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ORIGINAL ARTICLE

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The combination of irrigation regime and water cutoff date increases the yield and water use efficiency of castor bean (*Ricinus communis* L.)

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Abstract

Castor bean (*Ricinus communis* L.) is a fibrous and fast-growing plant with increasing economic importance due to its ability to generate energy and in the pharmaceutical and chemical industries. This research aimed to determine the best combination of irrigation regime and irrigation cutoff date (ICD) that maximizes grain and oil yields and water use efficiency (WUE) in the castor bean hybrid AG IMA 110204. The experiments were conducted in greenhouses in randomized blocks using subdivided plots and four replicates. The plots were allocated to five irrigation regimes based on soil water tension: 20, 30, 40, 50, and 60 kPa, corresponding to I1, I2, I3, I4, and I5, respectively. The subplots show the four ICDs: 120, 130, 140, and 150 days after sowing (DAS). The I1, I2, and I3 treatments showed the highest values and did not differ in the two cycles for the following variables: weight of 100 grains, grain yield, oil yield, WUE of the grain (WUE-grains), and WUE of the oil (WUE-oil). When the irrigation cutoff was 120 DAS, in both cycles, the water regimes I1, I2, and I3 presented the highest values and did not differ in terms of grain or oil yields or WUE-grains or WUE-oil. Higher grain and oil yields with lower water demand for castor

Abbreviations: DAS, days after sowing; ICD, irrigation cutoff date; WUE, water use efficiency.

bean were obtained with the combination of 40 kPa soil water tension to define the time of irrigation and the irrigation cutoff at 120 DAS.

1 | INTRODUCTION

Castor bean (*Ricinus communis* L.), native to East Africa, is a fibrous and fast-growing plant. In Brazil, it has growing economic importance due to its use for generating energy and in the pharmaceutical and chemical industries (Albuquerque et al., 2014).

Castor oil has an essential and specific characteristic in withstanding high temperatures without losing viscosity due to its high solvency in alcohol transesterification, which occurs without heating (Souza et al., 2007a). In addition to its use as an energy source for engines, castor oil is also important for the production of various products, such as lubricants, cosmetics, paints, medicines, and foam mattresses (Veríssimo et al., 2009).

Castor bean has a high potential as a feedstock to produce biodiesel because of its lower cetane number than diesel. It also helps reduce the net greenhouse gases, primarily carbon dioxide, as the plant will potentially capture the CO_2 emitted from fuel burning during photosynthesis (Osorio-González et al., 2020).

Under a limited water supply where other species would not make a crop, castor bean plants can still produce a low seed yield because of their drought tolerance. However, productivity can only be optimized using genotypes with high yield potential and adequate water supply (Severino et al., 2012).

Rios et al. (2013) observed that castor bean fruit mass and grain yield decreased linearly with increasing water restriction for all racemes, with soil moisture near field capacity showing the highest values.

With the development of new cultivars with high productive potential and desirable characteristics for mechanized harvesting (Severino et al., 2012), castor bean expanded to the Brazilian cerrado, more specifically to the midwest region, becoming a second crop choice, even to be included in the rotation with other annual crops (Souza-Schlick et al., 2012). However, more efficient production technologies, including irrigation, are needed to maximize crop yield (Souza-Schlick et al., 2011).

There is little information in the literature about the irrigation management of castor bean cultivars obtained through genetic improvement aimed at high productivity and mechanized harvesting, especially compared to better-known oilseeds, such as soybean and sunflower (Auld et al., 2001). The castor bean hybrid AG IMA 110204 (RNC-32752) is a relatively new variety, explaining the lack of specific irrigation studies. Conventional irrigation practices generally address water requirements and timing but lack optimization for high-yielding hybrids. In Brazil, few studies have thoroughly examined the water use efficiency (WUE) of castor beans, considering the soil–plant–atmosphere system (Carvalho et al., 2020). Understanding water needs at different phenological stages and optimal irrigation cutoffs are essential for rational water management, allowing real-time monitoring of water relationships throughout the crop cycle (Oliveira et al., 2010). Proper water management can significantly impact the vegetative development and productivity of castor beans, enhancing WUE and crop performance (Gomes et al., 2013).

The genetic improvement of castor bean aims to produce hybrid cultivars that, in addition to being indehiscent, have a shorter cycle, smaller stature, greater uniformity, and high productivity—characteristics that are indispensable for the mechanization process. In this way, the crop has proven to be of great importance in the country's agro-industrial sector. The castor bean hybrid AG IMA 110204 (RNC-32752) exhibits high productive potential and the possibility of mechanized harvesting (de Araújo Nascimento et al., 2022); however, it requires more studies about when to irrigate, the date of water cutoff, and the WUE are needed to achieve effective irrigation management throughout the crop cycle.

This research aimed to determine the best combination of irrigation regime and irrigation cutoff date (ICD) that maximizes crop and oil yields and WUE in Castor Bean (*R. communis* L.), cultivar AG IMA 110204.

The hypothesis of this research is that the adequate combination of the soil water tension that defines the moment to irrigate with the ICD results in greater yield and WUE in the castor bean hybrid AG IMA 110204.

2 | MATERIALS AND METHODS

2.1 | Study area

This work was carried out in the Center-South region of Sao Paulo State, Brazil, in the experimental area of the Faculty of Agronomic Sciences (FCA)—Sao Paulo State University (UNESP), in a greenhouse with an area of 161 m^2, located at the geographic coordinates 22°51′6.12″ S and 48°25′45.44″ O.

The weather variability inside the greenhouse was characterized by a hot, humid, and temperate (mesothermal) climate, classified as Cfa according to the Köppen classification. The average temperature was 22.6°C and the average humidity was 72%.

The greenhouse is 7 m wide and 23 m long, 161 m^2, covered by plastic with 150 µm and treated against ultraviolet rays (15% solar radiation filter). The front and side covers consisted of Clarinet anti-insect mesh, allowing excellent ventilation inside the greenhouse.

2.2 | Experimental material and design

The castor bean hybrid AG IMA 110204 (RNC-32752) was chosen due to its favorable characteristics, such as high yield potential, cultivation with higher plant density, and the possibility of mechanized harvest (Nascimento et al., 2022). It is a small hybrid (1.70 cm) that presents the ideal conditions for mechanization, fast flowering (approximately 30 days after sowing [DAS]), a productive cycle of 160 days, a potential yield between 1500 and 3000 kg ha^{-1}, and an average oil concentration at 47% (De Sá et al., 2015). The hybrid is recommended for biofuel production and is also an option for crop rotation and nematode reduction in cotton areas.

A spacing of 1.0 m between rows and 0.33 m between plants (30,000 plants ha^{-1}) was maintained during planting. Three seeds were placed in a 5-cm deep pit, and 20 DAS, thinning was performed to maintain only one plant.

The statistical design adopted was randomized blocks using subdivided plots and four replicates. The plots allocated the irrigation regimes based on five levels of soil water tensions: 20, 30, 40, 50, and 60 kPa, corresponding to groups I1, I2, I3, I4, and I5, respectively. When the soil water tension reached the values corresponding to each treatment, irrigation was carried out to obtain a soil water tension of 10 kPa, which was adopted as the soil tension at field capacity (dos Santos et al., 2018). In the subplots, the four dates of irrigation cutoff were 120, 130, 140, and 150 DAS, identified as A, B, C, and D, respectively. The irrigation cutoff is the interruption of irrigation at the end of the crop cycle. This practice is used to stimulate the maturation phase, promote the drying of plants, and increase the concentration of oil in seeds by reducing the water content of plants. Thus, there were a total of 20 treatments, with four repetitions.

The first cycle was conducted between January 1, 2020 and June 8, 2020, and the second cycle was conducted between March 23, 2020 and August 29, 2020, totaling 160 days of the crop cycle. As the second cycle started before finishing the first cycle, they were carried out in different greenhouses but with the same dimensions, statistical design, and location.

