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Scientific Article

Leaf gas exchange, chlorophyll indices and yield of castor bean in contrasting water environments

Trocas gasosas foliares, índices de clorofila e produtividade de mamoneira em ambientes hídricos contrastantes

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ABSTRACT - Castor bean is a crop known to be drought tolerant, but like other crops, it shows reductions in yield under conditions of low water availability. Therefore, the objective whit this study was to evaluate leaf gas exchange, chlorophyll indices and yield of castor bean cultivars subjected to two contrasting water environments in the semi-arid region of Bahia, Brazil. Twelve castor bean cultivars were planted in a split-plot randomized block design, with the plot allocated to the contrasting water environments. Environment 1 was composed of irrigation close to field capacity, and environment 2 had about 30% of field capacity. Yield, leaf gas exchange, and chlorophyll content were evaluated. Statistical analyses were performed using Bayesian analysis with a variant of Hamiltonian Monte Carlo (HMC) to obtain Markov chains via Monte Carlo (MCMC). The MCMC were convergent and well mixed. In environment 2, the cultivars EBDA MPA 34, EBDA 17, and IAC 2028 showed yield above 1,700 kg ha^{-1}. Cultivar IAC 226 showed an increase of 9.98% in its yield in environment 2. Therefore, cultivars EBDA MPA 34, IAC 2028, IAC 226, and EBDA 17 are recommended to castor bean breeding programs as promising parents for studies under conditions of low water availability. Cultivars EBDA MPA 11 and BRS Paraguaçu showed high yield in both environments and are recommended for cultivation because they are responsive to the increase in water availability.

Keywords: *Ricinus communis* L.. Photosynthesis. Transpiration. Stomatal conductance.

RESUMO - A mamoneira é uma cultura conhecida como tolerante à seca, contudo, assim como outras culturas, apresenta reduções na produtividade sob condições de baixa disponibilidade hídrica. Sendo assim, o objetivo com o presente estudo foi avaliar as trocas gasosas foliares, os índices de clorofila e a produtividade de cultivares de mamoneira submetidas a dois ambientes hídricos contrastantes no semiárido baiano. Doze cultivares de mamona foram plantadas em parcela subdividida em blocos casualizados, onde na parcela foi alocado os ambientes hídricos contrastante, o ambiente 1 foi composto por irrigação próxima a capacidade de campo e o ambiente 2 com cerca de 30% da capacidade de campo. Foram avaliadas a produtividade, trocas gasosas foliares e teores de clorofila. As análises estatísticas foram realizadas por meio da análise bayesiana com uma variante da *Hamiltonian Monte Carlo* (HMC) para a obtenção das cadeias ocultas de Markov via Monte Carlo (MCMC). As MCMC foram convergentes e bem misturadas. No ambiente 2 as cultivares EBDA MPA 34, EBDA 17 e IAC 2028 apresentaram produtividade acima de 1.700 kg ha^{-1}. A cultivar IAC 226 apresentou um aumento de 9,98% em sua produtividade no ambiente 2. Já as cultivares EBDA MPA 34, IAC 2028, IAC 226 e EBDA 17 são recomendadas aos programas de melhoramento da cultura como genitores promissores para estudos em condições de baixa disponibilidade hídrica. As cultivares EBDA MPA 11 e BRS Paraguaçu apresentam alta produtividade nos dois ambientes sendo indicadas ao cultivo por serem responsivas ao aumento da disponibilidade hídrica.

Palavras-chave: *Ricinus communis* L.. Fotossíntese. Transpiração. Condutância estomática.

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INTRODUCTION

Castor bean (*Ricinus communis* L.) is a non-edible crop that has been drawing attention on the world stage due to the versatility of use of its oil, which contains approximately 90% ricinoleic acid in its composition (YEBOAH et al., 2020). The oil has numerous applications in the pharmaceutical industry, in the production of biodiesel, in the manufacture of cosmetics, lubricants for jet engines, aircraft and space rockets, and bone prostheses (RIOS et al., 2020).

The global castor oil market was estimated to be around US$ 1,180 million in 2018 and is expected to reach US$ 1,470 million by the end of 2025 (RAO et al., 2021). This crop develops well in arid and semi-arid climates around the world and is cultivated in approximately 30 countries, with the main world producers in 2021 being India with 89%, Mozambique with 3.9%, Brazil with 1.9% and China with 1.14% of the 1.83 million tons produced (FAOSTAT, 2023).

The high consumption of castor oil, combined with the stagnation of castor bean production technologies, triggers a scenario in which world production is insufficient to meet global demand (LU et al., 2019). Studies have been carried out with this crop to overcome this obstacle, especially in relation to the effects of environmental conditions, such as salinity (ZIOTTI et al., 2019), heavy metals (KUMAR et al., 2021; PEIXOUTO et al., 2021), cold (WANG et al., 2022), water deficit and water use efficiency (WUE) (CARVALHO et al., 2020; NASCIMENTO et al., 2022).

One of the major global problems is the proper use of water for irrigation, so water management in irrigated and rainfed agriculture is a relevant factor. In this context, plant breeding programs aimed at increasing WUE have been initiated and are heavily based on high-quality agronomic, morphological, physiological and molecular data generated under conditions of low water availability. Physiological data based on gas exchange and chlorophyll content have been shown to be important tools to assist in the selection of genotypes with greater tolerance to adverse conditions (ZEIST et al., 2018).

Among the statistical methodologies used to analyze field data is Bayesian modeling, which has the advantage of greater flexibility in the models to be used and guaranteed convergence (NUVUNGA et al., 2019), enabling the construction of more accurate credibility intervals for the estimates (ZHAO et al., 2016). The differences between management conditions may not be detected by classical methods of data analysis, which justifies the adoption of alternative approaches such as Bayesian analysis, aiming at results that support an increase in the production efficiency of the crop (SANTOS et al., 2021).

