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Salt and nutritional stress on the physiological characteristics and productivity of the peanut crop

Estresse salino e nutricional nas características fisiológicas e na produtividade da cultura do amendoim

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Highlights

DK$^+$ helps maintain physiological processes, enabling production in saline conditions.
K fertilization boosts photosynthesis and CO_2 diffusion to carboxylation sites.
Pod weight is strongly correlated with transpiration and water use efficiency.

Abstract

Peanut production has been highlighted in the Northeast region of Brazil; however, salinity in irrigation water negatively affects the agronomic performance of crops. Potassium fertilization, in turn, may mitigate salt stress and enhance the agronomic performance of peanut plants. Therefore, this study aimed to evaluate the effect of potassium fertilization as a strategy to mitigate salt stress on peanut agronomic performance. The experiment was conducted in the experimental area of the Auroras Seedling Production Unit, belonging to the Universidade da Integração Internacional da Lusofonia Afro-

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Brasileira, in Redenção, state of Ceará. A completely randomized design in a 5 × 2 factorial arrangement, with five replications, was adopted. The first factor consisted of five potassium rates (0, 12.5, 25, 37.5, and 50 kg ha−1, corresponding to 0, 25, 50, 75, and 100% of the recommended rate), and the second factor consisted of two irrigation water salinity levels (0.8 and 4.0 dS m−1). Potassium fertilization, combined with irrigation using moderately saline water, led to increases in pod diameter, pod length, and pod number in peanut plants. However, higher salinity significantly reduced these variables. On the other hand, when applied in isolation, brackish water negatively affected pod weight, yield, and water use efficiency.
Key words: *Arachis hypogaea* L. Potassium. Biosaline agriculture.

Resumo

A produção de amendoim tem se destacado na região Nordeste do Brasil, mas a salinidade na água de irrigação afeta negativamente o desempenho agronômico das culturas agrícolas. No entanto, a fertilização com potássio pode mitigar o estresse salino e maximizar o desempenho agronômico da cultura do amendoim. O objetivo foi, portanto, avaliar o efeito da fertilização com potássio como estratégia para mitigar o estresse salino no desempenho agronômico do amendoim. O experimento foi conduzido na área experimental da Unidade de Produção de Mudas Auroras, pertencente à Universidade da Integração Internacional da Lusofonia Afro-Brasileira, Redenção, Estado do Ceará. Foi utilizado o delineamento inteiramente casualizado em arranjo fatorial 5 × 2 com cinco repetições. O primeiro fator incluiu cinco doses de potássio (0, 12,5, 25, 37,5 e 50 kg ha^{-1}, equivalentes a 0, 25, 50, 75 e 100 % da dose recomendada) e o segundo fator envolveu dois níveis de salinidade da água de irrigação (0,8 e 4,0 dS m^{-1}). A fertilização potássica, associada à irrigação com água de baixa salinidade, proporcionou aumento positivo no diâmetro, comprimento e número de vagens da cultura do amendoim. No entanto, a salinidade mais alta reduziu significativamente essas variáveis. Por outro lado, quando usado isoladamente, o uso de água salobra afetou negativamente a massa da vagem, a produtividade e a eficiência do uso da água.
Palavras-chave: *Arachis hypogaea* L. Potássio. Agricultura biossalina.

Introduction

Peanut (*Arachis hypogaea* L.) is one of the most widely cultivated oilseeds in Brazil and worldwide due to its high nutritional value. It is used for fresh consumption, in the canning industry, biodiesel production, and confectionery. The average yield in Brazil is 2,873 kg ha^{-1} (Goes et al., 2021; Companhia Nacional de Abastecimento [CONAB], 2024).

Peanut production has expanded in the Northeast region; however, it faces challenges related to high salt concentrations in irrigation water, despite the crop being considered moderately tolerant, with a salinity threshold of 2.5 dS m^{-1} (Rhoades et al., 2000). Salt stress affects plant metabolism, compromising physiological and biochemical processes, resulting in disturbances in water relations, alterations in nutrient uptake and utilization, accumulation of toxic ions, and, consequently, reduced crop productivity (H. C. Sousa et al., 2023a; Abreu et al., 2024).

One strategy to mitigate salt stress is mineral fertilization with potassium, which contributes to maintaining ionic homeostasis and reducing oxidative stress by limiting the formation of reactive oxygen species (Hasanuzzaman et al., 2018). Additionally, this macronutrient plays a key role in osmotic regulation, stomatal opening and closing, carbon assimilation, and protein synthesis, and is essential for the growth, development, and maturation of grains and fruits (Taiz et al., 2024; J. T. M. Sousa et al., 2023b).

Therefore, it is important to highlight that previous studies have reported promising results regarding the use of potassium fertilization under saline conditions. Freitas et al. (2021) concluded that potassium fertilization partially mitigated the harmful effects of salinity on peanut morphology and physiology. Similarly, Abreu et al. (2024) reported increased pod number and pod weight in peanut plants subjected to potassium fertilization under salt stress. In this context, the present study aimed to evaluate the effect of potassium fertilization as a strategy to mitigate salt stress on the agronomic performance of peanuts.

Material and Methods

The experiment was conducted from February to May 2023 at the Auroras Seedling Production Unit, belonging to the Universidade da Integração Internacional da Lusofonia Afro-Brasileira, in Redenção, state of Ceará. The geographical coordinates of the site are latitude 04°13'25" S, longitude 38°43'48" W, at an altitude of 95 m.

The regional climate is classified as Aw (tropical rainy), characterized by high temperatures and rainfall concentrated in the summer and fall seasons (Alvares et al., 2013). Figure 1 shows the meteorological data recorded during the experimental period.

