

Article

Gas Exchange and Chlorophyll Fluorescence Responses of Açaí and Juçara Palms Under Salt Stress

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Abstract

The genus *Euterpe*, which includes açaí palm (*Euterpe oleracea*) and juçara palm (*Euterpe edulis*), plays an important socioeconomic and environmental role in Brazil. However, soil and water salinization is a global issue that compromises agricultural productivity by affecting plant physiological and metabolic processes. This study aimed to evaluate the physiological responses of young açaí and juçara plants under salt stress. The experiment was conducted in a randomized complete block design in a 5 × 2 factorial arrangement, consisting of five irrigation water salinity levels (0.1, 1.0, 2.0, 3.0, and 5.0 dS m^{−1}) and two *Euterpe* species (açaí and juçara), with four replicates. After 104 days of stress exposure, gas exchange, chlorophyll ‘a’ fluorescence, relative chlorophyll index (SPAD), and sodium, chloride, and phenolic compounds were evaluated. Increasing salinity caused linear reductions in the maximum quantum yield and potential photochemical efficiency of PSII, accompanied by an increase in F₀/F_m, indicating impaired PSII photochemical performance and photoinhibition. Stomatal conductance and transpiration also decreased significantly with increasing salinity, with reductions of up to 41.33% and 35.48%, respectively, at the highest salinity level. Salt stress negatively affected the physiological performance of both palm species through stomatal limitation and reduced photosystem II efficiency. However, açaí plants exhibited greater tolerance to salt stress than juçara plants.

Keywords: *Euterpe oleracea*; *Euterpe edulis*; fluorescence of chlorophyll; gas exchange



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1. Introduction

The exploitation of natural resources in the Amazon region represents an economically important activity driven by the wide diversity of non-timber forest products (NTFPs), which play a fundamental role in floodplain, seasonally flooded, and upland forest ecosystems. These environments, characterized by high soil moisture, provide an important source of income for traditional and quilombola communities based on family farming systems [1,2].

Concerns regarding the conservation of native species have increased interest in Juçara palm (*Euterpe edulis* Mart.) not only for heart-of-palm extraction, but also for fruit production and pulp processing, which are highly similar to those of açaí palm fruits produced in the Amazon region. Both açaí and juçara palms play important ecological roles in flooded environments, especially along riverbanks, due to their tolerance to high soil moisture conditions, contributing to sediment retention and water quality preservation [3,4].

The recognition of açaí palm (*Euterpe oleracea* Mart.) as an economically important fruit crop is relatively recent. Fruit extraction from native forests represents an important production chain in Brazil. In recent years, the increasing demand for processed açaí pulp, particularly in the South and Southeast regions of the country, has stimulated the expansion of technified cultivation systems not only in the Amazon region, but also in several other Brazilian states [5,6].

Plant species differ considerably in their tolerance to environmental stresses such as cold, heat, drought, flooding, and salinity. Water in its liquid form is essential for plant growth, acting not only as a medium for metabolic reactions but also for nutrient transport within plant tissues. Although some species can survive dehydration and freezing conditions, plant growth is not possible in the absence of liquid water [7]. In this context, soil and water salinization has become a global problem, affecting approximately 1.1 billion hectares, corresponding to nearly 7% of the Earth's surface, and is considered one of the main causes of crop productivity losses worldwide [8,9].

Salinity can interfere with virtually all physiological and metabolic processes in plants [10]. Its effects depend on several factors, including species, cultivar, phenological stage, salt composition, stress intensity and duration, irrigation management, and edaphoclimatic conditions [11,12].

Salt stress affects plant development through a two-phase process, beginning with an immediate osmotic effect followed by ionic toxicity during prolonged exposure. Excessive accumulation of sodium (Na^+) and chloride (Cl^-) ions in plant tissues disrupts the K^+/Na^+ balance and cellular homeostasis, resulting in nutritional imbalance and impairment of essential physiological functions [13,14].

In addition, salt stress promotes ultrastructural damage to chloroplasts and disrupts thylakoid membrane organization, directly affecting photochemical efficiency and inhibiting key enzymes such as ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), thereby severely impairing photosynthesis [15]. Salinity-induced photochemical inhibition involves reductions in photosystem II (PSII) quantum efficiency and impairment of electron transport, favoring the generation of reactive oxygen species (ROS) and the occurrence of photoinhibition [16].

