the growth stage and stalk elongation phase, sucrose accumulation is reduced, whereas if it occurs during the maturation phase, water stress results in greater sucrose accumulation [63]. The greatest accumulation of POL, of 18.01% (Table 4), was identified at 420 DAP (crop maturation phase), precisely the period of water deficit for the region, specifically in June 2019 (Figure 2). The concentration of RS showed significant differences between cultivars under both split-irrigation management systems with 20 mm + 40 mm and 30 mm + 30 mm, where RB92579 showed 15.94 and 18.30% smaller values than SP80–1816, respectively, which showed no significant differences among irrigation treatments, while RB92579 showed higher rates under both split-irrigation with 20 mm + 40 mm and 30 mm + 30 mm (Table 5). Only these management systems in both cultivars have reference values (<0.80%) above those recommended by Consecana [36]. Lower values of RS are desirable, as glucose and fructose can reduce copper oxide from the cupric to the cuprous state, being the main precursors of the darker color of sugar in the industrial process [35]. Values below 0.80% are within the recommended standard for this qualitative index [35].

Neither fresh stalk weight nor plant weight showed any significant differences among split-irrigation management or between cultivars. However, RB92579 showed 76.73 and 72.95% higher mean values for fresh stalk weight and plant weight, respectively, than SP80–1816 under split-irrigation with 60 mm + 00 mm (Table 5).

Water deficit can affect the whole plant, from root hairs to stomata [64]. However, complementary irrigation provides linear increments in sugarcane yield with increasing water supply, reaching increments above 100% compared to rainfed cultivation [65]. Under water stress, gas exchange between the leaf and the atmosphere generally decreases, thereby reducing water loss due to stomatal closure, although at the expense of a reduction in atmospheric CO_2 availability, which is essential for photosynthetic reactions [66]. The inhibition of chlorophyll biosynthesis results in decreased absorption of the light energy required for photosynthetic productivity [67], thereby affecting the accumulation of biomass and, consequently, the productivity of sugarcane [65].

4. Conclusions

Sugarcane plant height increased over time (180 to 420 DAP), confirmed by the average statistics both as a function of split-irrigation management and as a function of cultivars. And when the averages of the cultivars were compared, SP80–1816 had greater development.

It is noteworthy that both sugarcane cultivars responded positively to split-irrigation management, as °Brix, POL, and BP, except the fiber, were positively influenced by split-irrigation management.

Sugarcane cultivar RB92579 showed higher mean values for growth and industrial quality-related parameters in treatments with a greater volume of water supplied at the initial phase, while the SP80–1816 cultivar responded in a more homogenous manner across all split-irrigation management systems.

The cultivar RB92579 presented the highest values of shoot productivity (187.15 t ha^{-1}) and cane production (158.51 t ha^{-1}) in the split-irrigation management of 60 mm + 00 mm. Higher water amounts supplied during the plant growth phase mean higher and better growth parameters and technological attributes of sugarcane. Therefore, the use of split-irrigation with applications of 40 mm and 60 mm is recommended. The lowest values of RS (a desirable characteristic for the industry) were recorded for SP80–1816; however, both cultivars showed values within the desirable standards.

Adopting split-irrigation strategies can optimize water use and improve productivity, especially in regions where water availability is a challenge.

We recommend that future research explores different combinations of irrigation volumes and their interactions with environmental variables, in addition to investigating the impact of irrigation practices on other cultivars. Additional studies could also focus on how these practices can be integrated into sustainable cropping systems, promoting not only water efficiency but also crop resilience in the face of climate change.

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