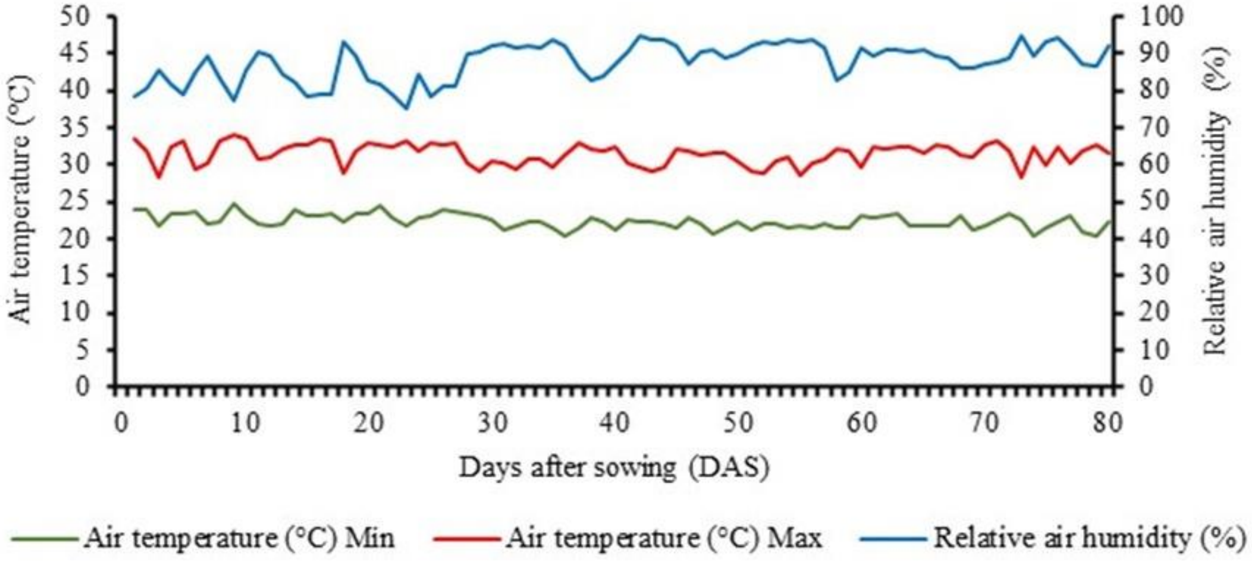

Figure 1. Average values for relative humidity and maximum (Max) and minimum (Min) temperatures during the experimental cycle.

The experimental design was completely randomized in a 5 × 2 factorial arrangement, with five replications. The first factor consisted of five potassium rates (0, 12.5, 25, 37.5, and 50 kg ha^{-1}), corresponding to 0, 25, 50, 75, and 100% of the recommended rate. The second factor consisted of two irrigation water salinity levels (0.8 and 4.0 dS m^{-1}).

The soil used in the pots is classified as Argissolo Vermelho-Amarelo (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2018). It was analyzed at the Soil and Water Laboratory of the Soil Science Department of the Universidade Federal do Ceará to determine its chemical attributes, following the methodology described by Teixeira et al. (2017) (Table 1).

Table 1
Chemical attributes of the substrate used before the treatments were applied

OM[1]	N	Mg^{2+}	K^{+}	Ca^{2+}	Na^{+}	P	pH	ESP[2]	ECse[3]
----- g kg^{-1} -----		----------- cmolc dm^{-3} ------------			----mg dm^{-3}----		H_2O	(%)	dS m^{-1}
8	0.8	0.3	0.99	0.39	112	68.6	6.5	0.14	0.37

[1]OM: organic matter; 2ESP: exchangeable sodium percentage and 3ECse: electrical conductivity of the saturation extract

Peanut cultivar BR-1, belonging to the Valencia group, was grown in polyethylene pots with a volumetric capacity of 8 L. Thinning was performed 10 days after sowing (DAS), leaving only the most vigorous plant.

Peanut plants were fertilized according to soil chemical analysis and the recommendations of Fernandes (1993), with 15 kg ha^{-1} of N, 62.5 kg ha^{-1} of P_2O_5, and 50 kg ha^{-1} of K_2O. For a plant stand of 10,000 plants, the maximum rate per plant during the cycle was 1.5 g of N, 6.25 g of P_2O_5, and 5 g of K_2O, using urea (45%), single superphosphate (18%), and potassium chloride (60%) as sources. The following potassium fertilization rates were applied: 0, 1.25, 2.5, 3.75, and 5.0 g pot^{-1}, corresponding to 0, 25, 50, 75, and 100% of the recommended rate, respectively.

To prepare irrigation water with an electrical conductivity of 4.0 dS m^{-1}, the salts NaCl, $CaCl_2{\cdot}2H_2O$, and $MgCl_2{\cdot}6H_2O$ were dissolved in the unit's water supply (0.8 dS m^{-1}) at a ratio of 7:2:1, respectively, following the relationship between ECw and molar concentration (mmolc L^{-1} = EC × 10), as described by Richards (1954).

Irrigation was carried out manually on a daily basis using a water balance approach, based on the drainage lysimeter principle, with pots adapted as micro-lysimeters to maintain soil at field capacity, according to Eq. 1:

Equation 01: $VI = \frac{Vp - Vd}{1 - LF}$

where:

VI - Volume of water applied during irrigation (mL);

Vp - volume of water applied in the previous irrigation (mL);

Vd - volume of water drained (mL); and

LF - leaching fraction (0.15).

At 50 DAS, the following physiological variables were evaluated: photosynthetic rate (A, μmol CO_2 m^{-2} s^{-1}), leaf temperature (LT), transpiration rate (E, mmol H_2O m^{-2} s^{-1}), stomatal conductance (gs, mol H_2O m^{-2} s^{-1}), and instantaneous intrinsic carboxylation efficiency (A/Ci). Measurements were performed using an infrared gas analyzer (LCi System, ADC, Hoddesdon, UK) in an open system with an air flow rate of 300 mL min^{-1}. Readings were taken between 09h00 and 10h00 under artificial radiation (1,200 μmol m^{-2} s^{-1}).

