ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.30, n.4, e298756, 2026
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

Original Article

Physiological and nutritional responses of Surinam cherry to pyroligneous extract under salinity[1]

Respostas fisiológicas e nutricionais da pitangueira ao uso de extrato pirolenhoso sob salinidade

Adriana dos S. Ferreira[2], Aian dos S. Viana[3], Ramon S. Melo[2], Patrycia E. C. Amorim[2], João E. da S. Ribeiro[2*], Francisco V. da S. Sá[4] & Vander Mendonça[2]

[1] Research developed at Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil
[2] Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil
[3] Universidade Federal do Rio Grande do Norte, Natal, RN, Brazil
[4] Universidade Estadual da Paraíba, Catolé do Rocha, PB, Brazil

HIGHLIGHTS:

The tolerance limit for Surinam cherry seedlings is up to 2.5 dS m^{-1} in terms of water salinity.
The 2% pyroligneous extract at an irrigation water salinity of 2.5 dS m^{-1} improves K and Mg contents, and phytomass.
Brackish water salinity of 4.5 to 6.5 dS m^{-1} negatively affects gas exchange and nutritional characteristics.

ABSTRACT: Salinity stress demands effective mitigation strategies, such as the use of pyroligneous extract, which helps reduce its negative effects on plants. The objective of this study was to evaluate the effects of pyroligneous extract on gas exchange, nutritional attributes, and phytomass of *Eugenia uniflora* (Surinam cherry) seedlings irrigated with brackish water. The experiment was performed in a greenhouse using a randomized block design in a 4 × 3 factorial scheme, corresponding to four levels of irrigation water salinity (0.5, 2.5, 4.5, and 6.5 dS m^{-1}) and three concentrations of pyroligneous extract (0, 1, and 2%). Gas exchange variables analyzed included: photosynthetic rate, leaf transpiration, stomatal conductance, internal CO_2 concentration, water use efficiency, intrinsic carboxylation efficiency, and intrinsic water use efficiency. Agronomic characteristics evaluated included fresh phytomass and the foliar and root contents of Na^+, K^+, Ca^{2+}, and Mg^{2+}. Irrigation with water of 2.5 dS m^{-1}, when combined with the application of 2% pyroligneous extract, led to significant improvements in stomatal conductance, foliar potassium and magnesium contents, as well as calcium content in the root tissues of Surinam cherry seedlings. Although this salinity level alone contributed to the physiological balance of the plants, the use of pyroligneous extract is a promising tool for mitigating salt stress in irrigated cropping systems.

Key words: *Eugenia uniflora* L., abiotic elicitor, salt stress, wood vinegar

RESUMO: O estresse salino exige estratégias eficazes de mitigação, como o uso do extrato pirolenhoso, que contribui para reduzir seus efeitos negativos nas plantas. O objetivo deste estudo foi avaliar os efeitos do extrato pirolenhoso nas trocas gasosas, atributos nutricionais e fitomassa de pitangueiras irrigadas com águas salinas. O experimento foi conduzido em casa de vegetação, adotando um delineamento em blocos casualizados, em esquema fatorial 4 × 3, correspondente a quatro níveis de salinidade da água de irrigação (0,5; 2,5; 4,5 e 6,5 dS m^{-1}) e três concentrações de extrato pirolenhoso (0, 1 e 2%). As variáveis de troca gasosa analisadas incluíram: taxa fotossintética, transpiração foliar, condutância estomática, concentração interna de CO_2, eficiência do uso da água, eficiência intrínseca de carboxilação e eficiência intrínseca do uso da água. Para as características agronômicas, avaliaram-se a fitomassa fresca e o teor foliar e radicular de Na^+, K^+, Ca^{2+} e Mg^{2+} na planta. A irrigação com água de 2,5 dS m^{-1}, quando associada à aplicação de extrato pirolenhoso a 2%, promoveu melhorias significativas na condutância estomática, nos teores foliares de potássio e magnésio, bem como no teor de cálcio nos tecidos radiculares de mudas de pitangueira. Embora esse nível de salinidade, isoladamente, tenha contribuído para o equilíbrio fisiológico das plantas, o uso do extrato pirolenhoso é uma ferramenta promissora para mitigar o estresse salino em sistemas de cultivo irrigado.

Palavras-chave: *Eugenia uniflora* L., elicitor abiótico, estresse salino, vinagre de madeira

• Ref. 298756 – Received 11 Jul, 2025
* Corresponding author - E-mail: j.everthon@hotmail.com
• Accepted 25 Nov, 2025 • Published 16 Jan, 2026
Editors: Toshik Iarley da Silva & Hans Raj Gheyi

Introduction

Surinam cherry (*Eugenia uniflora* L.), belonging to the Myrtaceae family, is traditionally used in folk medicine for the treatment of hypertension and inflammation, and has a potential antivenom effect (Fidelis et al., 2022; Danielle-Silva et al., 2024). In addition to its pharmacological properties, it is also recognized as a regional food, bearing fruits rich in vitamins C and A, which contribute to enriching the local diet (Fidelis et al., 2022).

The cultivation of medicinal and fruit species, such as the Surinam cherry, can be affected by adverse environmental conditions, including soil salinization (Nofal et al., 2024). Excessive presence of salts in the soil triggers adverse osmotic and ionic effects, compromising the integrity of cell membranes, lead to stomatal closure, and reducing the photosynthetic efficiency of plants (Gul et al., 2022). In addition, salinity levels interfere with the absorption of essential nutrients, such as potassium, magnesium, and calcium (Ma et al., 2022; Yang et al., 2024), negatively impacting phytomass growth and accumulation (Dadach et al., 2023).

Secondary soil salinization constitutes the main threat to irrigated agricultural land (Gul et al., 2022). The absence of adequate management, especially of drainage systems, intensifies soil degradation and compromises crop productivity (Devkota et al., 2022), including the cultivation of Surinam cherry in the semi-arid regions of northeastern Brazil. In this context, biostimulants have emerged as a promising strategy to mitigate the effects of salinity, promoting sustainable management practices, such as the use of pyroligneous extract, also known as wood vinegar (Ouattara et al., 2023). This by-product of vegetable smoke distillation is commercialized in liquid form, with 80–90% water and more than 200 soluble compounds, including nitrogen, phenols, organic acids, alcohols, and esters (Iacomino et al., 2024).

Pyroligneous extract is effective in mitigating the effects of salinity. In calendula (*Calendula officinalis* L.), its application has been associated with biochar-optimized water relations and improved soil conditions (Abbaszadeh et al., 2022). In melon (*Cucumis sativus* L.), it reduced salt stress and increased root fresh mass (Afsharipour et al., 2025). Additionally, it enhanced the efficiency of nutrient use (N, P, and K) in acidophilous plants such as azalea, *Rhododendron* × hybrid 'Jiangnanchunzao' (Zhou et al., 2023). Despite advances in using pyroligneous extract in agricultural species, few studies have addressed its effects on fruit trees native to Brazil, such as Surinam cherry, especially under salt stress. Therefore, the objective of this study was to evaluate the effects of pyroligneous extract on gas exchange, nutritional attributes, and phytomass of Surinam cherry seedlings irrigated with brackish waters.

