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Nutrients in 'Gigante' forage cactus pear under different saline water irrigation depths and planting densities[1]

Nutrientes em palma forrageira 'Gigante' sob diferentes lâminas de irrigação com água salina e densidades de plantio

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HIGHLIGHTS:
Irrigation with saline water improves the nutritional status of forage cactus pear.
Planting densities interfere with nutrient concentrations in cladode tissues of forage cactus pear.
Cl^- input by saline water demands attention with electrical conductivity and potassium source.

ABSTRACT: Climate variability tends to increase the occurrence of extreme drought conditions in semi-arid regions, thereby compromising crop yield, including that of drought-tolerant plants such as forage cactus pear. Irrigation of cactus with saline water has enabled good results, and its combination with changes in planting densities may promote changes in the production response of this crop. A field experiment spanning two crop cycles was carried out to evaluate nutrient concentrations in 'Gigante' forage cactus pear (*Opuntia ficus-indica* Mill) under different saline water irrigation depths and planting densities. A randomized block design was used with treatments arranged in split-split plots. Two irrigation intervals (7 and 14 days) were assigned to plots, four planting densities (20,000; 40,000; 60,000 and 80,000 plants ha^{-1}) to subplots, and four irrigation depths of saline water of electrical conductivity 2.91 dS m^{-1} (0, 11, 22 and 33% of reference evapotranspiration) to sub-subplots. The irrigation depths were applied only in the period of the year without rain. Intermediate planting densities (43,002 and 54,687 plants ha^{-1}) promote lower P, Ca and Fe concentrations in cladode tissues of forage cactus pear. Irrigating 'Gigante' cactus forage with saline water up to 33% ETo increases the concentrations of N, P, Ca, Mg, B, Cu, Mn and Zn in cladode tissues. Irrigation levels between 16 and 25% of ETo with saline water resulted in the highest concentrations of K, S and Na.

Key words: *Opuntia ficus-indica* Mill, semi-arid region, water stress, nutritional status

RESUMO: Variações climáticas tendem a aumentar a ocorrência de condições extremas de seca em ambientes semiáridos e isso pode comprometer o rendimento mesmo de culturas tolerantes como palma forrageira. A irrigação da palma com água salina têm possibilitado bons resultados, e sua combinação com modificações nas densidades de plantio pode refletir em mudanças na resposta produtiva da cultura. Um experimento de campo em dois ciclos de cultivo foi realizado para avaliar as concentrações de nutrientes em palma forrageira 'Gigante' (*Opuntia ficus-indica* Mill) irrigada sob diferentes laminas de água salina e densidades de plantio. O delineamento experimental foi em blocos casualizados em esquema de parcelas subsubdivididas, sendo alocados nas parcelas dois turnos de rega (7 e 14 dias), nas subparcelas quatro densidades de plantio (20.000; 40.000; 60.000 e 80.000 plantas ha^{-1}) e nas subsubparcelas quatro lâminas de irrigação com água salina de condutividade elétrica de 2,91 dS m^{-1} (0, 11, 22 e 33% da evapotranspiração de referência - ETo). As lâminas de irrigação foram aplicadas somente no período do ano sem chuva. Densidades de plantio intermediárias (43.002 e 54.687 plantas ha^{-1}) promovem menores concentrações de P, Ca e Fe nos tecidos dos cladódios de palma forrageira 'Gigante'. Irrigação de palma forrageira 'Gigante' com água salina até a lâmina 33% da ETo, possibilita aumento das concentrações de N, P, Ca, Mg, B, Cu, Mn e Zn nos tecidos dos cladódios. Lâminas de irrigação entre 16 e 25% da ETo com água salina, promove máximas concentrações de K, S e Na.

Palavras-chave: *Opuntia fícus-indica* Mill, região semiárida, estresse hídrico, estado nutricional

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Introduction

The ability to produce forage under adverse conditions has drawn attention to cactus pear (*Opuntia ficus-indica* Mill). This crop has been studied in several places worldwide for potential uses, including livestock feed (Mayer & Cushman, 2019), human consumption (Barba et al., 2020), bioenergy production (Owen et al., 2015), combating desertification (Nefzaoui et al., 2014), and pharmaceutical products (Ammar et al., 2018).

