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Phosphorus doses alter the ionic homeostasis of cowpea irrigated with saline water[1]

Doses de fósforo alteram a homeostase iônica do feijão-caupi irrigado com água salina

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HIGHLIGHTS:

Irrigation using water with electrical conductivity above 2.5 dS m^{-1} is not adequate for 'Paulistinha' cowpea.
Increment in phosphorus dose does not increase phosphorus content in cowpea plant.
Under salt stress conditions, cowpea plants require lower doses of phosphorus.

ABSTRACT: Soil and water salinization problems are increasingly common in arid and semi-arid regions, so it is necessary to adopt technologies that enable the use of these natural resources in agriculture, allowing satisfactory plant development. Thus, the objective of this study was to evaluate the effects of saline water irrigation associated with phosphate fertilization on soil salinity and on phytomass accumulation and nutrient concentration in cowpea plants. The study was carried out in a greenhouse using a randomized block design in a 5 x 3 factorial scheme consisting of five electrical conductivity of irrigation water electrical conductivities (0.5, 1.5, 2.5, 3.5 and 4.5 dS m^{-1}) and three phosphorus doses (60, 100 and 140% of the recommended dose - 60 kg P_2O_5 ha^{-1}), with five repetitions. Plants were cultivated in 8 dm^3 lysimeters until the flowering stage and, during this period, soil salinity, phytomass accumulation and nutrient concentration in the plant tissue were evaluated. Irrigation with water with electrical conductivity above 2.5 dS m^{-1} increased soil salinity and sodium concentration in the tissues to toxic levels, reducing phytomass accumulation and concentrations of macronutrients in cowpea plant tissue, except for nitrogen. Application of 60% of the recommended dose of phosphorus for cowpea improves its ionic homeostasis, increasing the absorption of potassium and calcium, but does not reduce the deleterious effects of high salinity on phytomass accumulation.

Key words: *Vigna unguiculata*, mineral nutrition, single superphosphate, salt stress

RESUMO: Os problemas de salinização da água e do solo são cada vez mais frequentes em regiões áridas e semiáridas, sendo necessária a adoção de tecnologias que viabilizem o uso desses recursos naturais na agricultura, permitindo que haja desenvolvimento vegetal satisfatório. Com isso, objetivou-se estudar os efeitos da irrigação com água salina associada a doses de fósforo sobre a salinidade do solo e acúmulo de fitomassa e o teor de nutrientes em plantas de feijão-caupi. A pesquisa foi realizada em casa de vegetação usando o delineamento de blocos casualizados em esquema fatorial 5 x 3 constituído de cinco condutividades elétricas da água de irrigação (0,5; 1,5; 2,5; 3,5 e 4,5 dS m^{-1}) e três doses de fósforo (60, 100 e 140% da dose recomendada - 60 kg P_2O_5 ha^{-1}), com cinco repetições. As plantas foram cultivadas em lisímetros de 8 dm^3, até à fase de floração, e nesse período foi avaliado a salinidade do solo, o acúmulo de fitomassa e os teores de nutrientes no tecido vegetal. A irrigação com água com condutividade elétrica acima de 2,5 dS m^{-1} elevou a salinidade do solo e teor de sódio nos tecidos a níveis tóxicos, reduzindo a fitomassa e os teores de macronutrientes no tecido vegetal do feijão-caupi, com exceção do nitrogênio. A aplicação de 60% da dose recomendada de fósforo para o feijão-caupi melhora a homeostase iônica da cultura, aumentando a absorção de potássio e cálcio, porém sem diminuir os efeitos deletérios da alta salinidade no acúmulo de fitomassa.

Palavras-chave: *Vigna unguiculata*, nutrição mineral, superfosfato simples, estresse salino

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Introduction

Due to its characteristics of rusticity and earliness, cowpea (*Vigna unguiculata* L.) is a plant considered adapted to arid and semi-arid climate conditions, constituting the main subsistence crop and source of protein of plant origin in these regions (Freire Filho et al., 2017).

In the Brazilian semi-arid region, cowpea is widely cultivated under rainfed conditions during raining periods and under irrigated conditions during the dry season, mainly in the irrigated perimeters of this region (Freitas et al., 2019). Irrigation in the semi-arid region is usually performed using saline water with high concentrations of sodium chloride salts (Medeiros et al., 2003; Sá et al., 2020). The use of saline water in agriculture poses high risks of salinization and environmental degradation of soils, since salinity is an environmental stress that limits crop yield, particularly in arid and semi-arid regions (Praxedes et al., 2010; Sá et al., 2017).

Irrigation with saline water reduces growth, photosynthesis and biomass accumulation of cowpea (Oliveira et al., 2017; Sá et al., 2018). Such reduction may be related to phosphorus deficiency, since the decrease in P cycling between the cytoplasm and stroma, caused by nutrient deficiency, can lead to decreases in the consumption and production of ATP and NADPH, reducing plant photosynthesis (Sá et al., 2017). Thus, an adequate dose of phosphorus can minimize the effects of salt stress on cowpea. The objective of this study was to assess the effects of irrigation with saline water associated with phosphorus doses on soil salinity, phytomass accumulation and nutrient concentrations in the shoots of cowpea plants.