Material and Methods

The experiment was conducted in a greenhouse from July to December 2023 at the Federal Rural University of the Semi-Arid Region (UFERSA), located in the municipality of Mossoró, Rio Grande do Norte, Brazil. The site is located at the geographic coordinates 5° 11′ 31" S latitude and 37° 20′ 40" W longitude, at an average altitude of 15 m. The climate of the region is classified as BSwh, indicating a hot and dry semi-arid climate (Alvares et al., 2013). The data on maximum and minimum temperatures and relative air humidity (Figure 1) were collected daily by the Automatic Meteorological Station of UFERSA in Mossoró, RN, in the external area of the greenhouse.

The treatments consisted of the combination of four levels of electrical conductivity of the irrigation water (ECw - 0.5 (control), 2.5, 4.5, and 6.5 dS m^{-1}) and three concentrations of pyroligneous extract (PE - 0, 1, and 2%), distributed in randomized blocks in a 4 × 3 factorial arrangement with four replications. The brackish water treatments applied to the Surinam cherry are based on the methodology proposed by Rodrigues Filho et al. (2023) for guava (*Psidium guajava* L.). The concentrations of PE used were defined according to the recommendations indicated by the manufacturer on the commercial product (SP Pesquisa e Tecnologia®).

The Surinam cherry seeds were obtained from fruits harvested at full maturity from mother plants of the didactic orchard of UFERSA, at the Mossoró Campus (5° 12′ 20" S, 37° 19′ 17" W, 15 m). After harvest, the seeds were manually removed from the pulp and left to dry for 24 hours, in an open ambient. Three seeds were sown in each plastic pot with a capacity of 4 dm^3, filled with a substrate in a 2:1 (v/v) proportion of soil and commercial substrate (Maxfertil®) composed of pine bark, ash, vermiculite, peat, sawdust, bio-stabilizers, and additives. Irrigation was carried out daily. At 90 days after sowing (DAS), thinning was carried out to maintain plant vigor, keeping one plant per pot. Simultaneously, 100 mg of P dm^{-3}, using single superphosphate, were applied to the Surinam cherry seedlings. This dose is considered adequate for the healthy development of plants, as recommended for guava plants by Corrêa et al. (2003). Before applying the treatments, a sample of the soil and substrate mixture was collected and analyzed to determine its chemical and physical characteristics, following methodologies as described by Teixeira et al. (2017) (Table 1).

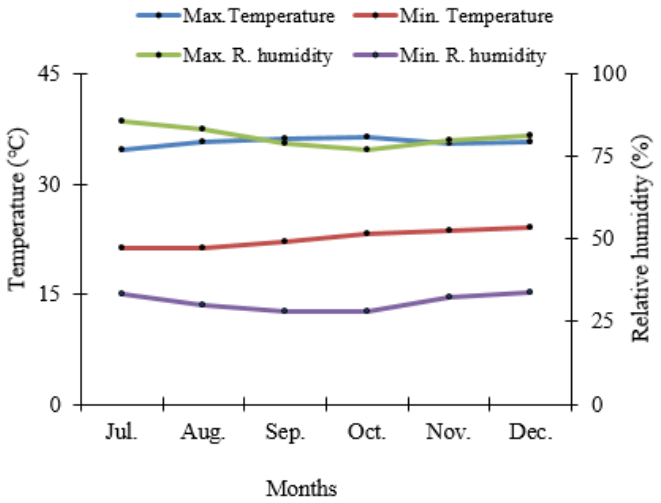


Figure 1. Average air temperatures and maximum and minimum relative humidity of the air (RH) recorded throughout the experiment (July 2 to December 29, 2023)

Table 1. Chemical and physical properties of the substrate used in the experiment before the application of the treatments

Coarse sand	Fine sand	Sand	Silt	Clay	Textural classification	ECse	pH
(dag kg^{-1})						(dS m^{-1})	(H_2O)
53	29	82	7	11	Sand	0.41	5.70

P[1]	Na^+	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	$H^+ + Al^{3+}$	SB	CEC	V	ESP
(mg dm^{-3})	(cmol$_c$ dm^{-3})								(%)	
185.4	0.55	0.68	6.31	1.75	0.04	3.14	9.29	12.43	75	4

pH - Hydrogen potential; P, K^+, Na^+: Mehlich 1 Extractant; SB - Sum of exchangeable bases (Ca^{2+} + Mg^{2+} + K^+ + Na^+); CEC - Cation exchange capacity [SB + (H^+ + Al^{3+})]; V% - (SB/CEC) 100; ESP - Exchangeable sodium percentage = [Na^+]/CEC x 100

At 180 DAS, with the plants already developed, irrigation control began, carried out daily by the weighing lysimeter, determining the volume of water evaporated or transpired over 24 hours, maintaining substrate at 60% field capacity (Girardi et al., 2016).

Irrigation waters with different electrical conductivities were prepared by dissolving NaCl in the local-supply water (ECw = 0.5 dS m^{-1}). The amounts of salt were determined based on the relationship between ECw and salt concentration, as described by Richards (1954) (mg L^{-1} ≈ 640 × ECw). The electrical conductivity of the irrigation water was checked with a portable conductivity meter (Akso EC BASIC, TDS, ppm, EC, SALT) to ensure the accuracy of the adjustments. Subsequently, the samples were subjected to chemical analysis to determine the concentrations of anions and cations (Table 2).

The pyroligneous extract (PE) was subjected to a chemical analysis. The product sample showed the following characteristics: pH of 2.6 and an electrical conductivity (EC) of 1.15 dS m^{-1}. The concentrations of organic matter, carbon (C), nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and sodium (Na) were 8.07, 4.68, 1.45, 0.06, 2.5, 0.20, 1.20, and 0.30 g L^{-1}, respectively, with a C/N ratio of 3.23. Micronutrients iron (Fe), copper (Cu), manganese (Mn), boron (B), and zinc (Zn) were detected at concentrations of 52.0, 5.0, 4.0, 91.0, and 2.0 mg L^{-1}, respectively.

The PE concentrations were prepared by dilution in the supply water, following the proportions: 0 (0 mL of PE in 1000 mL of water), 1% (10 mL of PE in 990 mL of water), and 2% (20 mL of PE in 980 mL of water). The 1 and 2% PE solutions showed mean electrical conductivities of 0.59 and 0.61 dS m^{-1}, and pH values of 4.89 and 4.03, respectively. The solution was prepared on the day of each biweekly application. During the experiment, five weekly applications of the extract were made to the soil using a graduated cylinder.

Stomatal conductance (gs, mol H_2O m^{-2} s^{-1}), net photosynthesis rate (A, µmol CO_2 m^{-2} s^{-1}), leaf transpiration rate (E, mmol H_2O m^{-2} s^{-1}), and internal CO_2 concentration (Ci, µmol CO_2 mol^{-1} air) in Surinam cherry leaves were determined 80 days after treatments with the aid of a portable gas exchange and fluorescence analyzer (model GFS-3000). The measurements were carried out between 8:00 a.m. and 10:00 a.m., using artificial light with an intensity of 1.200 µmol m^{-2} s^{-1}, a reference CO_2 concentration of 400 µmol mol^{-1} air, and at ambient temperature. From the data obtained, the following physiological relationships were calculated: water use efficiency (WUE = A/E), intrinsic water use efficiency (iWUE = A/gs), and intrinsic carboxylation efficiency (iCE = A/Ci).

At 80 days after the application of the treatments, the Surinam cherry seedlings were collected and separated into leaves, stems, and roots. Then, the samples were weighed on an analytical scale (precision of 0.0001 g) to determine the fresh mass. Subsequently, the material was dried in an oven with forced air circulation at 65 °C until it reached a constant weight, and then the dry mass of the shoots and roots was determined. The dried leaf and root samples were ground in a Wiley mill (0.5 mm) and stored in plastic flasks. They were then incinerated in an electric muffle furnace at 500–550 °C. Ca and Mg contents were determined by atomic absorption spectrophotometry, and those of Na and K were determined by flame emission photometry, according to Carmo et al. (2000).