Although palm species generally show satisfactory development under saline conditions, tolerance to elevated salinity levels varies according to the species. In this context, the aim of this study was to evaluate the physiological responses of young açaí and juçara plants under salt stress.

2. Results

2.1. Relative Chlorophyll Content and Chlorophyll Fluorescence

No significant differences were observed between species or salinity levels for relative chlorophyll content (SPAD), with similar mean values for both açai and juçara, averaging 39.41 SPAD units (Table 1). However, açai showed slightly higher performance than juçara, exhibiting approximately 5% higher leaf greenness, whereas juçara showed a 5% reduction relative to the overall mean.

Table 1. Relative chlorophyll content (SPAD) and chlorophyll a fluorescence parameters, including maximum quantum yield of PSII (F_v/F_m), basal non-photochemical quantum yield (F_0/F_m), maximum photochemical efficiency of PSII (F_v/F_0), and performance index (PI) [mean across five electrical conductivity levels] in açai and juçara plants at 16 months after sowing, subjected to irrigation water salinity (EC).

Species	SPAD	F_v/F_m	F_0/F_m	F_v/F_0	PI
Açai	41.22 a ¹	0.751 a	0.249 a	3.138 a	2.02 a
Juçara	37.61 a ¹	0.712 a	0.288 a	2.836 a	1.54 a
Mean	39.41	0.73	0.27	2.99	1.78
CV%	16.7	11.94	32.79	20.67	60.13

¹ Means followed by the same letters within the column do not differ significantly at $p \leq 0.05$ by Tukey's test. CV = coefficient of variation.

Chlorophyll fluorescence parameters were similar between species, with comparable mean values for F_v/F_m , F_0/F_m , and F_v/F_0 (Table 1). Açai maintained PSII quantum yield approximately 3% above the overall mean, whereas juçara showed a 24% reduction in its photosynthetic performance index compared to the mean.

Regarding salinity, significant linear decreases were observed for F_v/F_m and F_v/F_0 and increases for F_0/F_m with increasing electrical conductivity of irrigation water (ECw), regardless of species (Figure 1). As shown in Figure 1a, the highest F_v/F_m value (0.77) was observed in the control treatment (ECw = 0.1 dS m⁻¹), with a reduction of 4% from ECw = 1.0 dS m⁻¹ and reaching a 20% decrease at ECw = 5.0 dS m⁻¹. Increasing salinity resulted in a linear reduction of 33% in F_v/F_0 when comparing the highest salinity level to the control. In contrast, F_0/F_m increased by 69% with increasing salinity (Figure 1b,c), indicating that both species were under salt stress.

2.2. Gas Exchange

Statistically, açai and juçara plants showed similar responses for most gas exchange variables, except for net photosynthetic rate and water-use efficiency (Table 2). From a physiological perspective, however, most responses differed between the species evaluated. The predominance of statistical similarity may be associated with the high variability (CV%) inherent to the physiological nature of these variables, as well as to species-specific genetic characteristics and their independent responses to increasing electrical conductivity in the growth medium.

Açai plants exhibited higher mean values for most gas exchange variables, except for intercellular CO₂ concentration, for which juçara showed the highest mean value, approximately 13% greater than that observed in açai plants. Compared with juçara, açai showed increases of 28% in stomatal conductance, 49% in net photosynthetic rate, 22% in transpiration, 19% in water-use efficiency, and 6% in leaf temperature (Table 2).