As semi-arid regions constrain crop production and climate variability tends to increase extreme drought conditions, yields of cactus pear may be lower than its yield potential. To overcome it, adopting crop practices, such as irrigation, plays a major role in improving yields.

Climate change is expected to reduce fresh water availability for irrigation in arid and semi-arid regions around the world (Connor et al., 2012). Therefore, using low-quality water, such as saline water, in crop production systems assumes great importance. Positive yield responses of 'Orelha de Elefante Mexicana' and 'Gigante' forage cactus pear irrigated with water having EC of 2.5 and 3.6 dS m^{-1} have been reported, indicating the absence of negative effects of salinity on the crop (Diniz et al., 2017; Fonseca et al., 2019).

Studies on planting densities indicate increases in yield of forage cactus pear (Silva et al., 2014; Fonseca et al., 2020); however, little research has been conducted on combining irrigation scheduling and planting densities.

Information about nutrient concentrations gives insight into the nutritional status of plants under different managements, especially for cactus pear, as this crop takes up a greater amount of nutrients from the soil (Silva et al., 2016; Donato et al., 2017a; Lédo et al., 2021). Besides, increasing plant population densities increases competition for nutrients (Novais & Mello, 2007), but irrigation may reduce competition due to the greater yield response capacity of the crop when more soil water is available (Fonseca et al., 2019).

Therefore, this study evaluated nutrient concentrations in 'Gigante' forage cactus pear under irrigation with saline water and plant population densities under semi-arid conditions.

Material and Methods

A field experiment spanning two crop cycles was conducted in an experimental area of the Instituto Federal Baiano, campus Guanambi, located in Southwestern Bahia state, Brazil (14° 13' 30" S and 42° 46' 53" W, and altitude of 525 m). Mean annual rainfall and temperature are 664 mm and 26 °C, respectively. The experiment was carried out from September 2017 to October 2019.

The soil of the experimental area is an Oxisol. Before planting, soil samples were collected in the experimental area, which included two areas with different land-use histories. One of them was previously cultivated with irrigated forage cactus pear and the other had never been cultivated. In each area, soil samples were randomly collected at 0-0.20 m depth for chemical testing and textural classification (Table 1).

Despite the different land-use histories, the fertility of both areas is comparable (Donato et al., 2017c), which justifies the use of the same management strategy. The higher salinity found in the area with prior cultivation is because the previous cactus pear crop was irrigated with saline water, which, together with chemical fertilization, added salts to the soil.

Table 1. Chemical attributes and textural class of soil of the experimental area before planting

Properties	Unit	Area	
		With prior cultivation	Without cultivation
pH (H_2O)		7.5	7.5
SOM[1]	dag kg^{-1}	0.8	0.5
P	mg dm^{-3}	50.1	74.3
K^+	mg dm^{-3}	183	140
Na^+	$cmol_c$ dm^{-3}	0.1	0.1
Ca^{2+}	$cmol_c$ dm^{-3}	1.7	1.3
Mg^{2+}	$cmol_c$ dm^{-3}	0.8	0.3
Al^{3+}	$cmol_c$ dm^{-3}	0	0
H + Al	$cmol_c$ dm^{-3}	1.4	1.4
S.B.[2]	$cmol_c$ dm^{-3}	3.1	2.1
ECEC[3]	$cmol_c$ dm^{-3}	3.1	2.1
CEC[4]	$cmol_c$ dm^{-3}	4.5	3.5
V[5]	%	70	60
B	mg dm^{-3}	0.5	0.3
Cu	mg dm^{-3}	0.3	1
Fe	mg dm^{-3}	42.6	20.8
Mn	mg dm^{-3}	58.8	53
Zn	mg dm^{-3}	4.8	0.9
Prem	mg L^{-1}	42.4	37.4
EC[6]	dS m^{-1}	1.9	0.9
ESP[7]	%	2.22	2.94
Textural class		Sandy clay loam	

[1]Soil organic matter; [2]Sum of bases; [3]Effective cation exchange capacity; [4]Cation exchange capacity at pH 7.0; [5]Base saturation; [6]Electrical conductivity; [7]Exchangeable sodium percentage

The soil in the experimental area has, at tensions 10 and 1,500 kPa, moisture values of 0.253 and 0.125 and m^3 m^{-3}, respectively, which correspond to the field capacity and permanent wilting point.