Material and Methods

The study was carried out from October 2015 to February 2016, in a greenhouse of the Department of Environmental and Technological Sciences of the Federal Rural University of the Semi-Arid (UFERSA), Mossoró, RN, Brazil (5º 11' S latitude, 37º 20' W longitude, and 18 m of altitude). In the greenhouse, the maximum values of temperature and relative humidity of air were 41.2 ºC and 86% and the minimum values were 20.4 ºC and 20%, respectively. During the experiment, the average daily temperature and air relative humidity were 29.8 ºC and 53%, respectively.

The experiment was conducted in randomized blocks, in a 5 x 3 factorial scheme, consisting of five electrical conductivity of irrigation water electrical conductivities (S_1 = 0.5; S_2 = 1.5; S_3 = 2.5; S_4 = 3.5 and S_5 = 4.5 dS m^{-1}) and three doses of phosphorus [D_1 = 60; D_2 = 100 and D_3 = 140% of the dose recommended by Cavalcanti (2008) - 60 kg P_2O_5 ha^{-1}], with five replicates, totaling 75 experimental plots, sown in 8-dm^3 lysimeters, leaving 2 plants per pot after thinning.

The soil used in the experiment came from a virgin area of the experimental farm of UFERSA, campus of Mossoró, classified as Ultisol. Soil samples were collected in the 0-30 cm layer and analyzed at the Soil, Water and Plant Analysis Laboratory - LASAP of the Federal Rural University of the Semi-Arid, following the methodology of Teixeira et al. (2017) (Table 1).

Fertilization was performed based on soil chemical characteristics and the technical bulletin of fertilizer recommendation for the state of Pernambuco, Brazil (Cavalcanti, 2008). For the research conditions (soil), the recommendation for cowpea crop is 60 kg ha^{-1} of P_2O_5, 20 kg ha^{-1} of K_2O and 50 kg ha^{-1} of N for one cultivation cycle. Soil analysis was used as the basis to stipulate the doses of P_2O_5 (D_1 = 36; D_2 = 60 and D_3 = 84 kg ha^{-1}) for the 7 dm^3 of soil, applied in the form of single superphosphate (D_1 = 0.7; D_2 = 1.17 and D_3 = 1.64 g per pot of P_2O_5), as basal, and planting was carried out after 20 days (incubation period), aiming at the release of phosphorus for the young plants. As the soil had a sandy texture, nitrogen fertilization (urea, 45% N) was applied as topdressing, at 14, 21 and 27 days after sowing, and potassium fertilization (potassium chloride, 60% K_2O) was applied at 28 and 35 days after sowing.

After physical and chemical characterization of the soil, in addition to stipulating fertilization, the soil was placed in pots with capacity of 8 dm^3, of which 7 dm^3 were filled with soil, 0.5 dm^3 was filled with bovine manure, aiming to increase moisture retention and the negative charges of the soil, and 0.5 dm^3 was filled with crushed stone at the bottom to facilitate drainage. The lysimeters were filled in the following order: screen; crushed stone; 2 dm^3 of soil; and mixture of soil (5 dm^3): bovine manure (0.5 dm^3): phosphorus doses, stipulated for each treatment.

After preparing the soil, one irrigation was applied, leaving the soil close to its maximum water retention capacity. Subsequent irrigations with saline water according to each treatment were performed once a day in order to leave the soil with moisture close to the maximum retention capacity, based on the drainage lysimetry method. In addition to the water depth applied, a leaching fraction equivalent to 0.20 of the accumulated volume was applied every seven days. The volume of water applied per container was obtained by difference between the previous depth applied minus the average drainage, divided by the number of containers.

Table 1. Physical and chemical characteristics of the soil collected in the 0-0.30 m layer and chemical characteristics of bovine manure used in cowpea cultivation

Soil						
Clay	Silt	Sand	BD	PD	Porosity	Textural Class
(dag kg^{-1})			(kg dm^{-3})		(%)	
10.0	1.0	89.0	1.57	2.51	37.45	Loamy Sand

EC 1:2.5 (dS m^{-1})	pH H_2O	P (mg dm^{-3})	K^+	Ca^{+2}	Mg^{+2}	Na^+	Al^{3+}	H^++Al^{3+}	SB	T	OM (g kg^{-1})	ESP (%)
			($cmol_c$ dm^{-3})									
0.16	6.72	1.20	0.20	1.40	0.50	0.05	0.00	0.70	2.15	2.85	13.23	1.75