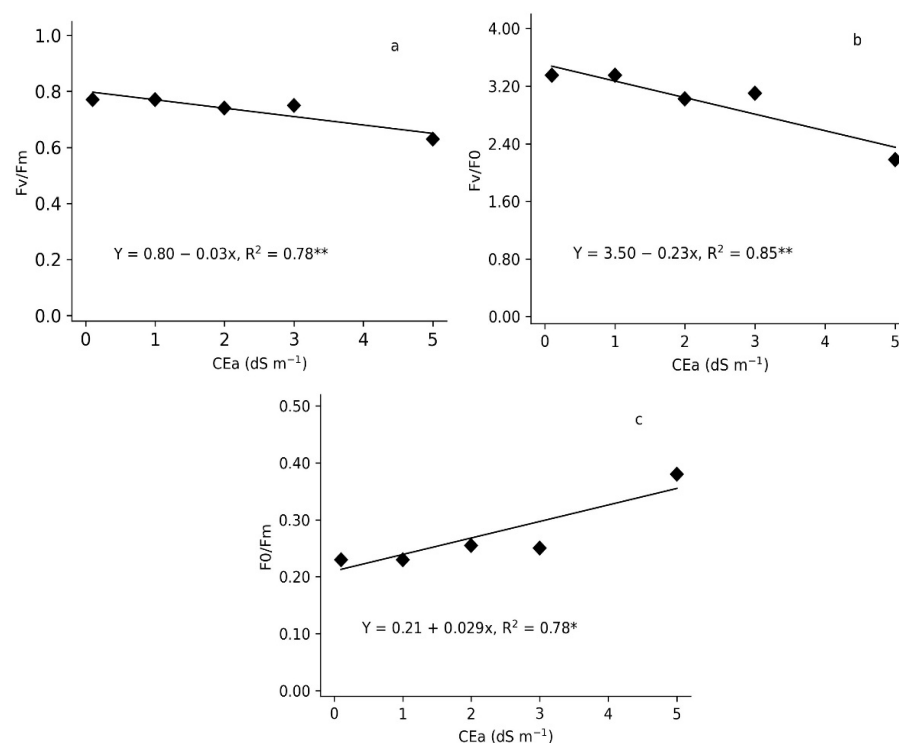


Figure 1. Maximum quantum yield of PSII (F_v/F_m) (a), basal non-photochemical quantum yield (F_0/F_m) (b), and maximum photochemical efficiency of PSII (F_v/F_0) (c) [mean of both *Euterpe* species] in açai and juçara plants at 16 months after sowing, subjected to increasing irrigation water salinity (EC). Regression (* $p = 0.05$ and ** $p = 0.01$).

Table 2. Mean values of gas exchange variables, including leaf temperature (T_{leaf}), stomatal conductance (g_s), net photosynthetic rate (A), transpiration (E), water-use efficiency (WUE), and intercellular CO_2 concentration (C_i) [mean across the five irrigation water electrical conductivity levels] in young açai and juçara plants at 16 months after sowing under increasing salinity levels (EC) in the irrigation water.

Species	T_{leaf} °C	g_s ($\text{mol de H}_2\text{O m}^{-2} \text{s}^{-1}$)	A ($\mu\text{mol de CO}_2 \text{m}^{-2} \text{s}^{-1}$)
Açaí	37.72 a	0.037 a	4.11 a
Juçara	35.67 a	0.029 a	2.75 b
Mean	35.69	0.033	3.430
CV%	2.01	46.74	30.50
Species	E ($\text{mmol de H}_2\text{O m}^{-2} \text{s}^{-1}$)	WUE (A/E)	C_i
Açaí	1.16 a ¹	3.46 a	200.05 a
Juçara	0.95 a	2.91 b	225.90 a
Mean	1.10	3.18	212.98
CV%	30.76	24.46	2.01

Means followed by the same letter within the column do not differ significantly at the 5% probability level according to Tukey's test. CV = coefficient of variation.

Higher reductions in stomatal conductance were observed with increasing salinity levels, decreasing from 0.036 to $0.021 \text{ mol H}_2\text{O m}^{-2} \text{s}^{-1}$ in the control treatment and under EC of 5.0 dS m^{-1} , respectively (Figure 2a). The highest net photosynthetic rate was observed in the control treatment and decreased linearly with increasing salinity, reaching its lowest value at the highest salinity level. Net photosynthetic rates were 4.48 and $2.34 \mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$ in the control and 5 dS m^{-1} treatments, respectively (Figure 2b). Similarly, transpiration reflected the effects observed for stomatal conductance and net photosynthetic rate, decreasing from $1.24 \text{ mmol H}_2\text{O m}^{-2} \text{s}^{-1}$ at EC of 0.1 dS m^{-1} to $0.80 \text{ mmol H}_2\text{O m}^{-2} \text{s}^{-1}$

at EC of 5.0 dS m⁻¹ (Figure 2c). The reductions in stomatal conductance, net photosynthetic rate and transpiration under the highest electrical conductivity treatment were 41.33%, 48% and 35.48%, respectively, compared with the control.

