ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.26, n.11, p.863-874, 2022
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v26n11p863-874

Nutritional status, Na^+ and Cl^- concentrations, and yield of sugarcane irrigated with brackish waters[1]

Estado nutricional, concentrações de Na^+ e Cl^- e produtividade em cana-de-açúcar irrigada com águas salobras

José E. F. de Morais[2*], Ênio F. de F. e Silva[2], Larissa G. L. de Andrade[2], Sirleide M. de Menezes[2], Weliston de O. Cutrim[2], Daniel da C. Dantas[2], Geronimo F. da Silva[2] & Mário M. Rolim[2]

[1] Research developed at Universidade Federal Rural de Pernambuco, Departamento de Engenharia Agrícola, Recife, PE, Brazil. Article extracted from the first author's Doctoral Thesis

[2] Universidade Federal Rural de Pernambuco, Departamento de Engenharia Agrícola, Recife, PE, Brazil

HIGHLIGHTS:

Salinity above 0.5 dS m^{-1} reduced the foliar concentrations of N, P, K^+, Mg^{2+}, S, Fe^{2+}, Mn^{2+}, Cu^{2+}, and Zn^{2+} in plant-cane.
Salinity of 8 dS m^{-1} without leaching fraction decreases yield by 43 and 47% in plant-cane and first ratoon, respectively.
With leaching fraction of 0.17 the yield is 26 and 28% higher in plant-cane and first ratoon, respectively.

ABSTRACT: Salinization reduces the osmotic potential of soil solutions and promotes the accumulation of toxic ions (Na^+ and Cl^-) in plants, causing nutritional imbalance and yield reductions. Thus, the objective of the present study was to evaluate foliar concentrations of nutrients and Na^+ and stalk yields in sugarcane RB92579 under different electrical conductivities of irrigation water and leaching fractions (LF). The experiment was conducted in drainage lysimeters in a 5 × 2 factorial scheme with five electrical conductivities of irrigation water - ECw (0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}) without (LF1 = 0) or with a leaching fraction (LF2 = 0.17), and four replicates. Increased ECw decreased the concentrations of N, P, K, Mg, S, Fe, Mn, Cu, and Zn and increased those of Ca, Cl, and Na, reducing the biomass production in two cycles (plant-cane and first ratoon). The use of a leaching fraction of 0.17 mitigated the deleterious effects of salinity on nutrient concentration and yield.

Key words: *Saccharum* spp., salt stress, mineral nutrition, yield, leaching fraction

RESUMO: A salinização reduz o potencial osmótico da solução do solo e promove o acúmulo de íons tóxicos (Na^+ e Cl^-) nas plantas, causando desequilíbrio nutricional e reduções no rendimento. Assim, objetivou-se avaliar as concentrações foliares de nutrientes, Na^+ e rendimento de colmos em cana-de-açúcar RB92579 sob diferentes valores de condutividade elétrica da água de irrigação e frações de lixiviação (FL). O experimento foi conduzido em lisímetros de drenagem em esquema fatorial 5 × 2: cinco condutividades elétricas da água de irrigação - CEa (0,5; 2,0; 4,0; 6,0 e 8,0 dS m^{-1}) sem fração de lixiviação (FL1 = 0) e com (FL2 = 0,17), com quatro repetições. O aumento da CEa diminuiu as concentrações de N, P, K, Mg, S, Fe, Mn, Cu e Zn, e aumentou as concentrações de Ca, Cl e Na, e reduziu a produção de biomassa em dois ciclos (planta cana e soca). O uso da fração de lixiviação 0,17 mitigou os efeitos deletérios da salinidade nos nutrientes e na produtividade.

Palavras-chave: *Saccharum* spp., estresse salino, nutrição mineral, rendimento, fração de lixiviação

• Ref. 261560 – Received 28 Feb, 2022
* Corresponding author - E-mail: joseedson50@hotmail.com
• Accepted 08 July, 2022 • Published 15 July, 2022
Editors: Geovani Soares de Lima & Hans Raj Gheyi

Introduction

Brazil is the world's largest producer of sugarcane, sugar, and ethanol. In 2020/2021, 8.61 million hectares of sugarcane was harvested and 654.52 million tons was produced, with average productivity of 76.01 Mg ha^{-1} (CONAB, 2021).

Northeast Brazil, with a mean productivity of 58.01 Mg ha^{-1}, has low pluvial precipitation (300 to 800 mm per year). Thus, sugarcane must be irrigated to obtain satisfactory yields (Dingre & Gorantiwar, 2021; Jafari & Bazrekar, 2022). According to Rodolfo Junior et al. (2016), irrigated crops can produce 100-150 Mg ha^{-1}, with a water consumption of 1500-2000 mm per year.

Approximately 80% of sugarcane growing areas in Brazil are located in regions with water scarcity and/or coastal areas with high concentrations of soluble salts (e.g., K^+, Mg^{2+}, CO_3^{2-}, SO_4^{2-}, HCO_3^-, Na^+, and Cl^-) (Sá et al., 2021), due to the source material, high rates of evapotranspiration, saline intrusion of seawater, salt deposition by rain and wind, and fertilizer usage, which intensify salinization and/or sodification of soils (Mahmoodzadeh & Karamouz, 2019; German et al., 2020; Yu et al., 2021).

The accumulation of salts in the soil reduces the osmotic potential and water availability, and excessive absorption of some ions can cause phytotoxicity (Assaf et al., 2022; Kavian et al., 2022), resulting in changes in plant metabolism and nutritional imbalance, thereby directly impacting the productivity of crops (Munns, 2011; Ali et al., 2022) such as sugarcane, which is a glycophyte with a salinity threshold (saturation extract of soil) of 1.7 dS m^{-1}.

Few studies have evaluated the concentrations of nutrients in sugarcane plants under saline stress conditions, and none as extensively as that of the present work. Thus, the objective of this study was to evaluate the foliar concentrations of nutrients and inorganic solutes (Na^+ and Cl^-) and the stalk yield of sugarcane RB92579 under different electrical conductivities of irrigation water and leaching fractions.

Material and Methods

The experiment was conducted at the Agricultural Engineering Department of the Universidade Federal Rural de Pernambuco (UFRPE), Recife, PE (8°01'06" S, 34°56'49" W, altitude 6.5 m). The total area is 2400 m^2 (32 × 75 m), and contains an automatic weather station (Campbell Scientific, CR1000) used to obtain meteorological data (rainfall, air temperature, relative air humidity, wind speed, and solar global radiation) for irrigation management and a lysimetric station with 40 drainage lysimeters.

The soil used in the drainage lysimeters corresponds to a layer of 0-0.40 m that is classified as a Spodosol Humod, with the following physical-chemical and water attributes: sand = 890 g kg^{-1}, silt = 30 g kg^{-1}, clay = 80 g kg^{-1}, textural class = sand, soil bulk density = 1.69 kg dm^{-3}, particle density = 2.63 kg dm^{-3}, volumetric moisture (0.1 atm) = 6.15%, volumetric moisture (15 atm) = 1.34%, organic matter = 15.35 g kg^{-1}, $pH_{(H2O)}$ = 6.5, P = 49 mg dm^{-3}, K^+ = 0.08 $cmol_c$ dm^{-3}, Ca^{2+} = 1.6 $cmol_c$ dm^{-3}, Mg^{2+} = 0.65 $cmol_c$ dm^{-3}, Na^+ = 0.06 $cmol_c$ dm^{-3}, Cu = 0.78 mg dm^{-3}, Zn = 0.43 mg dm^{-3}, Mn = 0.62 mg dm^{-3}, $H^+ + Al^{3+}$ = 3.05 $cmol_c$ dm^{-3}, Al^{3+} = 0 $cmol_c$ dm^{-3}, cation exchange capacity = 5.44 $cmol_c$ dm^{-3}, base saturation = 43.9%, aluminum saturation = 0%, and ECe = 0.79 dS m^{-1}.

Two cultivation cycles of sugarcane RB92579 were evaluated: plant-cane planted in November 2016 and harvested in November 2017, and first ratoon harvested in November 2018. Grinding wheels were used for planting in single rows spaced 1.2 m apart with 10 plants m^{-1}.

For the plant-cane, basal mineral fertilization was performed with 20 kg ha^{-1} of N, 40 kg ha^{-1} of P_2O_5, and 35 kg ha^{-1} of K_2O in the form of urea, simple superphosphate, and potassium chloride, respectively. At 45 and 150 days after planting (DAP), topdressing was conducted using 20 kg ha^{-1} of N and 35 kg ha^{-1} of K_2O. Micronutrients were applied to the leaves, with 1.3 kg ha^{-1} of Cu, 2.0 kg ha^{-1} of Zn, and 2.6 kg ha^{-1} of Mn. For the ratoon cane, fertilization with 30 kg ha^{-1} of N and 40 kg ha^{-1} of K_2O was performed, along with foliar application of micronutrients in the same amount as that of the plant-cane at 30, 90, and 150 days after cutting (DAC).