Over the experimental period, the meteorological variables were collected in an automatic weather station installed near the experimental area (Figure 1).

A randomized block design was used, with treatments arranged in split-split plots. Two irrigation intervals (7 and 14 days) were assigned to plots, four planting densities (20,000; 40,000; 60,000 and 80,000 plants ha^{-1}) to subplots, and four irrigation levels (0, 11, 22, and 33% of ETo) to sub-subplots, for a total of 32 treatments replicated three times, that is, 96 experimental units. Irrigation intervals and planting densities were choosen based on the studies of Fonseca et al. (2019) and Fonseca et al. (2020), respectively.

The irrigation depths were applied only in the period of the year without rain in the two production cycles. Irrigation scheduling was based on reference evapotranspiration (ETo) data provided by a weather station. Evapotranspiration was calculated using the Penman-Monteith method. Irrigation time for each treatment was determined using an equation for continuous wet strip (Santos & Brito, 2016). The irrigation system consisted of PVC main and manifold lines with a diameter of 50 mm. Lateral lines measuring 16 mm in diameter had in-line labyrinth drip emitters with flow rate of 2.4 L h^{-1} and spaced 0.30 m apart.

Irrigation water came from a tubular well and its chemical characteristics and classification are shown in Table 2.

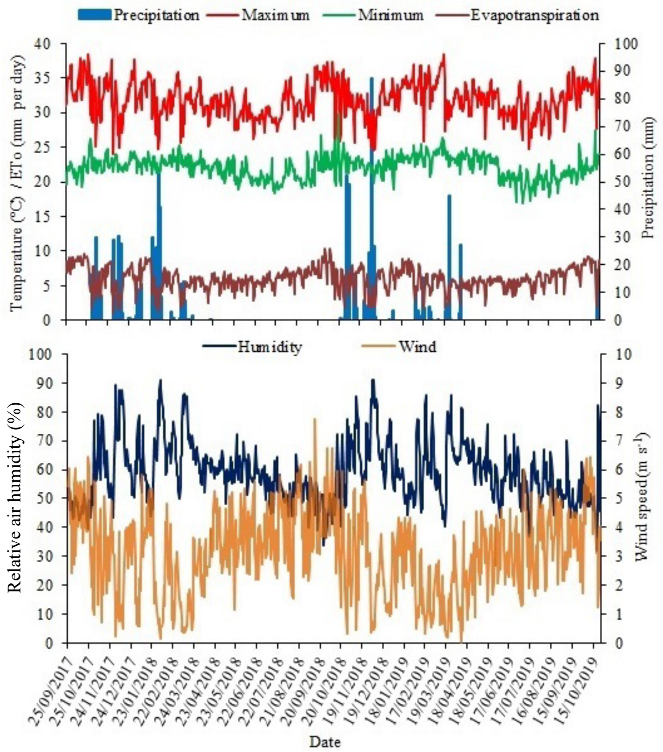


Figure 1. Data on maximum and minimum temperatures, reference evapotranspiration, precipitation (A), relative humidity of air, and wind speed collected (B) during the experiment

Table 2. Chemical characteristics and classification of the water used in the experiment

Characteristics	Unit	Value	Unit	Value
pH	-	6.30		
Electrical conductivity (EC)	dS m^{-1}	2.91		
Calcium (Ca^{++})	$mmol_c L^{-1}$	15.83	mg L^{-1}	322.93
Magnesium (Mg^{++})	$mmol_c L^{-1}$	9.13	mg L^{-1}	111.02
Potassium (K^+)	$mmol_c L^{-1}$	0.28	mg L^{-1}	10.95
Sodium (Na^+)	$mmol_c L^{-1}$	8.26	mg L^{-1}	189.90
Carbonate (CO_3^{2-})	$mmol_c L^{-1}$	0.00	mg L^{-1}	0.00
Bicarbonate (HCO_3^-)	$mmol_c L^{-1}$	5.20	mg L^{-1}	317.25
Chloride (Cl^-)	$mmol_c L^{-1}$	26.40	mg L^{-1}	942.44
SAR	$(mmol_c L^{-1})^{1/2}$	2.34		
HCO_3^-/Ca^{++}		0.33		
Ca^0	$mmol_c L^{-1}$	4.76		
SAR^0	$(mmol_c L^{-1})^{1/2}$	3.13		
SAR ≤ 18.87 - 4.44 log ECw	$(mmol_c L^{-1})^{1/2}$	16.82		
Classification[1]	-	C4S1 (high salinity)		