The soil present at the experimental site had the following characteristics: organic matter = 7 g dm^{-3}; pH ($CaCl_2$) = 4.2; P (resin) = 13.0 mg dm^{-3}; K+ = 2.0 mmol dm^{-3}; $Ca2^{+}$ = 18 mmol dm^{-3}; Mg+2 = 12.0 mmol dm^{-3}; H+Al = 21.0 mmol dm^{-3}; CEC (cation exchange capacity) = 85.0 mmol dm^{-3}; S = 18.0 mg dm^{-3}; B = 0.25 mg dm^{-3}; Cu = 3.5 mg dm^{-3}; Fe = 12.0 mg dm^{-3}; Mn = 4.5 mg dm^{-3}; Zn = 1.6 mg dm^{-3}; 82% base saturation; and textural classification = sandy loam, with 63.4% sand, 32.3% clay, and 4.3% silt.

Planting fertilization was carried out by applying the following amounts of N, P, and K: 50, 30, and 80 kg ha^{-1}, respectively, as recommended by De Sá et al. (2015). The application of nitrogen was carried out through fertigation and began 40 DAS, according to Da Eira et al. (2014). Five fertigation treatments were applied at 7-day intervals, with 10 kg N ha^{-1} applied in each one.

Core Ideas

- Castor bean showed sensitivity to the increase in water tension and to irrigation suspension.
- Morphological and production characteristics varied depending on the water tension.
- An increase in water tension in the soil reduced the production of grains and oil.
- The water use efficiency increased at a soil water tension of 40 kPa.
- Water tension in the soil of 50 and 60 kPa were the ones that most affected the yield.

TABLE 1 The coefficients of the Van Genutchten equation to represent the soil retention curve for layers 0–20 cm and 20–40 cm.

	Parameters				
Layer (cm)	σ	m	n	θ_r	θ_s
0–20	0.100	0.351	1.541	0.146	0.233
20–40	0.100	0.541	2.179	0.166	0.264

Note: σ: scale parameter (1/cm), related to the inverse of the air-entry pressure; n: shape parameter (dimensionless), related to the pore-size distribution; m: shape parameter (dimensionless), often assumed to be $m = 1 - 1/n$; n: θ_r: residual water content (cm^3/cm^3) θ_s: saturated water content (cm^3/cm^3).

2.3 | Irrigation management

In each treatment, irrigation management was performed using two sets of tensiometers installed in the 0–20 and 20–40 cm soil layers. Tensiometers at 0–20 cm were used to decide when to irrigate, while 20–40 cm range sensors were adopted to avoid water percolation.

The data for the soil–water retention curve were previously obtained by the Richards extractor method (Richards, 1965) and subsequently adjusted by the Soil Water Curve Relation software, version 3.0 (Dourado-Neto et al., 2000). The software adopted the Genuchten equation (van Genuchten, 1980), Equation (1), whose coefficients are shown in Table 1.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha\,\Psi)^n]^m} \tag{1}$$

where θ is the soil water content (cm^3 cm^{-3}), θ_r is the residual water content (cm^3 cm^{-3}), θ_s is the saturated water content (cm^3 cm^{-3}), Ψ is the matrix potential modulus (kPa), and α, n, and m are the model's empirical parameters.

2.4 | Irrigation system

A drip irrigation system was used, with a noncompensated dripper tube (Netafim—Typhoon Plus) for each planting line, having the following characteristics: spacing between emitters of 20 cm and an average emitter flow rate of 1 L h^{-1} at the operating pressure of 10 mca.

The wetted area of each emitter, obtained by the field test, was 0.08 m^2 (width of the wet strip of 0.4 m and length of 0.2 m), and the application depth (Z) was 20 cm in the first 45 DAS and 40 cm for the rest of the cycle (Barreto et al., 2008). The emitter application rate was 12.5 mm h^{-1}, and the Christiansen uniformity coefficient (CUC) was 95%.

The irrigation times for irrigation regimes I1, I2, I3, I4, and I5 were 27.9, 42.9, 51.9, 58.0, and 62.4 min, respectively, estimated from corresponding to Equations (2–4).

$$L_l = \frac{\theta_c - \theta_a}{10} \times Z \tag{2}$$

$$L_b = \frac{L_l}{E} \tag{3}$$

$$t = \frac{L_b}{I_S} \tag{4}$$

where L_l is the net irrigation depth (mm), θ_c is the soil moisture at field capacity (10 kPa), θ_a is the soil moisture for each treatment (20, 30, 40, 50, and 60 kPa), Z is the soil depth (cm), L_b is the gross irrigation depth (mm), E is the irrigation system efficiency (%), 95% in this case, t is the irrigation time (h), and I_S is the emitter application rate (mm h^{-1}).

Irrigation regime treatments began 41 DAS, because during the first 40 days the crop was managed similarly, maintaining the moisture close to 10 KPA, to ensure seed germination and crop establishment.

Meteorological data, temperature, and solar radiation were obtained using an agrometeorological station model, Campbell Scientific CR10X, installed inside the greenhouse, with an HMP45C sensor and a pyranometer to measure the air temperature and solar radiation, respectively.

2.5 | Crop production components

The variables analyzed were stem diameter, obtained with the aid of a Vernier caliper and measured at 10 cm from the ground; plant height, determined from the ground level to the top of the plant with the help of a measuring tape; the number of racemes per plant, obtained as the ratio between the total number of racemes and the total number of plants; the number of fruits per raceme, calculated as the ratio between the total number of capsules and the total number of racemes in each plant; the mass of 100 grains, obtained using a digital scale with an accuracy of four decimal places; crop yield, obtained as the ratio between the mass of the grains and the cultivated area (kg ha^{-1}); and oil yield (kg (oil) ha^{-1}) calculated as the ratio between the oil content of grains (kg) and the cultivated area. The oil content was determined using nuclear magnetic resonance, which measures the absorption of electromagnetic radiation of up to 750 MHz by the nuclei of atoms and WUE (kg m^{-3}), calculated by the ratio between the mass of grains and the amount of water utilized in the cycle.

Analysis of variance was performed, and when significant, the Tukey test was adopted for comparisons between means, considering the significance level of 5% ($p \leq 0.05$).

3 | RESULTS AND DISCUSSION

3.1 | Crop water requirements

The total irrigation depth applied in each treatment during the first and second cycles is shown in Figure 1. Initially, in both cycles, all plots received the same irrigation depth during the first crop stage (I), from 0 to 40 DAS (Figure 1b,d). The application of the irrigation regimes began at 41 DAS.

The highest irrigation depth occurred in treatment 20 kPa (I1) in all subplots, and these values decreased with increasing soil water tension, as shown in Figure 1a,c. For the treatment with the irrigation cutoff at 150 days (D) in the first crop cycle (Figure 1a), I1 applied 528.9 mm, while treatments I2, I3, I4, and I5 showed irrigation depths 5.5%, 12.1%, 15.4%, and 19.4% smaller, respectively. In the second cycle (Figure 1c), treatment I1 received 510.3 mm of irrigation depth, while the subsequent treatments were 4.7%, 9.3%, 14.5%, and 18.7% lower, respectively, than I1.

In the treatment with an ICD of 120 DAS (A), in the first cycle (Figure 1a), the highest irrigation depth was 427.7 mm for treatment I1, while I2, I3, I4, and I5 were 6.5%, 13.4%, 15.8%, and 16.3% lower, respectively. The same behavior also occurred in the second crop cycle (Figure 1c). In both cycles, the stage with the highest water demand was the third crop growth stage, known as mid-season (III—from 76 to 120 DAS; Figure 1b,d).