The experimental design was completely randomized, in a 5 × 2 factorial scheme, with four replicates: five values of irrigation water electrical conductivity - ECw (0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}) without (LF1 = 0) or with leaching fraction (LF2 = 0.17). The experiment corresponding to 100 and 120% of the crop evapotranspiration (ETc), totaling 40 experimental plots, with each plot composed of a drainage lysimeter (1 m^3) with 12 plants. The electrical conductivity was obtained by the addition of NaCl and $CaCl_2.H_2O$ (Pró-Análise) in a 1:1 molar ratio (Ca:Na) in the local supply water (ECw = 0.5 dS m^{-1}), according to Richards (1954):

$$Qs = 640 \times ECw, \text{ when } ECw < 5.0 \text{ dS m}^{-1} \quad (1)$$

$$Qs = 800 \times ECw, \text{ when } ECw > 5.0 \text{ dS m}^{-1} \quad (2)$$

where:

Qs - quantity of salts (mg L^{-1}); and,

ECw - desired value for the electrical conductivity of water (dS m^{-1}).

The salts were mixed in five water tanks (1000 L), coupled with horizontal-axis centrifugal electric pumps (Model QB80, 0.5 CV). A drip irrigation system was used with self-compensating drippers (PCJ/CNL Netafim™ type), spaced at 0.30 m, with a unit flow of 4.1 L h^{-1} and application intensity of 11.40 mm h^{-1}, and one drip line per row of plants.

The application of treatments started 60 days after planting and 45 days after cutting for plant-cane and first ratoon, respectively, with daily irrigation. ETc was obtained as the product of the reference evapotranspiration (ETo) by the cultivation coefficient (Kc) and location coefficient (Kl). ETo was estimated using the Penman-Monteith method, with data from the automatic weather station, the Kc corresponded to each phenological phase of the plant, and the Kl was obtained by the percentage of wetted area of the irrigation system according to Allen et al. (1998).

At 150 days after planting (plant-cane) and cutting (first ratoon), the diagnostic leaf +3 (DL +3) of one plant per plot was collected to determine the nutritional status. Subsequently, the leaves were dried in an oven with forced-air circulation (65 °C) to a constant dry mass and processed in a Wiley-type mill with a 2 mm sieve. The quantification of the concentrations of the macronutrients (g kg^{-1}) nitrogen (N), phosphorus (P), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sulfur (S); micronutrients (mg kg^{-1}): copper (Cu^{2+}), iron (Fe^{2+}), manganese (Mn^{2+}), zinc (Zn^{2+}), and chloride (Cl^-); as well as the sodium ion (g kg^{-1}): sodium (Na^+) was performed according to Malavolta et al. (1997).

At 365 days after planting or the first cutting, the plant-cane and first ratoon were harvested, respectively, and all plants were cut and divided into stalks to calculate the productivity in tons per hectare (TCH). To determine the TCH, the fresh phytomass obtained in each lysimeter was divided by the area of 1.656 m^2 (1.38 m lysimeter length by 1.2 m spacing between plant rows) and multiplied by 10000.

Data were submitted to normality (Shapiro-Wilk test), homoscedasticity, and analysis of variance. The significant effect of electrical conductivity was then analyzed using regression analysis ($p \leq 0.05$). The unfolding of the leaching conditions at each salinity level was compared using Tukey's test ($p \leq 0.05$). The analyses were performed using Sisvar statistical software (Ferreira, 2019).

Results and Discussion

The interaction between irrigation water electrical conductivity (ECw) and the leaching fraction exerted significant effects ($p \leq 0.05$) on foliar concentrations of all nutrients except Zn^{2+} in plant-cane and Na^+ in plant-cane and first ratoon ($p \leq 0.05$). The Zn^{2+} concentration in the plant-cane was affected by these factors individually ($p \leq 0.05$) (Table 1).

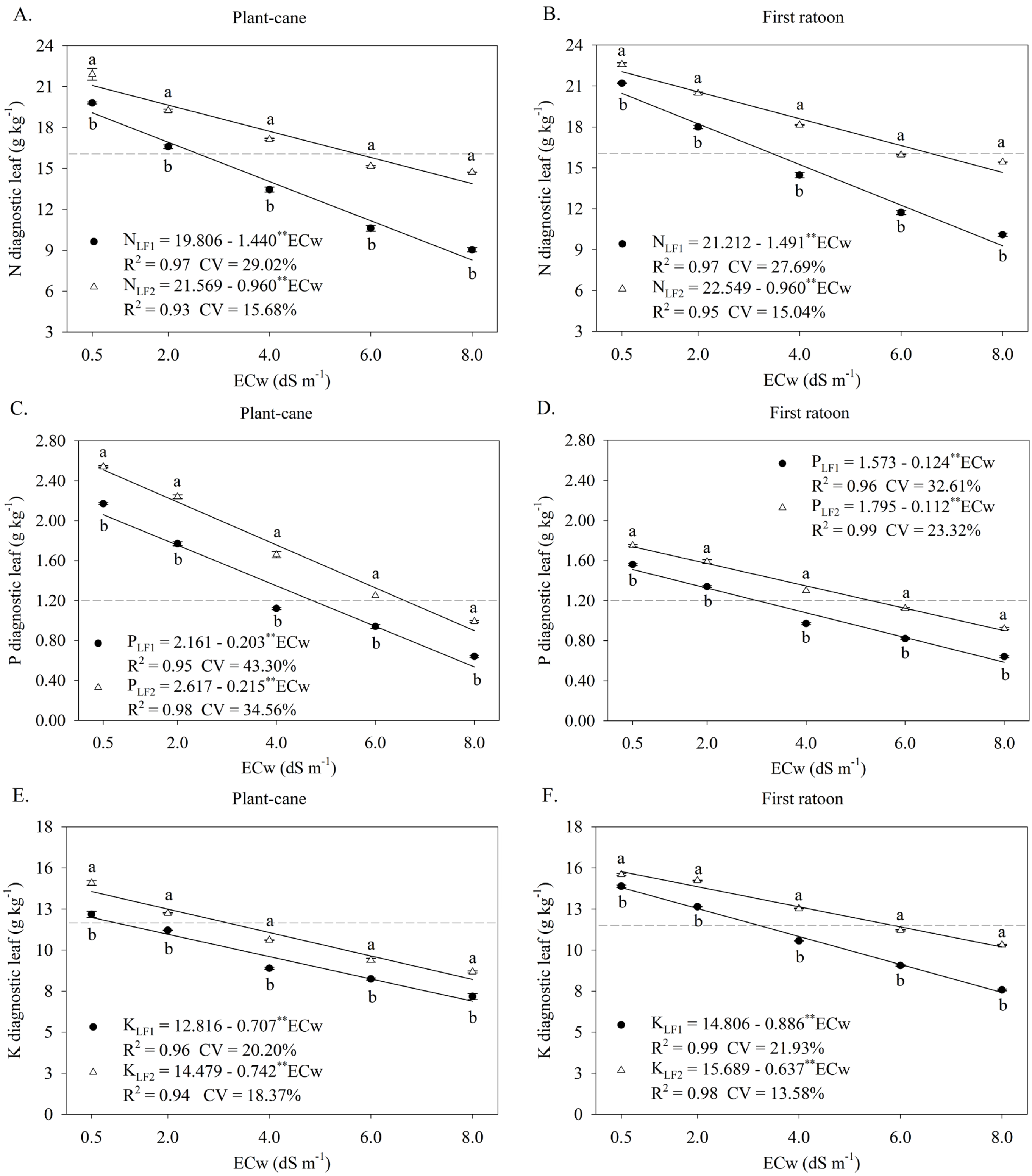
Figure 1A shows decreases of 1.44 and 0.96 g kg^{-1} of dry mass in N concentration for each unit increase in electrical conductivity for the conditions without (LF1) and with leaching fraction (LF2), respectively. For the LF1 condition, the mean values estimated by the regression equation of leaf N concentration were 19.09 and 8.29 g kg^{-1} for irrigation water electrical conductivities of 0.5 and 8.0 dS m^{-1}, respectively, which is a reduction of 56.6%, while the LF2 condition showed average concentrations of 21.09 and 13.89 g kg^{-1} (34.14%). According to Huang et al. (2019), when urea is hydrolyzed, ammonia and CO_2 are produced by the urease enzyme, and N decreases due to ammonia volatilization. This process is intensified in soils with high pH levels, which is a typical characteristic of sodic or saline sodic soils. In the present study, the pH of the irrigated soil with an ECw of 8 dS m^{-1} presented average values of 8.3 and 7.4 for LF1 and LF2, respectively.