[1] Classification of Richards (1954)

Table 3. Amounts of elements supplied by each irrigation level and irrigation interval

Irrigation levels	Irrigation interval	Ca^{++}	Mg^{++}	K^+	Na^+	HCO_3^-	Cl^-
				1st crop cycle (kg ha^{-1})			
11% of ETo	7	445.53	153.17	15.10	261.99	437.69	1.290.45
22% of ETo	7	891.06	306.34	30.21	523.98	875.39	2.580.90
33% of ETo	7	1.336.59	459.51	45.31	785.97	1.313.08	3.871.35
11% of ETo	14	458.01	157.46	15.53	269.33	449.95	1.326.59
22% of ETo	14	916.02	314.92	31.05	538.66	899.90	2.653.18
33% of ETo	14	1.374.02	472.38	46.58	807.98	1.349.86	3.979.77
				2nd crop cycle (kg ha^{-1})			
11% of ETo	7	485.22	166.81	16.45	285.33	476.68	1.405.41
22% of ETo	7	970.44	333.63	32.90	570.66	953.37	2.810.81
33% of ETo	7	1.455.66	500.44	49.35	855.99	1.430.05	4.216.22
11% of ETo	14	472.62	162.48	16.02	277.92	464.30	1.368.90
22% of ETo	14	945.23	324.96	32.05	555.83	928.61	2.737.80
33% of ETo	14	1.417.85	487.44	48.07	833.75	1.392.91	4.106.70

The water is classified as C4S1 according to the Richards' classification (Richards, 1954).

Based on water test results, the amounts of elements supplied by each irrigation level and interval between irrigation events were determined (Table 3).

Cladodes of forage cactus pear, cultivar Gigante, were planted between September 25 and October 1, 2017. The area was plowed and harrowed in order to improve the physical properties of the soil for planting. The cladodes, collected from healthy plants, were planted in 0.20-m-deep furrows.

Plants were arranged in a triple-row pattern spaced 3 m apart to allow mechanization, while the single rows composing the triple rows were spaced 1 m apart. The spacings between plants within the row were 0.30, 0.15, 0.10 and 0.075 m, corresponding to the planting densities of 20,000, 40,000, 60,000 and 80,000 plants ha^{-1}, respectively.

Each experimental unit consisted of three 5.5-m-long rows of plants. Observational plants were those located in the three 3.5-m-long central rows (17.5 m^2.)

Fertilization was based on the recommendation proposed by Donato et al. (2017c) for cactus pear. Basal application consisted of 30 Mg ha^{-1} of cattle manure and 150 kg ha^{-1} of P_2O_5 as single superphosphate. Top dressing was carried out with 300 kg ha^{-1} of K_2O split into two applications at 70 and 120 days after planting. After harvesting the first cycle and beginning of the second, 60 Mg ha^{-1} of cattle manure and 300 kg ha^{-1} of K_2O were applied, the latter split in two.

The manure used (Donato et al., 2017a) had the following composition: OM = 67.73 dag kg^{-1}, ash = 36.27 dag kg^{-1}, total carbon = 29.98 dag kg^{-1} and pH = 7.42, moisture on dry basis (d.b.) at 65 °C = 16.72%; macronutrient contents: Ca, Mg, K, N and S = 1.7, 0.2, 2.5, 5.2 and 2.3 g kg^{-1} (EPA 3051/APHA 3120B), in this order, P = 4.7 g kg^{-1} (APHA 4500-CP); micronutrient contents (EPA 3051/APHA 3120B): B, Cu, Zn, Mn and Fe = 2.1, 45.2, 200.5, 391.8 and 1,932.4 mg kg^{-1}, respectively; and density = 0.38 g cm^{-3} (Brasil, 2014).