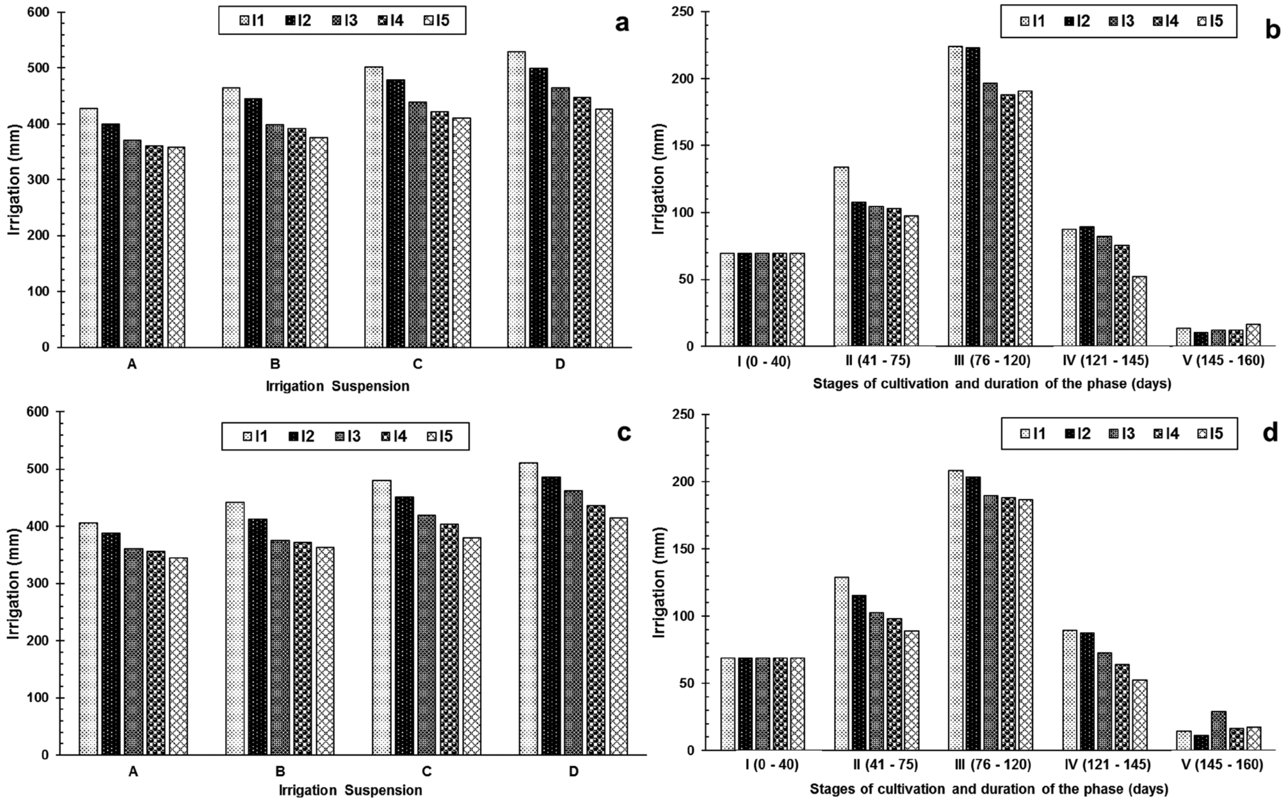

FIGURE 1 Water requirement (mm) of castor bean cultivated in Sao Paulo State, Brazil: (a) first cycle, for different irrigation cutoff dates; (b) first cycle, for different stages in the crop cycle; (c) second cycle, for different irrigation cutoff dates; and (d) second cycle, for different stages in the crop cycle. I1, I2, I3, I4, and I5 corresponding to levels of soil water tensions of 20, 30, 40, 50, and 60 kPa, respectively; A, B, C, and D corresponding to dates of irrigation cutoff: 120, 130, 140, and 150 days after sowing (DAS), respectively.

Previous research on castor bean with the cv. AL Guarany 2002 variety has demonstrated the importance of maintaining optimal soil moisture levels, showing the greatest gains in all production components when soil moisture was maintained close to field capacity with an effective water depth of 486 mm (Rios et al., 2013). Similarly, Dias et al. (2015) estimated water requirement values of 577.9 and 552.3 mm in two cycles for the castor bean variety BRS Energia variety. Beltrão and Severino (2006) recommended maintaining a water depth between 450 and 600 mm during the crop cycle to achieve maximum productivity. Furthermore, Patel et al. (1998) reported that the water requirements of castor beans varied from 466 to 1178 mm, depending on the type of soil, variety, and location.

In the second cycle, a slight decrease in the irrigation depths was observed for all treatments compared with the values of the first cycle. The difference can be associated with the climatic conditions in each cycle. Figure 2 shows that for the second cycle, solar radiation and temperature inside the greenhouse had lower values than in the first cycle.

The average temperature and global solar radiation values during the first crop cycle were 24.52˚C and 16.52 MJ m^2, respectively. In the second cycle, the mean values were 21.34˚C and 11.30 MJ m^2 for temperature and global solar radiation, respectively. Although the temperature values were lower in the second cycle, they are within the temperature range (between 20˚C and 30˚C) recommended by Moshkin (1986) as ideal for developing castor bean.

Climatic factors interfere with several chemical and biological reactions of plants, causing a wide impact on the characteristics of two important processes for the plant: photosynthesis and photorespiration (Taiz et al., 2015). According to Azevedo and Beltrão (2007), the highest net photosynthesis rate in castor bean occurs at 23˚C.

3.2 | Effects of soil water tension and ICD on crop production components

Stem diameter and plant height had higher values in treatments I1, I2, and I3 compared to treatments I4 and I5, with no significant difference observed among treatments I1, I2, and I3 in both cycles. The treatments irrigated when soil water tension reached 50 kPa (I4) or 60 kPa (I5) may have induced a water stress process in the plants and generated lower values of stem diameter and plant height.