According to Cavalcanti (2008), properly nourished plant-cane has foliar N concentrations of 16 g kg^{-1}, represented by

Table 1. Summary of analysis of variance for leaf concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), chloride (Cl), and sodium (Na) in plant-cane and first ratoon under different irrigation water electrical conductivity (ECw) and leaching fraction (LF)

Plant-cane							
Source of variation	DF	Mean squares – Macronutrients					
		N	P	K	Ca	Mg	S
Leaching fraction (LF)	1	139.31**	1.68**	23.07**	29.20**	0.62**	4.69**
Electrical conductivity (ECw)	4	108.41**	3.24**	39.34**	29.23**	1.02**	4.37**
LF × ECw	4	4.18**	0.01**	0.29**	2.62**	0.02**	0.18**
Error	30	0.128	0.001	0.047	0.003	0.001	0.006
CV (%)	%	2.28	2.47	2.05	0.93	1.70	3.47
Source of variation	DF	Micronutrients					
		Cu	Fe	Mn	Zn	Cl	Na
Leaching fraction (LF)	1	4.44**	1830.74**	456.97**	18.76**	4333503.32**	80.28**
Electrical conductivity (ECw)	4	5.40**	3611.03**	551.50**	317.80**	5765025.82**	68.87**
LF × ECw	4	0.13**	23.63*	16.63**	1.16ns	418185.08**	4.15*
Error	30	0.001	7.447	1.459	0.969	3221.234	0.059
CV (%)	%	0.70	2.93	3.30	3.68	8.89	4.37
First ratoon							
Source of variation	DF	Mean squares – Macronutrients					
		N	P	K	Ca	Mg	S
Leaching fraction (LF)	1	116.38**	0.72**	36.23**	54.00**	1.36**	4.92**
Electrical conductivity (ECw)	4	114.70**	1.02**	42.19**	73.53**	0.76**	3.01**
LF × ECw	4	4.73**	0.01**	1.21**	3.99**	0.09**	0.26**
Error	30	0.049	0.001	0.008	0.002	0.001	0.002
CV (%)	%	1.32	1.92	0.76	0.75	2.11	2.21
Source of variation	DF	Micronutrients					
		Cu	Fe	Mn	Zn	Cl	Na
Leaching fraction (LF)	1	2.07**	1165.21**	332.35**	145.46**	20712203.63**	101.21**
Electrical conductivity (ECw)	4	7.52**	3451.96**	2956.84**	523.09**	7993398.65**	153.69**
LF × ECw	4	0.20**	79.95*	123.93**	8.80**	743030.93**	12.01*
Error	30	0.002	4.382	39.301	0.762	11421.797	0.057
CV (%)	%	0.77	2.19	2.50	2.31	9.35	1.46

DF - Degree of freedom; CV - Coefficient of variation; **, *, ns - Signifcant at $p \leq 0.01$ and $p \leq 0.05$, and not signifcant by the F test, respectively



** - Significant p ≤ 0.01, by the F test. Means followed by different letters indicate a significant difference (p ≤ 0.05) by the Tukey's test in the leaching fractions at same ECw value
---- Macronutrient concentrations considered adequate (diagnostic leaf +3) according to Cavalcanti (2008)

Figure 1. Nitrogen (N) (A and B), phosphorus (P) (C and D), and potassium (K^+) (E and F) concentrations in plant-cane and first ratoon, respectively, submitted to irrigation water electrical conductivity (ECw) without (LF1) and with (LF2) leaching fraction

the dashed line in Figure 1A, which could be observed up to an ECw of 2.64 and 5.80 dS m^{-1} for LF1 and LF2 conditions, respectively. In the unfolding of LF within each ECw, significant differences ($p \leq 0.05$) were observed in N concentration, with increments of 10.49, 16.09, 26.22, 41.58, and 67.62% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively, for LF2 compared to LF1.

According to Zhang et al. (2019), the leaching fraction associated with an efficient drainage system promotes the displacement of salts from irrigation water and/or those already existing in the soil to depths beyond the root zone.

In general, the first ratoon (Figure 1B) showed higher foliar N concentrations when compared to the plant-cane, and although similar reductions were observed for LF1 (54.6%) and LF2 (33.5 %) in the ECw of 8.0 dS m^{-1} when compared to plants irrigated with supply water (0.5 dS m^{-1}), the concentrations were greater than the critical values recommended by Cavalcanti (2008) of 3.49 and 6.65 dS m^{-1} for LF1 and LF2, respectively. Lira et al. (2019) evaluated leaf nutrient concentrations in sugarcane RB867515 subjected to irrigation water electrical conductivity (0.5, 2.0, 3.5, 5.0 and 6.5 dS m^{-1}) and the conditions without (LF = 0) and with leaching fractions (LF = 0.17) in Recife, PE, and obtained reductions of 61.62 and 26.88% for N, for the respective leaching conditions, with an ECw of 6.5 dS m^{-1}.

In the unfolding of the LF within each ECw for N, there were significant differences ($p \leq 0.05$) with increments of 7.77, 12.89, 22.05, 35.67, and 58.06% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively of LF2 compared to LF1.

For P in the plant-cane (Figure 1C), there were decreases of 0.203 and 0.215 g kg^{-1} for each unit increase in electrical conductivity for the conditions LF1 and LF2, respectively. For LF1, the mean values of leaf P concentrations were 2.06 and 0.54 g kg^{-1} (73.92%) for salinities of 0.5 and 8.0 dS m^{-1}, respectively, while for LF2, the concentrations were 2.50 and 0.89 g kg^{-1}, which is a percentage reduction of 64.25. At salinities of 4.73 (LF1) and 6.59 dS m^{-1} (LF2), leaf P values were above the critical value recommended by Cavalcanti et al. (2008) of 1.2 g kg^{-1}. By the unfolding of the LF within each ECw, significant differences were observed ($p \leq 0.05$) with increments of 21.85, 24.62, 30.24, 40.72, and 67.04% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively for LF2 compared to LF1.

In the first ratoon (Figure 1D), a similar response was observed, with reductions of 0.124 and 0.112 g kg^{-1} unit increments of ECw promoted to LF1 and LF2, respectively. Up to salinities of 3.0 and 5.29 dS m^{-1} for LF1 and LF2, respectively, leaf concentrations were above the critical value recommended by Cavalcanti (2008). For the unfolding of the LF within each ECw, there were significant differences ($p \leq 0.05$) with increments of 13.20, 13.97, 15.25, 16.95, and 19.32% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively in LF2 compared to LF1.

Phosphorus has an important role in several functions of sugarcane, such as protein formation, photosynthesis, cell division, and energy storage. It is critical in the first three months of vegetative growth, and is one of the nutrients that most contributes to production (Parra et al., 2022).

ECw promoted unitary decreases of 0.707 and 0.742 g kg^{-1} in K^+ values (Figure 1E) for LF1 and LF2, respectively. For LF1, the mean foliar concentration values were 12.46 and 7.16 g kg^{-1} for salinities of 0.5 and 8.0 dS m^{-1}, respectively, which is a reduction of 56.6%, and for LF2 the means were 14.11 and 8.54 g kg^{-1} (39.45%). Plant-cane has an average foliar K^+ content of 12 g kg^{-1} according to Cavalcanti (2008), and the present research showed ECw values of up to 1.15 and 3.34 dS m^{-1} for LF1 and LF2, respectively. The unfolding of the LF within each ECw revealed significant differences ($p \leq 0.05$) between LF2 compared to LF1, with increments of 13.20, 13.97, 15.25, 16.95, and 19.32% for ECw of 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively.

For the first ratoon (Figure 1F), each unit increment of ECw promoted reductions in K^+ values of 0.886 and 0.637 g kg^{-1} for LF1 and LF2, respectively. The average concentrations were above the limit considered critical by Cavalcanti (2008) of 3.17 and 5.79 dS m^{-1} for LF1 and LF2, respectively, with higher electrical conductivity than observed in the first cycle. According to Taiz et al. (2017), the culms of potassium-deficient plant-cane are thin and weak, with abnormally short internodes. High values of Na^+ in the soil inhibit the absorption of nutrients, mainly that of K^+ due to the ionic antagonism between these monovalent ions by competing for absorption and transport sites in the plasma membrane (Ali et al., 2021; Cirillo et al., 2022; Zhang et al., 2022).

By unfolding the LF within each ECw, significant differences ($p \leq 0.05$) in K^+ of 21.85, 24.62, 30.24, 40.72, and 67.04% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively, were observed between LF2 and LF1.