The data were initially subjected to tests of normality (Shapiro-Wilk test) and homogeneity of variances (Cochran test), followed by analysis of variance ($p \leq 0.05$). The means related to the salinity of the irrigation water were subjected to polynomial regression ($p \leq 0.05$), while the means related to the pyroligneous extract were compared by Tukey test ($p \leq 0.05$). Statistical analyses were performed using the SISVAR software, version 5.6 (Ferreira, 2019).

Results and Discussion

Interaction was observed between pyroligneous extract concentrations and water salinity levels ($p \leq 0.05$) for the leaf stomatal conductance of Surinam cherry plants (Table 3). In addition, the salinity of the irrigation water alone had a significant effect on all the variables analyzed ($p \leq 0.01$) (Table 3).

In Surinam cherry plants subjected to irrigation with saline water, a linear reduction was observed for the physiological variables, including internal CO_2 concentration (Ci), net photosynthesis rate (A), and leaf transpiration rate (E). This response occurred independently of the concentrations of

Table 2. Chemical composition of irrigation water, including anion and cation concentrations

EC	pH	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	CO_3^{2-}	HCO_3^-	SAR	Cations	Anions	Hardness
(dS m^{-1})	(H_2O)	(mmol$_c$ L^{-1})							(mmol L^{-1})$^{0.5}$			(mg L^{-1})
0.5	8.50	0.26	4.59	0.74	1.46	2.40	0.10	3.50	4.4	7.0	6.0	110
2.5	8.10	0.25	27.11	4.50	4.70	23.0	0.40	3.20	12.6	36.6	26.6	460
4.5	8.30	0.25	48.13	2.00	3.70	39.0	0.40	3.00	28.5	54.1	42.4	285
6.5	8.30	0.25	67.30	2.00	4.00	55.0	0.40	3.00	38.9	73.5	58.4	300

EC - Electrical conductivity; pH - Hydrogen potential; SAR - Sodium adsorption ratio; CO_3^{2-} - Carbonate; HCO_3^- - Bicarbonate.

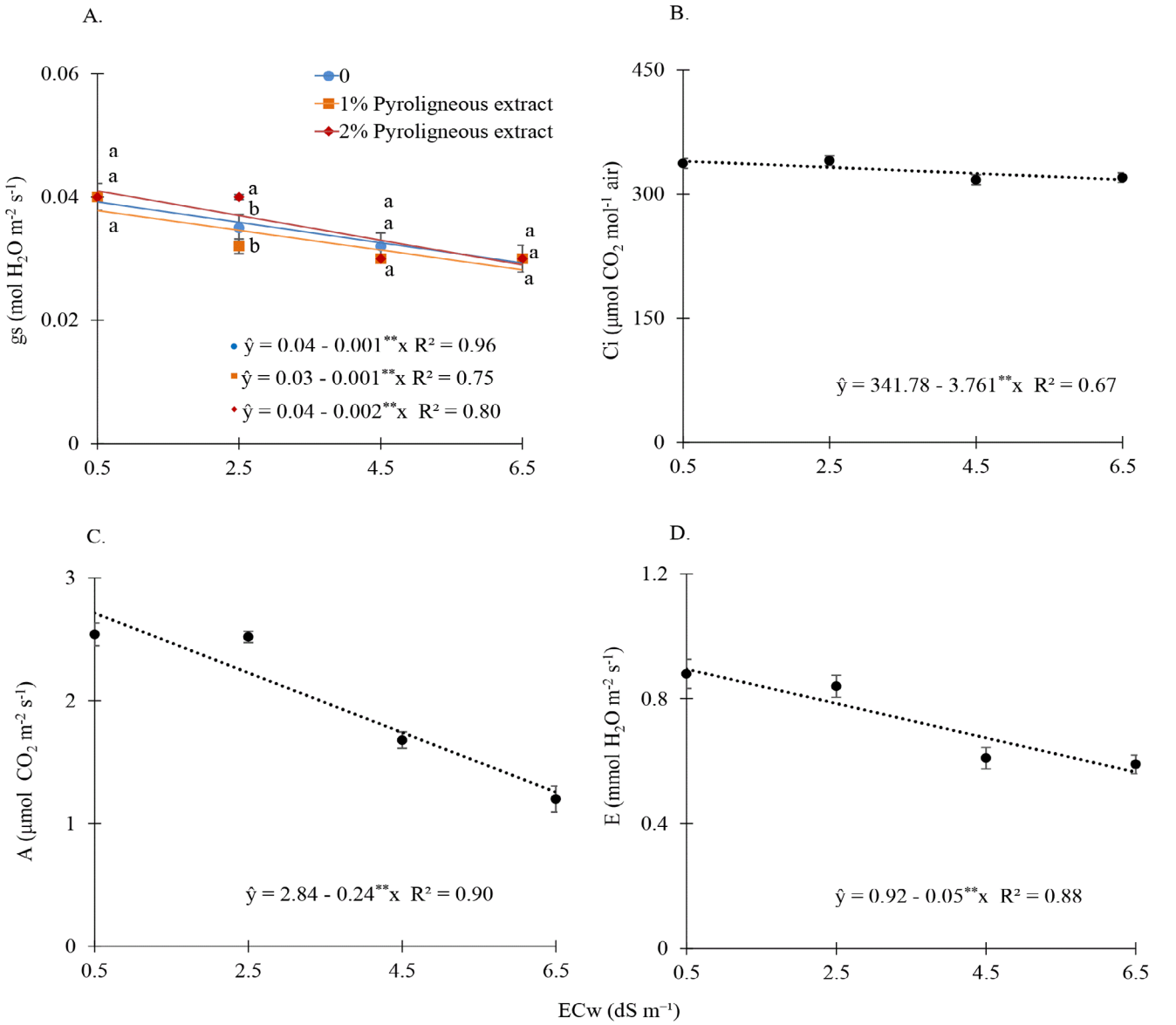
Table 3. Summary of the analysis of variance for stomatal conductance (gs), leaf transpiration rate (E), net photosynthesis rate (A), internal CO_2 concentration (Ci), water use efficiency (WUE), intrinsic water use efficiency (iWUE), and intrinsic carboxylation efficiency (iCE) of Surinam cherry seedlings under different levels of electrical conductivity of irrigation water and subjected to the application of pyroligneous extract (PE) via soil 80 days after treatment

Source of variation	D.F.	Mean squares						
		gs	E	A	Ci	WUE	iWUE	iCE
Salinity (S)	3	$2 \times 10^{-4**}$	0.28^{**}	5.22^{**}	1685.61^{**}	2.27^{**}	2879.14^{**}	$3 \times 10^{-5**}$
Pyroligneous extract (PE)	2	1.5×10^{-5ns}	0.01^{ns}	0.02^{ns}	59.29^{ns}	0.11^{ns}	33.30^{ns}	3×10^{-7ns}
S × PE	6	$1.7 \times 10^{-5*}$	0.009^{ns}	0.02^{ns}	26.00^{ns}	0.08^{ns}	43.75^{ns}	3×10^{-7ns}
Blocks	3	1.7×10^{-5ns}	0.0002^{ns}	0.03^{ns}	18.73^{ns}	0.06^{ns}	74.32^{ns}	1×10^{-7ns}
Residual	33							
C.V. (%)		7.21	9.59	8.05	2.10	12.19	8.76	9.45

D.F. - Degrees of freedom; C.V. - Coefficient of variation; ns, *, ** - Not significant, significant at $p \leq 0.05$, and $p \leq 0.01$ by the F-test, respectively

pyroligneous extract applied, indicating that salt stress was the primary factor driving these changes (Figure 2).