Bovine manure														
N	P	K	Ca	Mg	Na	Zn	Cu	Fe	Mn	pH	OC	CEC	C/N	EC
(g kg^{-1})						(mg kg^{-1})				H_2O	(%)	($cmol_c$ dm^{-3})		(dS m^{-1})
14.85	3.25	1.16	16.11	3.07	0.66	65	15	3.77	121	6.53	10.70	34.24	7.21	2.56

P, K^+, Na^+ - Extracted with Mehlich 1; Al^{3+}, Ca^{2+}, Mg^{2+} - Extracted with 1.0 M KCl at pH 7.0; BD - Soil bulk density; PD - Particle density; EC - Electrical conductivity; SB - Sum of bases; T - Cation exchange capacity; OM - Walkley-Black Wet Digestion; ESP - Exchangeable sodium percentage

The saline solutions with differents electrical conductivities were prepared by adding sodium chloride - NaCl (A.R.) salts, which compose 70% of the salt ions found in sources of water used for irrigation, in small properties of the Assu-Mossoró agricultural center, Brazil (Medeiros et al., 2003).

Irrigation water with various values of electrical conductivities was prepared considering the relationship between electrical conductivity of water (ECw) and salt concentration ($10{*}mmol_c\ L^{-1} = 1\ dS\ m^{-1}$ of ECw) according to Rhoades et al. (1992), valid for the ECw range from 0.1 to 5.0 dS m^{-1}, which encompass the tested ECw values. The solutions were prepared using municipal water existing in the site (ECw = 0.53 dS m^{-1}), to which the salt was added as needed. To prepare the waters, the salt was weighed according to each treatment, and water was added until reaching the desired electrical conductivity (EC), measured using a portable conductivity meter, which has its conductivity adjusted to a temperature of 25 °C. After preparation, the salinized waters were stored in 150-L plastic containers, properly protected to avoid evaporation, entry of rainwater and contamination with materials that could compromise their quality.

After irrigation with saline water, sowing was performed with the cowpea cv. Paulistinha, for being an early cultivar, 20 days after application of phosphorus doses, using 10 seeds per pot. Fifteen days after sowing with the total emergence of seedlings, thinning was performed, leaving only two plants per pot.

At 49 days after sowing, during the transition of the vegetative and reproductive stages of the cowpea crop, the shoots of one of the plants were collected to obtain the shoot dry phytomass (SDP), and the material was placed in an air circulation oven, at 65 °C, and dried until reaching constant weight. After drying, the material was weighed on an analytical scale, with accuracy of 0.001 g. Subsequently, SDP was crushed to determine the concentrations of nitrogen (N), potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg) and sodium (Na). Mineral composition analyses were performed by wet digestion, using the methodology described by Tedesco et al. (1995), with some adaptations of EMBRAPA (2009) to determine nitrogen concentration. After the data were obtained, the ratios of these potassium, calcium and magnesium ions with sodium ions (Na^+/K^+; Na^+/Ca^{2+} and Na^+/Mg^{2+}) were determined.

After collecting the plants, soil samples were collected and analyzed for salinity, represented by the following variables: electrical conductivity of soil saturation extract (ECse) (dS m^{-1}), hydrogen potential (pH) and sodium absorption ratio (SAR) $(mmol\ L^{-1})^{0.5}$ of the saturation extract, according to the methodology of Richards (1954), and exchangeable sodium percentage (ESP) (%), following the methodology of EMBRAPA (2009).

The data obtained were subjected to analysis of variance at $p \leq 0.05$ and, in cases of significance, linear or quadratic polynomial regression analysis at $p \leq 0.05$ was performed for the irrigation water salinity factor, and Tukey test at $p \leq 0.05$ was applied for the phosphorus doses factor, using the statistical program SISVAR® (Ferreira, 2011).

Results and Discussion

There was significant influence ($p \leq 0.05$) of the interaction between irrigation water salinity and phosphorus doses on potassium concentration and on the sodium/potassium and sodium/calcium ratios, whereas irrigation water salinity alone caused significant effect ($p \leq 0.05$) only on shoot dry phytomass,

Table 2. Summary of the analyses of variance for the variables: electrical conductivity of saturation extract (ECse), pH of saturation extract (pHse), sodium absorption ratio (SAR), exchangeable sodium percentage (ESP), shoot dry phytomass (SDP), concentration of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na), sodium/potassium ratio (Na/K), sodium/calcium ratio (Na/Ca) and sodium/magnesium ratio (Na/Mg) in the shoots of cowpea plants cv. Paulistinha under different water salinities and doses of phosphorus at 49 days after sowing