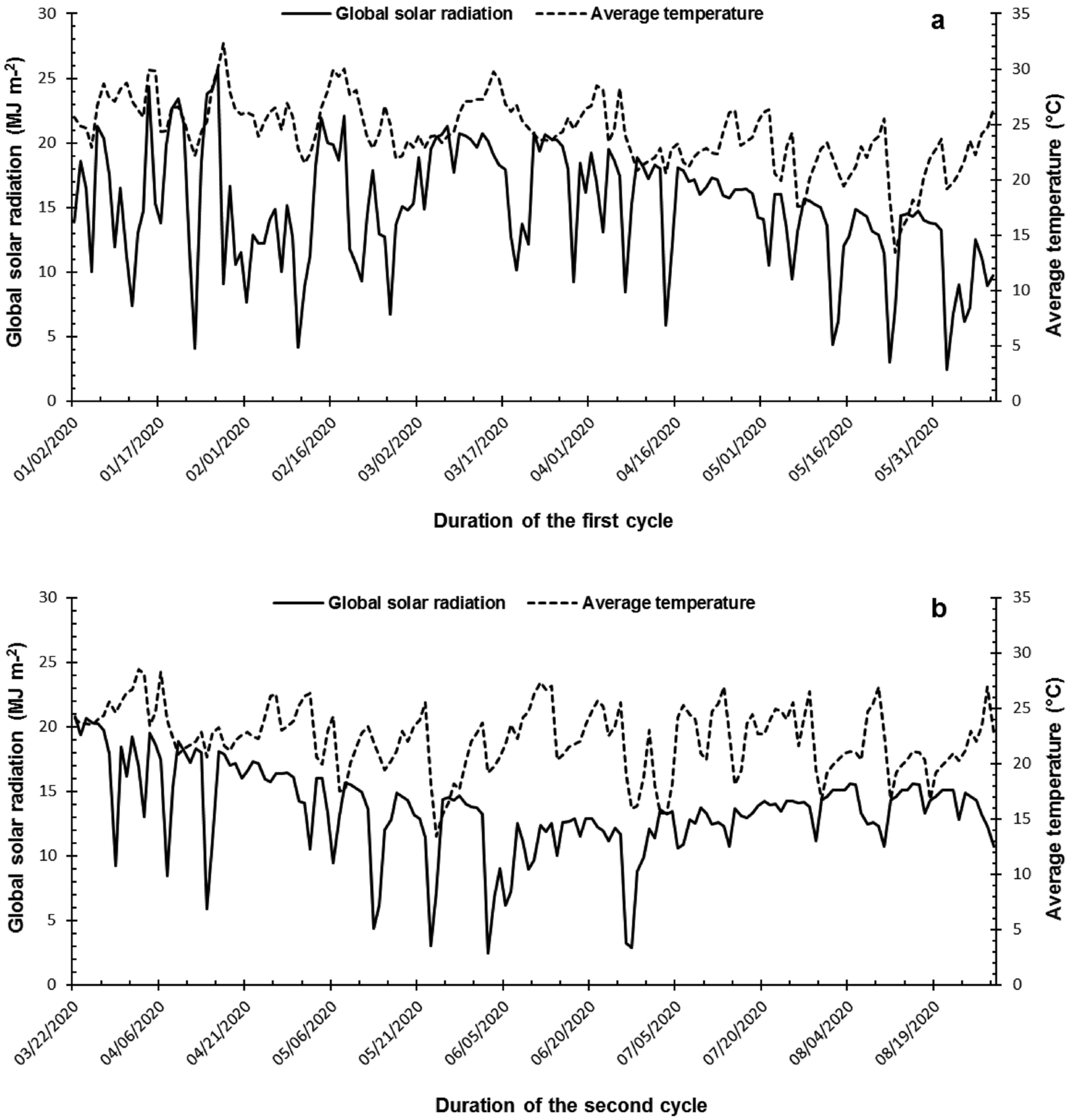

FIGURE 2 Global solar radiation and average air temperature in the two cycles of castor bean cultivation in Botucatu/SP, Brazil.

Afshar et al. (2015) and Litvin et al. (2016) showed that water stress during the vegetative growth stage affects cell division and cell elongation, thus reducing the increase in plant diameter and height.

ICDs, irrigation regimes, and interaction between them did not significantly affect the number of racemes per plant in either of the two crop cycles (Table 2).

When working with castor bean, it is not enough to analyze only the number of racemes produced per plant but also the number of fruits in each raceme; the fruit is a capsule (Figure 3) with three grains containing commercial oil.

A significant difference was observed for the effect of the soil water tension treatments ($p \leq 0.05$) on the number of fruits per raceme. Higher numbers of capsules per raceme were obtained with I1, I2, and I3 for both cycles and the lowest was found with I5 and I4. The increase in the soil water tension that defines when to irrigate generated a decrease in the number of capsules per raceme.

The study conducted by De Freitas et al. (2010) confirmed a decrease in the number of capsules as water stress increased, a fact also reported by another study with different types of oleaginous plants (Bannayan et al., 2008).

The number of capsules is the main component of the castor bean yield and depends on the physiological and environmental conditions during grain formation and filling. In this study, treatments I4 and I5 may have impaired water absorption by plants during floral development, pollination, and grain filling. Such conditions can limit the number of racemes capsules, mainly because of the water stress during the filling of the grains (Rotundo & Westgate, 2010). Souza et al. (2007b) also obtained similar results in irrigated castor bean without

TABLE 2 Effect of irrigation regimes (I) and irrigation cutoff dates (ICD) on the morphological characteristics of castor bean and production components in two crop cycles.

First cycle		Stem diameter (cm)					Plant height (cm)					Number of racemes per plant (unit)					Number of fruits per raceme (unit)				
Treatment	*df*	A	B	C	D	Average	A	B	C	D	Average	A	B	C	D	Average	A	B	C	D	Average
First cycle																					
I1		3.25	3.59	3.40	3.54	3.44a	164.50	164.00	160.88	163.88	163.31a	5.63	6.13	5.75	6.13	5.91	38.73	37.65	40.78	37.73	38.71a
I2		3.64	3.66	3.40	3.45	3.53a	161.25	159.50	152.25	161.00	158.5a	5.25	6.00	6.25	6.25	5.94	41.53	36.85	36.85	36.03	37. 81a
I3		3.09	3.38	3.38	3.33	3.29a	153.13	155.25	151.25	156.50	154.03a	6.00	6.50	5.75	5.63	5.97	39.05	34.93	38.05	38.98	37.75a
I4		2.76	2.84	2.84	3.04	2.86b	145.50	144.88	139.00	146.50	143.96b	6.38	5.63	5.63	5.13	5.69	30.80	32.35	32.78	34.90	32.70b
I5		2.48	2.61	2.34	2.54	2.49c	135.13	139.38	136.25	136.38	136.78b	5.50	5.63	6.13	5.00	5.56	27.05	30.20	28.40	32.60	29.56b
Average		3.04	3.22	3.07	3.18	3.13	151.90	152.60	147.93	152.85	151.32	5.75	5.98	5.90	5.63	5.81	35.43	34.40	35.37	36.05	35.31
ANOVA																					
ICD	3					ns					ns					ns					ns
I	4					*					*					ns					*
ICD × I	12					ns					ns					ns					ns
Second cycle																					
I1		3.48	3.40	3.38	3.42	3.42a	120.43	118.48	119.83	122.95	120.42a	4.60	5.33	5.13	5.03	5.02	37.73	39.15	38.78	34.63	37.56a
I2		3.39	3.35	3.43	3.37	3.38a	117.15	121.38	119.93	121.20	119.91a	4.88	5.38	4.75	4.90	4.98	38.75	35.35	37.65	34.83	36.64a
I3		3.25	3.25	3.32	3.30	3.28a	117.23	118.28	115.25	116.95	116.92a	4.83	4.85	5.00	4.85	4.88	35.55	36.13	37.75	36.48	36.47a
I4		2.58	2.64	2.60	2.56	2.59b	107.10	109.28	106.70	106.90	107.49b	4.20	5.20	5.15	4.70	4.81	28.43	32.55	32.08	32.40	31.36b
I5		2.28	2.32	2.32	2.31	2.31c	97.38	96.78	95.55	98.58	97.06b	4.75	5.10	4.73	4.85	4.86	25.58	28.73	27.70	29.90	27.97c
Average		2.99	2.99	3.01	2.99	3.00	111.86	112.84	111.45	113.32	112.36	4.65	5.17	4.95	4.87	4.91	33.21	34.38	34.79	33.65	34.0
ANOVA																					
ICD	3					ns					ns					ns					ns
I	4					*					*					ns					*
ICD × I	12					ns					ns					ns					ns

Note: According to the Tukey test, the means within a column that does not share the same letter differ significantly ($p < 0.05$); I1, I2, I3, I4, and I5 correspond to soil water tension levels of 20, 30, 40, 50, and 60 kPa, respectively; and A, B, C, and D correspond to irrigation cutoff date of 120, 130, 140, and 150 days after sowing (DAS), respectively. Unit, number of racemes per plant.

Abbreviation: ANOVA, analysis of variance.

*$p < 0.05$; ns, not significant.