Stomatal conductance (gs) was negatively influenced by the increase in water salinity, showing a linear decrease in all treatments (Figure 2A). However, the rate of this reduction varied with the pyroligneous extract (PE) concentrations. These results indicate that, at a salinity level of 2.5 dS m^{-1}, the higher concentration of PE can improve water availability in the roots and reduce diffusion limitations, resulting in greater stability of stomatal conductance (Yang et al., 2024).

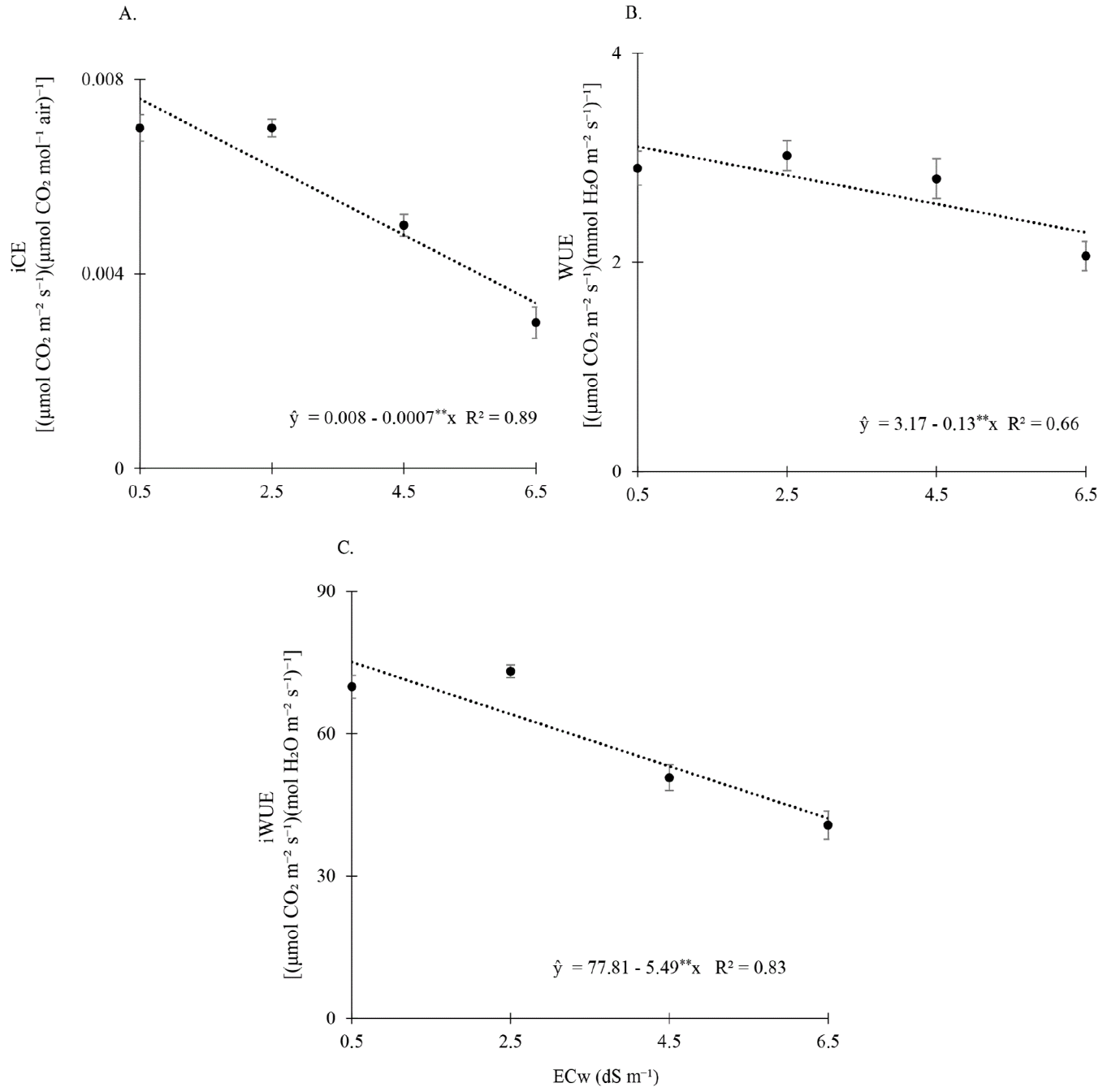


The same letters do not differ significantly for different concentrations of pyroligneous extract within each salinity level by Tukey's test ($p > 0.05$). ** - Significant at $p \leq 0.01$ by the F-test. Vertical bars represent the standard error (n = 4)

Figure 2. Stomatal conductance (A) under the combined effect of pyroligneous extract and water salinity; and internal CO_2 concentration - Ci (B), net photosynthesis rate - A (C), and leaf transpiration rate - E (D) of Surinam cherry seedlings grown in pots, under the isolated effect of water salinity evaluated at 80 days after the application of the treatments

The increase in irrigation water salinity (ECw) promoted a linear decrease in physiological variables. For each unit increase (1 dS m^{-1}) in ECw, net photosynthesis (A) decreased by 0.24 µmol CO_2 m^{-2} s^{-1} (Figure 2C) and transpiration (E) decreased by 0.05 mmol H_2O m^{-2} s^{-1} (Figure 2D). Similarly, the intercellular CO_2 concentration (Ci) decreased by 3.76 µmol CO_2 mol^{-1} air per unit increase in ECw (Figure 2B). This combined pattern strongly suggests that stomatal limitations primarily caused the reduction in photosynthesis. The plants reduced stomatal conductance (gs) to reduce transpiration (E) and water loss. The concentration of the pyroligneous extract modulated this stomatal response. This is a key mechanism for maintaining water balance under saline conditions (Gul et al., 2022). This stomatal closure, however, also limited the influx of atmospheric CO_2, directly causing the linear decline in the photosynthetic rate (A). The relative stability of Ci indicates that the biochemical photosynthetic machinery was likely not the primary limiting factor. Similar findings on water balance maintenance have been reported for other Myrtaceae species (Micco et al., 2021).

The increase in irrigation water salinity led to linear declines in instantaneous carboxylation efficiency (iCE) (Figure 3A), water use efficiency (WUE) (Figure 3B), and intrinsic water use efficiency (iWUE) (Figure 3C). The decrease in iCE, along with the reductions in A and gs and the slight variation in Ci observed earlier (Figures 2A–C), indicates a greater contribution of stomatal limitations on A with the increase in water salinity, rather than biochemical limitation in carboxylation. Simultaneous reductions in WUE and iWUE indicate that the decline in A outpaced the



** - Significant at p ≤ 0.01 by the F-test. The vertical bars represent the standard error of the mean (n = 4)

Figure 3. Intrinsic carboxylation efficiency (iCE, A), water use efficiency (WUE, B), and intrinsic water use efficiency (iWUE, C) of Surinam cherry seedlings under the isolated effect of salinity, evaluated at 80 days after the application of the treatments

reductions in E and gs, making gains in water use efficiency under salt stress unfeasible. These results converge with observations in guava plants, in which iCE and water use efficiency are maintained at lower water electrical conductivity and decrease with increasing salinity (Silva et al., 2024).