Thus, the objective of the present study was to evaluate leaf gas exchange, chlorophyll indices and yield of castor bean cultivars subjected to two contrasting water environments via Bayesian analysis.

MATERIAL AND METHODS

Plant material and growing conditions

The experiment was carried out in the experimental field of the Federal Institute of Education, Science and Technology of Bahia (IF Baiano), Guanambi campus, located in the district of Ceraíma, Southwest of Bahia, Brazil, with latitude of 14º13'30" S, longitude of 42º46'53" W, altitude of 525 m, average annual precipitation of 663.69 mm and tropical semi-arid climate (BSwh/AW') according to Köppen's classification (ALVARES et al., 2013), characterized by high average annual temperatures, with an annual average of 26.0 ºC. The soil of the experimental area is classified as *Latossolo Vermelho Amarelo distrófico típico* (Oxisol) (SANTOS et al., 2018; NASCIMENTO et al., 2022), sandy clay loam texture, which was prepared with one plowing and one harrowing operation. The experiment was set up in April, twelve days after the last rainfall event of that month, and continued until the beginning of October, before the rainfall events that occurred at the end of this month, totaling 180 days. During this period, an automatic weather station located near the experimental area collected meteorological data (Figure 1).

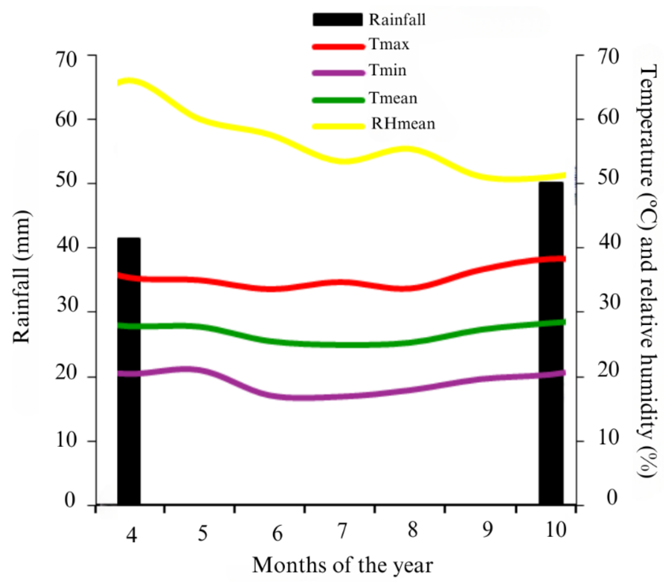

Figure 1. Rainfall, temperatures and relative humidity during the year of the experiment.

The experiment was set up in split-plots in a randomized block design with three replicates, comprising 12 castor bean cultivars and two contrasting environments regarding the amount of water used in irrigation. The contrasting water environments were considered as plots and the cultivars were considered as subplots. Plots were composed of nine plants (three rows of three plants), with spacing of 2 m between rows and 1 m between plants, totaling a population of 5000 plants per hectare. The central plant of each plot was used for evaluations to avoid interference between the irrigation depths.

The irrigation depth adopted was defined according to Nascimento et al. (2022) and Carvalho et al. (2020), applied using an 8 L/h dripper for one hour, reaching moisture close to field capacity (θ_{fc}=0.249 m^3 m^{-3}, corresponding to the matric potential of -10 kPa), and standardized until the flowering stage for all cultivars, with water availability close to field capacity. From flowering, irrigation depth close to field capacity was maintained in environment 1 (E1) and 30% of the irrigation depth used in environment 1 was used in environment 2 (E2).

Yield, leaf gas exchange and chlorophyll indices

Yield (YLD) was obtained at the end of the cycle considering the weight of seeds, corrected to moisture content of 10%, with subsequent estimation of average yield in kg ha^{-1}. Leaf gas exchange was measured with an infrared gas analyzer (IRGA), LCPro$^+$ Portable Photosynthesis System (ADC BioScientific Limited, UK), with temperature, ambient irradiance and air flow of 200 mL min^{-1}. Leaf gas exchange measurements were carried out in the central plant, with three readings per treatment.

Measurements were performed between 8 and 10 a.m., from 7 days after the beginning of the application of differentiated irrigation, starting in June and carried out every 15 days until reaching a total of five readings. The following parameters were obtained: leaf temperature (*LT*) (°C), internal carbon concentration (*Ci*) (µmol CO_2 mol^{-1}), stomatal conductance (*gs*) (H_2O mol m^{-2} s^{-1}), transpiration rate (*E*) (mmol H_2O m^{-2} s^{-1}), net photosynthesis rate (*A*) (µmol CO_2 m^{-2} s^{-1}), with water use efficiency (WUEi - *A/E*) calculated as the ratio between net photosynthesis and transpiration [(µmol CO_2 m^{-2} s^{-1})/(mmol H_2O m^{-2} s^{-1})] and instantaneous carboxylation efficiency (CEi - *A/Ci*) [(µmol CO_2 m^{-2} s^{-1})/(µmol CO_2 mol^{-1})] calculated as the ratio between net photosynthesis and internal carbon concentration. Chlorophyll *a*, chlorophyll *b* and total chlorophyll contents were determined with a portable chlorophyll meter (Clorofilog Falker®) following the same period of reading performed with IRGA, and the results were obtained in FCI - Falker chlorophyll index. These readings were performed in three leaves from each plot (repetition) and three measurements per leaf (replicate), with subsequent calculation of the average chlorophyll content per leaf.