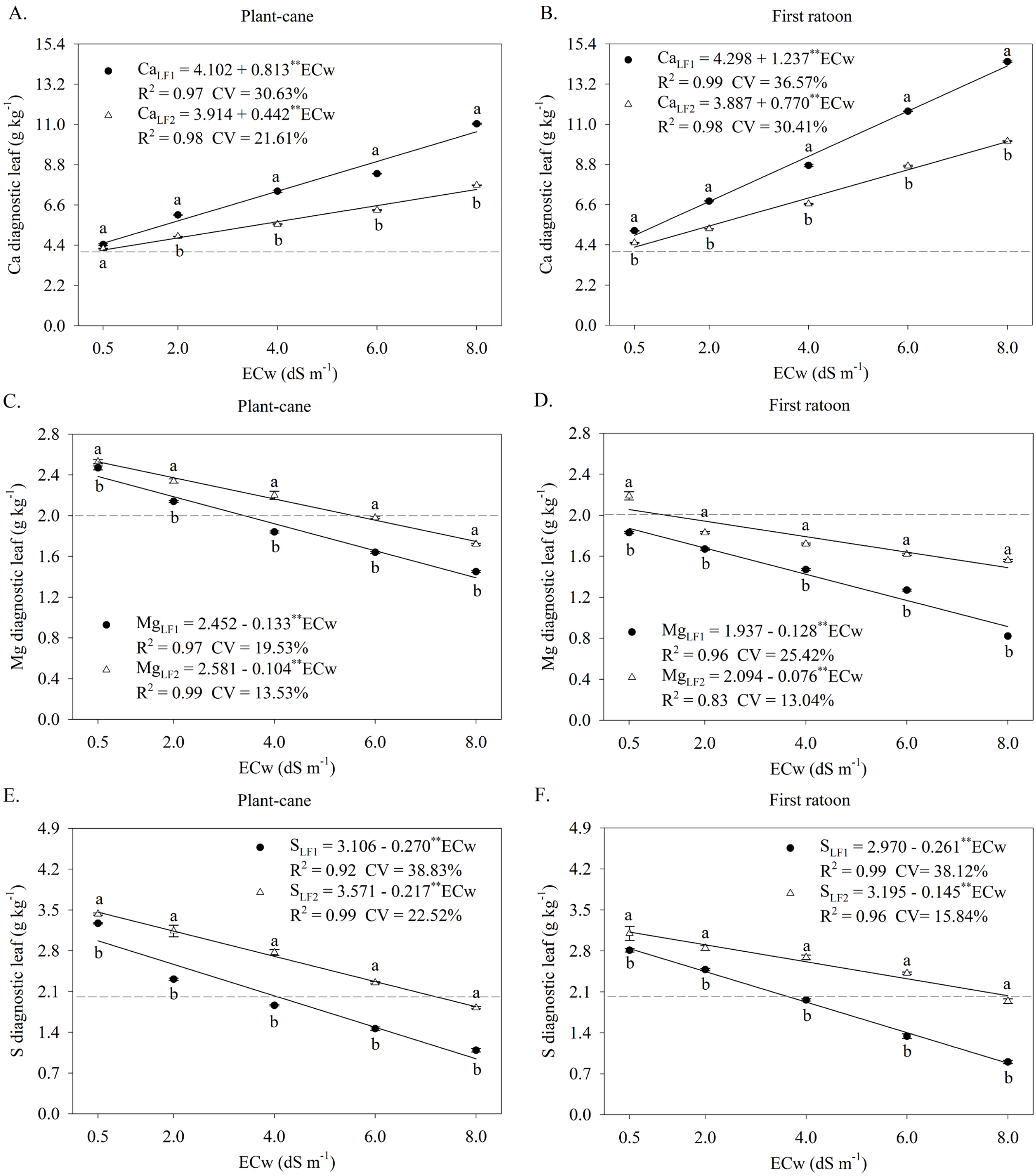
In plant-cane (Figure 2A), there was an increase of 0.813 and 0.442 g kg^{-1} in Ca^{2+} content for each unit increase in ECw for LF1 and LF2, respectively. Under LF1, the average foliar Ca^{2+} concentrations ranged from 4.51 and 10.61 g kg^{-1} for electrical conductivities of 0.5 and 8.0 dS m^{-1}, respectively, which is an expressive increase of 135.24%; in LF2 the values were 4.14 and 7.45 g kg^{-1} (80.17%). Ca^{2+} was above the critical value recommended by Cavalcanti et al. (2008) for all ECw levels evaluated. The analysis of the LF unfolding within each ECw showed significant differences ($p \leq 0.05$) of 19.38, 29.43, 36.77, and 42.36% in Ca^{2+} concentrations for 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively between LF1 and LF2.

Figure 2B reveals significant increases in foliar Ca^{2+} values in the first ratoon compared to those of plant-cane. Each unit increment in irrigation water electrical conductivity increased Ca^{2+} concentrations by 1.237 and 0.770 g kg^{-1} without and with the leaching fraction, respectively. In the LF1 and LF2 conditions, percentage increases of 188.70 and 135.18%, respectively, were observed in the ECw of 8.0 dS m^{-1} when compared to plants irrigated with supply water (0.5 dS m^{-1}), which is above the critical level recommended by Cavalcanti et al. (2008) of 4 g kg^{-1}. Lira et al. (2019) observed an average increase of 41% in foliar Ca^{2+} concentrations in sugarcane plants irrigated with brackish water. According to those authors, high concentrations of Ca^{2+} inhibit the uptake of K^+ and Mg^{2+} by plants.

In the unfolding of the LF within each ECw for Ca^{2+}, there were significant differences ($p \leq 0.05$) with increments of 15.09, 24.78, 32.71, 37.77, and 41.28% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively, between LF1 and LF2.

For Mg^{2+} (Figure 2C) in the plant-cane, decreases of 0.133 and 0.104 g kg^{-1} were observed for each unit increment of ECw for LF1 and LF2, respectively. In the LF1 condition, mean values of leaf Mg^{2+} of 2.38 and 1.38 g kg^{-1} (reduction of 41.82%) were observed, and in LF2, 2.52 and 1.74 g kg^{-1} (reduction of 30 .84%) were revealed for ECws of 0.5 and 8.0 dS m^{-1}, respectively. Up to electrical conductivities of 3.40 (LF1) and 5.39 dS m^{-1} (LF2), leaf Mg^{2+} values were above the critical limit recommended by Cavalcanti (2008) of 2.0 g kg^{-1}. There were significant differences ($p \leq 0.05$) in the unfolding of the LF within each ECw, with increments of 6.02, 8.55, 12.76, 18.32, and 26.01% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively for LF2 compared to LF1.

In the first ratoon (Figure 2D), the increase in ECw promoted reductions in Mg^{2+} values, with reductions of 0.128 and 0.076 g kg^{-1} per dS m^{-1} increase in water salinity for the LF1 and LF2 conditions, respectively. In LF1, all ECw values



** - Significant $p \leq 0.01$ by the F test. Means followed by different letters indicate significant difference ($p \leq 0.05$) by the Tukey's test in the leaching fractions at same ECw value
---- Macronutrient concentrations considered adequate (diagnostic leaf +3) according to Cavalcanti (2008)

Figure 2. Calcium (Ca^{2+}) (A and B), magnesium (Mg^{2+}) (C and D), and sulfur (S) (E and F) concentrations in plant-cane and first ratoon, respectively, submitted to irrigation water electrical conductivity (ECw) without (LF1) and with (LF2) leaching fraction

were below those recommended by Cavalcanti (2008), with a reduction of 51.25% in the foliar content of plants irrigated with 8.0 dS m^{-1} compared to those irrigated with supply water. Under LF2, the reduction for these conditions of ECw was 27.72%, with values maintained above 2.0 g kg^{-1} (Cavalcanti, 2008) to an ECw of 1.24 dS m^{-1}. By the unfolding of the LF within each ECw, significant differences ($p \leq 0.05$) were observed with increments of 9.77, 15.53, 25.61, 40.12, and 62.76% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively in LF2 compared to LF1.

In plant-cane, S concentrations decreased by 0.270 and 0.217 g kg^{-1} for each unit increment of ECw under the LF1 and LF2 conditions, respectively (Figure 2E). The increase in ECw promoted reductions in leaf S concentrations of 68.16 and 47.00% for LF1 and LF2, respectively, at ECw = 8.0 dS m^{-1} when compared to 0.5 dS m^{-1}. According to Cavalcanti (2008), the leaf S content of well-nourished plant-cane is 2 g kg^{-1}, which was observed in the present study up to salinities of 4.10 and 7.24 dS m^{-1} under LF1 and LF2 conditions. The analysis of the LF unfolding within each ECw showed significant differences ($p \le 0.05$) with increments of 16.54, 22.25, 33.42, 52.69, and 93.97% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively, in LF2 compared to LF1.