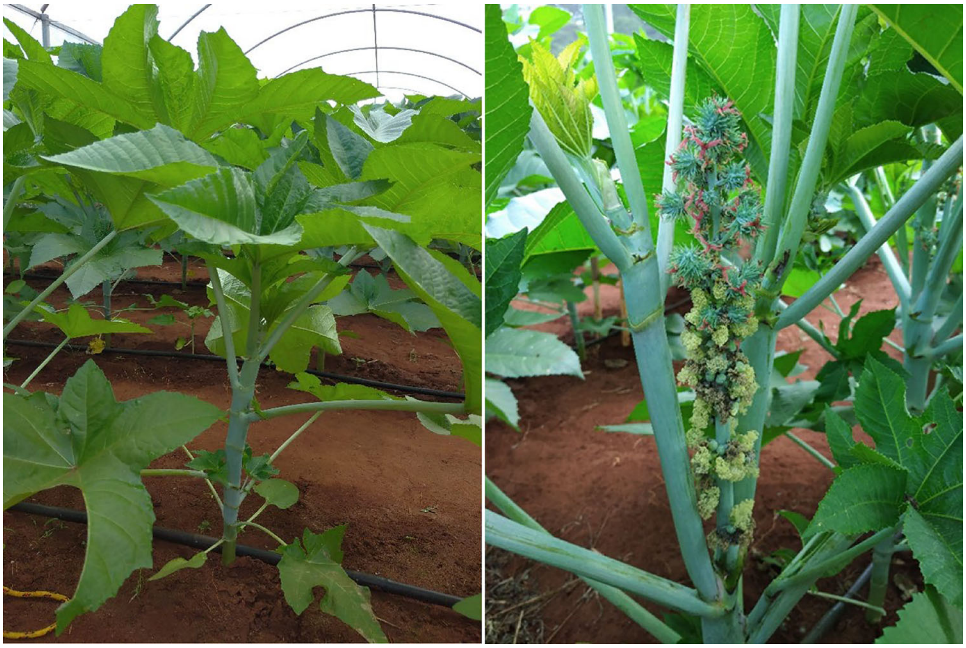

FIGURE 3 Castor bean crop after and before flowering.

water deficiency; the number of fruits per raceme increased by 23 units compared to the rainfed crop.

3.3 | Weight of 100 grains

Sarwar and Chaudhry (2008) report that, for a given plant density, in addition to the number of racemes per plant and the number of capsules per raceme, the yield of castor bean also depends on the weight of 100 grains.

Note that 100 grain weight was affected only by the irrigation regimes ($p < 0.05$) (Table 3). Higher grain weights were obtained in treatments I1, I2, and I3, with no difference in both cycles, followed by I4 and I5. Rios et al. (2013) also observed a reduction in the weight of 100 grains of castor bean with the increase in the soil water tension that defines when to irrigate.

Ozer et al. (2020) and Mirzaei et al. (2013) found a statistically significant difference in the weight of a thousand grains of oleaginous crops under different irrigation treatments.

3.4 | Grain and oil yields

In cycles 1 and 2, the highest grain and oil yields occurred in treatments I1, I2, and I3, which did not differ on all evaluated ICDs (Table 4). In this way, the best option is to irrigate when the soil water tension reaches −40 kPa (I3) because it allows a water economy compared to I1 and I2, as observed in Figure 1.

On average, considering both cycles, there was a reduction in grain and oil productivity by 20% with increasing soil water tension between treatments I1 and I5.

Reddy et al. (2004) noted that any factor that affects the growth and development processes of plants will affect the overall development of the canopy and, consequently, production.

Dias et al. (2015), Ramanjaneyulu et al. (2013), and Rios et al. (2013) demonstrated that the productivity of castor bean grains was increased by depth irrigation. For castor beans, water is the environmental factor with the greatest impact on growth and influences grain production, especially in dry regions (Severino et al., 2012).

The adverse effects of water stress are reflected in the reduced number of grains when this occurs before anthesis (time to maturity of a flower) and reducing the seed weight when stress occurs after anthesis, particularly during grain filling (Rajala et al., 2011). It was found that the water stress that occurred during the filling of the grains influenced the reduction in the number of fruits and in the weight of the grains, which, consequently, decreased the final productivity.

Water stress contributes to the decline in photosynthesis due to the greater stomatal resistance and the lower biochemical efficiency of chloroplasts, the closure of stomata, and the decrease in carbohydrate production and accumulation (Flexas et al., 2013; Reddy et al., 1996). Additionally, water deficiency decreases the leaf area, causing less biomass accumulation and impaired dry matter partitioning for the plant's generative and vegetative organs (Zhou et al., 2013).

Grain and oil yields in castor bean did not differ in terms of the date of suppression of irrigation in treatments I1, I2, I3, and I4 in the first cycle or in treatments I1, I2, and I3 in the second cycle (Table 4). Irrigation at 120 DAS would be the

TABLE 3 Effect of irrigation regimes (I) and irrigation cutoff dates (ICD) on the weight of 100 grains of castor bean in two crop cycles.

Weight of 100 grains (g)											
		First cycle					Second cycle				
Treatment	*df*	A	B	C	D	Average	A	B	C	D	Average
I1		34.96	35.65	35.01	35.66	35.32a	34.58	35.86	35.46	35.85	35.43a
I2		35.01	33.92	34.69	35.11	34.68a	35.65	34.35	35.07	35.54	35.15a
I3		35.20	34.05	34.15	34.39	34.44a	35.74	34.53	34.50	35.19	34.99a
I4		32.37	31.67	31.42	32.80	32.06b	32.85	32.02	31.63	33.01	32.37b
I5		28.78	29.49	29.82	31.19	28.76c	28.76	29.54	30.99	31.66	30.24c
Average		33.26	32.96	33.83	33.27	33.51	33.91	33.26	33.53	34.25	33.64
ANOVA											
ICD	3					ns					ns
I	4					*					*
ICD × I	12					ns					ns

Note: According to Tukey's test, the means within a column that do not share the same letter differ significantly at the $p \leq 0.05$ level; I1, I2, I3, I4, and I5 correspond to levels of soil water tension levels of 20, 30, 40, 50, and 60 kPa, respectively; and A, B, C, and D correspond to ICDs of 120, 130, 140, and 150 DAS, respectively.
Abbreviation: ANOVA, analysis of variance.
*$p < 0.05$; ns, not significant.

TABLE 4 Effect of irrigation regimes and irrigation cutoff dates on castor bean grains and oil yield in two crop cycles.

	Grain productivity (kg of grain ha^{-1})				Oil productivity (kg of oil ha^{-1})			
Treatment	A	B	C	D	A	B	C	D
First cycle								
I1	4948.75aA	5016.25aA	5047.50aA	5163.0aA	1733.0aA	1732.71aA	1749.52aA	1781.26aA
I2	4657.25abA	4832.5aA	4777.25aA	4737.25abA	1595.14abA	1713.73aA	1647.06abA	1635.52abA
I3	4701.25abA	4549.5abA	4612.50abA	4669.75abA	1594.9abA	1685.10aA	1663.38aA	1690.65abA
I4	4212.0bA	4057.25bcA	4058.0bA	4336.0bA	1469.03bA	1407.64bA	1432.84bcA	1500.49bA
I5	3436.0cB	3677.5cB	4132.25bA	4264.0bA	1184.76cB	1262.8bB	1406.67cA	1480.55bA
Second cycle								
I1	4328.88aA	4361.77aA	4343.13aA	4488.43aA	1515.38aA	1495.07aA	1536.25aA	1535.54aA
I2	4323.65aA	4203.1abA	4326.55aA	4240.23abA	1497.67aA	1492.47aA	1496.21abA	1530.19aA
I3	4149.03aA	4134.25abA	4224.35abA	4206.7abA	1466.79aA	1488.49aA	1487.24abA	1498.1aA
I4	3467.13bB	3954.8bcA	3938.8bA	4080.45bA	1211.87bB	1374.55aA	1367.63bcA	1415.83abA
I5	3385.9bC	3585.33cBC	3764.6bAB	3833.3bA	1163.43bC	1227.43bBC	1344.61cAB	1370.32bA

Note: According to the Tukey test, the means within a column that does not share the same lowercase letter and within the same row in an uppercase letter differ significantly at levels $p < 0.05$; I1, I2, I3, I4, and I5 correspond to soil water tension levels of 20, 30, 40, 50, and 60 kPa, respectively; and A, B, C, and D correspond to irrigation cutoff date of 120, 130, 140, and 150 days after sowing (DAS), respectively.

most indicated option, resulting in higher grain and oil yields with lower water demand. As shown in Figure 1, the 120 DAS treatment received the least amount of applied water.