SV	DF	Probability of F test						
		ECse	pHse	SAR	ESP	SDP	N	P
Block	4	0.747	0.949	0.698	0.704	0.000	0.263	0.076
Sal	4	0.000**	0.110^{ns}	0.000**	0.000**	0.000**	0.000**	0.000**
Doses	2	0.216^{ns}	0.628^{ns}	0.848^{ns}	0.850^{ns}	0.368^{ns}	0.370^{ns}	0.357^{ns}
Sal x Doses	8	0.073^{ns}	0.263^{ns}	0.003**	0.004**	0.150^{ns}	0.817^{ns}	0.304^{ns}
Error	56	--	--	--	--	--	--	-
Doses (P_2O_5)		Means						
		(dS m^{-1})		$(mmol\ L^{-1})^{0.5}$	(%)	(g)	(g kg^{-1})	
D_1 - 60%		9.26 a	7.87 a	16.08 a	17.94 a	2.82 a	25.70 a	2.11 a
D_2 - 100%		8.58 a	7.90 a	16.47 a	18.40 a	2.64 a	27.04 a	2.37 a
D_3 - 140%		8.97 a	7.91 a	15.51 a	18.22 a	2.76 a	26.02 a	2.32 a

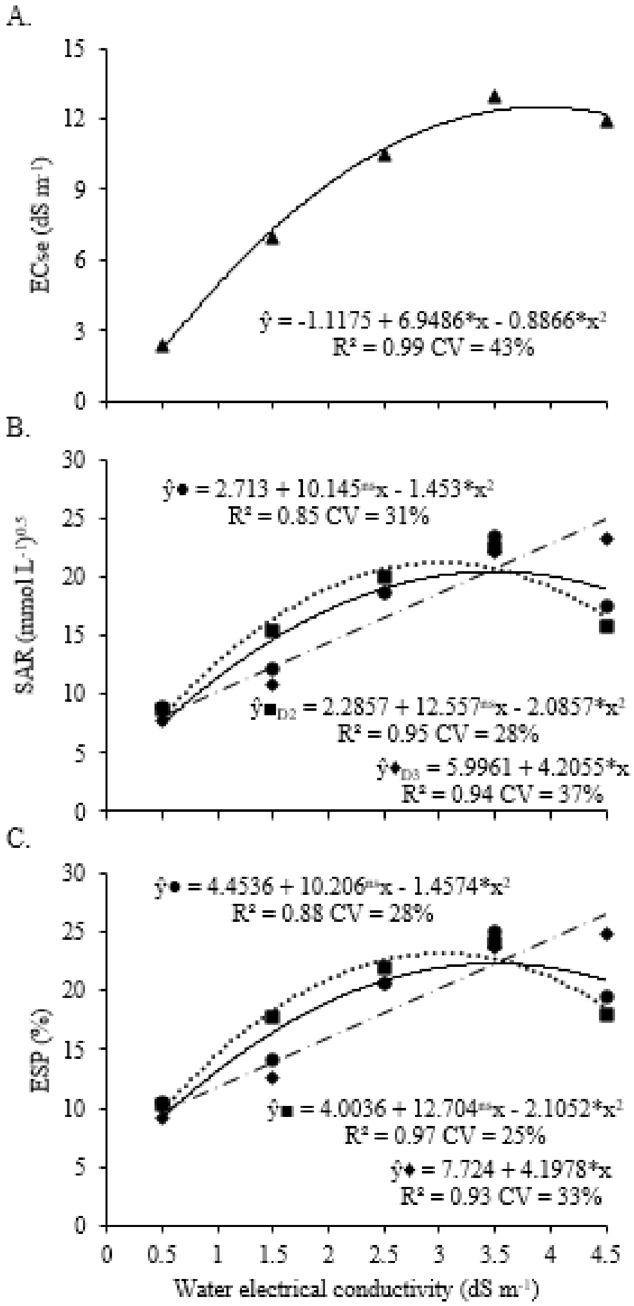
SV	DF	Probability of F test						
		K	Ca	Mg	Na	Na/K	Na/Ca	Na/Mg
Block	4	0.602	0.128	0.817	0.001	0.079	0.440	0.849
Sal	4	0.000**	0.000**	0.000**	0.000**	0.000**	0.000**	0.000*
Doses	2	0.001**	0.001**	0.507^{ns}	0.131^{ns}	0.914^{ns}	0.015*	0.429^{ns}
Sal x Doses	8	0.000**	0.109^{ns}	0.223^{ns}	0.556^{ns}	0.011*	0.000**	0.492^{ns}
Error	56	-	-	-	-	-	-	-
Doses (P_2O_5)		Means - Tukey ($p \leq 0.05$) (g kg^{-1})						
D_1 - 60%		28.13 a	16.67 a	5.34 a	12.11 a	0.65 a	1.22 b	3.72 a
D_2 - 100%		28.01 a	12.87 b	5.52 a	12.42 a	0.62 a	1.66 ab	3.70 a
D_3 - 140%		23.68 b	12.31 b	5.18 a	10.75 a	0.65 a	1.93 a	3.19 a

ns, *,** - Not significant, significant at $p \leq 0.05$ and at $p \leq 0.01$, respectively, by F test. Sal - Water salinity; Means followed by equal letters in the column do not differ by Tukey test at $p \leq 0.05$

nitrogen, phosphorus, potassium, calcium, magnesium and sodium concentration and sodium/magnesium ratio (Table 2). For calcium concentration, there was a simple effect ($p \leq 0.01$) of phosphorus doses (Table 2).