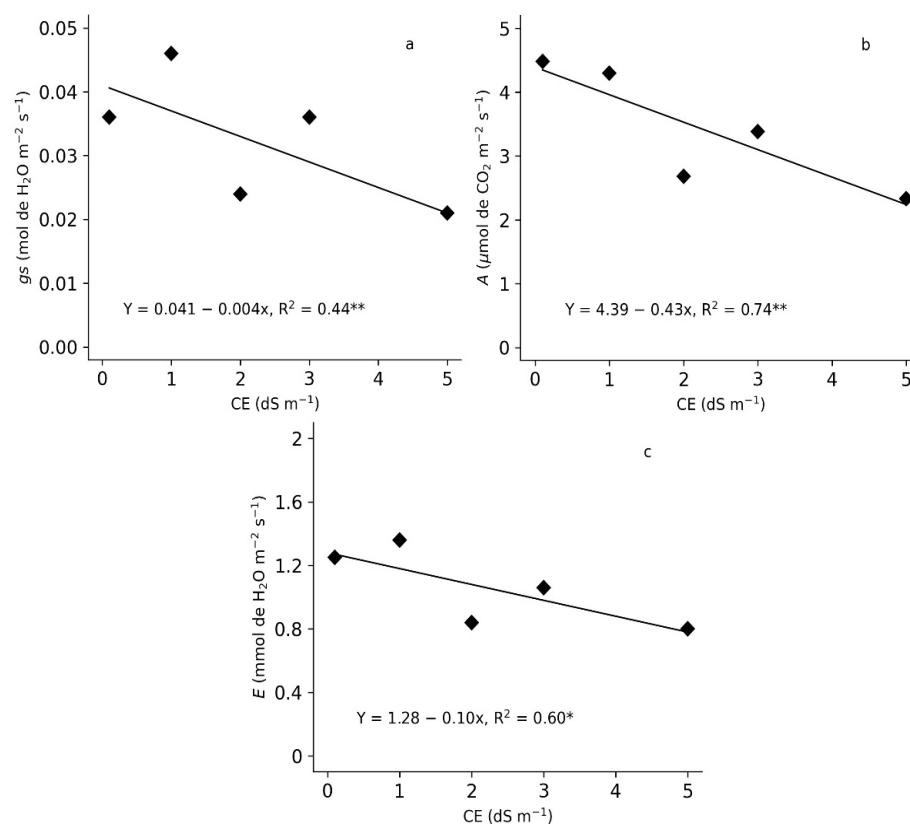


Figure 2. Stomatal conductance (gs) (a), net photosynthesis (A) (b), and transpiration (E) (c) [mean across both *Euterpe* species] in açai and juçara plants at 16 months after sowing under increasing irrigation water salinity levels (EC). Regression (* $p = 0.05$ and ** $p = 0.01$).

2.3. Sodium, Chloride, and Phenolic Compounds

Regarding salinity, the addition of NaCl to the irrigation water increased Na⁺ and Cl⁻ ion concentrations in plant tissues. No statistical differences were observed between species for Na⁺ and Cl⁻ contents or accumulation; however, the plants differed in relation to phenolic compound content and accumulation (Table 3).

Table 3. Leaf concentration (Conc., g kg⁻¹) and shoot accumulation (Acc., mg plant⁻¹) of sodium (Na⁺), chloride (Cl⁻), and phenolic compounds in açai and juçara plants at 16 months after sowing under increasing salinity levels (EC) in the irrigation water.

Species	Na ⁺		Cl ⁻		Phenolic Compounds	
	Conc. g kg ⁻¹	Acc. mg Plant ⁻¹	Conc. g kg ⁻¹	Acc. mg Plant ⁻¹	Conc. g kg ⁻¹	Acc. mg Plant ⁻¹
Açaí	2.65 a ¹	50.72 a	0.98 a	22.20 a	30.37 a	434.02 a
Juçara	3.11 a ¹	61.58 a	1.11 a	25.20 a	16.09 b	265.12 b
Mean	2.88	56.15	1.04	23.68	23.22	349.57
CV%	31.6	34.17	42.42	48.66	9.34	28.07

¹ Means followed by different letters within the column differ significantly at the 5% probability level according to Tukey's test. CV = coefficient of variation.

For phenolic compounds, the highest mean values were observed in plants for both concentration and accumulation. Açai increased phenolic compound production by 31%

for concentration and 24.2% for accumulation relative to the overall mean, whereas juçara showed reductions of 31% and 24.2%, respectively (Table 3).