In the first cycle, for treatment I5, higher grain and oil yields were obtained with irrigation cutoffs at 140 and 150 DAS compared to 120 and 130 DAS cutoffs. In the second cycle, for treatment I4, grain and oil yields were higher with irrigation suppression at 130, 140, and 150 DAS. These yields did not differ significantly from each other but were higher than 120 DAS. In treatment I5, higher grain and oil yields were observed with irrigation suppression at 150 DAS compared to 120 DAS. This indicates that the partial water deficit caused by the I5 treatment was mitigated by the longer irrigation cycle in both cycles.

In general, the irrigation regimes affected the yield components, and the correlation matrix between the variables analyzed in this study is shown in Table 5. The grain and oil yields increased and were positively correlated with the diameter, height, number of capsules per raceme, and weight of 100 grains. According to Neto et al. (2009) and Severino and Auld

TABLE 5 Correlation matrix between the variables analyzed.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Diameter	1	–	–	–	–	–	–
(2) Height	0.759*	1	–	–	–	–	–
(3) Number of racemes	0.088	0.131	1	–	–	–	–
(4) Number of fruits	0.585*	0.547*	−0.281	1	–	–	–
(5) Weight of 100 grains	0.651*	0.738*	0.238	0.412*	1	–	–
(6) Grain yield	0.649*	0.635*	0.208	0.668*	0.619*	1	–
(7) Oil yield	0.647*	0.624*	0.217	0.661*	0.604*	0.984*	1

*The correlation is significant at the 0.05 level.

TABLE 6 Water use efficiency (WUE) for grain and oil in two crop cycles.

	WUE for grains (kg grain m^{-3})				WUE for oil (kg oil m^{-3})			
Irrigation regimes	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
First cycle								
I1	1.15aA	1.07abAB	1.01aB	0.97aB	0.4052aA	0.373abAB	0.3487aB	0.335aB
I2	1.18aA	1.085abAB	0.998aBC	0.947aC	0.399aA	0.385abAB	0.344aBC	0.3272aB
I3	1.23aA	1.118aA	1.047aB	1.01aB	0.431aA	0.4227aA	0.3782aB	0.3635aB
I4	1.14aA	1.03bB	0.962aB	0.969aB	0.407aA	0.3593bB	0.3337aB	0.335aB
I5	0.96bA	0.9825bA	1.075aA	0.945aA	0.33bA	0.3365bA	0.349aA	0.3272aA
Second cycle								
I1	1.067aA	0.985bAB	0.9bBC	0.88aC	0.361aA	0.336aA	0.315aB	0.303aB
I2	1.113aA	1.02abB	0.95abB	0.87aC	0.368aA	0.356aA	0.33aAB	0.309aB
I3	1.15aA	1.102aA	1.0aB	0.91aC	0.384aA	0.367aA	0.345aAB	0.317aB
I4	0.975bA	1.06abB	0.97abB	0.925aB	0.298bB	0.338aA	0.318abAB	0.306aB
I5	0.98bA	0.99bA	0.98abA	0.93aA	0.287bB	0.30bB	0.316abA	0.310aA

Note: According to the Tukey test, the means within a column that do not share the same lowercase letter and within the same row in an uppercase letter differ significantly at levels $p < 0.05$; I1, I2, I3, I4, and I5 correspond to soil water tension levels of 20, 30, 40, 50, and 60 kPa, respectively; and A, B, C, and D correspond to ICDs of 120, 130, 140, and 150 DAS, respectively.
*$p < 0.05$; ns, not significant.

(2013), the increase in water stress also decreased castor oil production.

3.5 | Water use efficiency

The WUE for grain and oil as a function of irrigation regimes and dates of irrigation cutoff are shown in Table 6.

3.6 | WUE—grain

In the first cycle, the highest WUE values for grains occurred in I1, I2, and I3, which did not differ among themselves in treatments with irrigation cutoffs at 120 and 130 DAS. From 140 DAS, there was no differentiation in WUE between irrigation regimes (Table 6).

In the second cycle, WUE was higher with I1, I2, and I3 only with an irrigation cutoff at 120 DAS, with no differentiation between these treatments; when the cutoff occurred at 130 DAS, I3 presented WUE higher than I1 and I5. With water suppression at 140 DAS, I3 was higher than I1, while at 150 DAS, all water regimes had the same WUE. In both cycles, increasing the irrigation period resulted in equal WUE between water treatments (Table 6).

Regarding the irrigation suppression date, in the first cycle, the highest grain WUE occurred at 120 DAS for treatments I1, I2, I3, and I4. In treatment I5, there was no difference between ICDs.

In the second cycle, there was a higher value of WUE grains with irrigation cutoff at 120 DAS for treatments I2 and I4. In I1 and I3, WUE was higher at 120 and 130 DAS, while in I5, there was no difference in efficiency for the dates of water suppression.

Thus, in both cycles, treatments I1, I2, I3, and I4 had the greatest WUE when water suppression occurred earlier. Treatment I5 did not show this tendency, as it exhibited low grain yield across all ICDs (Table 4).

These findings align with those of Gomes et al. (2013), who indicated that more efficient irrigation could favor crop development, leading to improved vegetative growth and productivity, thereby enhancing WUE. Additionally, Barros Júnior et al. (2008) report that the WUE values of castor beans under water stress and adequate moisture conditions were similar to those observed in this study. Other studies, such as that of de Araújo Nascimento et al. (2022), reported lower WUE values, with some as low as 0.48 kg m^{-3}.

3.7 | WUE-oil

In the first cycle, regarding WUE-oil, the highest values for water suppression at 120 DAS were obtained with I1, I2, I3, and I4, which did not differ. At 130 DAS, I1, I2, and I3 showed the highest values of WUE-oil without any significant difference. From water suppression to 140 DAS, irrigation regimes did not differ regarding WUE-oil (Table 6).

In the second cycle, the irrigation cutoffs at 140 DAS and 150 DAS presented the same values of WUE-oil in all evaluated water regimes. For water suppression at 130 DAS, WUE-oil was superior in I1, I2, I3, and I4, without differentiating between them. Likewise, I1, I2, and I3 did not differ from each other and presented the highest WUE-oil values when the irrigation cut occurred at 120 DAS. (Table 6).

In both cycles, for all ICDs, it was found that treatments I1, I2, and I3 had the highest WUE-oil values without differing from each other. In this way, irrigation when the soil water tension reaches −40 kPa (I3) is the most indicated because it generates the highest efficiency with the lowest water demand.

For WUE-oil, in the first cycle, water suppression in treatments I1, I2, and I3 resulted in higher values at 120 DAS and 130 DAS. In treatment I4, higher values were obtained at 120 DAS, while treatment I5 did not show a significant difference between ICDs.

For the second cycle, in treatments I1 and I2, the highest WUE-oil values occurred with water suppression at 120 and 130 DAS compared to 140 and 150 DAS. In I3, 120 and 130 DAS resulted in values greater than 150 DAS. In I4, the highest WUE-oil occurred at 130 DAS, greater than at 120 DAS and 150 DAS. At I5, 120 and 130 DAS resulted in higher WUE-oil values than 120 and 130 DAS.

In both cycles, water suppression at 120 DAS resulted in higher WUE-oil values for treatments I1, I2, and I3.

Raj et al. (2010) and Sharma et al. (2010) observed a significant increase in the productivity of water and the WUE with the rise of supplementary irrigation in the castor bean crop. These findings support the results of this study, indicating that early water suppression optimizes WUE.

This study demonstrated that determining the optimal soil water tension and identifying the best ICDs can maximize crop production, improve WUE, and increase the profitability of the AG IMA 110–204 cultivar, which shows great promise for grain producers in Brazil.

3.8 | Considerations and recommendations

The castor bean water demand decreased from I1 to I5, and crop stage III (76–120 DAS) had the highest irrigation requirement.

The irrigation regimes and water supply cutoff dates did not affect the number of racemes per plant. However, treatments I1, I2, and I3 resulted in more fruits per raceme in both cycles.