Soil salinity increased due to the electrical conductivity of irrigation water, regardless of phosphorus doses, and when plants were irrigated with water of 3.9 dS m^{-1}, the highest ECse of 12.5 dS m^{-1} was obtained (Figure 1A).

SAR and ESP showed a quadratic behavior under fertilizations D_1 and D_2 and an increasing linear behavior in the soil of plants fertilized with D_3. The highest values of SAR, 20.4, 21.2 and 24.92 (mmol $L^{-1})^{0.5}$, and ESP, 22.3, 23.2 and 26.6%, were observed under irrigation with waters with electrical conductivities of 3.5, 3.0 and 4.5 dS m^{-1} for the phosphate fertilizations D_1, D_2 and D_3, respectively (Figures 1B and C). These results indicate that the leaching fraction (LF) adopted was not sufficient to reduce the accumulation of salts in the soil, as the salt concentration factor observed here was 6.94 (Figure 1C), whereas according to Ayers & Westcot (1999) for LF of 0.15 the values are around 3.0. Such excessive accumulation of salts is perhaps due to the inefficiency of LF and flow of water through preferential paths because of small size of lysimeters.



●D_1 = 60, ▪D_2 = 100 and ♦D_3 = 140% of the recommendation of P_2O_5; ns not significant ($p > 0.05$) and *significant at $p \leq 0.05$ by F test

Figure 1. Electrical conductivity of the soil saturation extract - ECse (A) as a function of the electrical conductivity of irrigation water, and sodium absorption ratio - SAR of the soil saturation extract (B), exchangeable sodium percentage - ESP (C) of the soil cultivated with cowpea cv. 'Paulistinha' under three doses of phosphorus as a function of the electrical conductivity of irrigation water at 49 days after sowing

The increase in irrigation water salinity linearly reduced the shoot dry phytomass accumulation of cowpea plants by 14.16% per unit increase in water electrical conductivity (Figure 2A). Along with the reduction in phytomass accumulation, there was a linear increase in nitrogen concentration in cowpea shoots, of the order of 13.72% per unit increase in water electrical conductivity (Figure 2B).

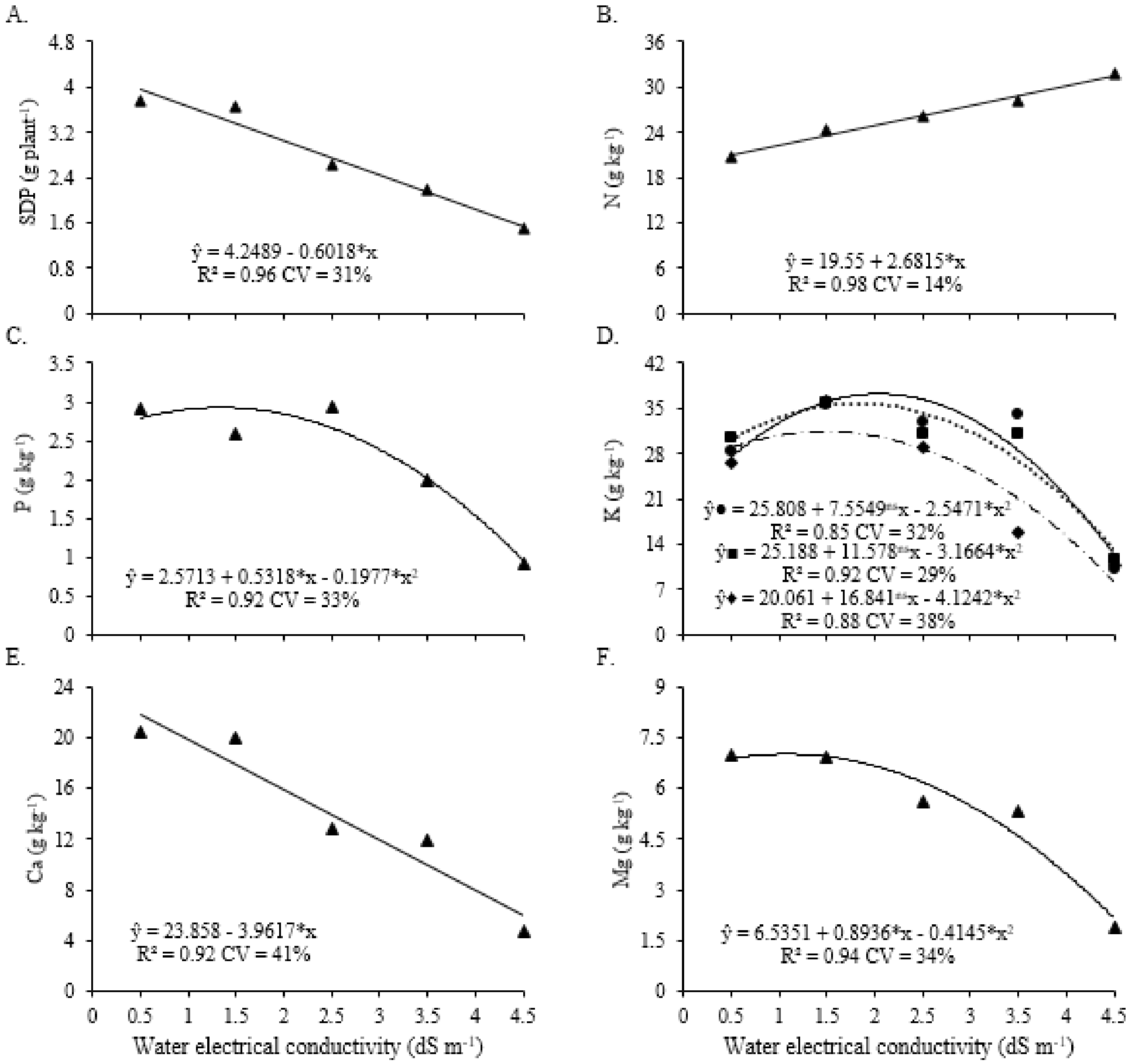
Phosphorus and magnesium concentration in cowpea shoots showed a quadratic behavior as a function of increasing salinity and increased up to water electrical conductivities of 1.34 and 1.10 dS m^{-1}, respectively, with subsequent reductions up to the value of 4.5 dS m^{-1} (Figures 2C and F).