3. Discussion

Increasing irrigation water salinity caused consistent changes in the physiological responses of both *Euterpe* species. The linear reductions in stomatal conductance, transpiration, and net CO₂ assimilation, together with the changes in chlorophyll fluorescence parameters, indicate that salinity affected both CO₂ diffusion and the photochemical functioning of the photosynthetic apparatus.

The physiological response of plants to salt stress is a complex process involving distinct phases, including ionic imbalance and cellular water deficit [13]. The immediate plant response to salinity is associated with the osmotic component of stress, characterized by reduced substrate water potential, which restricts water uptake by roots [15]. This process triggers a series of signaling pathways; after sensing Na⁺ accumulation and hyperosmotic conditions, plants increase Ca²⁺ levels and activate reactive oxygen species (ROS) signaling pathways involved in ion balance maintenance and osmotic homeostasis, inducing phytohormonal signaling, particularly through the abscisic acid pathway, ultimately resulting in stomatal closure [17]. This mechanism was evidenced in the present study by the linear reduction in stomatal conductance and transpiration, leading to decreased net photosynthetic rate with increasing electrical conductivity of the irrigation water (Figure 2a–c).

As salt exposure continued, ionic effects associated with the accumulation of Na⁺ and Cl[−] in plant tissues may also have contributed to the physiological responses. Although the species did not differ statistically in Na⁺ and Cl[−] concentration or accumulation, juçara plants showed numerically higher mean values than açai plants (Table 3). Therefore, these numerical differences should not be interpreted as evidence of contrasting ionic tolerance between the species. Excessive Na⁺ and Cl[−] accumulation may disrupt ion homeostasis, interfere with K⁺, Ca²⁺, and Mg²⁺ nutrition, and impair metabolic and enzymatic processes [18].

Net CO₂ assimilation decreased linearly from the control treatment to the highest irrigation water salinity level, with estimated values ranging from 4.35 to 2.24 μmol CO₂ m^{−2} s^{−1}, respectively, according to the fitted regression equation (Figure 2b). Similar trends were observed for stomatal conductance and transpiration, indicating that reduced stomatal aperture contributed to the decline in carbon assimilation by restricting CO₂ diffusion into the leaf. However, the gas-exchange responses alone do not demonstrate that photosynthetic inhibition was exclusively or predominantly stomatal.

The concurrent reductions in stomatal conductance, transpiration, and net CO₂ assimilation indicate an important stomatal contribution to photosynthetic inhibition through restricted CO₂ diffusion. However, the absence of a significant change in intercellular CO₂ concentration does not demonstrate the predominance of stomatal limitation, because C_i reflects the balance among stomatal conductance, mesophyll conductance, and biochemical CO₂ consumption.

The changes in chlorophyll fluorescence demonstrate that a non-stomatal, photochemical component was also involved. Reduced CO₂ assimilation decreases the use of excitation energy in carbon metabolism, which may increase excitation pressure on PSII and favor the formation of reactive oxygen species [18]. In the present study, the reductions in F_v/F_m and F_v/F₀ with increasing salinity indicate lower maximum and potential photochemical efficiency of PSII, respectively [19]. The accompanying increase in F₀/F_m is mathematically complementary to the reduction in F_v/F_m and reflects a decline in maximum PSII efficiency rather than an independent measurement of thermal energy dissipation.

At the higher salinity levels, F_v/F_m values were below the range commonly reported for non-stressed leaves, indicating increasing photochemical stress [20,21]. The reduction in F_v/F_0 further supports the occurrence of impaired PSII photochemical activity [22,23]. The relatively high F_0/F_m values observed under the control treatment indicate a pre-existing limitation in maximum PSII efficiency; however, the causes of this response cannot be determined from the present experiment. However, because temperature and relative humidity effects were not independently tested, this possibility should be interpreted cautiously.

When species means were compared across salinity levels, açai plants exhibited higher net CO_2 assimilation and water-use efficiency than juçara plants (Table 2). These differences indicate higher overall physiological performance of açai under the experimental conditions. Nevertheless, because the salinity responses presented in Figures 1 and 2 represent means across species, these main effects should not be interpreted as evidence that the species differed in the magnitude of their response to increasing salinity.