Statistical analyses

Statistical analyses were performed using the R 4.2.0 program (R CORE TEAM, 2022). The Bayesian approach was applied by using the *No-U-Turn sampler* (NUTS), a variant of the *Hamiltonian Monte Carlo* (HMC), using the "*rstanarm*" package to obtain the hidden Markov chains via Monte Carlo (MCMC). The analysis was carried out using the "*stan_lmer*" function, considering the factors cultivar and interaction (cultivar x low water availability) as random and the factors repetition and water availability as fixed. For the model, three independent chains were defined with 4000 iterations each, *burn-in* (*Warmup*) of 50% and "*adapt_delta = 0.95*". For the prior distribution, hierarchical shrinkage priors were used, which are normal with zero mean and standard deviation, which is also a random variable, defined in the model as "*prior=hs(df = 3)*", being explored by the "*bayesplot*" package.

For the obtained data of gas exchange and chlorophyll indices, individual analyses were initially performed for each reading following the same Bayesian model, and the results (posterior means) were grouped for joint analysis. In the joint analysis, reading days were considered to be repetitions and the hypotheses of interest were tested by calculating the 95% credibility intervals for the parameters. For the yield variable, the same model of the individual analyses was used. To construct the radar graphs, the results obtained for all variables were standardized, and the "*fmsb*" package was used to plot the graphs.

RESULTS AND DISCUSSION

With the data analysis, it was observed that the iterations of the hidden Markov chains via Monte Carlo (MCMC) showed stability in the trace plot; however, for the net photosynthesis rate (*A*) variable, a more purple color was observed in the center of the graph, but it does not prevent the perception of data convergence (Figure 2). The simulated values, in relation to the number of iterations of the estimated parameters, showed that the MCMC chain was convergent and well mixed, with the distribution density close to the actual value, i.e., the values seem to oscillate around the mean, without trend aspects (Figure 2).

Using the hidden Markov chains via Monte Carlo (MCMC) method allows numerical approximation or sampling of the high-dimensional posterior distribution, thus expanding the inference of more complex statistical models (MEYER; CHOPARD; SALAMIN, 2017). When the algorithm converges, the distribution of interest is reached, that is, the posterior distribution has reached, approximately, its observed distribution. Thus, it allows greater flexibility to construct reliable intervals for unknown parameters, since all inference processes are based on posterior distribution (NUVUNGA et al., 2019).

After verifying the convergence of the MCMC chains, the posterior means, the standard deviation and the credibility interval (95%) were obtained for all the variables studied in the two contrasting water environments. In relation to the standard deviation (data not shown), all variables showed slightly higher values in environment 1 (E1). It was also observed that the credibility intervals were small, with variation of few units for all parameters, except YLD and *Ci*, which have a greater amplitude (data not shown). This demonstrates a great precision in the estimation of the parameters, because in the iterative process the values obtained were very close to the values observed. Thus, these parameters, credibility interval and standard deviation, indicate that the selection of genotypes is reliable.

Leaf temperature (*LT*) is an important parameter for decision-making on water deficit tolerance. Plants under ideal water regime are expected to have lower leaf temperatures than plants under water stress, as there is greater water availability for regulating their temperature, thus dissipating much of the heat absorbed from solar radiation (TAIZ et al., 2017). The cultivars EBDA MPA 11, IAC 226, IAC 20, EBDA MPA 01 and BRS Paraguaçu showed higher *LT* in environment 2 (E2). This was expected, indicating that the cultivars used their stomatal closure mechanism to cope with the water deficit. However, it was also observed that the cultivars IAC Guarani, IAC 2028, EBDA 17 and BRS Nordestina showed the opposite behavior, with a 0.5 °C to 2.71 °C higher *LT* in the environment without water deficit (environment 1). This fact indicates that these cultivars have other osmotic control mechanisms under conditions of low water availability. Keeping leaf temperature equal to or slightly lower than the temperature of the environment without deficit proves the cooling capacity of the leaves through transpiration, as the thermal properties of the water contribute to temperature regulation, helping to ensure that the plants do not cool down or heat up too quickly (RUGGIERO et al., 2017).