Potassium concentrations increased up to 1.48, 1.83 and 2.04 dS m^{-1} for doses corresponding to 60 (D_1), 100 (D_2) and 140% (D_3) of the P_2O_5 recommendation, respectively (Figure 2D), and then decreased up to the irrigation water conductivity of 4.5 dS m^{-1} (Figure 2D). Plants fertilized with D_3 obtained the lowest potassium concentration, at all water salinities, except for the electrical conductivity of 0.5 dS m^{-1}, when compared to treatments D1 and D_2 (Figure 2D).

Calcium concentrations were reduced linearly with the increase in irrigation water salinity, and there were unit reductions of 3.9617 g kg^{-1} (corresponding to 16.61%) per unit increase in water electrical conductivity (Figure 2E). Regarding phosphorus doses, Ca concentrations in the shoots were 29.5 and 35.4% higher, respectively, in plants fertilized with D_1 than in those fertilized with D_2 and D_3 (Table 2).

Sodium concentrations in the shoots of cowpea plants increased linearly as irrigation water salinity increased, and there was 5.17 times more sodium in the tissues of plants under the water electrical conductivity of 4.5 dS m^{-1} compared to plants in the control treatment (0.5 dS m^{-1}) (Figure 3A). The increase in sodium concentrations caused an exponential increase in the sodium/potassium, sodium/calcium and sodium/magnesium ratios, mainly from the water electrical conductivity of 2.5 dS m^{-1} (Figures 3B, C and D). In the interaction between water salinity and phosphorus doses, it was found that the plants of treatment D_3 had the lowest Na^+/K^+ and Na^+/Ca^{2+} ratios from the water electrical conductivity of 1.5 dS m^{-1} compared to the treatments D_1 and D_2 (Figures 3B and C). The Na^+/Mg^{2+} ratio showed a sharp increase, from 1:1 at the water electrical conductivity of 1.5 dS m^{-1} to 9.3:1 at the water electrical conductivity of 4.5 dS m^{-1}, regardless of phosphorus doses (Figure 3D).

Irrigation with saline water increased soil salinity to levels that are extremely high for cowpea when the plants were irrigated with water of 4.5 dS m^{-1}, with values of ECse, SAR and ESP of up to 12.5 dS m^{-1}, 24.92 (mmol $L^{-1})^{0.5}$ and 26.6%, respectively



●D_1 = 60, ▪D_2 = 100 and ♦D_3 = 140% of P_2O_5 recommendation; ns - Not significant ($p > 0.05$) and * - Significant at $p \leq 0.05$ by F test