All crop practices were carried out to provide ideal conditions for the development of the crop. Weeds were removed with a hoe between the rows of plants within the triple row and with a tractor-mounted rotary hoe between the triple rows.

Irrigation started 205 days after planting (DAP), corresponding to the region's rainy season and the period necessary for the establishment of the crop. Evaluations of the first cycle were performed at 386 DAP, right before the rainy season, which corresponded to the end of the cycle. At the end of the evaluations of the first cycle, irrigation was suspended for 196 days due to rains during this period. After the wet season, irrigation was resumed. Evaluations in the second cycle were carried out 368 days after the harvest of the first cycle.

At the end of each cycle, the nutrient concentrations in the tissues of forage cactus cladodes were evaluated. To determine the nutrient concentrations, tissue samples were collected from cladodes at different positions in the plant. Tissue samples were collected from cladodes using a hole saw (5.00 cm in diameter and 4.00 cm in depth) in a battery-powered drill (Silva et al., 2016; Donato et al., 2017a).

After collection, the samples were sent to the Soil and Plant Tissue Laboratory of the Agricultural Research Corporation of Minas Gerais – EPAMIG Norte – for analysis. The following nutrient concentrations were determined: N, P, K, S, Ca and Mg expressed in g kg^{-1}; and B, Fe, Mn, Zn, Cu, and Na expressed in mg kg^{-1}. Analytical determinations followed the methodologies recommended by Malavolta et al. (1997): N, sulfuric digestion with the Kjeldahl method; P, K, S, Ca, Mg, Cu, Fe, Mn, Zn and Na, nitric-perchloric digestion; and B, dry digestion. Sodium (Na) is a micronutrient for plants having the crassulacean acid metabolism, such as forage cactus pear, as the mechanism requires the nutrient (Broadley et al., 2012).

At the end of each cycle, soil samples were collected to verify how irrigation with high-salinity water affected soil salinity (Table 4). The samples were randomly collected for each treatment, at depths of 0-0.20 and 0.20-0.40 m, and a distance of 20 cm from the row of plants, and sent to the EPAMIG Norte laboratory for testing, according to the method described by Richards (1954).

Data were tested for normality and by analysis of variance at a 0.05 significance level for type I error. Significant interactions were studied. Regression models were fitted to the single effect of irrigation level and planting density. Models were chosen based on the significance of the beta coefficient of t-test and mean square of regression, coefficient of determination, and how well the model fitted to the observed data. Statistical analysis was carried out with the statistical software 'R' (R Development Core Team, 2012).

Table 4. Electrical conductivity of saturated soil paste extract following application of saline water in the first and second crop cycle

Irrigation levels	Electrical conductivity (dS m^{-1})			
	1st cycle		2nd cycle	
	0-0.20 m	0.20-0.40 m	0-0.20 m	0.20-0.40 m
0% of ETo	2.24	1.45	1.27	0.91
11% of ETo	2.94	1.68	2.48	1.69
22% of ETo	3.03	1.59	2.24	1.64
33% of ETo	2.08	1.39	1.87	2.13

Results and Discussion

The interaction between planting densities and irrigation intervals was significant ($p \leq 0.01$) for cladode P concentrations in the first cycle and significant ($p \leq 0.05$) for Fe concentrations in the first cycle and Ca concentrations in the second cycle. In the first cycle, cladode Na concentrations varied with the interaction between irrigation levels and irrigation intervals ($p \leq 0.01$).

No effect of interactions was observed on the concentrations of other nutrients ($p > 0.05$). Irrigation intervals had no independent effect on cladode content of any nutrient ($p > 0.05$). No models could be fitted to the independent effect of planting density on cladode nutrient levels in the first and second cycles.