In first ratoon (Figure 2F), leaf S values were similar to those observed in the first cycle, with reductions of 68.94 and 34.83% for LF1 and LF2, respectively. Without leaching, the S concentrations remained above the critical value mentioned by Cavalcanti (2008) to ECw = 3.72 dS m^{-1}; however, in treatments with a leaching fraction of 0.17 (LF2), the concentrations were above the critical value for all saline concentrations evaluated. Sulfur is a constituent of essential amino acids (e.g., cysteine, methionine, and cystine) involved in the production of chlorophyll, and has a structural function in the plant; therefore, its deficiency directly affects yield (Taiz et al., 2017). In the unfolding of LF within each ECw to S, there were significant differences ($p \le 0.05$) with increments of 9.97, 18.67, 35.77, 65.62, and 130.72% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively in LF2 compared to LF1.

There were decreases in foliar values of Cu^{2+} in the plant-cane (Figure 3A) of 0.299 and 0.234 g kg^{-1} per dS m^{-1} increase in the conditions without and with the leaching fraction, respectively. Mean values of leaf Cu^{2+} concentrations of 6.60 and 4.36 mg kg^{-1} (-33.98%) were observed in LF1 and 7.03 and 5.27 mg kg^{-1} (-26.45%) in LF2, at salinities of 0.5 and 8.0 dS m^{-1}, respectively. For this micronutrient, Cavalcanti (2008) recommended an average leaf content of 6 mg kg^{-1} of dry mass. In the present study, higher and/or equal values were observed in the leaves of plants irrigated with ECws of up to 2.51 (LF1) and 4.90 dS m^{-1} (LF2). The unfolding of the LF within each ECw showed significant differences ($p \le 0.05$) with increments of 6.52, 8.58, 11.85, 15.90, and 21.07% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively in LF2 compared to LF1.

In the first ratoon (Figure 3B), the foliar values of Cu^{2+} were higher than those obtained for plant-cane. The average values of Cu^{2+} content for LF1 were 7.53 and 4.81 g kg^{-1} (36.07%) and for LF2 were 7.68 and 5.60 g kg^{-1} (-27.06%), respectively, for salinities of 0.5 and 8.0 dS m^{-1}. The foliar concentrations of this nutrient remained above the critical limit recommended by Cavalcanti (2008) (6 mg kg^{-1}) up to ECw values of 4.72 (LF1) and 6.55 dS m^{-1} (LF2). By analyzing the LF unfolding within each ECw, significant differences ($p \le 0.05$) were observed with increments of 3.98, 7.16, 11.17, and 16.38% for 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively, in LF2 compared to LF1.

Decreases of 6.556 and 7.374 mg kg^{-1} per unit increment of ECw were observed for the foliar concentrations of Fe^{2+} (Figure 3C) under the LF1 and LF2 conditions, respectively. Under LF1, for ECw 0.5 and 8.0 dS m^{-1}, foliar Fe^{2+} concentrations of 109.83 and 60.66 mg kg^{-1} (reduction 44.77%) were observed, whereas for LF2, the concentrations were 126.31 and 71.01 mg kg^{-1} (reduction 43.79%) for the respective salinities. According to Cavalcanti (2008), well-nourished cane plants have a foliar Fe^{2+} content of 100 mg kg^{-1}, which can be observed in the present study up to an ECw of 2.00 and 4.07 dS m^{-1} for LF1 and LF2, respectively. The unfolding of the LF within each ECw showed significant differences ($p \le 0.05$) with increments of 15.01, 15.25, 15.67, 16.24, and 17.05% for ECw of 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively in LF2 compared to LF1.

In first ratoon (Figure 3D), foliar Fe^{2+} concentrations were similar to those in plant-cane, showing reductions of 48.47 and 37.00% under LF1 and LF2 conditions, respectively. The leaf Fe^{2+} concentrations remained above that recommended by Cavalcanti (2008) to ECw = 2.84 and 4.29 dS m^{-1} for LF1 and LF2, respectively. With the unfolding of LF within each ECw, significant differences ($p \le 0.05$) were observed with increments of 7.12, 11.67, 18.08, and 27.71% in Fe^{2+} concentrations for 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively for LF2 compared to LF1.

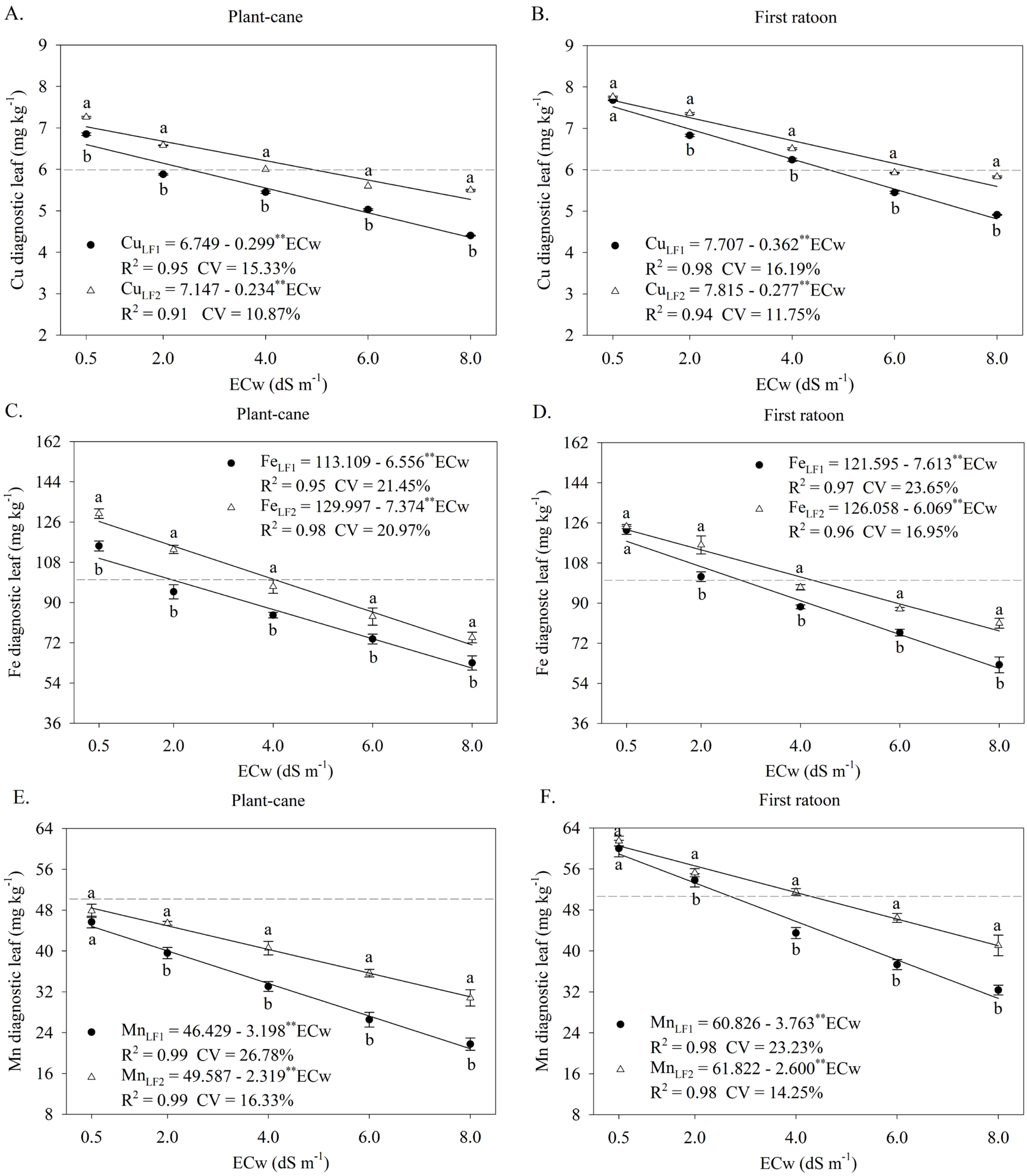
In Figure 3E, reductions of 3.198 and 2.319 mg kg^{-1} per unit increment of ECw in Mn^{2+} values were observed for LF1 and LF2, respectively, resulting in reductions of 53.50 (LF1) and 35.91% (LF2) with an ECw = 8.0 dS m^{-1} when compared to supply water in plant-cane (ECw = 0.5 dS m^{-1}). For Mn^{2+}, Cavalcanti (2008) recommended a leaf content of 50 mg kg^{-1}, but in the present study, for both leaching fractions, the foliar concentrations of this nutrient were found to be below the critical value. The presence of other cations in the soil solution (e.g., Ca^{2+} and Mg^{2+}) influenced the availability of Mn^{2+} for plants and affected their development, since this is an important enzyme activator (e.g., decarboxylases and dehydrogenases) involved in the Krebs cycle (Taiz et al., 2017).