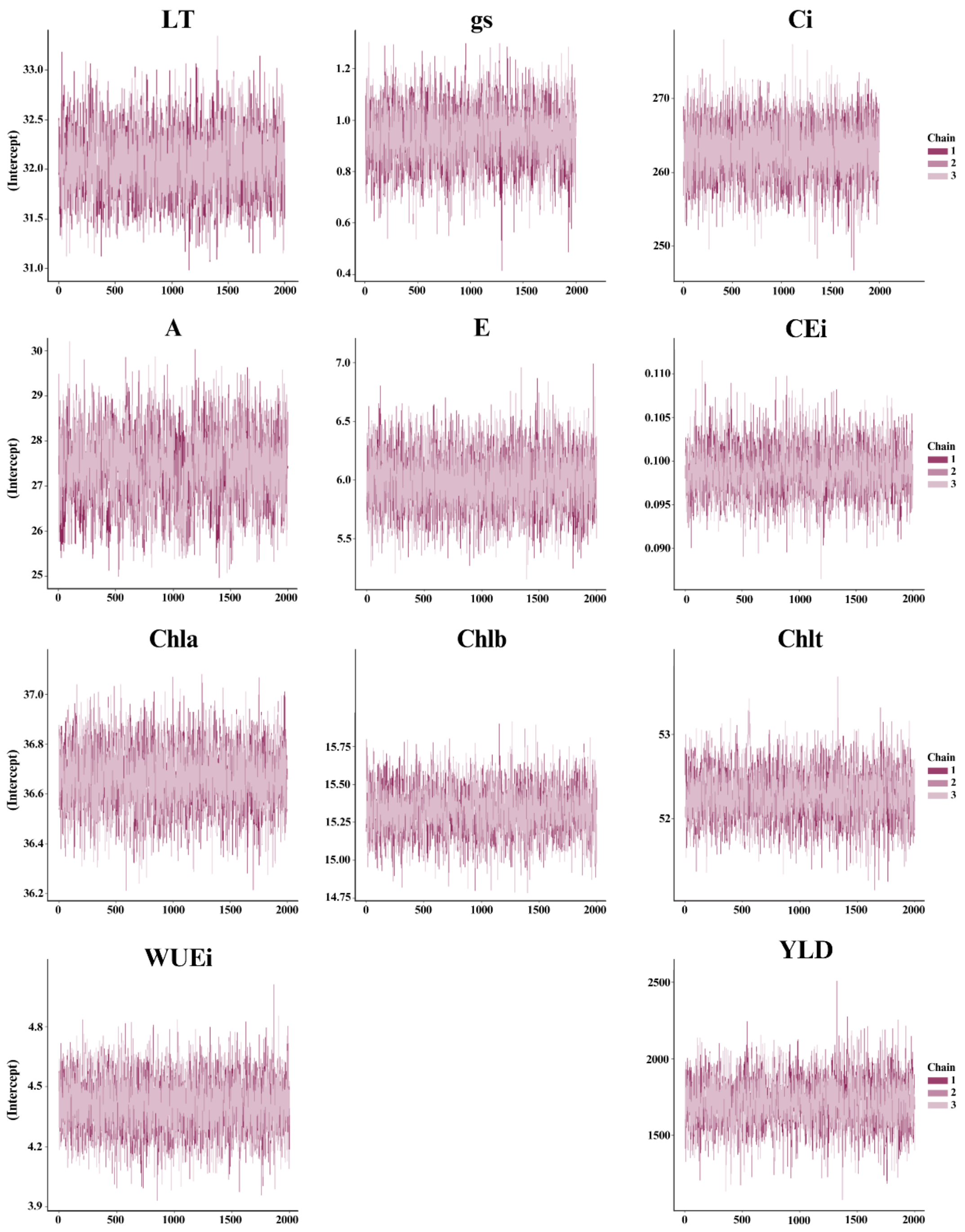

Figure 2. Trace plots of the iterations of the hidden Markov chains via Monte Carlo (MCMC) for the variables (LT) Leaf temperature, (gs) Stomatal conductance, (Ci) Internal CO_2 concentration, (A) Net assimilation rate, (E) Transpiration rate, (CEi) Instantaneous carboxylation efficiency (A/Ci), (Chla) Chlorophyll *a* content, (Chlb) Chlorophyll *b* content, (Chlt) Total chlorophyll content, (WUEi) Water use efficiency (A/E) and (YLD) Total yield.

All cultivars showed a decrease in internal CO_2 concentration (*Ci*) in environment 2, except EBDA MPB 35, EBDA 17 and BRS Paraguaçu, which had higher values in E2 (differences of 15.4, 16.14 and 9.36 μmol m^{-2} s^{-1}, respectively), and IAC 2028, which showed similar values between the two environments (Figures 3 and 4). For a plant to work efficiently, there must be a balance in gas exchange, seeking to maximize CO_2 absorption to perform photosynthesis with minimal water loss through transpiration (LAWSON; BLATT, 2014). Among the cultivars, EBDA 17 stands out for having the second highest Ci value in both environments, surpassing cultivars in the water environment without deficit. In addition, the cultivar also had better leaf temperature in the stress environment, corroborating the hypothesis of a secondary mechanism for coping with water stress. Another cultivar that differs from the others is IAC 2028, which had similar values of *Ci* and leaf temperature in both environments, showing tolerance to water deficit.