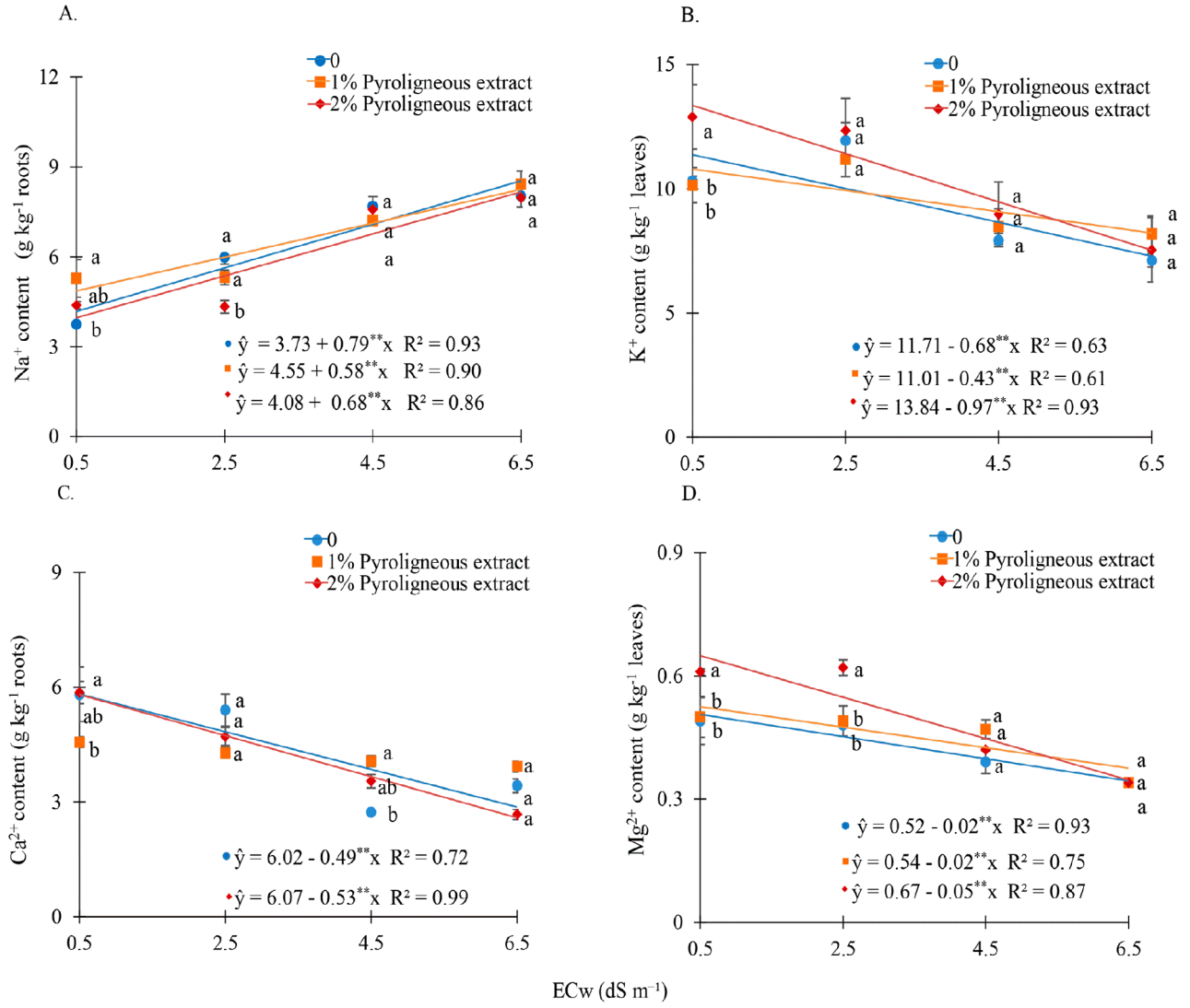
Leaf and root nutritional contents were affected by the salinity level ($p \leq 0.01$) (Table 4). An interaction was observed between salinity levels and the application of pyroligneous extract in the leaf potassium and magnesium contents ($p \leq 0.05$) (Table 4). In the root tissues, sodium and calcium levels were also influenced by the interaction between the factors ($p \leq 0.01$). Furthermore, there was an effect of interaction between the factors salinity and pyroligneous extract on shoot fresh mass and total fresh mass ($p \leq 0.01$) (Table 4).

The increase in salt levels compromised the nutritional balance of the Surinam cherry seedlings (Figure 4). Sodium

Table 4. Summary of the analysis of variance of sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) contents in leaf tissues, and Na, K, and Ca contents in the roots and shoot fresh mass (SFM), and total fresh mass (TFM) of Surinam cherry seedlings subjected to irrigation with brackish waters and to different concentrations of pyroligneous extract

Source of variation	D.F.	Mean squares								
		Leaf contents				Root contents			SFM	TFM
		Na	K	Ca	Mg	Na	K	Ca		
Salinity (S)	3	38.61**	49.64**	9.36**	0.10**	37.31**	1.82**	12.49**	29.84**	88.23**
Pyroligneous Extract (PE)	2	0.38^{ns}	5.71**	1.14^{ns}	0.02**	0.98^{ns}	0.02^{ns}	0.10^{ns}	1.06^{ns}	0.08^{ns}
S × PE	6	0.63^{ns}	2.45*	0.29^{ns}	0.008*	1.55**	0.08^{ns}	2.23**	2.92**	4.18**
Blocks	3	1.06^{ns}	0.19^{ns}	0.26^{ns}	0.006^{ns}	0.74^{ns}	0.05^{ns}	0.23^{ns}	0.41^{ns}	0.95^{ns}
Residual	33									
C.V. (%)		11.94	9.49	17.44	11.47	8.87	7.51	17.46	8.70	6.31

D.F. - Degrees of freedom; C.V. - Coefficient of variation; ns, *, ** - No-significant, significant at $p \leq 0.05$, and $p \leq 0.01$ by the F-test, respectively



The same letters do not differ significantly for different concentration of pyroligneous extract within each salinity level by Tukey's test ($p > 0.05$). ** - Significant at $p \leq 0.01$ by the F-test. Vertical bars represent the standard error (n = 4)