The unfolding of LFs within each ECw for Mn^{2+} showed significant differences ($p \le 0.05$) with increments of 12.28, 19.84, 30.95, and 48.88% for 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively, for LF2 in comparison to LF1.

For the first ratoon (Figure 3F) with LF1 at salinities of 0.5 and 8.0 dS m^{-1} the foliar Mn^{2+} concentrations were 58.94 and 30.72 mg kg^{-1} (reduction of 47.88%) and for LF2 the values were 60.52 and 41.02 mg kg^{-1} (difference of 32.22%) for the respective salinities. The average concentrations were above the limit considered critical by Cavalcanti (2008) up to ECws of 2.88 and 4.55 dS m^{-1}, for LF1 and LF2, respectively. Soils affected by salts usually have an alkaline pH, which reduces the availability of Mn^{2+} due to the lower solubility of the related compounds (Farhangi-Abriz & Ghassemi-Golezani, 2021). At the end of the experiment, the mean pH levels of the soil irrigated with ECw of 8 dS m^{-1} were 8.3 and 7.4 for LF1 and LF2, respectively, which are common values in saline and saline-sodic soils according to Richards (1954).

With the unfolding of LF within each ECw, significant differences were observed ($p \le 0.05$) with increments of 6.23, 12.34, 20.85, and 33.53% in Mn^{2+} concentrations for 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively for LF2 compared to LF1.

Leaf Zn^{2+} concentrations in plant-cane (Figure 4A) were affected by both electrical conductivity and leaching fraction, but not by their interaction ($p > 0.05$). There was a decrease of 2.072 mg kg^{-1} of dry mass for each unit increment of ECw, which is a reduction of 44.28% in the electrical conductivity of 8.0 dS m^{-1} when compared to 0.5 dS m^{-1}. According to Cavalcanti (2008), the recommended foliar content of Zn^{2+} in sugarcane is 10 mg kg^{-1}; however, Malavolta et al. (1997) recommend a range of 25-50 mg kg^{-1}; thus, for the lower limit of this range, an ECw up to 4.94 dS m^{-1} is acceptable.

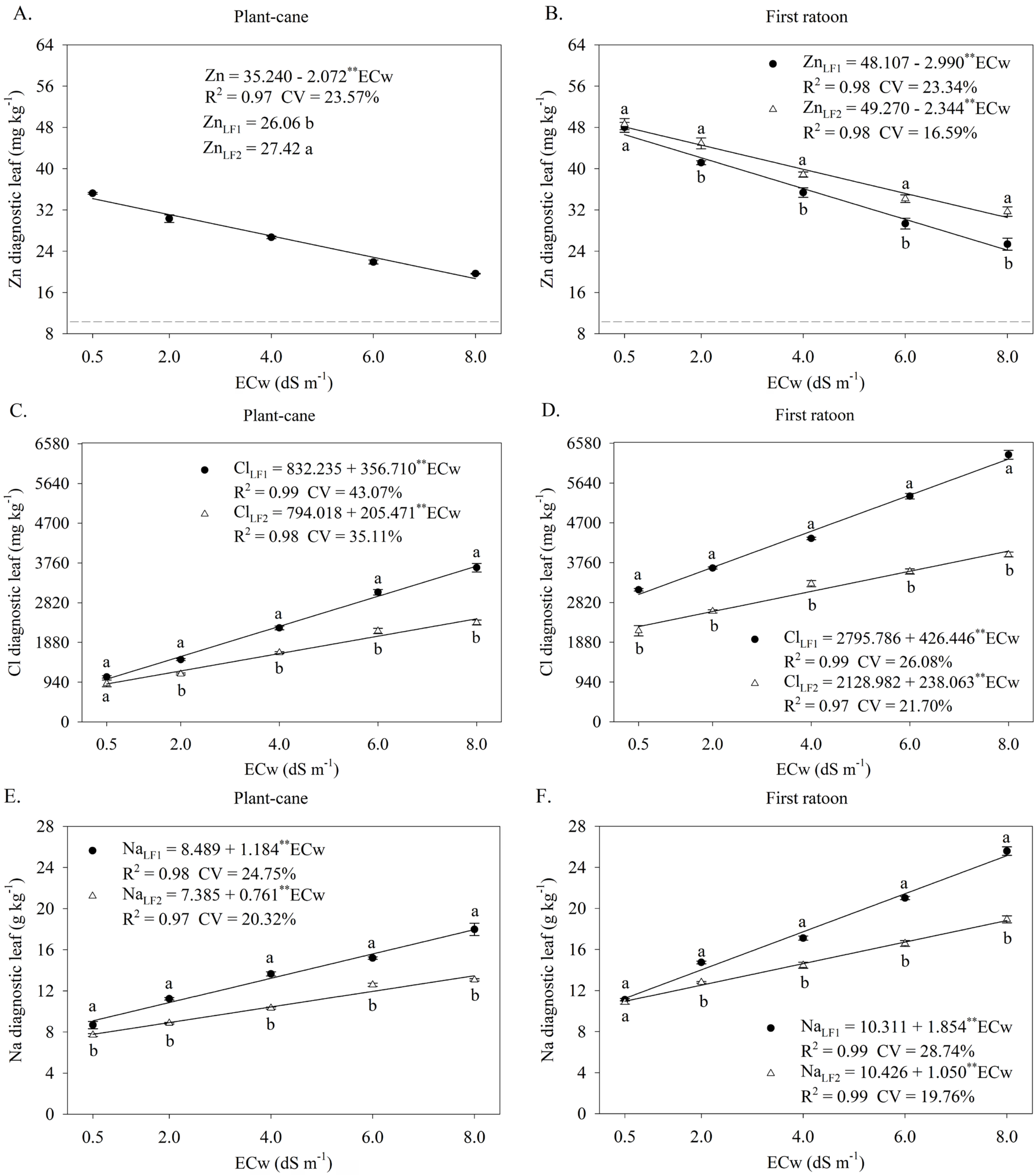


** - Significant $p \leq 0.01$, by the F test. Means followed by different letters indicate significant difference ($p \leq 0.05$) by the Tukey's test in the leaching fractions at same ECw value
---- Micronutrient concentrations considered adequate (diagnostic leaf +3) according to Cavalcanti (2008)

Figure 3. Copper (Cu^{2+}) (A and B), iron (Fe^{2+}) (C and D), and manganese (Mn^{2+}) (E and F) concentrations in plant-cane and first ratoon, respectively, submitted to irrigation water electrical conductivity (ECw) without (LF1) and with (LF2) leaching fraction

In the first ratoon (Figure 4B), there was a significant effect of the interaction between ECw and leaching conditions ($p \leq 0.01$) for Zn^{2+} concentrations. Decreases were 2.990 (LF1) and 2.344 mg kg^{-1} (LF2), with reductions of 48.11 and 36.55% between the ECws of 0.5 and 8.0 dS m^{-1}, respectively. Considering the foliar concentrations recommended by Malavolta et al. (1997), the results of the present study were within range. With the LF unfolding within each ECw, significant differences were observed ($p \leq 0.05$) with increments of 5.83, 10.37, 16.71, and 26.18% in Zn^{2+} concentrations for 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively in LF2 compared to LF1.

There were increases in leaf Cl^- values in plant-cane (Figure 4C) of 356.710 and 205.471 mg kg^{-1} dS m^{-1} for LF1 and LF2, respectively. For LF1, mean values of 1010.59 and 3685.92 mg kg^{-1} (increase of 264.73%) were observed in the LF1 condition and 896.75 and 2437.79 mg kg^{-1} (171.85%) under LF2 at