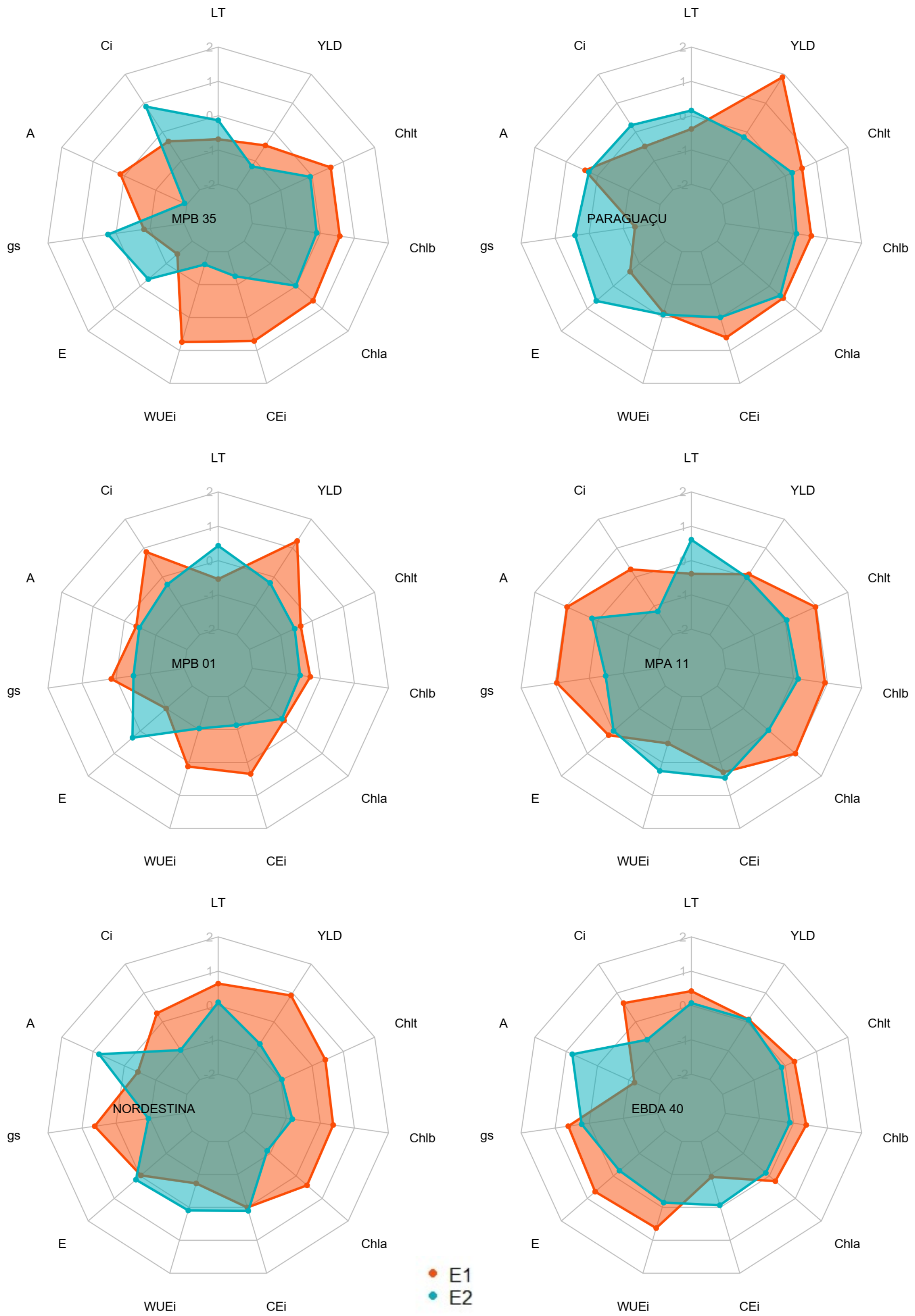

Figure 3. Radar graph of the normalized posterior means of physiological parameters and yield in castor bean cultivars subjected to contrasting water environments (E1 – irrigation depth close to field capacity, E2 – 30% of the irrigation depth of E1). (*LT*) Leaf temperature, (*gs*) Stomatal conductance, (*Ci*) Internal CO_2 concentration, (*A*) Net photosynthesis rate, (*E*) Transpiration rate, (*CEi*) Instantaneous carboxylation efficiency, (Chla) Chlorophyll *a* content, (Chlb) Chlorophyll *b* content, (Chlt) Total chlorophyll content, (WUEi) Intrinsic water use efficiency, and (YLD) Total yield.

Figure 4. Radar graph of the normalized posterior means of physiological parameters and yield in castor bean cultivars subjected to contrasting water environments (E1 – irrigation depth close to field capacity, E2 – 30% of the irrigation depth of E1). (*LT*) Leaf temperature, (*gs*) Stomatal conductance, (*Ci*) Internal CO_2 concentration, (*A*) Net photosynthesis rate, (*E*) Transpiration rate, (*CEi*) Instantaneous carboxylation efficiency, (Chla) Chlorophyll *a* content, (Chlb) Chlorophyll *b* content, (Chlt) Total chlorophyll content, (WUEi) Intrinsic water use efficiency, and (YLD) Total yield.

Regarding the net photosynthesis rate (A), the cultivars EBDA 40, IAC 226, IAC 20 and BRS Nordestina had higher values in environment 2 (Figures 3 and 4). Carvalho et al. (2019), in a greenhouse experiment with the cultivars BRS Energia and BRS Paraguaçu, found similar values for net photosynthesis rate between the cultivars (26 μmol CO_2 m^{-2} s^{-1}). This value was within the range observed in the present study, ranging from 26.66 to 28.55 μmol of CO_2 m^{-2} s^{-1} in the two contrasting water environments (Figures 3 and 4). On the other hand, the cultivars IAC Guarani, EBDA MPB 01 and BRS Paraguaçu showed similar values in the contrasting environments, indicating that the water deficit did not alter their net photosynthesis rate. This may not be associated with stomatal conductance, since all cultivars (except EBDA MPB 35, EBDA 17 and BRS Paraguaçu) showed lower values for *gs* in E2 compared to E1 (Figures 3 and 4), indicating a tendency to restrict water loss by transpiration and possibly preventing a decrease in the water potential of the plants.

It is known that, under conditions of stress, stomatal movement is an important means of plant defense against excessive water loss and eventual death by desiccation (TAIZ et al., 2017). Stomatal closure, i.e., a decrease in *gs*, leads to a reduction in transpiration with an increase in resistance to CO_2 uptake, consequently affecting the photosynthetic process (DALBERTO; MARTINAZZO; BACARIN, 2017). In this context, the cultivars studied showed a reduction in *gs* in environment 2, except for EBDA MPB 35, EBDA 17 and BRS Paraguaçu, which had higher *gs* in environment 2 (Figures 3 and 4). The cultivars EBDA MPA 34 and IAC 2028 showed similar values in both environments. When considering *Ci* and *gs* together, the cultivars EBDA MPB 35, EBDA 17 and BRS Paraguaçu have high stomatal conduction and, consequently, high internal CO_2 concentration, indicating that they use other physiological mechanisms for water regulation, keeping the stomata open for longer. This is reflected in the net photosynthesis rate of these cultivars; the cultivar BRS Paraguaçu had equal values between the environments, and the cultivar EBDA 17 showed a small loss of expression. On the other hand, the cultivar EBDA MPB 35 had a significant reduction in the net photosynthesis rate when subjected to environment 2, with the lowest value (24.95 μmol of CO_2 m^{-2} s^{-1}). According to Carvalho et al. (2019), this will result in a lower growth of plants under water stress.