At 85 DAS, plants were harvested and the following variables were analyzed: pod weight (PW, g $plant^{-1}$), measured using a scale with 0.001 g precision; pod length (PL, mm) and pod diameter (PD, mm), measured with a digital caliper; pod number (PN), obtained by counting; and yield (Y, g pot^{-1}), determined using an analytical balance. Water use efficiency (WUE) was calculated as the ratio between yield (g pot^{-1}) and the total volume of water applied per pot (L), and then converted to kg ha^{-1} mm^{-1}.

Data normality was assessed using the Shapiro-Wilk test, homogeneity of variances using the Bartlett test, and independence of errors using the Durbin-Watson test. After meeting these assumptions, the data were subjected to analysis of variance using the F test. When significant effects were observed, regression analysis was performed for potassium levels. For salinity levels, when significant, means were compared using Tukey's test ($p \leq 0.05$). Pearson's correlation analysis was also conducted to evaluate relationships among the studied variables. All statistical analyses were performed using RStudio (R Core Team [R], 2022).

Results and Discussion

An isolated effect of irrigation with brackish water was observed at the 1% significance level for the variables CO_2 assimilation rate (A), transpiration (E), and stomatal conductance (Gs) (Table 2). Similarly, an isolated effect of potassium doses was observed for transpiration (E), stomatal conductance (Gs), intercellular CO_2 concentration (Ci), intrinsic carboxylation efficiency (A/Ci), and intrinsic water use efficiency (A/Gsi). A significant interaction ($p \leq 0.01$) between potassium rates and irrigation water salinity was observed for the SPAD index.

Table 2

Summary of the analysis of variance for CO2 assimilation rate (A), transpiration (E), stomatal conductance (gs), intercellular CO2 concentration (Ci), leaf temperature (LT), instantaneous water use efficiency (A/E), intrinsic carboxylation efficiency (A/Ci), intrinsic water use efficiency (A/Gsi) and SPAD index in peanut plants as a function of potassium rates and irrigation with brackish water

SV	DF	Mean square								
		A	E	gs	Ci	LT	A/E	A/Ci	A/Gsi	SPAD
Potassium rate (R)	4	8.31^{ns}	0.53**	10.31**	1390.18**	0.026^{ns}	0.026^{ns}	0.00004^{ns}	101.73**	7.69^{ns}
Water salinity (WS)	1	96.59**	4.12**	15.53**	62.50^{ns}	0.225^{ns}	0.494^{ns}	0.0007**	17.62^{ns}	6.80^{ns}
Interaction (R × WS)	4	2.31^{ns}	0.27^{ns}	8.73^{ns}	482.93^{ns}	0.068^{ns}	0.311^{ns}	0.000007^{ns}	11.98^{ns}	33.36**
Residue	30	4.38	0.13	2.61	559.63	0.063	0.327	0.00003	14.77	9.38
Total	39									
CV (%)	-	19.36	13.22	26.25	6.49	0.85	16.92	19.11	13.61	7.52

SV: source of variation; DF: degrees of freedom; *Significant at 5% probability by the F-test; **Significant at 1% probability by the F-test; ns: not significant.

Increasing irrigation water electrical conductivity from 0.8 to 4.0 dS m^{-1} resulted in a significant reduction ($p < 0.05$) in CO_2 assimilation rate (24%) (Figure 2A).