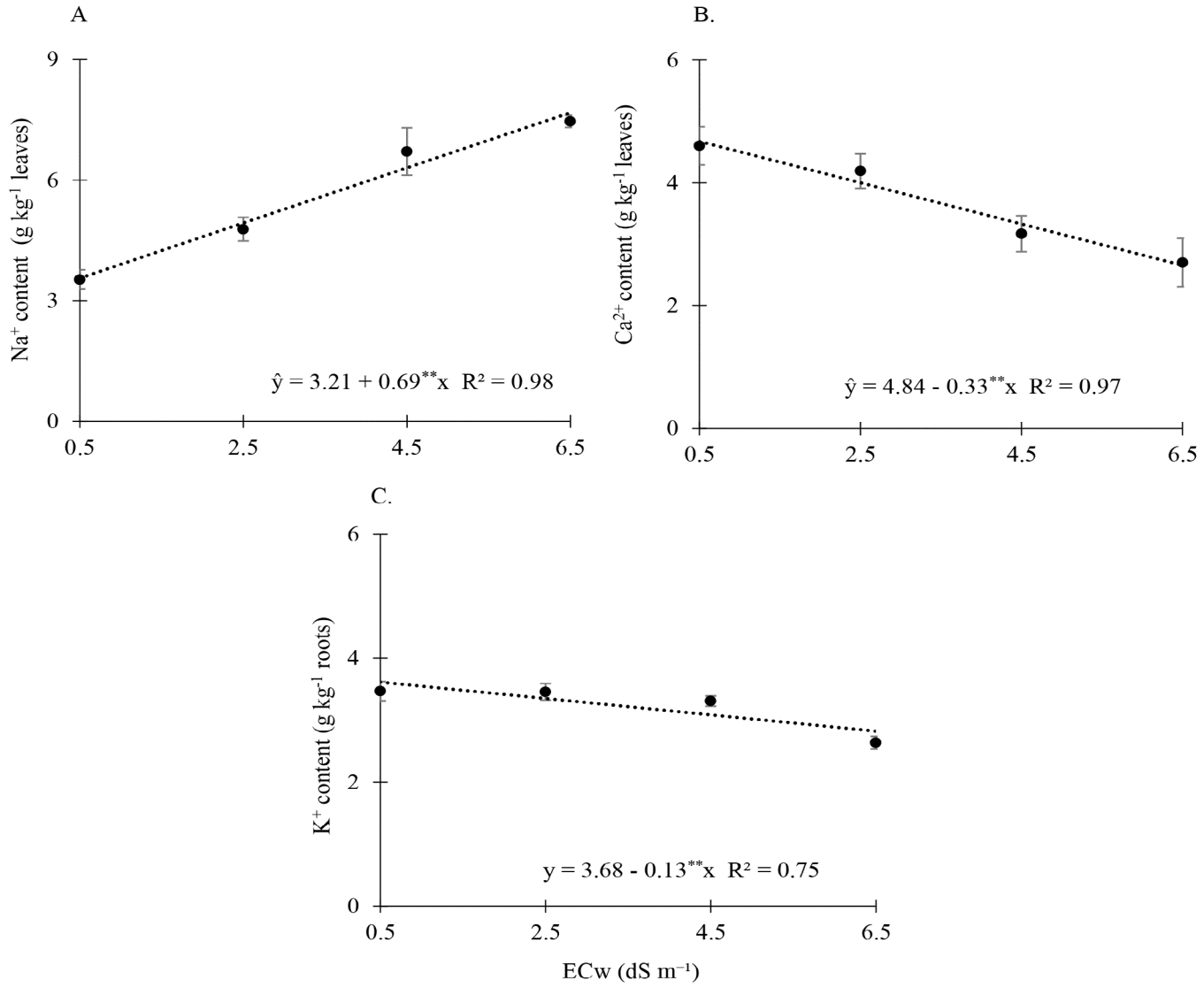
Figure 4. Contents of sodium (Na^+, A) and calcium (Ca^{2+}, C) in the roots, and potassium (K^+, B) and magnesium (Mg^{2+}, D) in the leaf tissues of Surinam cherry seedlings subjected to irrigation with brackish water and the application of pyroligneous extract, at 80 days after the application of the treatments

(Na^+) in the roots increased linearly with the increase in ECw (Figure 4A), while calcium (Ca^{2+}) in the roots (Figure 4C) and potassium (K^+) and magnesium (Mg^{2+}) in the leaves (Figures 4B and 4D) decreased. The application of pyroligneous extract (PE) was not enough to reverse these trends. The concentration of 2% was associated with lower Na^+ in the roots and higher Mg^{2+} in the leaves under moderate salinity, while for K^+, the highest concentration promoted increases only under non-saline conditions. For Ca^{2+} in the roots, the treatments of PE did not present differences at the salinity level of 4.5 dS m^{-1}.

Although in the present study the pyroligneous extract was not sufficient to reverse the nutritional imbalances caused by salinity, this limited effectiveness may be related to the concentration and frequency of application, which might not have been sufficient to promote ionic homeostasis under high-salt stress. In addition, the predominance of sodium ions in the soil solution may have restricted the extract's ability to enhance nutrient uptake. Nevertheless, previous studies indicate that this product has the potential to improve plant performance under saline irrigation by reducing Na^+ uptake and the expression of salt transporter genes (Ma et al., 2022).

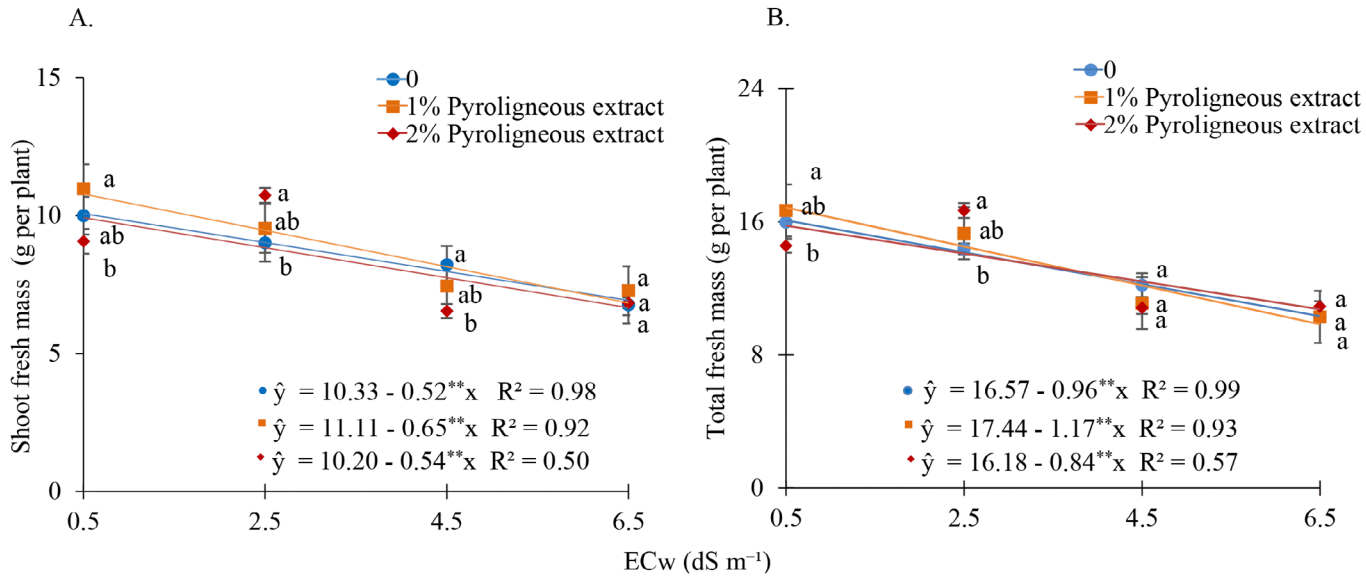
Yang et al. (2024) also observed that the efficiency of pyroligneous extract increased when combined with biochar, which helped retain cations and improve soil structure, resulting in reductions of more than 30% in soluble salts. In contrast, the isolated application of the extract in the present study may have been insufficient to promote similar improvements. Although the extract's acidic nature can enhance the solubility of K-, Ca-, and Mg-bearing minerals (Najafi-Ghiri et al., 2022), these benefits might have been offset by ion competition in the rhizosphere. Such interactions could explain the limited increases in K^+, Ca^{2+}, and Mg^{2+} contents despite their physiological importance for osmotic regulation, membrane stability, and photosynthetic metabolism (Mirsoleimani et al., 2023; Zhou et al., 2023; Afsharipour et al., 2025).