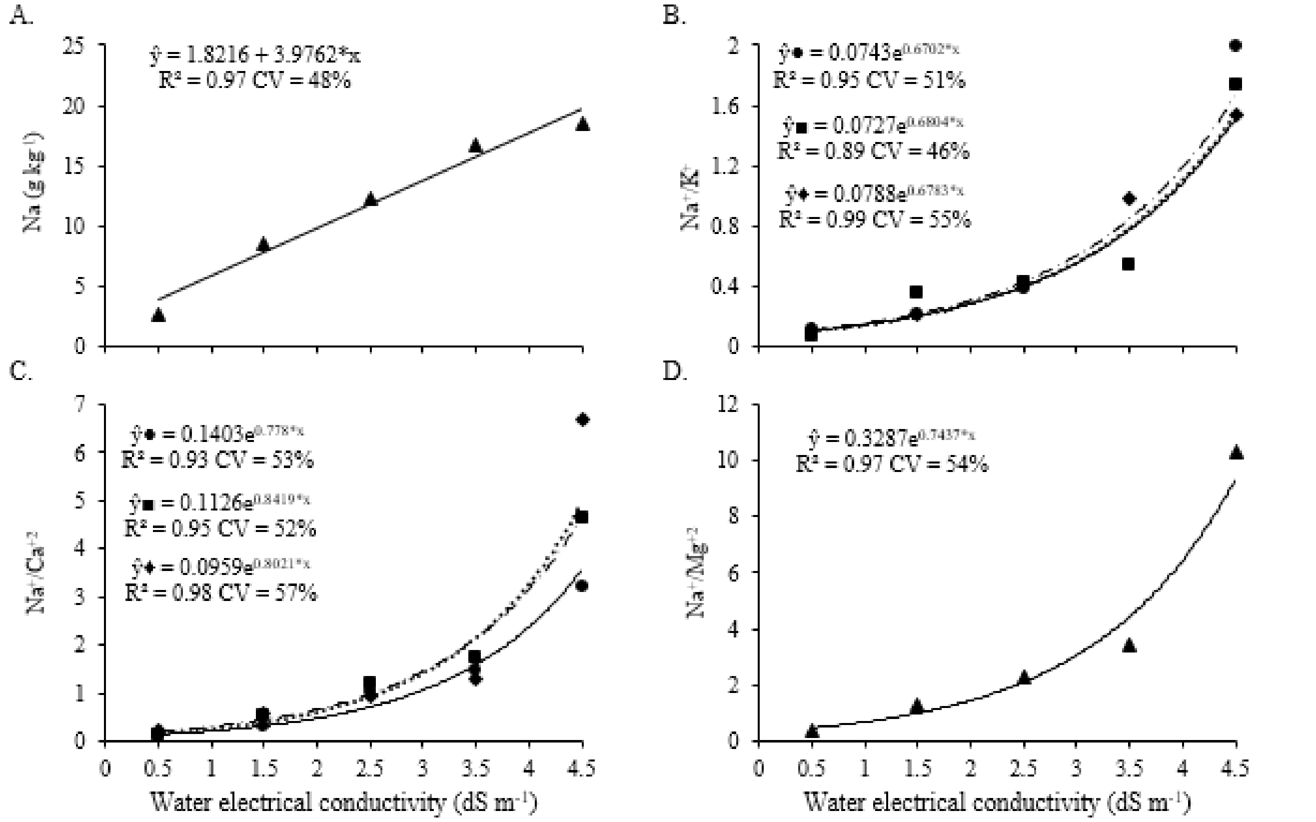
Figure 2. Shoot dry phytomass - SDP (A) and concentrations of nitrogen - N (B), phosphorus - P (C), calcium - Ca (E) and magnesium - Mg (F) in shoots of cowpea plants cv. Paulistinha as a function of electrical conductivity of irrigation water and potassium concentrations - K (D) as a function of electrical conductivity of irrigation water at each phosphorus doses at 49 days after sowing

(Figures 1A, B and C), causing a drastic reduction of 61% in phytomass accumulation as water electrical conductivity increased from 0.5 to 4.5 dS m^{-1} (Figure 2A). Under the conditions of the experiment, irrigation with water with electrical conductivity above 1.5 dS m^{-1} caused soil salinization and, under conditions of irrigation with water with electrical conductivity above 2.5 dS m^{-1}, the soils of all treatments were saline-sodic at the end of the experiment (Richards, 1954). Salinity affects the establishment and development of plants, leading to a significant loss of yield or even their death (Gómez-Bellot et al., 2013; Acosta-Motos et al., 2017).

Reduction in the phytomass accumulation of cowpea plants as a function of the increase in irrigation water salinity has also been observed in the literature and is attributed to the osmotic and ionic effects caused by salt stress, which reduce photosynthetic activity and the processes of absorption, transport, assimilation and distribution of nutrients (Praxedes et al., 2010; Calvet et al., 2013). Under severe stress conditions, there is also the accumulation of reactive oxygen species (ROS), causing photoinhibition, photooxidation in chloroplasts and inhibition of photosynthesis, in addition to lipid peroxidation, damage to DNA, and disturbance in the dynamics of transport of mineral nutrients (Ashraf, 2009; Turan & Tripathy, 2013; Huang, 2018).

Nitrogen was the only nutrient whose concentration increased in the tissues of cowpea plants, as a function of the electrical conductivity of irrigation water (Figure 2B). Nitrogen is a nutrient with different functions and can be found with abundance in plant tissues, especially in pigments present in stem and leaves. Thus, it is possible that under salt stress there has been an increase in the concentration of pigments per area, due to the limitation of biomass, as well as increased synthesis of nitrogen compounds, such as amino acids and proteins, used in the osmoregulation process, in order to minimize the effects of osmotic stress inside plants (Calvet et al., 2013).