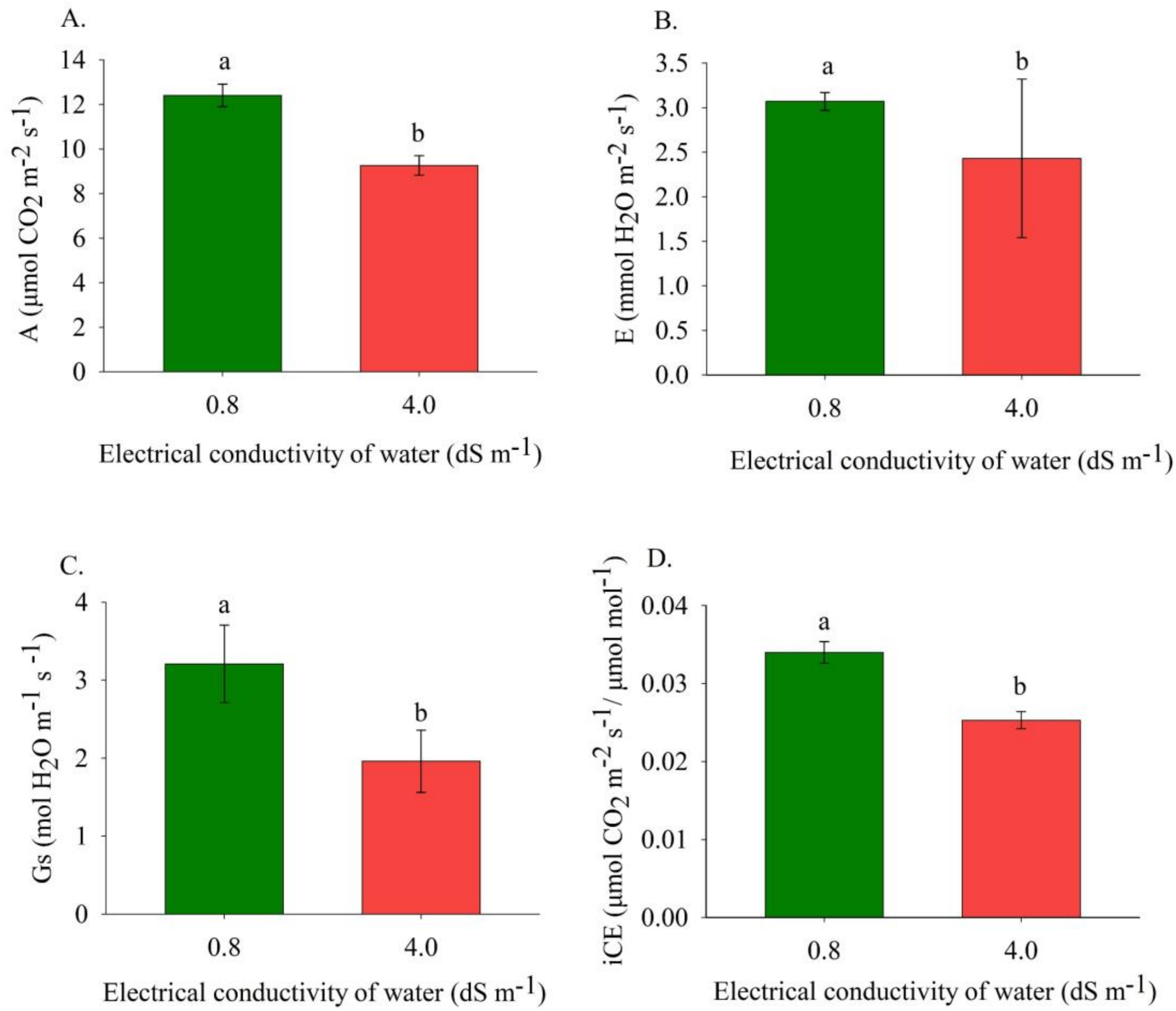

Figure 2. CO_2 assimilation rate (A), transpiration (B), stomatal conductance (C), and intrinsic carboxylation efficiency (D) of the peanut crop as a function of irrigation with brackish water. Vertical lines represent the standard error of the mean (n = 4). Means followed by the same letter are not significantly different from each other by Tukey's test ($p \leq 0.05$).

This effect can be attributed to the reduction in osmotic potential at the root surface caused by high ion concentrations in the soil solution, which limits water uptake by roots (Zhang et al., 2022; X. Wang et al., 2024). Additionally, salt stress reduces the activity of reaction centers and inhibits electron transport from Photosystem II (PSII) to Photosystem I (PSI) (Zahra et al., 2022).

Salt stress reduced transpiration by 16.67% compared to the control treatment (Figure 2B). This effect may result from limited water availability, leading to stomatal closure as an adaptive mechanism to prevent loss of cell turgor (Hnilickova et al., 2021).

Stomata regulate CO_2 influx into the leaf and water vapor efflux to the atmosphere (Zhang et al., 2022). When they close, stomatal conductance decreases, reducing water vapor flow and, consequently, transpiration. These results are consistent with those reported by Silva et al. (2022), who observed significant reductions in transpiration in peanut plants irrigated with brackish water. Similarly, G. S. Oliveira et al. (2024), in a pot experiment with peanut plants under saline irrigation, also reported reduced transpiration rates.

Irrigation with low-salinity water resulted in significantly higher stomatal conductance compared to brackish water, with a reduction of 38.94% under saline conditions (Figure 2C). Reduced stomatal conductance decreases intercellular CO_2 concentration, limiting the activity of enzymes such as RUBISCO, thereby restricting carboxylation and reducing net photosynthesis (Hnilickova et al., 2021). Consistent with the present findings, G. S. Oliveira et al. (2024) also reported higher stomatal conductance under lower salinity conditions in peanut cultivation.

Salt stress resulted in significantly lower values compared to low-salinity water and negatively affected intrinsic carboxylation efficiency, reducing it by 24.24% (Figure 2D). It is important to note that salt stress increases intercellular CO_2 concentration due to a reduction in photosynthetic rate (Taiz et al., 2024). F. R. Oliveira et al. (2022), when evaluating salt stress in sugar beet crops, observed a similar trend. According to these authors, salt stress negatively affected intrinsic carboxylation efficiency.

The reduction in intrinsic carboxylation efficiency (A/Ci) is associated with the decrease in transpiration rate (E) caused by previously applied stress conditions. Dourado et al. (2022) reported that water use efficiency expresses the amount of carbon fixed during photosynthesis for each molecule of water that is lost during the process. By closing stomata to reduce excessive water loss through transpiration, plants can utilize CO_2 accumulated in substomatal chambers, thereby minimizing water loss under stress conditions (Taiz et al., 2024).

Stomatal conductance in peanut plants exhibited a quadratic response to potassium rates (Figure 3A). The highest estimated value (3.36 mol H_2O m^{-2} s^{-1}) was observed at a potassium rate of 63 kg ha^{-1}. This response may be attributed to the essential role of potassium in regulating physiological processes such as nutrient translocation, protein synthesis, enzyme activation, and photosynthesis, as well as water uptake through its control of guard cell turgor during stomatal movement (El-Mageed et al., 2023).