Despite the functional alterations observed in the photosynthetic apparatus, salinity did not significantly affect the relative chlorophyll index (SPAD) in either species (Table 1). Thus, relative chlorophyll abundance was maintained during the experimental period, whereas PSII functional responses were affected by increasing irrigation water salinity. This finding reinforces the importance of integrating pigment-related and physiological measurements when assessing the responses of *Euterpe* species to environmental conditions, because changes in physiological performance are not necessarily accompanied by proportional changes in other plant attributes [24].

The production of secondary metabolites, including phenolic compounds such as anthocyanins, flavonoids, and lignoids, occurs naturally in plants; however, in açai and juçara species, this production is particularly pronounced because their stems, flowers, and fruits are naturally rich in these compounds [25,26]. This characteristic contributes to their adaptive capacity and survival under environmental stimuli and various stress conditions, including salinity. The accumulation of these compounds is associated with signaling metabolic pathways involved in stress mitigation, particularly in response to reactive oxygen species, which are highly reactive and capable of interacting with biomolecules, thereby altering biochemical and physiological activities [27]. However, the differences observed in phenolic compound concentration and accumulation represent species main effects and should not, by themselves, be interpreted as evidence of salinity-induced phenolic production.

The maintenance of the SPAD index despite the reductions in F_v/F_m and F_v/F_0 and the increase in F_0/F_m is physiologically consistent because these measurements characterize different attributes of the photosynthetic apparatus. The SPAD index provides an indirect estimate of relative chlorophyll abundance and leaf greenness, whereas chlorophyll fluorescence provides information on PSII photochemistry, electron transport, and the use and dissipation of absorbed excitation energy. Therefore, PSII functionality may decline without a proportional change in the relative chlorophyll index [28]. Under the conditions of the present study, salinity impaired PSII functional efficiency without causing a detectable alteration in relative chlorophyll abundance.

The concurrent reductions in stomatal conductance, transpiration, and net CO_2 assimilation indicate an important stomatal contribution to photosynthetic inhibition through restricted CO_2 diffusion. However, the simultaneous changes in chlorophyll fluorescence parameters demonstrate an additional non-stomatal component associated with impairment of PSII photochemistry. The absence of a significant change in intercellular CO_2 concentration does not exclude either mechanism, because this variable reflects the balance among stomatal conductance, mesophyll conductance, and biochemical CO_2 consumption. Because CO_2 -response curves and mesophyll conductance were not evaluated, the relative

contributions of stomatal, mesophyll, biochemical, and photochemical limitations could not be quantitatively partitioned [29]. Physiological responses reported for date palm seedlings exposed to seawater similarly indicate that salinity tolerance in palms involves coordinated adjustments in gas exchange, water relations, and ion homeostasis [30].

Overall, the reduction in photosynthetic performance under salt stress involved both stomatal and non-stomatal components. Reduced stomatal conductance restricted CO₂ diffusion, whereas the declines in Fv/Fm and Fv/F₀ indicated impairment of PSII photochemistry. These responses occurred without a significant change in the relative chlorophyll index, showing that PSII functional efficiency was more responsive to salinity than relative chlorophyll abundance under the conditions of this study.

4. Materials and Methods

4.1. Plant Material and Experimental Design

The experiment was conducted in a greenhouse without active control of air temperature or relative humidity. These environmental variables were monitored using a WATCH DOG Weather Station (Spectrum Technologies, Inc., Aurora, IL, USA), programmed to record data at 1 h intervals. During the experimental period, air temperature ranged from 17.7 to 30.0 °C, whereas relative humidity ranged from 68.5% to 98.5% (Figure 3). Seedlings were initially produced in 290 cm³ plastic tubes filled with a substrate composed of sand and Basaplant[®] Hortaliças BX (Indústria e Comércio de Insumos Agrícolas Ltd.a, São Paulo, Brazil). Juçara seeds were collected from a forest area in Venda Nova, Espírito Santo State, Brazil, and provided by the Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural (Incaper). Açaí seeds, originating from the Amazon region and genetically improved by Embrapa (Brasília, Brazil) for upland cultivation, were supplied by the Active Germplasm Bank of Embrapa Amazônia Oriental, Belém, Pará State, Brazil.