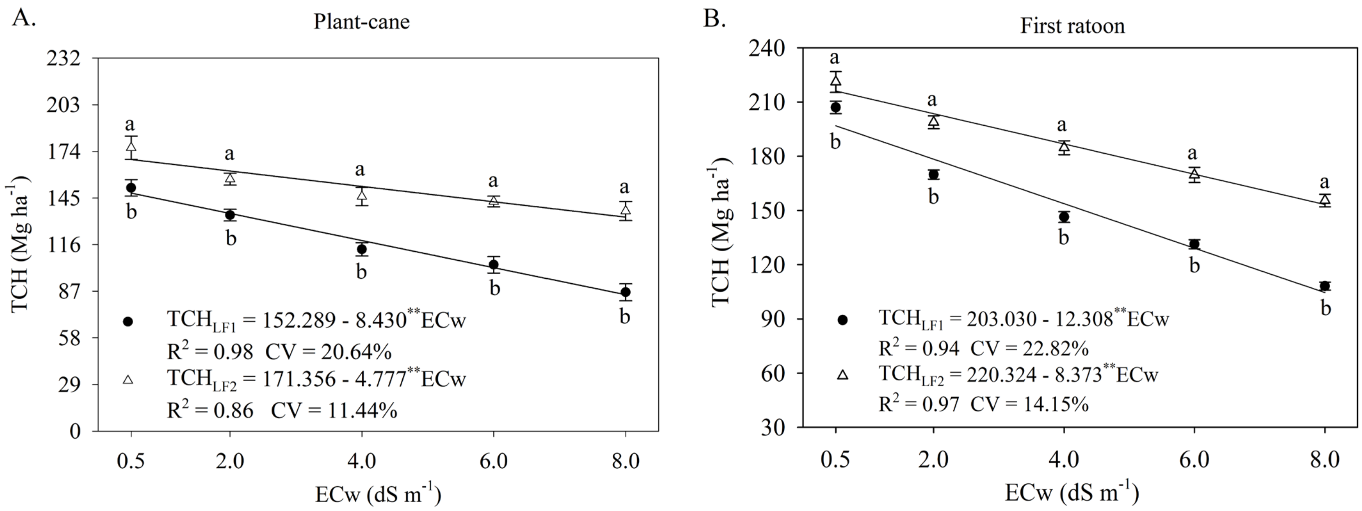
** - Significant $p \leq 0.01$ by the F test. Means followed by different letters indicate a significant difference ($p \leq 0.05$) by the Tukey's test in the leaching fractions at same ECw value
---- Micronutrient concentrations considered adequate (diagnostic leaf +3) according to Cavalcanti (2008)

Figure 4. Concentrations of zinc (Zn^{2+}) (A and B), chloride (Cl^-) (C and D), and sodium (Na^+) (E and F) in plant-cane and first ratoon, respectively, submitted to irrigation water electrical conductivity (ECw) without (LF1) and with (LF2) leaching fraction

salinities of 0.5 and 8.0 dS m^{-1}, respectively. In the literature, there are no recommendations for the ideal foliar chloride content for sugarcane cultivation. According to Malavolta et al. (1997), plants generally show excellent growth in the range of 340-2200 mg kg^{-1} and high concentrations of this ion in plants can cause toxicity, such as leaf tip and margin burning, tanning, early yellowing, leaf abscission, and competitive effects with NO_3^- and SO_4^{2-}. Based on the upper limit of the aforementioned range, higher values were observed with salinities greater than 3.83 (LF1) and 6.84 dS m^{-1} (LF2).

For Cl^-, by unfolding the LF within each ECw, significant differences were observed ($p \leq 0.05$) with increments of 28.27, 39.81, 46.66, and 51.22% for 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively for LF1 compared to LF2.

In the first ratoon (Figure 4D), even greater Cl^- foliar concentrations were observed. In the LF1 condition, the average



** - Significant $p \leq 0.01$ by the F test. Means followed by different letters indicate a significant difference ($p \leq 0.05$) by the Tukey's test in the leaching fractions at same ECw value

Figure 5. Stalks yield (TCH) in plant-cane (A) and first ratoon (B), respectively, subjected to irrigation water electrical conductivity (ECw) without (LF1) and with (LF2) leaching fraction

values of Cl^- content were 3009.01 and 6207.35 mg kg^{-1} (106.29%) and in LF2, concentrations 2248.01 and 4033.49 mg kg^{-1} (79.42%) were observed for ECws of 0.5 and 8.0 dS m^{-1}, respectively. Lira et al. (2019) obtained Cl^- concentrations for variety RB867515 of 2902.62 and 1812.40 mg kg^{-1} at an electrical conductivity of 6.5 dS m^{-1} in LF1 (0) and LF2 (0.17), respectively. The unfolding of the LF within each ECw, showed significant differences ($p \leq 0.05$) with increments of 33.85, 40.06, 46.12, 50.52, and 53.93%, for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively in LF1 compared to LF2.

In plant-cane, the foliar Na^+ concentrations (Figure 4E) for salinities of 0.5 and 8.0 dS m^{-1} were 9.08 and 17.96 g kg^{-1} (LF1) and 7.77 and 13.47 g kg^{-1} (LF2), revealing increases of 97.79 and 73.50%, for the respective leaching conditions. For Na^+, by unfolding the LF within each ECw, significant differences were observed ($p \leq 0.05$) with increments of 16.94, 21.89, 26.81, 30.47, and 33.31% for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively under LF1 compared to LF2.

The first ratoon (Figure 4F) presented a similar percentage increase; however, the foliar concentrations of this ion were higher. There are no reports in the literature on adequate leaf sodium content in sugarcane. According to Taiz et al. (2017), when cytosolic values of Na^+ exceed 100 mM, this ion becomes cytotoxic, causing protein denaturation and membrane destabilization, with the main symptoms of burns or necrosis along the edges.

By analyzing the LF unfolding within each ECw, significant differences were observed ($p \leq 0.05$) with increments of 11.92, 21.22, 28.15, and 33.55% for 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively, for LF1 compared to LF2.

There was a significant effect of the interaction between the electrical conductivity of irrigation water under the conditions without (LF1) and with (LF2) leaching on sugarcane stalk yield (RB92579) in plant-cane and ratoon-cane ($p \leq 0.05$).

For the yield of stalks in plant-cane (Figure 5A), there were decreases of 8.430 and 4.777 Mg ha^{-1} per unit increment of ECw in LF1 and LF2, respectively. The highest yield of stalk green mass was obtained when LF2 was adopted in plants irrigated with ECw = 0.5 dS m^{-1} (TCH = 168.97 Mg ha^{-1}), while at a water salinity of 8.0 dS m^{-1} for this condition, the TCH was 133.14 Mg ha^{-1} (reduction of 21.20%). In the LF1 condition, the values obtained for TCH were 148.07 and 84.85 Mg ha^{-1}, for the respective ECw values, which is a reduction of 42.71%. On average, the production of stems in LF2 was 28.91% higher than that of the LF1 condition.

The analysis of the LF unfolding within each ECw showed significant differences ($p \leq 0.05$) for TCH with increments of 14.11, 19.47, 28.40, 40.32, and 56.91% for 0.5, 2.0, 4.0, 6.0 and 8.0 dS m^{-1}, respectively for LF1 compared to LF2.

In the first ratoon (Figure 5B), average yields for LF1 were 196.88 and 104.57 Mg ha^{-1} (reduction of 46.9%) for ECw = 0.5 and 8.0 dS m^{-1}, respectively. For LF2, the TCH for the respective salinities were 216.13 and 153.34 Mg ha^{-1}, which is a percentage reduction of 29.11. In LF2, the TCH was on average 21.91% higher than that of LF1. Lira et al. (2019) evaluated the variety RB867515 under irrigation with brackish water (ECw = 0.5, 2.0, 3.5, 5.0, and 6.5 dS m^{-1}) without (LF = 0) and with (LF = 0.17) the leaching fraction, and observed an average reduction of 28.64% in yield when irrigated with 6.5 dS m^{-1}.

The unfolding of LF within each ECw for TCH revealed significant differences ($p \leq 0.05$), with increments of 9.78, 14.11, 21.48, 31.66, and 46.64%, for 0.5, 2.0, 4.0, 6.0, and 8.0 dS m^{-1}, respectively for LF1 compared to LF2.

Soil salinity induces osmotic stress, water deficit, ionic imbalance such as K^+ deficiency and Na^+ toxicity, stomatal closure, reduced photosynthesis, and, consequently, reduced plant yield (Morton et al., 2019; Wang et al., 2020). In cases where electrical conductivity values are harmful to plants, the use of cropping strategies to reduce soil salinity, such as the leaching fraction, is key to successful irrigation; however, the success of this operation depends on the existence of an efficient drainage system that removes excess water (Puga et al., 2016; Zhang et al., 2019; Yu et al., 2020).

Conclusions

1. The increase in electrical conductivity of irrigation water decreases the foliar concentrations of N, P, K^+, Mg^{2+}, S, Fe^{2+},

Mn^{2+}, Cu^{2+}, and Zn^{2+} and increases the concentrations of Ca^{2+}, Cl^-, and Na^+ in plant-cane and first ratoon.

2. The effects of electrical conductivity on foliar concentrations of macronutrients and micronutrients, as well as sodium and yield are minimized when using a leaching fraction of 0.17.

3. Stalk yield decreases with the increase in irrigation water electrical conductivity.

Acknowledgments

The authors thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES - Financing Code 001) for the financial support.