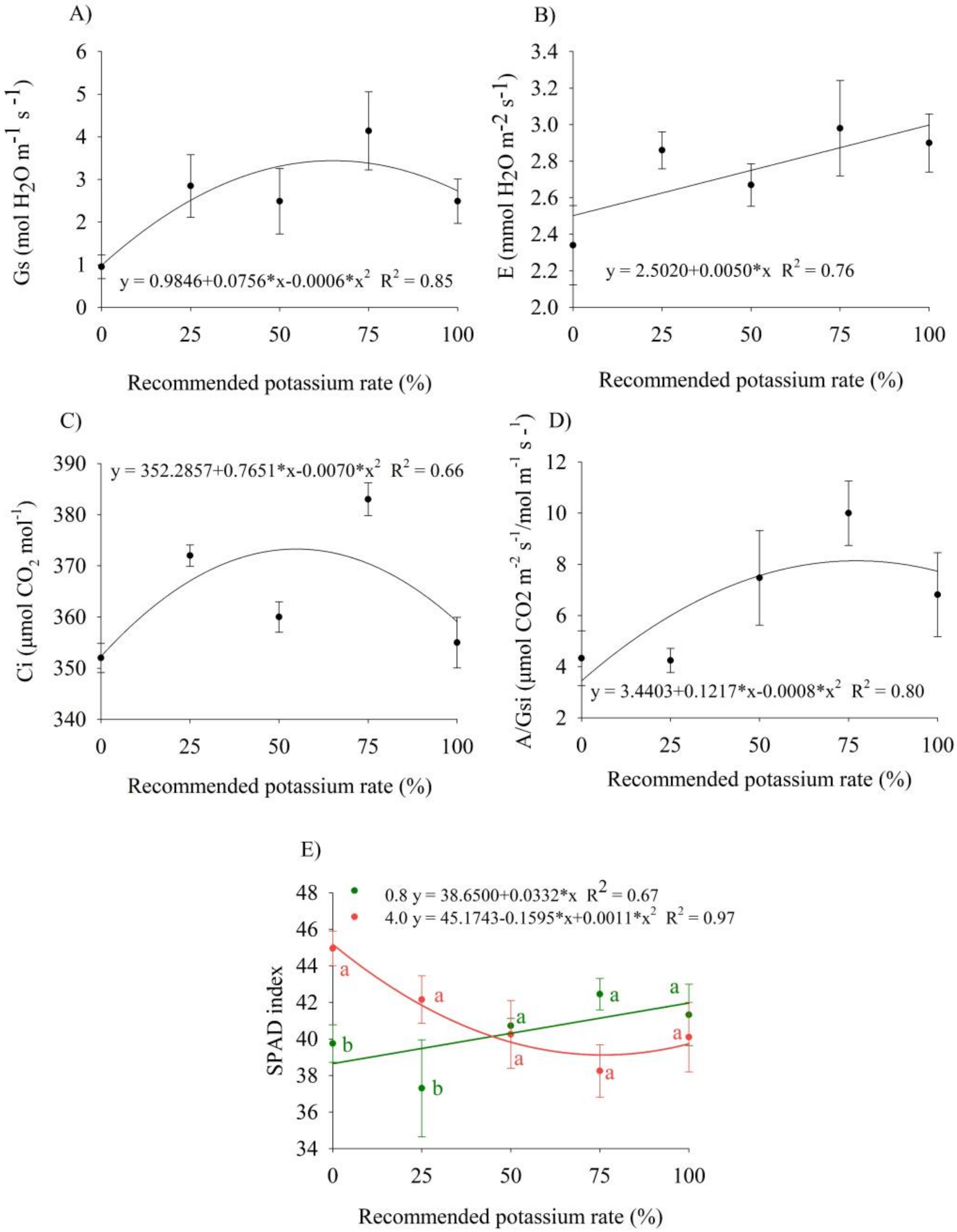

Figure 3. Stomatal conductance (A), transpiration (B), intercellular CO_2 concentration (C), intrinsic water use efficiency (D), and SPAD index (E) of the peanut crop as a function of the interaction between different rates of potassium and irrigation with brackish water.
Vertical lines represent the standard error of the mean (n = 4). Means followed by the same letter are not significantly different from each other by Tukey's test ($p \leq 0.05$).

Transpiration in peanut plants showed a linear increase with increasing potassium rates (Figure 3B). The regression indicated a 0.7% increase in transpiration between plants without potassium fertilization and those receiving 100% of the recommended rate. Potassium, one of the nutrients involved in plant water regulation, directly influences stomatal conductance (Figure 3A), which in turn controls transpiration rates (Sardans & Peñuelas, 2021). Thus, increased stomatal conductance resulted in greater water loss through vapor, highlighting the relationship between potassium availability and transpiration in peanut plants.

Consistent with the present findings, Pinheiro et al. (2022), studying passion fruit under brackish irrigation and potassium rates, reported no significant interaction between these factors. Similarly, Qi et al. (2019), evaluating potassium deficiency in maize hybrids, observed reduced gas exchange in plants grown under potassium deficiency.

Intercellular CO_2 concentration showed the best fit to a quadratic model. According to the regression equation, Ci reached a maximum at approximately 54.65% of the recommended potassium rate, with an estimated value of 373 μmol CO_2 mol^{-1}, decreasing at higher potassium rates (Figure 3C). This response may be associated with the "fertilization effect" of potassium, which enhances photosynthetic activity, increases CO_2 diffusion to carboxylation sites, and consequently reduces Ci (Bing et al., 2022). Under optimal conditions, however, some species such as sesame (Fang et al., 2023) may exhibit the opposite trend, with Ci increasing alongside potassium uptake and stomatal conductance.

Intrinsic water use efficiency (Figure 3D) also showed a quadratic response to potassium fertilization, with a maximum estimated value of 8.06 μmol CO_2 m^{-2} s^{-1} per mol H_2O m^{-2} s^{-1} at approximately 76.06% of the recommended potassium rate. Corroborating these data, studies in sunflower and Cakile maritima have shown that potassium deficiency reduces photosynthetic rate, stomatal conductance, and plant water relations, ultimately decreasing intrinsic water use efficiency (Houmani et al., 2022; Pourghasemian et al., 2020).

The SPAD index under low-salinity water (0.8 dS m^{-1}) showed a linear increase, with an 8.59% rise compared to the control at 100% of the recommended potassium rate (Figure 3E). In the most saline water, however, a quadratic model provided the best fit, with a minimum value of 39.39 at 72.5% of the recommended potassium rate.

The linear increase in SPAD values in plants irrigated with 0.8 dS m is likely related to the role of potassium in preventing the decomposition of the chlorophyll formed and promoting the biosynthesis of photosynthetic pigments. Potassium plays a key role in stomatal regulation and energy transfer, contributing to ion homeostasis, membrane integrity, and antioxidant activity (Naciri et al., 2021).

Under salt stress conditions, however, plants exhibit reduced photosynthetic rates and redirect energy toward defense mechanisms, increasing the production of reactive oxygen species. This leads to inhibition of chlorophyll synthesis and accelerated degradation via chlorophyllase (Souza et al., 2023). Similar results were reported by El-Mageed et al. (2023) in wheat, where SPAD values increased significantly with potassium application.

According to the analysis of variance, a significant interaction at the 5% probability level ($p \leq 0.05$) between potassium rates and irrigation water salinity was observed for pod diameter (PD), pod length (PL), and pod number (PN). Additionally, all evaluated variables showed a significant effect at the 1% probability level ($p \leq 0.01$) for the isolated factor of brackish water irrigation (Table 3).