Another interesting parameter to observe in studies on water deficit is the transpiration rate (E); the cultivars IAC Guarani, EBDA MPB 01, IAC 20, EBDA MPB 35 and BRS Paraguaçu showed higher values for this parameter in the environment with lower water availability (Figures 3 and 4). The great challenge to increase water use efficiency is to improve the balance of water lost through transpiration with efficient CO_2 absorption (RUGGIERO et al., 2017). In this context, the plant must be efficient in using transpiration water to regulate leaf temperature and maintain turgidity and the mass flow of water in the soil, even under deficit, so that there is no need for stomatal closure. If stomatal closure occurs, this event should be for a short period, of greater solar intensity, so that the decrease in CO_2 absorption and the decrease in photosynthesis do not negatively influence yield. Thus, the yield and water use efficiency of the plant depend on the efficient control of gas exchange (leaf/atmosphere) performed by the stomata (LAWSON; BLATT, 2014).

Water deficit affected the instantaneous carboxylation efficiency (*CEi*) in the two cultivars evaluated by Dalberto, Martinazzo and Bacarin (2017), who found reduction in *CEi* values from 15 days of evaluation in the cultivar BRS Gabriela and after 8 days in the cultivar IAC Guarani. This differs from the results observed in the present study, in which the cultivars IAC Guarani and IAC 20 were the ones with the highest *CEi* values in the stress environment, a difference of almost 18% between the cultivars that had the lowest values, namely EBDA MPB 01 and EBDA MPB 35 (Figures 3 and 4).

Photosynthetic pigments are important, as they participate in processes related to the absorption of light energy for subsequent conversion into ATP and NADPH+H (TAIZ et al., 2017). However, water stress causes a reduction in chlorophyll and a progressive decline in the photosynthetic capacity of plants (SALEHI; TASDIGHI; GHOLAMHOSEINI, 2016), so the analysis of photosynthetic pigments is an important tool for evaluating photosynthesis processes under water stress conditions.

For the chlorophyll *a* (*Chla*) content, the values of all cultivars were around 36 FCI. Under conditions of low water availability, the cultivar EBDA 17 showed an increase of around 1.73% in *Chla*, while the cultivar IAC 226 showed an increase of less than 1.1% in this environment (Figures 3 and 4). In relation to chlorophyll *b* (*Chlb*), the maintenance of a higher content of this enzyme under water deficit conditions suggests a greater photosynthetic capacity for these genotypes (SALEHI; TASDIGHI; GHOLAMHOSEINI, 2016). Most of the cultivars had values around 15 FCI between the two environments. The cultivar BRS Nordestina showed an increase of approximately 3.8% in *Chlb* content in environment 1, whereas the other cultivars that also showed higher values in environment 1, such as EBDA MPA 11, IAC 2028, EBDA 40, EBDA MPB 01, EBDA MPB 35 and Paraguaçu showed an increase below 2.30% compared to environment 2 (Figures 3 and 4). On the other hand, the cultivars EBDA 17 and IAC 226 showed higher values in environment 2, with increments of 8.42% and 3.4% respectively, whereas the others that were not mentioned had increments below 1.5% (Figures 3 and 4). The same behavior is observed for total chlorophyll. Thus, cultivars that maintain higher values for photosynthetic pigments under water deficit have a better ability to tolerate this condition, due to the close relationship between chlorophylls and photosynthetic potential (IQBAL et al., 2021).

Intrinsic water use efficiency (WUEi) is an important parameter to understand the plant's response to water stress. Unlike agronomic WUE, which is the ratio of plant production to the water consumed by the plant during the cycle, WUEi is obtained by the ratio of the photosynthetic rate to the transpiration rate, called transpiration ratio (TAIZ et al., 2017). WUE represents a parameter that aims to reduce competition for fresh water and increase yield and survival during periods of water stress (RUGGIERO et al., 2017). The values observed for WUEi in the present study were around 4 μmol CO_2 mmol of H_2O^{-1} (data not shown), hence lower than those found by Carvalho et al. (2019) in a greenhouse experiment. The authors evaluated the cultivars BRS Energia and BRS Paraguaçu and found values close to 7.5 μmol CO_2 mmol of H_2O^{-1} for WUEi among the two cultivars. This difference may have occurred due to the location of the experiment, since the present study was conducted in the field, while the researchers' experiment was carried out in a greenhouse, in addition to the peculiarities of agroecological and conventional cultivation.

Also in relation to WUEi, the cultivars that showed an increase in their values in environment 2 compared to environment 1 were EBDA MPA 11 (3%), IAC Guarani (3%), BRS Nordestina (3%) and EBDA MPA 34 (5.73%) (Figures 3 and 4). The reduction in WUEi may be due to the decrease in stomatal conductance, which reduces the efficiency of CO_2 assimilation through photosynthesis (CARVALHO et al., 2019), which may have been the response to the treatment by the other cultivars. What can be observed is that, when the photosynthesis rate rose, transpiration followed this increase, causing the differences to get closer. That is, when the photosynthesis of the cultivars EBDA 40, IAC 226, IAC 20 and BRS Nordestina was higher in environment 2, the transpiration rate in environment 2 was also higher than in environment 1.

Agricultural crops tend to reduce their yield when subjected to water stress; however, the cultivar IAC 226 showed a higher yield in environment 2, with a mean of 1641.8 kg ha^{-1}, an increase of 9.98% compared to environment 1 (Figures 3 and 4). This may have been caused by the higher value of photosynthetic rate, which may be related to the minimum transpiration rate, that is, the priority of the plant is to maintain maximum photosynthesis, with the least possible water loss (ROUX; LEONHARDT, 2018; MONTILLET et al., 2021). In other words, the cultivar uses other water regulation mechanisms that generate additional advantages for it, so that even in situations of water deficit there is no decrease in yield. For example, a higher concentration of sugar in the leaves can increase leaf water potential and leaf area, besides reducing the photooxidation activity of chlorophyll (SALEHI; TASDIGHI; GHOLAMHOSEINI, 2016).