The 20 (I1), 30 (I2), and 40 (I3) treatments showed the highest values and did not differ between themselves in the two cycles for the variables weight of 100 grains, grain yield, oil yield, WUE-grains, and WUE-oil. Therefore, irrigating when 40 kPa is reached is the most recommended because it obtained the best yield performance with lower water demand than 20 and 30 kPa.

When the irrigation cutoff was performed at 120 DAS, in both cycles, the water regimes I1, I2, and I3 showed the highest values and did not differ for the variables grain and oil yields, as well as WUE-grains and WUE-oil. In general, there was no difference among the water regimes for the other suppression dates (130, 140, and 150 DAS) for these same variables. Therefore, an irrigation cutoff at 120 DAS can be recommended because it generates the best productivity and WUE for grains and oil, with lower water demand.

4 | CONCLUSIONS

It can be concluded that castor bean is susceptible to drought stress, having significant reductions in stem diameter, plant height, number of fruits per raceme, weight of 100 grains, and yield with an increase in the soil water tension that defines irrigation.

The 20 (I1), 30 (I2), and 40 kPa (I3) treatments showed the highest values and did not differ among themselves in the two cycles for the variables weight of 100 grains, grain yield, oil yield, WUE-grains, and WUE-oil.

When the irrigation cutoff was performed at 120 DAS, in both cycles, water regimes I1, I2, and I3 presented the highest values and did not differ in grain and oil yields, WUE-grains, or WUE-oil.

Higher grain and oil yields with lower water demand for castor bean hybrid AG IMA 110204 (RNC-32752) were obtained with the combination of soil water tension 40 kPa to define the moment to irrigation and the irrigation cutoff at 120 DAS.

AUTHOR CONTRIBUTIONS

Alberto Mario Arroyo Avilez: Conceptualization; formal analysis; investigation; methodology; project administration; supervision; validation; writing—review and editing. **Andres Felipe Gaona Acevedo**: Investigation; validation; writing—original draf. **Luan Brioschi Giovanelli**: Conceptualization; writing—original draft. **João Carlos Cury Saad**: Conceptualization; investigation; writing—review and editing. **Ícaro Monteiro Galvão**: Formal analysis; visualization. **João Luis Zocoler**: Investigation; methodology; project administration; resources; writing—original draft; writing—review and editing. **Mauricio Dutra Zanotto**: Resources.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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REFERENCES

Afshar, R. K., Chaichi, M. R., Alipour, A., Jovini, M. A., Dashtaki, M., & Hashemi, M. (2015). Potential of milk thistle for biomass production in semiarid regions. *Crop Science*, *55*, 1295–1301. https://doi.org/10.2135/cropsci2014.10.0678

Albuquerque, S. C., Rocha, B., Albuquerque, R. F., Oliveira, J. S., Medeiros, R. M. T., Riet-correa, F., Evêncio-neto, J., & Mendonça, F. S. (2014). Spontaneous posisoning by *Ricinus communis* (Euphorbiaceae) in cattle. *Pesquisa Veterinária Brasileira*, *34*(9), 827–831.

Auld, D. L., Rolfe, R. D., & McKeon, T. A. (2001). Development of castor with reduced toxicity. *Journal of New Seeds*, *3*, 61–69. https://doi.org/10.1300/J153v03n03_03

Azevedo, D. M. P., & Beltrão, N. E. M. (2007). *O agronegócio da mamona no Brasil (No. 2. ed. rev. amp. Campina Grande)*. Embrapa Informação Tecnológica.

Bannayan, M., Nadjafi, F., Azizi, M., Tabrizi, L., & Rastgoo, M. (2008). Yield and seed quality of *Plantago ovata* and *Nigella sativa* under different irrigation treatments. *Industrial Crops and Products*, *27*, 11–16. https://doi.org/10.1016/j.indcrop.2007.05.002

Barreto, C. V. G., Sakai, E., Pires, R. C. M., & Arruda, F. B. (2008). Técnica de avaliação de bulbo úmido por múltiplos cortes em trincheira. *Irriga*, *13*(2), 160–169. https://doi.org/10.15809/irriga.2008v13n2p160-169

Barros Junior, G., Guerra, H. O. C., Cavalcanti, M. L. F., & D De Lacerda, R. (2008). Consumo de agua e eficiencia do uso para duas cultivares de mamona submetidas a estresse hídrico. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *12*, 350–355.

Beltrão, N. E. M., & Severino, L. S. (2006). *Mamona: O produtor pergunta e a Embrapa responde*. Embrapa.

Da Eira, A. T. A., Gonçalves, C., Guidetti, M. Z. P., Tucci, S. M. L., & Ferreira, C. E. (2014). *Instruções agrícolas para as principais culturas econômicas* (No. 200). https://www.iac.sp.gov.br/media/publicacoes/iacboletim200.pdf

de Araújo Nascimento, D., dos Santos Brito, A., da Silva, L. M. N., Peixouto, L. S., & Cotrim, V. F. (2022). Water use efficiency of castor bean under semi-arid conditions of Brazil. *Agricultural Water Management*, *260*, 107278. https://doi.org/10.1016/j.agwat.2021.107278

De Carvalho, I. C. B., Dos Santos Brito, A., De Araújo Nascimento, D., Peixouto, L. S., & Faria, H. H. N. (2020). Water use efficiency of castor bean variety in agroecological semiarid conditions. *Brazilian Journal of Development*, *6*(9), 73354–73373. https://doi.org/10.34117/bjdv6n9-698

De Freitas, C. A. S., Bezerra, F. M. L., Da Silva, A. R. A., Pereira Filho, J. V., & Feitosa, D. R. C. (2010). Comportamento de cultivares de mamona em níveis de irrigação por gotejamento em Pentecoste, CE. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *14*, 1059–1066. https://doi.org/10.1590/s1415-43662010001000006

De Sá, R. O., Galbieri, R., Bélot, J., Zanotto, M. D., Dutra, S. G., Severino, L. S., & Silva, C. J. (2015). *Mamona: Opção para rotação de cultura visando a redução de nematoides de galha no cultivo do algodoeiro* (Circular técnica Vol. 15). Embrapa.

Dias, J. M., de Azevedo, P. V., Bezerra, J. R. C., de Macêdo Beltrão, N. E., Oliveira, G. D. S., & Cavalcanti, M. I. P. (2015). *CONSUMO HÍDRICO E COEFICIENTE DE CULTIVO DA MAMONEIRA, CULTIVAR BRS ENERGIA*, 20, 429. IRRIGA. https://doi.org/10.15809/irriga.2015v20n3p429

dos Santos, H. G., Jacomine, P. K. T., dos Anjos, L. H. C., de Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., de Almeida, J. A., de Araujo filho, J. C., de Oliveira, J. B., & Cunha, T. J. F. (2018). *Sistema Brasileiro de Classificação de Solos* (5. ed.). Embrapa.

dos Souza, A. S., Távora, F. J. A. F., Pitombeira, J. B., & Bezerra, F. M. L. (2007a). Planting time and irrigation management for castor plant. II—effect on growth and productivity. *Revista Ciência Agronômica*, *38*, 422–429.

dos Souza, A. S., Távora, F. J. A. F., Pitombeira, J. B., & Bezerra, F. M. L. (2007b). Épocas de plantio e manejo da irrigação para a mamoneira. I—componentes de produção. *Revista Ciência Agronômica*, *38*, 414–421.