Literature Cited

Ali, A.; Raddatz, N.; Pardo, J. M.; Yun, D. J. HKT sodium and potassium transporters in *Arabidopsis thaliana* and related halophyte species. Physiologia Plantarum, v.171, p.546-558, 2021. https://doi.org/10.1111/ppl.13166

Ali, A. Y. A.; Ibrahim, M. E. H.; Zhou, G.; Zhu, G.; Elsiddig, A. M. I.; Suliman, M. S. E.; Elradi, S. B. M.; Salah, E. G. I. Interactive impacts of soil salinity and jasmonic acid and humic acid on growth parameters, forage yield and photosynthesis parameters of sorghum plants. South African Journal of Botany, v.146, p.293-303, 2022. https://doi.org/10.1016/j.sajb.2021.10.027

Allen, R. G.; Pereira, L. S.; Raes, D.; Smith, M. Crop evapotranspiration: Guidelines for computing crop water requirements. Rome: Food and Agriculture Organization, 1998. 300p. Drainage and Irrigation Paper, 56

Assaf, M.; Korkmaz, A.; Karaman, S.; Kulak, M. Effect of plant growth regulators and salt stress on secondary metabolite composition in Lamiaceae species. South African Journal of Botany, v.144, p.480-493, 2022. https://doi.org/10.1016/j.sajb.2021.10.030

Cavalcanti, F. J. A. Recomendações de adubação para o Estado de Pernambuco. 2.ed. Recife: Instituto Agronômico de Pernambuco, 2008. 198p.

Cirillo, V.; Molisso, D.; Aprile, A. N.; Maggio, A.; Rao, R. Systemin peptide application improves tomato salt stress tolerance and reveals common adaptation mechanisms to biotic and abiotic stress in plants. Environmental and Experimental Botany, v.199, p.1-10, 2022. https://doi.org/10.1016/j.envexpbot.2022.104865

CONAB - Companhia Nacional de Abastecimento. Acompanhamento da safra brasileira de cana-de-açúcar: safra 2020/2021. Available on: <https://www.conab.gov.br/info-agro/safras/cana/boletim-da-safra-de-cana-de-acucar>. Accessed on: May 2021.

Dingre, S. K.; Gorantiwar, S. D. Soil moisture based deficit irrigation management for sugarcane (*Saccharum offcinarum* L.) in semiarid environment. Agricultural Water Management, v.245, p.1-14, 2021. https://doi.org/10.1016/j.agwat.2020.106549

Farhangi-Abriz, S.; Ghassemi-Golezani, K. Changes in soil properties and salt tolerance of safflower in response to biochar-based metal oxide nanocomposites of magnesium and manganese. Ecotoxicology and Environmental Safety, v.211, p.1-11, 2021. https://doi.org/10.1016/j.ecoenv.2021.111904

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

German, L. A.; Hepinstall-Cymerman, J.; Biggs, T.; Parker, L.; Salinas, M. The environmental effects of sugarcane expansion: A case study of changes in land and water use in southern Africa. Applied Geography, v.121, p.1-9, 2020. https://doi.org/10.1016/j.apgeog.2020.102240

Huang, W.; She, Z.; Gao, M.; Wang, Q.; Jin, C.; Zhao, Y.; Guo, L. Effect of anaerobic/aerobic duration on nitrogen removal and microbial community in a simultaneous partial nitrification and denitrification system under low salinity. Science of the Total Environment, v.651, p.859-870, 2019. https://doi.org/10.1016/j.scitotenv.2018.09.218

Jafari, S.; Bazrekar, H. Relationship between drainage composition and clay minerals evolution under heavily irrigated sugarcane cultivation in southwest Iran. Catena, v.212, p.1-14, 2022. https://doi.org/10.1016/j.catena.2022.106088

Kavian, S.; Safarzadeh, S.; Yasrebi, J. Zinc improves growth and antioxidant enzyme activity in *Aloe vera* plant under salt stress. South African Journal of Botany, p.1-9, 2022. https://doi.org/10.1016/j.sajb.2022.04.011

Lira, R. M. de; Silva, E. F. de F.; Silva, G. F. da; Souza, D. H. S. de; Pedrosa, E. M. R.; Gordin, L. C. Content, extraction and export of nutrients in sugarcane under salinity and leaching fraction. Revista Brasileira de Engenharia Agrícola e Ambiental, v.23, p.432-438, 2019. http://dx.doi.org/10.1590/1807-1929/agriambi.v23n6p432-438

Mahmoodzadeh, D.; Karamouz, M. Seawater intrusion in heterogeneous coastal aquifers under flooding events. Journal of Hydrology, v.568, p.1118-1130, 2019. https://doi.org/10.1016/j.jhydrol.2018.11.012

Malavolta, E.; Vitti, G. C.; Oliveira, S. A. Avaliação do estado nutricional das plantas: princípios e aplicações. 2.ed. Piracicaba: Potafos, 1997. 319p.

Morton, M. J. L.; Awlia, M.; Al-Tamimi, N.; Saade, S.; Pailles, Y.; Negrao, S.; Tester, M. Salt stress under the scalpel-dissecting the genetics of salt tolerance. Plant Journal, v.97, p.148-163, 2019. https://doi.org/10.1111/tpj.14189

Munns, R. Plant adaptations to salt and water stress: differences and commonalities. Advances in Botanical Research, v.57, p.1-32, 2011. https://doi.org/10.1016/B978-0-12-387692-8.00001-1

Parra, J. S.; Souza, Z. M. de; Oliveira, S. R. de M.; Farhate, C. V. V.; Marques Júnior, J.; Siqueira, D. Phosphorus adsorption prediction through decision tree algorithm under different topographic conditions in sugarcane fields. Catena, v.213, p.1-11, 2022. https://doi.org/10.1016/j.catena.2022.106114

Puga, A. P.; Melo, L. C. A.; Abreu, C. A. de; Coscione, A. R.; Paz-Ferreiro, J. Leaching and fractionation of heavy metals in mining soils amended with biochar. Soil & Tillage Research, v.164, p.25-33, 2016. https://doi.org/10.1016/j.still.2016.01.008

Richards, L. A. Diagnosis and improvement of saline and alkali soils. Washington: USDA, 1954. 60p. Handbook, 60

Rodolfo Junior, F.; Ribeiro Junior, W. Q.; Ramos, M. L. G.; Rocha, O. C.; Batista, L. M. T.; Silva, F. A. M. da. Produtividade e qualidade de variedades de cana-de-açúcar de terceira soca sob regime hídrico variável. Nativa, v.4, p.36-43, 2016. http://dx.doi.org/10.14583/2318-7670.v04n01a08

Sá, C. S. B. de; Shiosaki, R. K.; Santos, A. M. dos; Campos, M. A. da S. Salinization causes abrupt reduction in soil nematode abundance in the Caatinga area of the Submedio San Francisco Valley, Brazilian semiarid region. Pedobiologia - Journal of Soil Ecology, v.85-86, p.1-6, 2021. https://doi.org/10.1016/j.pedobi.2021.150729

Taiz, L.; Zeiger, E.; Moller, I. M.; Murphy, A. Fisiologia e desenvolvimento vegetal. 6.ed. Porto Alegre: ArtMed, 2017. 888p.

Wang, W. Y.; Liu, Y. Q.; Duan, H. R.; Yin, X. X.; Cui, Y. N.; Chai, W. W.; Song, X.; Flowers, T. J., Wang, S. M. SsHKT1;1 is coordinated with SsSOS1 and SsNHX1 to regulate Na^+ homeostasis in Suaeda salsa under saline conditions. Plant Soil, v.449, p.117-131, 2020. https://doi.org/10.1007/s11104-020-04463-x

Yu, S.; Wu, J.; Wang, M.; Shi, W.; Xia, G.; Jia, J.; Kang, Z.; Han, D. Haplotype variations in qtl for salt tolerance in Chinese wheat accessions identifed by marker-based and pedigree-based kinship analyses. Crops Journal, v.8, p.1011-1024, 2020. https://doi.org/10.1016/j.cj.2020.03.007

Yu, X.; Xin, P.; Hong, L. Effect of evaporation on soil salinization caused by ocean surge inundation. Journal of Hydrology, v.597, p.1-14, 2021. https://doi.org/10.1016/j.jhydrol.2021.126200

Zhang, C.; Lia, X.; Kanga, Y.; Wang, X. Salt leaching and response of *Dianthus chinensis* L. to saline water drip irrigation in two coastal saline soils. Agricultural Water Management, v.218, p.8-16, 2019. https://doi.org/10.1016/j.agwat.2019.03.020

Zhang, M. X; Bai, R.; Nan, M.; Ren, W.; Wang, C.; Shabala, S.; Zhang, J. Evaluation of salt tolerance of oat cultivars and the mechanism of adaptation to salinity. Journal of Plant Physiology, v.273, p.1-14, 2022. https://doi.org/10.1016/j.jplph.2022.153708