The cultivars IAC 20, IAC Guarani, EBDA MPA 34, EBDA 17 and IAC 2028 showed a slight reduction in yield under conditions of low water availability, the last three with yield above 1,700 kg ha^{-1} in environment 2 (Figures 3 and 4). Bahia is the largest national producer, with an increase in production of 14.3% in the 23/24 harvest, reaching yield of 1,782 kg/ha due to the change in the profile of castor bean producers, who started to irrigate their production by drip systems (CONAB, 2024). These values are similar to those achieved by the cultivars under conditions of low water availability, revealing that some cultivars used in the present study can, momentarily, meet the need of farmers in the planting of more responsive cultivars that guarantee income in both rainfed and irrigated systems.

Among the cultivars mentioned above, only IAC 2028 has the polygon formed under conditions of low water availability within that formed by environment 1, despite having a yield loss of 0.35%, which shows that the physiological parameters are not responsible for maintaining yield for this crop (Figures 3 and 4). It can be caused by the architecture of the plant, a more robust root system in water absorption, among other factors.

The cultivar IAC Guarani showed no yield loss in the environment with low water availability (Figures 3 and 4). Dalberto, Martinazzo and Bacarin (2017), in a study with the cultivars AL Guarany 2002 and IAC Guarani under flooded conditions, observed higher values of the parameters *A*, *gs* and *E* in the cultivar IAC Guarani compared to the control plants and very similar values of *Ci*, reaching 13 µmol of CO_2 m^{-2} s^{-1} for *A*, 0.4 mol of H_2O m^{-2} s^{-1} for *gs* and 4 mmol from H_2O m^{-2} s^{-1} for *E*. These authors also observed that, for the cultivar IAC Guarani under flooded conditions, WUE was lower than that of control plants (DALBERTO; MARTINAZZO; BACARIN, 2017), unlike the present study, in which WUE was slightly higher under conditions of low water availability than in environment 1 (Figures 3 and 4).

The cultivars that showed the greatest reduction in yield in environment 2, with losses ranging from 21% to 39.9% were EBDA 40, EBDA MPB 35, EBDA MPB 01, EBDA MPA 11, BRS Paraguaçu and BRS Nordestina, in increasing order of yield reduction (Figures 3 and 4). Considering what occurred in the physiological parameters of these cultivars, increments in the values of *LT*, *Ci*, *gs* and *E* were observed in environment 2 (Figures 3 and 4), revealing that these cultivars do not have a good regulation of stomatal closure when subjected to water stress, which may be affecting their yield. However, the cultivar EBDA 40 had lower values for *LT*, *Ci*, *gs* and *E* in environment 2, diverging from the others, indicating that there is another mechanism that is influencing the reduction of yield in the environment under water deficit. These facts lead to the inference that the control of stomatal closure, whose function is to maintain the water content and turgidity of the leaf tissue (LAWSON; BLATT, 2014), thus helping to prevent water loss to the atmosphere through transpiration, was the main factor for the reduction in yield. In other words, a reduction in *gs* is costly for the plant, as it is closely associated with a reduction in the photosynthesis rate (CARVALHO et al., 2019).

In this context, the cultivars EBDA MPA 34, IAC 2028, IAC 226 and EBDA 17 are recommended to crop breeding programs as promising parents for studies under conditions of low water availability and with good water use efficiency (WUE) because they show lower yield losses in this environment (Figures 3 and 4). The cultivars EBDA MPA 11 and BRS Paraguaçu, despite having lost considerable values in yield in environment 2, are still very close to those mentioned above when cultivated under these conditions (Figures 3 and 4).

Thus, breeding programs for castor bean can increase the expression of desirable traits, such as yield, using cultivars as a source of genetic variability to obtain hybrids with high yield potential (OLIVEIRA et al., 2021), hence providing perspectives for new research in terms of both low water availability and increments in yield and oil content for the release of cultivars adapted to the main cultivation regions, especially those that undergo long periods of drought.

In view of the yield shown by the cultivars EBDA MPA 11 and BRS Paraguaçu under conditions of low water availability (Figures 3 and 4), it is important to highlight that they are recommended to small producers in the semi-arid region as a potential source of income under these conditions. If the producer has more resources and uses irrigation, these cultivars will respond to the investment in water resources and will produce more than 2,000 kg ha^{-1}, which is higher than the national average obtained in irrigated crops (CONAB, 2024). If the producer does not have available water resources, they produce at levels close to those shown by the cultivars with lower losses under conditions of low water availability.

CONCLUSIONS

Castor bean crop can meet market demands when produced in regions with low water availability, producing in an economically viable way. There was no physiological parameter that stood out in the differentiation of the cultivars when subjected to the two water environments, indicating that there is a combination of these traits regarding the response to water deficit in castor bean. Cultivar IAC 226 shows a positive response in the environment with low water availability, as it had an increase in yield. Cultivars EBDA MPA 11, IAC Guarani, BRS Nordestina and EBDA MPA 34 show the highest values for WUE in the water deficit environment with 30% field capacity. Cultivars EBDA MPA 34, IAC 2028, IAC 226 and EBDA 17 are recommended to crop breeding programs as promising parents for studies under conditions of low water availability. Cultivars EBDA MPA 11 and BRS Paraguaçu have high yield, in the presence and absence of water deficit, being recommended to castor bean breeding programs and family farmers for responding to the increase in water resources with increased yield.

REFERENCES

ALVARES, C. A. et al. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, 22: 711-728, 2013.

CARVALHO, I. C. B. et al. Eficiência de uso da água de mamoneiras nas condições agroecológicas do semiárido. **Brazilian Journal of Development**, 6: 73654-73373, 2020.