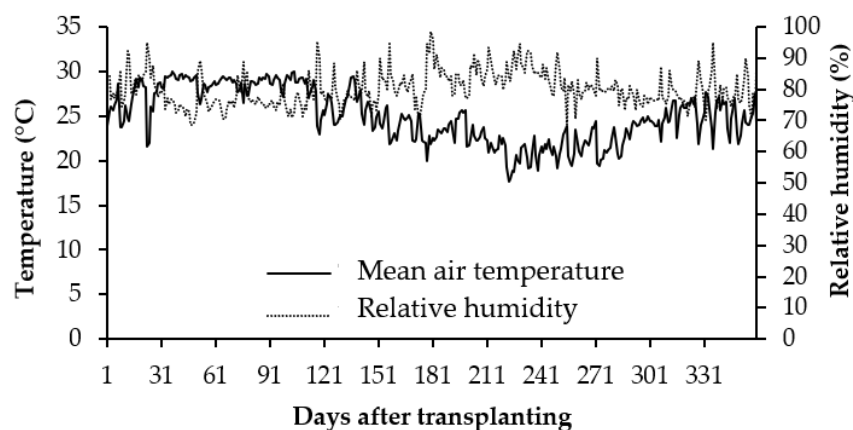


Figure 3. Mean air temperature (°C) and relative humidity (%) inside the greenhouse during the experimental period.

At 120 days after sowing, the seedlings were transplanted into 16 L black polyethylene pots filled with a substrate composed of soil, sand, and Basaplant[®] Hortaliças BX at a 1:1:1 ratio (v/v/v). The substrate was fertilized according to its chemical characteristics (Table 4) and the nutritional requirements of the plants, following Cravo et al. [31]. The experiment was arranged in a randomized complete block design in a 5 × 2 factorial arrangement. The first factor consisted of five irrigation water electrical conductivity levels (ECw: 0.1, 1.0, 2.0, 3.0, and 5.0 dS m^{−1}), with 0.1 dS m^{−1}, without NaCl addition, considered the control. The second factor consisted of two palm species: açaí (*Euterpe oleracea* Mart. cv. BRS Pará; registration no. 11.300 RNC/MAPA [32]) and juçara (*Euterpe edulis* Mart.). Ten

treatments were evaluated using four replicates, with two pots per experimental unit and one plant per pot.

Table 4. Chemical characteristics of the substrate (soil + sand + Basaplant®, 1:1:1, *v/v*) used for the growth of *Euterpe* species under irrigation water salinity. Campos dos Goytacazes, RJ, Brazil.

pH (H ₂ O)	S-SO ₄ --- mg dm ⁻³ ---	P	K	Ca	Mg	Na	Al	H + Al	C	OM
5.5	163	47	1.8	27.9	15.7	1.8	0.00	34.3	21.1	36.38
CEC mmol _c dm ⁻³	SB	V	m	ISNa	Fe	Cu	Zn	Mn	B	
81.5	47.2	58	0	2	37.68	0.45	4.29	30	0.43	

pH = hydrogen ion concentration, S = Sulfur, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, Na = sodium, Al = aluminum, H = hydrogen, C = carbon, OM = organic matter, CEC = cation exchange capacity, SB = sum of bases, V = base saturation, (%); m = aluminum saturation CEC = cation exchange capacity, (%); ISNa = sodium saturation index, Fe = Iron, Zn = zinc, Cu = copper, Mn = manganese, B = boron.

Saline solutions were prepared by adding sodium chloride (NaCl) to tap water with an initial electrical conductivity (EC_w) of 0.1 dS m⁻¹. The amount of salt required to obtain each salinity level (Table 2) was calculated using Equation (1):

$$Cs = 0.01 \times [(ECd - CEau)/Gp] \times Peq \quad (1)$$

where Cs = salt concentration (g L⁻¹); ECd = desired electrical conductivity (dS m⁻¹); EC_w = electrical conductivity of the supply water (dS m⁻¹); Peq = equivalent weight; and Gp = purity degree of the salt, according to Cavalcante et al. (2010) [33].

Irrigation was controlled by the gravimetric method, replacing the volume of water lost by evapotranspiration to maintain substrate moisture above 70% of field capacity (FC). Pots were weighed every 2 days at a fixed time to determine water consumption, and the required volume was reapplied. The volume of water applied per plant (V_a) was calculated as:

$$V_a = PM_{100\%} FC - P_a \quad (2)$$

where V_a = applied water volume (mL); P_a = current pot weight (kg); and PM_{100%FC} = mean pot weight at 100% field capacity (kg).