Dourado-Neto, D., Nielsen, D. R., Hopmans, J. W., Reichardt, K., & Bacchi, O. O. S. (2000). Software to model soil water retention curves (SWRC, version 2.00). *Scientia Agricola*, *57*. https://doi.org/10.1590/s0103-90162000000100031

Flexas, J., Niinemets, Ü., Gallé, A., Barbour, M. M., Centritto, M., Diaz-Espejo, A., Douthe, C., Galmés, J., Ribas-Carbo, M., Rodriguez, P. L., Rosselló, F., Soolanayakanahally, R., Tomas, M., Wright, I. J., Farquhar, G. D., & Medrano, H. (2013). Diffusional conductances to CO_2 as a target for increasing photosynthesis and photosynthetic water-use efficiency. *Photosynthesis Research*, *117*, 45–59. https://doi.org/10.1007/s11120-013-9844-z

Gomes, C. A., Lima, J. R. S., Padilha, K. M., Antonino, A. C. D., Borges Junior, J. C. F., Souza, E. S., & Montenegro, S. M. G. L. (2013). Uso de Água em cultivo de mamona no agreste meridional de Pernambuco. *Revista Brasileira de Recursos Hídricos*, *18*(4), 77–87. https://doi.org/10.21168/rbrh.v18n4

Litvin, A. G., Van Iersel, M. W., & Malladi, A. (2016). Drought stress reduces stem elongation and alters gibberellin-related gene expression during vegetative growth of tomato. *Journal of the American Society for Horticultural Science*, *114*, 591–597. https://doi.org/10.21273/JASHS03913-16

Mirzaei, A., Naseri, R., Moghadam, A., & Esmailpour-jahromi, M. (2013). The effects of drought stress on seed yield and some agronomic traits of canola cultivars at different growth stages. *Bulletin of Environment, Pharmacology and Life Sciences*, *2*, 115–121.

Moshkin, V. A. (1986). *Castor*. Kolos Publisher.

Neto, M. A., Alves Fernandes Távora, F., Crisóstomo, L., & Toscano Diniz, B. L. (2009). Adubação NPK e épocas de plantio para mamoneira. I—Componentes da produção e produtividade. *Revista Ciência Agronômica*, *40*, 578–587.

Oliveira, N. T., Castro, N. M. R., & Goldenfum, J. A. (2010). Influência da palha no balanço hídrico em lisímetros. *Revista Brasileira de Recursos Hídricos*, *15*(2), 93–103. https://doi.org/10.21168/rbrh.v15n2.p93-103

Osorio-González, C. S., Gómez-Falcon, N., Sandoval-Salas, F., Saini, R., Brar, S. K., & Ramírez, A. A. (2020). Production of biodiesel from castor oil: A review. *Energies*, *13*, 2467. https://doi.org/10.3390/en13102467

Ozer, H., Coban, F., Sahin, U., & Ors, S. (2020). Response of black cumin (*Nigella sativa* L.) to deficit irrigation in a semiarid region: Growth, yield, quality, and water productivity. *Industrial Crops and Products*, *144*, 112048. https://doi.org/10.1016/j.indcrop.2019.112048

Patel, B. D., Maliwal, G. L., Dudhatra, N. P., Kaswala, R. R., Patel, P. U., Raman, S., & Patel, M. (1998). Effect of drip irrigation on yield and water expense efficiency of castor. *Gujarat Agricultural University Research Journal*, *24*, 86–88.

Raj, A. D., Patel, B. S., & Mehta, R. S. (2010). Effect of irrigation methods on growth and economics of hybrid varieties of castor. *Indian Journal of Agricultural Sciences*, *80*, 795–800.

Rajala, A., Hakala, K., Mäkelä, P., & Peltonen-Sainio, P. (2011). Drought effect on grain number and grain weight at spike and spikelet level in six-row spring barley. *Journal of Agronomy and Crop Science*, *197*, 103–112. https://doi.org/10.1111/j.1439-037X.2010.00449.x

Ramanjaneyulu, A. V., Reddy, A. V., & Madhavi, A. (2013). The impact of sowing date and irrigation regime on castor (*Ricinus communis* L.) seed yield, oil quality characteristics and fatty acid composition during post rainy season in South India. *Industrial Crops and Products*, *44*, 25–31. https://doi.org/10.1016/j.indcrop.2012.10.008

Reddy, A. R., Reddy, K. R., Padjung, R., & Hodges, H. F. (1996). Nitrogen nutrition and photosynthesis in leaves of pima cotton. *Journal of Plant Nutrition*, *19*, 755–770. https://doi.org/10.1080/01904169609365158

Reddy, K. R., Koti, S., Davidonis, G. H., & Reddy, V. R. (2004). Interactive effects of carbon dioxide and nitrogen nutrition on cotton growth, development, yield, and fiber quality. *Agronomy Journal*, *96*, 1148–1157. https://doi.org/10.2134/agronj2004.1148

Richards, L. A. (1965). Physical conditions of water in soil. In C. A. Black, D. D. Evans, J. L. White, & F. E. Clark (Eds.), *Methods of soil analysis—Physical and mineralogical properties, including statistics of measurements and sampling* (pp. 128–152). ASA/SSSA.

Rios, G. F. A., de Carvalho, L. G., Silva, B. M., da Silva, W. G., Rezende, F. C., & Pereira, G. M. (2013). Component production of castor bean crop irrigated by different soil water tensions. *Agricultural Water Management*, *127*, 7–12. https://doi.org/10.1016/j.agwat.2013.05.007

Rotundo, J. L., & Westgate, M. E. (2010). Rate and duration of seed component accumulation in water-stressed soybean. *Crop Science*, *50*, 676–684. https://doi.org/10.2135/cropsci2009.05.0240

Sarwar, G., & Chaudhry, M. B. (2008). Short communication. Evaluation of castor (*Ricinus communis* L.) induced mutants for possible selection in the improvement of seed yield. *Spanish Journal of Agricultural Research*, *6*, 629–634. https://doi.org/10.5424/sjar/2008064-366

Severino, L. S., & Auld, D. L. (2013). Seed yield and yield components of castor influenced by irrigation. *Industrial Crops and Products*, *49*, 52–60. https://doi.org/10.1016/j.indcrop.2013.04.012

Severino, L. S., Auld, D. L., Baldanzi, M., Cândido, M. J. D., Chen, G., Crosby, W., Tan, D., He, X., Lakshmamma, P., Lavanya, C., Machado, O. L. T., Mielke, T., Milani, M., Miller, T. D., Morris, J. B., Morse, S. A., Navas, A. A., Soares, D. J., Sofiatti, V., … Zieler, H. (2012). A review on the challenges for increased production of castor. *Agronomy Journal*, *104*, 853–880. https://doi.org/10.2134/agronj2011.0210

Sharma, B. R., Rao, K. V., Vittal, K. P. R., Ramakrishna, Y. S., & Amarasinghe, U. (2010). Estimating the potential of rainfed agriculture in India: Prospects for water productivity improvements. *Agricultural Water Management*, *97*, 23–30. https://doi.org/10.1016/j.agwat.2009.08.002

Souza-Schlick, G. D., Soratto, R. P., Bottino, D., & Fernandes, A. (2012). Growth and yield of short height castor on different row spacings and plant populations. *Interciencia*, *37*, 49–57.

Souza-Schlick, G. D., de Soratto, R. P., Pasquali, C. B., & Fernandes, A. M. (2011). Desempenho da mamoneira IAC 2028 em função do espaçamento entre fileiras e população de plantas na safrinha. *Bragantia*, *70*, 519–528. https://doi.org/10.1590/s0006-87052011000300006

Taiz, L., Zeiger, E., Møller, I. M., & Murphy, A. (2015). *Plant physiology and development* (6th ed.). Sinauer Associates Incorporated.

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, *44*, 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Veríssimo, M. A., Silva dos A, S., Stähelin, D., Morais, P. P., Coimbra, J. L., & Guidolin, A. (2009). Rendimento de grãos de genótipos de mamona em épocas de semeadura, no planalto catarinense. *Revista de Ciências Agroveterinárias*, *8*, 129–138.

Zhou, S., Duursma, R. A., Medlyn, B. E., Kelly, J. W. G., & Prentice, I. C. (2013). How should we model plant responses to drought? An analysis of stomatal and nonstomatal responses to water stress. *Agricultural and Forest Meteorology*, *182–183*, 204–214. https://doi.org/10.1016/j.agrformet.2013.05.009

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