Table 3
Summary of the analysis of variance for pod diameter (PD), pod length (PL), pod number (PN), pod weight (PW), yield, and water use efficiency (WUE) as a function of potassium fertilization and salt stress

SV	DF	Mean square					
		PD	PL	PN	PW	Yield	WUE
Potassium rate (R)	4	1.57ns	9.72ns	1.12ns	3.96ns	99.08ns	0.30ns
Water salinity (WS)	1	79.40**	136.40**	19.89**	24.02**	2119.42**	6.54**
Interaction (R × WS)	4	2.41*	22.08*	0.88*	7.21ns	229.60ns	0.70ns
Residue	30	0.85	6.54	0.71	1.97	150.33	0.46
Total	39						
CV (%)	-	10.68	13.33	32.22	21.7	16.92	16.9

SV: source of variation; DF: degrees of freedom; *Significant at 5% probability by the F-test; **Significant by 1% F-test; ns: not significant.

Regression analysis (Figure 4A) indicated a quadratic effect of potassium rates on pod number, regardless of irrigation water salinity. For plants irrigated with low ECw, the minimum estimated value was 6.77 pods at 27.70% of the recommended potassium rate. On the other hand, under higher ECw, the minimum estimated value was 4.72 pods at 60.83% of the recommended potassium rate.

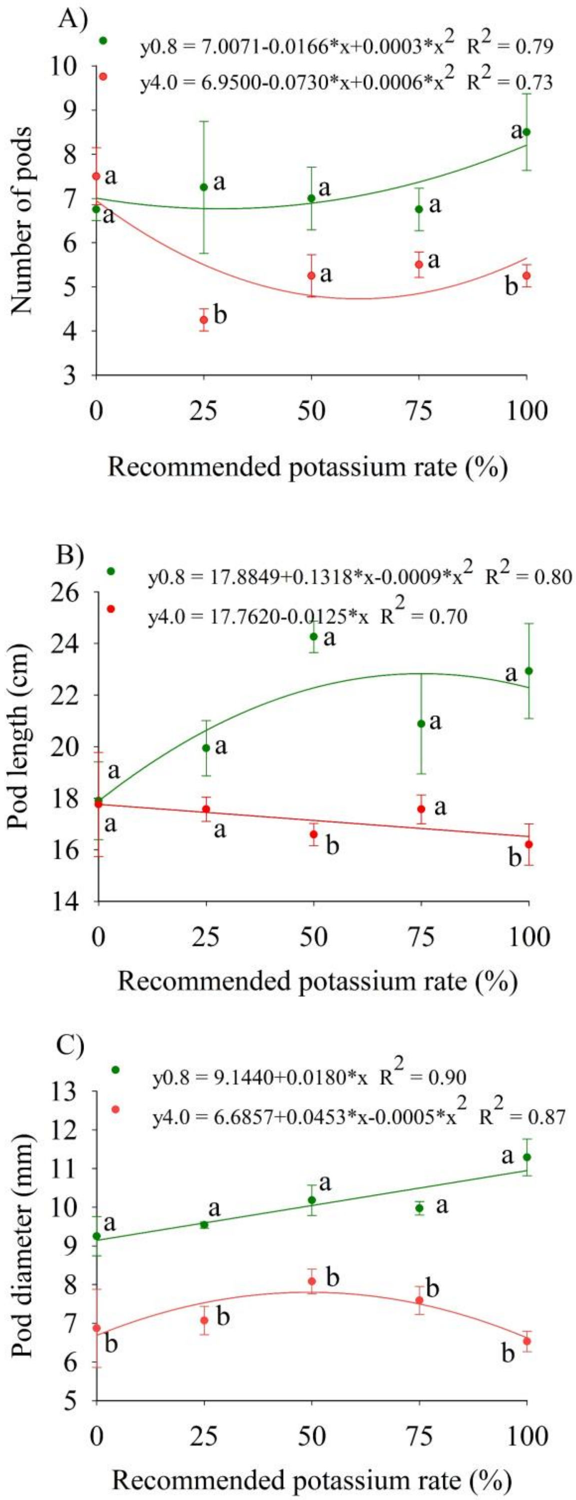

Figure 4. Number (A), length (B), and diameter (C) of peanut pods as a function of the interaction between different rates of potassium and irrigation with brackish water.
Vertical lines represent the standard error of the mean (n = 4). Means followed by the same letter are not significantly different from each other by Tukey's test ($p \leq 0.05$).

Regarding mean comparisons for pod number (Figure 4A), a significant difference between salinity levels was observed at potassium rates of 25% and 100% of the recommended rate, with irrigation water at 0.8 dS m^{-1} resulting in superior value.

Despite the lower number of pods observed in peanut plants irrigated with brackish water (4.0 dS m^{-1}) compared to those irrigated with lower-salinity water, the plants were still able to produce under saline conditions in this study. This response may be attributed to the role of K^+ in maintaining cellular water balance and preserving photosynthetic activity, ensuring the functioning of photosynthetic pigments as well as the stability of PSII reaction centers and electron transport (Rady et al., 2023). These factors likely contributed to the homeostasis of essential metabolic processes, resulting in the production of compounds that favored pod formation.

Dias et al. (2024), evaluating potassium and phosphorus fertilization as a strategy to mitigate salt stress in West Indian cherry, reported that the highest number of fruits (2.7 fruits per plant) was obtained under irrigation water salinity of 1.4 dS m^{-1} with the combined application of 45/45% of the recommended potassium and phosphorus rates.

Pod length (Figure 4B) fitted a quadratic model in plants irrigated with 0.8 dS m^{-1} water, whereas those irrigated with 4.0 dS m^{-1} exhibited a linear decrease with increasing potassium rates. Using water with the lowest ECw, pod length reached a maximum estimated value of 22.71 cm at a potassium rate of 73.22 kg ha^{-1}. In contrast, under brackish water conditions (4.0 dS m^{-1}), pod length decreased from 17.76 cm in the control treatment (0.0 kg ha^{-1}) to 16.20 cm at the highest potassium rate (100 kg ha^{-1}), corresponding to a reduction of approximately 0.2%, according to the regression equation.