Electrical conductivity of the prepared solutions was verified using a digital bench conductivity meter (model MCA-150.1, MS Tecnoyon, Piracicaba, SP, Brazil). Solutions were prepared weekly and stored in sealed containers in a cool, shaded environment to prevent changes due to temperature fluctuations and evaporation.

Treatments were initiated at 210 days after transplanting (DAT), when seedlings were fully established. Plants were subjected to three stress periods of 30 days each, interspersed with a leaching fraction corresponding to 20% of the total applied water volume, to minimize salt accumulation in the substrate (Table 5). Treatments were resumed after 7 days, when substrate moisture reached the minimum threshold (70% FC). The total duration of stress imposition was 104 days, after which evaluations were performed.

Table 5. Volume of water applied during stress periods and leaching fraction throughout the experimental period.

Stress Period (days)	Accumulated Volume (V _a) (L)	Leaching Fraction (V) (L)
30	2.82	0.57
60	5.10	1.02
90	6.00	----

4.2. Chlorophyll Fluorescence and Gas Exchange Analyses

Relative chlorophyll content was measured using a portable chlorophyll meter (SPAD-502, Konica Minolta, Tokyo, Japan). Chlorophyll *a* fluorescence was determined using a non-modulated fluorometer (Pocket PEA Chlorophyll Fluorimeter[®], Hansatech Instruments Ltd., Norfolk, UK) after the leaves had been dark-adapted for 30 min. The measured and calculated fluorescence parameters included initial fluorescence (F_0), maximum fluorescence (F_m), variable fluorescence ($F_v = F_m - F_0$), maximum quantum yield of PSII (F_v/F_m), maximum photochemical efficiency of PSII (F_v/F_0), basal non-photochemical quantum yield (F_0/F_m), and performance index (PI).

Gas exchange measurements were performed on the middle third of the most recently fully expanded leaf between 08:00 and 10:00 h using an infrared gas analyzer (LCpro-SD Portable Photosynthesis System[®], ADC BioScientific Limited, London, UK). The equipment was operated at a constant airflow of 300 mL min⁻¹ and a photosynthetic photon flux density of 1200 $\mu\text{mol m}^{-2} \text{s}^{-1}$. The evaluated variables were leaf temperature (T_{leaf} , °C), intercellular CO₂ concentration (C_i , $\mu\text{mol mol}^{-1}$), stomatal conductance (g_s , mol H₂O m⁻² s⁻¹), net photosynthetic rate (A , $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$), and transpiration rate (E , mmol H₂O m⁻² s⁻¹). Instantaneous water-use efficiency was calculated as the ratio between net photosynthetic rate and transpiration rate ($\text{WUE} = A/E$).

4.3. Sodium, Chloride, and Phenolic Compound Concentration and Content

Chemical analyses were performed using oven-dried leaf and stem tissues to determine foliar concentrations and shoot contents. Phenolic compounds were quantified based on the methodology for total soluble polyphenol content in alcoholic solution, using the method described by Anderson and Ingram (1994) [34], through reaction with the Folin–Dennis reagent and absorbance reading at 760 nm using a Specord UV-Vis spectrophotometer (Analytik Jena, Jena, Germany). Sodium (Na⁺) and chloride (Cl⁻) concentrations were determined according to the methodology recommended by Silva (1999) [35].

4.4. Statistical Analysis

Initially, data normality was assessed using the Shapiro–Wilk test. Data were subjected to analysis of variance (ANOVA) using the F-test ($p \leq 0.05$). When significant, means for species were compared using Tukey's test ($p \leq 0.05$). The effect of salinity levels (ECw) was evaluated by regression analysis. Statistical analyses were performed using Sisvar 5.6 software [36].

5. Conclusions

Salt stress reduces the physiological performance of young açai and juçara plants by promoting stomatal closure, decreasing gas exchange, and impairing the photochemical efficiency of photosystem II. The reduction in net photosynthesis was primarily associated with stomatal limitation and was further aggravated by photoinhibition at higher salinity levels, without significant changes in chlorophyll content. Açai plants exhibited greater tolerance to salt stress than juçara plants, as evidenced by higher photosynthetic rates and greater water-use efficiency.

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