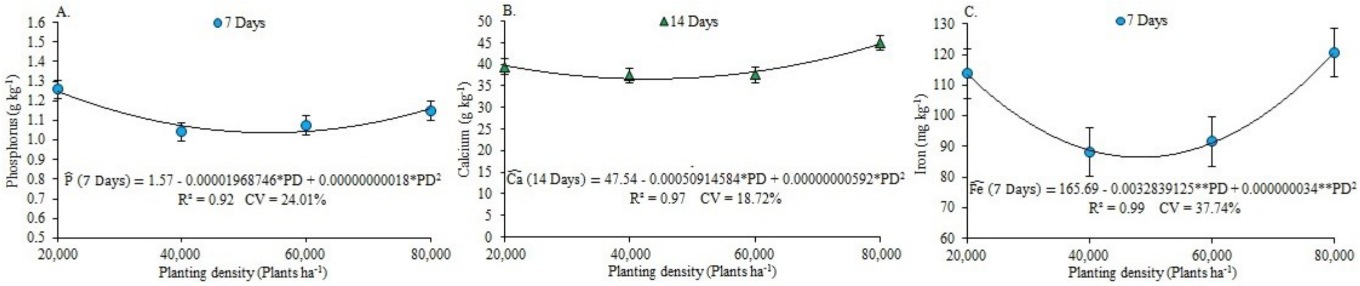
A quadratic model was fitted to cladode P concentrations in the first cycle as affected by a 7 days irrigation interval and planting densities (Figure 2A). The lowest cladode P content at a 7 days interval (1.03 g kg^{-1}) was estimated at a planting density of 54,687 plants ha^{-1}; from this density on, P concentrations kept on increasing until reaching an 11.18% increase at the highest density (80,000 plants ha^{-1}). For the irrigation interval of 14 days in the first cycle, there was no adjustment of regression models for P concentration as a function of planting densities, attested by the non-significance of the regression coefficients (P 14 Days = 0.76 + 2E-05^{ns}PD - 2E-10^{ns}PD^2; R^2 = 0.49).

In the second cycle for 7 days irrigation interval, there was no adjustment of regression models for Ca concentrations as a function of planting densities, attested by the non-significance of the regression coefficients (Ca 7 Days = 46.92 – 0.0002^{ns}PD + 2E-09^{ns}PD$^{2;}$ R^2 = 0.43). A quadratic model was fitted to cladode Ca concentrations as affected by a 14 days irrigation interval and planting densities (Figure 2B). The lowest Ca content (36.59 g kg^{-1}) when using a 14 days irrigation interval was estimated at the planting density of 43,002 plants ha^{-1}, increasing by 22.15% at the highest density (80,000 plants ha^{-1}).

In the first cycle, a quadratic model was fitted to the effect of 7 days irrigation interval combined with planting densities on cladode Fe concentrations (Figure 2C). The lowest Fe content (86.40 mg kg^{-1}) was estimated at the planting density of 48,293 plants ha^{-1}, and from this density on, Fe concentrations increased by 39.56% at the highest density (80,000 plants ha^{-1}). For the irrigation interval of 14 days in the first cycle, there was no adjustment of regression models for Fe concentrations as a function of planting densities, attested by the non-significance of the regression coefficients (Fe 14 Days = 88.30 + 0.7083^{ns}PD – 0.0073^{ns}PD^2; R^2 = 0.15).

The decrease in cladode tissue concentrations of P, Ca and Fe in plants at intermediate densities and subsequent increase at the highest plant density may be yield dependent. Yields peaked at densities between 60,000 and 70,000 plants ha^{-1}, thus a higher number of cladodes increases the dilution of nutrients and, in turn, tissue nutrient content decreases. By increasing the plant population density to 80,000 plants ha^{-1}, plant size and yield per plant decrease, which leads to a higher concentration of nutrients in the cladodes. Cavalcante et al. (2014) report that reducing the number of cladodes per plant as planting density increases results in a higher content of nutrients per cladode of forage cactus pear, and this indicates that the concentration of nutrients in the cladode tissue is higher when there is a lower number of cladodes per plant.