As observed for pod number, the mean comparison test for pod length indicated a significant effect of irrigation water salinity. Plants irrigated with the lowest ECw water showed significantly greater pod length at potassium doses of 50 and 100 kg ha^{-1} compared to those irrigated with high the highest ECw at the same rates.

One of the plant responses to salt stress is increased senescence, particularly under prolonged exposure to brackish irrigation. In this study, the salinity index associated with KCl application may have intensified this effect. Elevated salinity can induce premature leaf senescence, reducing the transport of photoassimilates to developing organs and consequently contributing to reduced pod size (Sen et al., 2022; Dias et al., 2024). Similar findings were reported by Abreu et al. (2024), who observed reduced pod length in peanut plants irrigated with brackish water, even at the highest potassium rate.

Pod diameter under the lowest salt concentration followed a linear regression model (Figure 4C), with an increase of 0.8% in plants receiving 100% of the recommended potassium rate compared to the control. In contrast, in plants irrigated with highest ECw, a quadratic model provided the best fit, with a maximum estimated diameter of 7.71 mm at 45.30% of the recommended potassium rate.

The comparison of ECw levels within potassium rates for pod diameter (Figure 4C) showed that irrigation with low-salinity water resulted in significantly larger pod diameters than irrigation with high-salinity water, regardless of potassium rate.

The fertilizer source used (KCl) contributes additional Cl^-, whose increase to close to 100 % of the rate can increase the availability of this ion in the soil solution. This can intensify salinity effects, disrupting cellular water relations and inhibiting photosynthetic capacity (Souza et al., 2023; L. Wang et al., 2020). This mechanism may explain the observed results, in which potassium rates around 50% of the recommended rate, combined with frequent brackish irrigation, were sufficient to produce larger pod diameters.

These findings are consistent with J. T. M. Sousa et al. (2023b), who reported reduced pod diameter with increasing ECw in peanut genotypes fertilized with mineral and organic fertilizers and irrigated with brackish water.

For pod weight (Figure 5A), irrigation with low-salinity water resulted in significantly higher values compared to high-salinity irrigation. The negative effect of salt stress on pod weight may be associated with reduced soil osmotic potential caused by salts in the irrigation water, leading to increased energy expenditure to maintain metabolic functions and resulting in lower fruit weight (Guilherme et al., 2021). Similar trends were reported by Abreu et al. (2024) and H. C. Sousa et al. (2023a), both of whom observed reductions in peanut pod weight under salt stress conditions.

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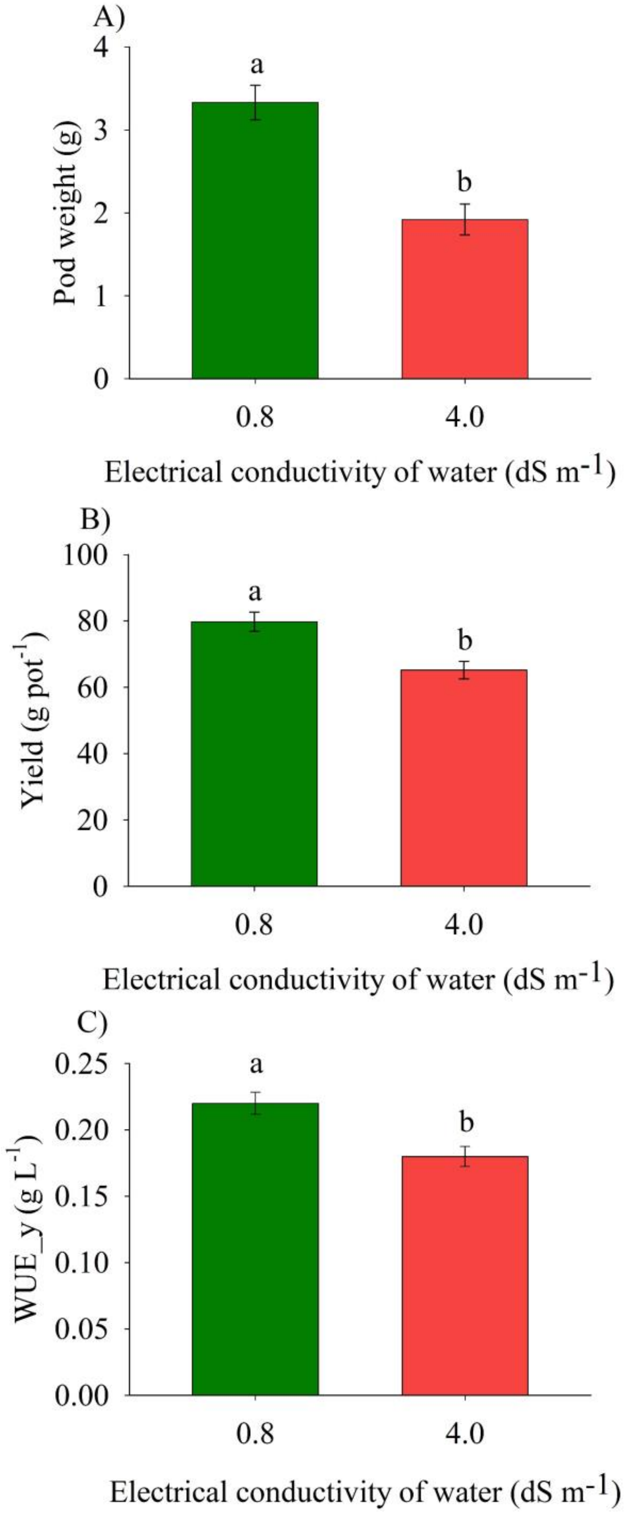

Figure 5. Pod dry weight (A), grain yield (B), and water use efficiency (C) of the peanut crop as a function of irrigation with brackish water.
The vertical lines represent the standard error of the mean (n = 4). Means followed by the same letter are not significantly different from each other according to Tukey's test ($p \leq 0.05$).