The increasing salinity levels linearly increased Na^+ content in the leaves (Figure 5A), while Ca^{2+} in the leaves (Figure 5B) and K^+ in the roots (Figure 5C) decreased with rising ECw. These linear decreases of these nutrients observed in the regressions reinforce that salinity strongly impairs nutritional



** - Significant at p ≤ 0.01 by the F-test. The vertical bars represent the standard error of the mean (n = 4)

Figure 5. Sodium (Na^+, A) and calcium (Ca^{2+}, B) contents in the leaves, and potassium (K^+, C) in the roots of Surinam cherry seedlings subjected to the isolated effect of salinity, evaluated at 80 days after the application of the treatments



The same letters do not differ significantly for different concentration of pyroligneous extract within each salinity level by Tukey's test ($p > 0.05$). ** - Significant at $p \leq 0.01$ by the F-test. Vertical bars represent the standard error (n = 4)

Figure 6. Shoot fresh mass (A), and total fresh mass (B) of Surinam cherry seedlings under the effect of salinity of irrigation water and application of pyroligneous extract, evaluated at 80 days after the application of the treatments

balance, while PE shows only a limited and condition-dependent capacity to mitigate such effects.

The linear increase of Na^+ in the leaves and the reduction of Ca^{2+} in leaves and K^+ in roots with increasing salinity levels (Figure 5) highlight the disruption of ionic homeostasis in Surinam cherry seedlings under salt stress. Similar patterns have been observed in other Myrtaceae species. Dadach et al. (2023) reported that *Myrtus communis* maintained growth under lower salinity, but higher levels caused reductions due to water deficit and ionic imbalance. Likewise, Nofal et al. (2024) observed that *Eugenia uniflora* displayed resistance at mild salt concentrations but suffered severe growth losses under higher stress, reinforcing the sensitivity of this species when ionic imbalance intensifies. This adaptive capacity in *E. uniflora* has been linked to genetic mechanisms, such as the expression of PDX1 family genes related to vitamin B6 metabolism, which contribute to reactive oxygen species (ROS) regulation and tolerance to salinity (Turchetto-Zolet et al., 2024). However, the regression trends observed in the present study suggest that, despite possible adaptive responses, Na^+ accumulation coupled with Ca^{2+} and K^+ depletion are central to the nutritional imbalance induced by salinity.

The shoot fresh mass (SFM) and total fresh mass (TFM) of Surinam cherry plants decreased linearly with increasing irrigation water salinity (Figure 6A and 6B); the application of pyroligneous extract (PE) was not sufficient to reverse this general trend. Nevertheless, at moderate salinity (2.5 dS m^{-1}), the 2% concentration promoted higher values of both SFM and TFM compared to the other treatments, while under non-saline and higher salinity conditions the differences among PE concentrations were less evident.

Previous studies, such as that of Ferreira et al. (2025), reported positive effects of pyroligneous extract on the total dry mass of Surinam cherry plants, with concentrations between 1 and 2% stimulating growth under saline conditions. However, in the present study, it was observed that only a 2% concentration of PE attenuated the rate of decline of total fresh mass (TFM), while a 1% concentration accentuated this reduction. This indicates that the threshold for beneficial effects is narrow and that insufficient concentrations can even aggravate losses. When the positive effect occurs (as observed with 2% PE), it may be associated with the adsorbent properties of PE, which reduce sodium bioavailability and oxidative stress, favoring plant growth (Afsharipour et al., 2025).

Conclusions

1. Irrigation water with electrical conductivity higher than 2.5 dS m^{-1} negatively affected most variables, regardless of the pyroligneous extract concentration, except for the Na^+ content, which increased with salinity.

2. Irrigation with brackish water of up to 2.5 dS m^{-1}, combined with the application of 2% pyroligneous extract, is recommended for Surinam cherry seedlings, as this association acts as a mitigator of salt stress, promoting better physiological and nutritional performance, and improved accumulation of phytomass.

3. The use of pyroligneous extract can be an accessible strategy for farmers in semi-arid regions, allowing the use of moderately brackish water in irrigation without compromising the growth of Surinam cherry seedlings.

Contribution of authors: Ferreira, A. dos Santos, Viana, A. dos Santos, and Sá, F. V. da S. de: worked on research, data acquisition, data analysis, implementation of computational simulations, and manuscript writing. Amorim, P. E. C. and Melo, R. S.: worked on the conceptualization of the problem and the literature review. Mendonça, V. de: acted as research advisor and made improvements and corrections to the manuscript. Ribeiro, J. E. da S.: advised and worked on data analysis, corrections, and improvements to the simulation models.

Data availability statement: The corresponding author declares that there is no data underlying the article texts.

Conflict of interest: The authors declare no conflict of interest.

Financing statement: This study was funded by the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Financing Code 001.

Literature Cited

Abbaszadeh, N.; Lajayer, H. M.; Gigli, M. T.; Poorbeyrami-eHir, Y.; Azarmi, R.; A. S. Investigation of the effects of biochar and wood vinegar on morpho-physiological traits of African marigold under salt stress. Horticultural Plants Nutrition, v.5, p.151-161, 2022. https://doi.org/10.22070/hpn.2023.15912.1168

Afsharipour, S.; Seyedi, A.; Dastjerdi, A. M. Salinity tolerance in *Cucumis sativus* seedlings: the role of pistachio vinegar in improving biochemical parameters and seedling vigor. BMC Plant Biology, v.25, e224, 2025. https://doi.org/10.1186/s12870-025-06237-y

Alvares, C. A.; Stape, J. L.; Sentelhas, P. C.; Gonçalves, J. L. de M.; Sparovek, G. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, v.22, p.711-728, 2013. https://doi.org/10.1127/0941-2948/2013/0507

Carmo, C. D. S.; Araujo, W. S. de; Bernardi, A. D. C.; Saldanha, M. F. C. Plant tissue analysis methods used at Embrapa Soils. Rio de Janeiro: Embrapa Soils, 2000. 41p. Technical Circular No. 6

Corrêa, M. C. de M.; Prado, R. de M.; Natale, W.; Pereira, L.; Barbosa, J. C. Response of guava to rates and placement of phosphate fertilizer. Revista Brasileira de Fruticultura, v.25, p.164-169, 2003. https://doi.org/10.1590/S0100-29452003000100045

Dadach, M.; Ahmed, M. Z.; Bhatt, A.; Radicetti, E.; Mancinelli, R. Effects of chloride and sulfate salts on seed germination and seedling growth of *Ballota hirsuta* Benth. and *Myrtus communis* L. Plants, v.12, e3906, 2023. https://doi.org/10.3390/plants12223906

Danielle-Silva, A.; Parente, A. M. E. S.; Sousa, F. S. de; Pontes, S. D.; Torres-Rêgo, M.; Cavalcanti, F. F.; Assunção, F. M. R.; Freitas, F. P. M. de; Lira, L. S. In vitro and in vivo anti-inflammatory and antiophidic effects of the extract and fraction of *Eugenia uniflora*. Journal of Ethnopharmacology, v.319, e117223, 2024. https://doi.org/10.1016/j.jep.2023.117223

Devkota, K. P.; Devkota, M.; Rezaei, M.; Oosterbaan, R. Managing salinity for sustainable agricultural production in salt-affected soils of irrigated drylands. Agricultural Systems, v.198, e103390, 2022. https://doi.org/10.1016/j.agsy.2022.103390