On the other hand, the increase in irrigation water salinity caused reduction in the concentrations of P, K, Ca and Mg in cowpea shoot tissue (Figures 2C, D, E and F). The reduction



●D_1 = 60, ▪D_2 = 100 and ♦D_3 = 140% of the recommendation of P_2O_5; [ns]not significant (p > 0.05) and *significant at p ≤ 0.05

Figure 3. Sodium content - Na (A), and sodium/magnesium ratio - Na^+/Mg^{2+} (D) in the shoots of cowpea plants cv. 'Paulistinha' as a function of electrical conductivity of irrigation water and sodium/potassium ratio - Na^+/K^+ (B), sodium/calcium ratio - Na^+/Ca^{2+} (C) as a function of electrical conductivity of irrigation water at each phosphorus doses at 49 days after sowing

in the concentrations of these macronutrients accompanied by a sharp increment in sodium concentration in plant tissue, and there was 5.17 times more sodium in the tissues of plants under the water electrical conductivity of 4.5 dS m^{-1} compared to plants in the control treatment (0.5 dS m^{-1}) (Figure 3A). These increments in sodium concentration exceeded the limits of ionic stability, verified by the exponential increase in the sodium/potassium, sodium/calcium and sodium/magnesium ratios, which denote the progressive increase in sodium concentrations and, in contrast, the decrease in the concentrations of K, Ca and Mg in cowpea plants (Figures 3B, C and D).

The increase in sodium concentration in the plant tissue also coincides with the increments of ECse, SAR and ESP and with the marked decrease in phytomass accumulation. Such reductions in phytomass accumulation are caused by osmotic effect and sodium toxicity (although plants showed no visual symptoms), which limit photosynthetic activity and the absorption of water and nutrients, thereby leading to reductions in plant growth and phytomass accumulation (Munns & Tester, 2008; Syvertsen & Garcia-Sanchez, 2014).

Some glycophytes, as well as cowpea, when subjected to moderate salt stress conditions, may exhibit as a mechanism of tolerance the compartmentalization of ions in the vacuoles of leaf mesophyll cells. In this process, there is a controlled distribution of ions (small amounts of Na) throughout the shoots, allowing these cells to maintain ionic stability. However, these plants, when exposed to severe stress, tend to have a rapid accumulation of sodium in the shoots, exceeding the capacity of compartmentalization of ions in vacuoles (Munns & Tester, 2008; Gupta & Huag, 2014). Thus, plants need to use other tolerance mechanisms, such as excretion of ions by the roots and the increase in the selectivity of membranes, which increase energy expenditure to very high levels to keep the ionic relations in the cytoplasm below the level of cytoplasmic toxicity, through the differentiated distribution of ions between the vacuole and the cytoplasm. This energy expenditure is responsible for limiting growth, phytomass accumulation and plant production (Gupta & Huag, 2014).

As for the Na^+/K^+ and Na^+/Ca^{2+} ratios, it was found that cowpea plants fertilized with 60% of the phosphorus recommendation (D_1) obtained lower values compared to those under the other phosphorus doses (D_2 and D_3), indicating that these plants absorbed more potassium and calcium than those of the other treatments, from a water of electrical conductivity of 2.5 dS m^{-1}, which corresponded to ECse of 10.7 dS m^{-1} (Figures 1A, 3B and C). Larceda et al. (2006), evaluating the interaction between salinity and phosphorus in forage sorghum plants, found that the optimum level of the nutrient for this species, in the absence of salt stress, can be toxic to it under salt stress conditions. However, some authors point out that increasing the doses of phosphorus (Sá et al., 2017) and potassium (Gurgel et al., 2010) brings benefits to the physiological responses and phytomass accumulation of species such as sweet sorghum and melon, respectively. This denotes that this characteristic can be variable depending on the species, variety and nutrient involved.

The decrease in phosphorus dose reduced the Na^+/K^+ and Na^+/Ca^{2+} ratios (Figures 3B, C). However, strong correlations between the increase in potassium and calcium concentrations in plant tissues mitigate salt stress (Munns et al., 2006; Munns & Tester, 2008; Gupta & Huag, 2014; Nanhapoa et al., 2017). In the present study, the increase of these nutrients in plant tissue did not mitigate salt stress in cowpea plants. Praxedes et al. (2010) also found no improvements in the salinity tolerance of cowpea, as a function of the increase in potassium concentrations in its leaf tissue.

Conclusions

1. Irrigation with water of electrical conductivity above 2.5 dS m^{-1} increased soil salinity and sodium concentration in the tissues, reducing phytomass and concentrations of macronutrients in cowpea tissue, except for nitrogen.

2. Using 60% of the recommended dose of phosphorus for cowpea improves its ionic homeostasis, with increase in potassium and calcium concentrations, but does not reduce the deleterious effects of salinity on phytomass accumulation.

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