According to the data presented in Figure 5B, irrigation with the highest salinity water resulted in significantly lower grain yield compared to the control, with a reduction of 23.45%. This result reflects the high salt concentration in the soil solution, which limits the absorption of water and essential nutrients, thereby affecting the productive performance of peanut plants (J. T. M. Sousa et al., 2023b). Goes et al. (2021), working with peanut crops, also reported a negative effect on productivity with increasing irrigation water electrical conductivity (1 and 4 dS m^{-1}). Similarly, H. C. Sousa et al. (2023a) observed reduced productivity in peanut plants grown in pots under saline irrigation conditions.

Water use efficiency data are presented in Figure 5C. Plants irrigated with the lowest salinity water showed significantly higher values than those irrigated with the water with the highest salinity. This result indicates that increased salt concentration in the soil reduces water uptake due to decreased osmotic potential. Consequently, plants absorb less water because of reduced suction capacity to overcome osmotic pressure. In addition, CO_2 assimilation is reduced due to increased stomatal resistance, which acts as a protective mechanism against salt stress and excessive water loss through transpiration, ultimately decreasing water use efficiency (Taiz et al., 2024; Canja et al., 2021). A reduction in water use efficiency under saline conditions was also reported by Silva et al. (2022) in peanut plants grown in pots and irrigated with brackish water.

Pearson's correlation analysis (Figure 6) showed that PN and PD were among the variables most strongly correlated with other physiological and productive traits. Pod number showed positive correlations with A, PW, PD, WUE_Y, and Y, while PD was positively correlated with intrinsic carboxylation efficiency, A, E, PW, PN, PL, Y, and WUE_Y. Additionally, WUE_Y and Y exhibited the strongest correlation observed in this study, reinforcing the interdependence between water use efficiency and productivity under the imposed conditions.

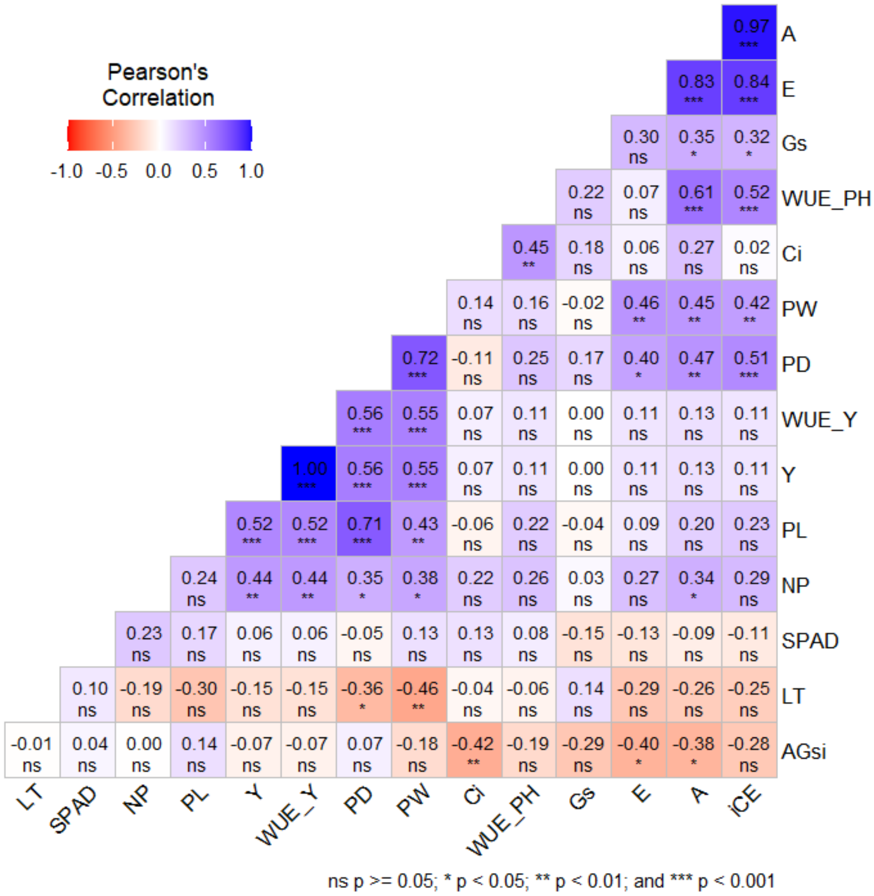

Figure 6. Pearson's correlation between the variables analyzed in this study. ns, *, ** and *** indicate differences not significant ($p > 0.05$) and significant at $p < 0.05$, 0.01, and 0.001, respectively. The color gradient scale corresponds to Pearson's correlation coefficient.

These correlations suggest that, under salt stress, the maintenance of variables such as PN, PD, and PW is associated with A, even though ANOVA did not detect a significant effect of K^+ application on A. Thus, the correlation analysis indicates that, regardless of treatment, K^+ rates indirectly influenced A, which in turn may have affected peanut production components. It is well established that K^+ plays critical roles under stress conditions, including osmotic adjustment, regulation of cellular water balance, and translocation of photoassimilates to reproductive structures (Souza et al., 2023; Zörb et al., 2014).

Even in the absence of a direct effect on A, adequate K^+ supply may have favored PN, PD, and PW under saline conditions, likely by enhancing assimilate absorption and partitioning (El-Mageed et al., 2022). Therefore, the positive correlations observed between A and PN, PD, and PW highlight the importance of maintaining photosynthetic activity, which directly influences crop production components under salt stress.

Conclusions

Potassium fertilization, when combined with irrigation using low-salinity water, positively influenced peanut pod development by increasing pod diameter, length, and number. However, irrigation with high-salinity water significantly reduced these parameters, regardless of potassium application. When applied in isolation, brackish water negatively affected pod weight, overall yield, and water use efficiency, highlighting the detrimental effects of salt stress on the agronomic performance of peanuts under controlled conditions.

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