Engela, M. R. G. da S.; Furlan, C. M.; Esposito, M. P.; Fernandes, F. F.; Carrari E.; Domingos M.; Paoletti, E.; Hoshika, Y. Metabolic and physiological alterations indicate that the tropical broadleaf tree *Eugenia uniflora* L. is sensitive to ozone, Science of the Total Environment, v.769, e145080, 2021. https://doi.org/10.1016/j.scitotenv.2021.145080

Ferreira, A. dos S.; Mendonça, V.; Souto, A. G. de L.; Sá, F. V. da S.; Ribeiro, J. E. da S. Pyroligneous acid extract as an attenuator of salt stress in Surinam cherry. Revista Brasileira de Engenharia Agrícola e Ambiental, v.29, e291047, 2025. https://doi.org/10.1590/1807-1929/agriambi.v29n8e291047

Ferreira, D. F. SISVAR: a computational analysis system for split plot designs with fixed effects. Revista Brasileira de Biometria, v.37, p.529-535, 2019. https://doi.org/10.28951/rbb.v37i4.450

Fidelis, E. M.; Savall, A. S. P.; Pereira F de O.; Quines, C. B.; Ávila, D. S.; Pinton, S. Pitanga (*Eugenia uniflora* L.) as a source of bioactive compounds for health benefits: A review. Arabian Journal of Chemistry, v.15, p.1-22, 2022. https://doi.org/10.1016/j.arabjc.2022.103691

Girardi, L. B.; Peiter, M. X.; Bellé, R. A.; Robaina, A. D.; Torres, R. R.; Kirchner, J. H.; Ben, L. H. B. Evapotranspiration and crop coefficients of potted *Alstroemeria* × *hybrida* grown in greenhouse. Irriga, v.21, p.817-829, 2016. https://doi.org10.15809/irriga.2016v21n4p817-829

Gul, Z.; Tang, Z. H.; Arif, M.; Ye, Z. An insight into abiotic stress and influx tolerance mechanisms in plants to cope in saline environments. Biology, v.11, e597, 2022. https://doi.org/10.3390/biology11040597

Iacomino, G.; Idbella, M.; Staropoli, A.; Nanni, B.; Bertoli, T.; Vinale, F.; Bonanomi, G. Exploring the potential of wood vinegar: chemical composition and biological effects on crops and pests. Agronomy, v.14, e114, 2024. https://doi.org/10.3390/agronomy14010114

Ma, J.; Islam, F.; Ayyaz, A.; Fang, R.; Hannan, F.; Farooq, M. A.; Ali, B.; Huang, Q.; Sun, R.; Zhou, W. Wood vinegar induces salinity tolerance by alleviating oxidative damages and protecting photosystem II in rapeseed cultivars. Industrial Crops and Products, v.188, e115763. 2022. https://doi.org/10.1016/j.indcrop.2022.115763

Micco, de V.; Arena, C.; Amitrano, C.; Rouphael, Y.; De Pascale, S.; Cirillo, C. Effects of NaCl and $CaCl_2$ salinization on morpho-anatomical and physiological traits of potted *Callistemon citrinus* plants. Forests, v.12, e1666, 2021. https://doi.org/10.3390/f12121666

Mirsoleimani, A.; Najafi-Ghiri, M.; Boostani, H. R.; Farrokhzadeh, S. Soil and plant nutrient relationships of citrus rootstocks influenced by potassium and wood vinegar application. Journal of Soils and Sediments, v.23, p.1439–1450, 2023. https://doi.org/10.1007/s11368-022-03408-4

Najafi-Ghiri, M.; Mirsoleimani, A.; Boostani, H. R.; Amin, H. Influence of wood vinegar and potassium application on soil properties and Ca/K ratio in citrus rootstocks. Journal of Soil Science and Plant Nutrition, v.22, p.334–344, 2022. https://doi.org/10.1007/s42729-021-00653-3

Nofal, E.; Shahin, S. M.; El-Tarawy, A.; Eshewy, W.; El-Ramady, H. Growth and quality of Brazilian cherry (*Eugenia uniflora* L.) ornamental shrubs under salinized irrigation water with natural Siwa halite. Egyptian Journal of Soil Science, v.64, p.777–789, 2024. http://dx.doi.org/10.21608/ejss.2024.273827.1733

Ouattara, H. A. A.; Niambké, F. B.; Yao, J. C.; Amusant, N.; Garnier, B. Wood vinegars: production processes, properties, and valorization. Forest Products Journal, v.73, p.239-249, 2023. https://doi.org/10.13073/FPJ-D-23-00021

Richards, L. A. Diagnosis and improvement of saline and alkali soils. Washington: US Department of Agriculture, 1954. 160p. https://doi.org/10.1126/science.120.3124.800.a

Rodrigues Filho, R. A.; Nobre, R. G.; Santos, A. S.; Teixeira, A. D. S.; Ferreira, A. P. N.; Soares, L. A. dos A.; Lima, G. S. de; Guedes, W. A.; Vasconcelos, E. S.; Silva, L. A.; Araújo, K. F. P. Morphology of 'Crioula' guava seedlings under irrigation with increasing salinity water and nitrogen/potassium fertilization. Brazilian Journal of Biology, v.83, e275322. 2023. https://doi.org/10.1590/1519-6984.275322

Silva, S. S. da; Lima, G. S. de; Ferreira, J. T.; Soares, L. A. A. dos.; Gheyi, H. R.; Nobre, R. G.; Silva, F. J. L. da.; Mesquita, E. F. de. Formation of guava seedlings under salt stress and foliar application of hydrogen peroxide. Revista Brasileira de Engenharia Agrícola e Ambiental, v.28, e276236, 2024. https://doi.org/10.1590/1807-1929/agriambi.v28n2e276236

Teixeira, P. C.; Donagemma, G. K.; Fontana, A.; Teixeira, W. G. Manual de métodos de análise de solo. 3. ed. Rio de Janeiro: Embrapa Solos, 2017. 573p. Available on: <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1085209>. Accessed on: Mar. 2025.

Turchetto-Zolet, A. C. C.; Salgueiro, F.; Guzman, F.; Veto, N.M.; Balbinott, N.; Rodrigues, N. F.; Pinheiro, M. M.; Margis, R. Gene expression divergence in *Eugenia uniflora* highlights adaptation across contrasting Atlantic forest ecosystems. *Plants,* v.13, e2719, 2024. https://doi.org/10.3390/plants13192719

UFERSA - Universidade Federal Rural do Semi-Árido. Estações meteorológicas automáticas (EMA). 2023. Available on: <https://siemu.ufersa.edu.br/hobolink/mossoro>. Accessed on: Mar. 2025.

Yang, L.; Tang, G.; Xu, W.; Zhang, Y.; Ning, S.; Yu, P.; Zhu, J.; Wu, Q.; Yu, P. Effect of combined application of wood vinegar solution and biochar on soil salinity properties and cotton stress tolerance. Plants, v.13, e2427, 2024. https://doi.org/10.3390/plants13172427

Zhou, H.; He, L.; Liu, X.; Gaoling, S.; Sun, X.; Su, J.; Li, C.; Chen, J.; Zwietem, L.; Pan, G. Diluted pyroligneous vinegar promoted Rhododendron growth by changing functional genes involved in N cycling in the rhizosphere. Geoderma, v.438, e116628, 2023. https://doi.org/10.1016/j.geoderma.2023.116628