CARVALHO, M. et al. *Ricinus communis* L.: Water Use Efficiency, Carbon Assimilation and Water Relations on Deficit Irrigation. **Journal of Experimental Agriculture International**, 30: 1-15, 2019.

CONAB - Companhia Nacional de Abastecimento. **Acompanhamento da safra brasileira de grãos**. Brasília, DF, v. 11 – Safra 2023/24, n. 8 - Oitavo levantamento, p. 1-139, maio 2024. Available at: <https https://www.conab.gov.br/info>. Access on: Jun. 05, 2024.

DALBERTO, D. S.; MARTINAZZO, E. G.; BACARIN, M. A. Chlorophyll a fluorescence reveals adaptation strategies in drought stress in *Ricinus communis*. **Brazilian Journal of Botany**, 40: 861-870, 2017.

FAOSTAT - Food and agriculture organization of the United Nations. **Crop and livestock statistics**. Available at: < https://www.fao.org/faostat/en/#data/QCL> Access on: Nov. 15, 2023.

IQBAL, R. et al. Assessing the potential of partial root zone drying and mulching for improving the productivity of cotton under arid climate. **Environmental Science and Pollution Research**, 28: 66223-66241, 2021.

KUMAR, V. et al. Phytoextraction of heavy metals and ultrastructural changes of Ricinus *communis* L. grown on complex organometallic sludge discharged from alcohol distillery. **Environmental Technology & Innovation**, 22: 101382, 2021.

LAWSON, T.; BLATT, M. R. Stomatal Size, Speed, and Responsiveness Impact on Photosynthesis and Water Use Efficiency. **Plant Physiology**, 164: 1556-1570, 2014.

LU, J. et al.The genetic mechanism of sex type, a complex quantitative trait, in *Ricinus communis* L. **Industrial Crops and Products**, 128: 590-598, 2019.

MEYER, X.; CHOPARD, B.; SALAMIN, N. Accelerating Bayesian inference for evolutionary biology models. **Bioinformatics**, 33: 669-676, 2017.

MONTILLET, J. L. et al. Plastidial and cytosolic thiol reductases participate in the control of stomatal functioning. **Plant, Cell & Environment**, 44: 1417-1435, 2021.

NASCIMENTO, D. A. et al. Water use efficiency of castor bean under semi-arid conditions of Brazil. **Agricultural Water Management**, 260: 107278, 2022.

NUVUNGA, J. J. et al. Bayesian factor analytic model: An approach in multiple environment trials. **PloS one**, 14: e0220290, 2019.

OLIVEIRA, C. E. S. et al. Genetic divergence and path analysis in wheat cultivars under heat stress. **Pesquisa Agropecuária Tropical**, 50: e65493, 2021.

PEIXOUTO, Y. S. et al. Potential of *Ricinus communis* for the removal of toxic metals from mining dumping sites. In: BAUDDH, K.; KORSTAD, J.; SHARMA, P. (Eds.). **Phytorestoration of Abandoned Mining and Oil Drilling Sites**. Elsevier, 2021. cap. 11, p. 263-286.

R CORE DEVELOPMENT TEAM. **R: A language and environment for statistical computing.** R Foundation for Statistical Computing, Vienna, Austria. 2022. Available at: <https://www.R-project.org/>. Access on: Jun. 15, 2024.

RAO, P. et al. Drip Irrigation in Castor Enhances Bean Yield, Saves Water and Increases Profitability. **Chronicle of Bioresource Management**, 5: 48-53, 2021.

RIOS, Í. C. et al. Chemical modification of castor oil fatty acids (*Ricinus communis*) for biolubricant applications: An alternative for Brazil's green market. **Industrial Crops and Products**, 145: 112000, 2020.

ROUX, B.; LEONHARDT, N. The regulation of ion channels and transporters in the guard cell. In **Advances in Botanical Research**, 87: 171-214, 2018.

RUGGIERO, A. et al. Improving Plant Water Use Efficiency through Molecular Genetics. **Horticulturae**, 3: 31-31, 2017.

SALEHI, A.; TASDIGHI, H.; GHOLAMHOSEINI M. Evaluation of proline, chlorophyll, soluble sugar content and uptake of nutrients in the German chamomile (*Matricaria chamomilla* L.) under drought stress and organic fertilizer treatments. **Asian pacific Journal of Tropical Biomedicine**, 6: 886-891, 2016.

SANTOS, F. A. S et al. Frequentist and Bayesian inference for gas exchanges of drip-irrigated bell pepper. **Pesquisa Agropecuária Tropical**, 51: e66435, 2021.

SANTOS, H. G. et al. **Sistema Brasileiro de Classificação de Solos**. 5. ed. Brasília, DF: EMBRAPA, 2018. 356 p.

TAIZ, L. et al. **Fisiologia e desenvolvimento vegetal**. 6 ed. Porto alegre, RS: Artmed, 2017. 888 p.

WANG, X. et al. Dynamic transcriptome profiling revealed key genes and pathways associated with cold stress in castor (*Ricinus communis* L.). **Industrial Crops and Products**, 178: 114610, 2022.

YEBOAH, A. et al. Castor oil (Ricinus communis): a review on the chemical composition and physicochemical properties. **Food Science and Technology**, 41: 399-413, 2020.

ZEIST, A. et al. Photosynthetic characteristics in species and interspecific hybrids of tomato. **Horticultura Brasileira**, 36: 362-370, 2018.

ZHAO, T. et al. Bayesian analysis of continuous time Markov chains with application to phylogenetic modelling. **Bayesian Analysis**, 11: 1203-1237, 2016.

ZIOTTI, A. B. et al. Photorespiration is crucial for salinity acclimation in castor bean. **Environmental and Experimental Botany**, 167: 103845, 2019.