In the first cycle, cladode P levels differed between irrigation intervals at planting densities of 20,000 and 40,000 plants ha^{-1} (Table 5). At the density of 20,000 plants ha^{-1}, the highest P



** - Significant at $p \leq 0.01$ and * - Significant at $p \leq 0.05$ by the t test

Figure 2. Cladode concentrations of P in the first cycle (A), Ca in the second cycle (B), and Fe in the first cycle (C) for 'Gigante' forage cactus pear as a function of planting density

content (1.26 g kg^{-1}) was obtained with a 7 days interval and was about 16.67% higher than the lowest content (1.08 g kg^{-1}), recorded with 14 days interval. At a density of 40,000 plants ha^{-1}, the highest P content (1.42 g kg^{-1}) was obtained with 14 days interval, which was 36.54% higher than that of the lowest content (1.04 g kg^{-1}) observed for 7 days irrigation interval. The higher P concentration in cladodes at 14 days irrigation interval and density of 40,000 plants ha^{-1} might be associated with the greater effect of competition among plants for nutrients compared to the density of 20,000 plants ha^{-1}. The competition combined with partial dryness of the soil caused by the longer time between irrigation events stimulates root growth, promoting increased absorption of water and nutrients, improving soil P uptake. As diffusion is the main transport mechanism of P in the soil and depends on its concentration gradient and distance from roots (Novais & Mello, 2007), a larger root system contributed to the exploration of greater soil volume and, consequently, to greater P uptake, which can be verified by the element concentration in cladode tissues.

Cladode Ca concentrations in the second cycle differed between the irrigation intervals at planting densities of 20,000, 60,000 and 80,000 plants ha^{-1} (Table 5). At 20,000 and 60,000 plants ha^{-1}, the highest cladode levels of Ca (43.97 and 41.90 g kg^{-1}), recorded at 7 days irrigation interval, were 11.40 and 11.55% higher than the lowest levels (39.47 and 37.56 g kg^{-1}) recorded at 14 days interval, respectively. At 80,000 plants ha^{-1}, Ca content (44.96 g kg^{-1}) was highest at 14 days interval, 14.93% greater than the lowest content (39.12 g kg^{-1}) recorded at 7 days irrigation interval. As mentioned, the root system grew due to the stimulus of the longest dry period of the soil between irrigation events (14 days) together with the effect of plant competition at the plant population of 80,000 plants ha^{-1}, which enabled greater soil exploration and better nutrition of plants with Ca.

The greater demand for nutrients promoted by the competition among plants at higher planting densities caused plants to expand their root system to explore larger volumes of soil, increasing nutrient uptake. Hassan et al. (2020), in a study on the effect of soil volume availability on root growth of *Opuntia ficus-indica*, found that restrictions on soil volume increase growth of thin lateral roots, which suggests an adaptive strategy to allow plants to support and increase root surface area, thereby improving the use of nutritional resources.

Cladode Fe concentrations in the first cycle were affected by irrigation intervals at planting densities of 20,000, 40,000 and 80,000 plants ha^{-1} (Table 5). At 20,000 and 80,000 plants ha^{-1}, the highest levels of Fe (113.79 and 120.52 mg kg^{-1}), respectively, were obtained at 7 days irrigation interval, with increases of 18.08 and 18.95% compared to the lowest levels (96.37 and 101.32 mg kg^{-1}) obtained at 14 days interval. At a density of 40,000 plants ha^{-1}, the highest Fe content (114.46 mg kg^{-1}) was obtained at 14 days interval and had an increase of 29.70% in comparison with the lowest value (88.25 mg kg^{-1}) obtained at 7 days irrigation interval.

Despite the variations in the levels of P, Ca and Fe in cladode tissues as affected by planting densities and irrigation intervals, plants showed no deficiency symptoms for these nutrients. Phosphorus and Fe concentrations remained within a satisfactory range and those of Ca remained within a range considered good or very good, according to nutrient concentration ranges established by the sufficiency range technique for 'Gigante' forage cactus pear under semi-arid conditions (Alves et al., 2019a, 2019b).

In the second cycle, there was no adjustment of regression models for the N concentrations as a function of irrigation levels, attested by the non-significance of the regression coefficients (N 2nd Cycle = 13.214 – 0.023^{ns}IL; R^2 = 0.42).

In the first cycle, the levels of N, P, Ca, and Mg varied in an increasing linear fashion as irrigation levels increased (Figures 3A, B, D and E). The models estimate increments of 1.02, 0.20, 7.32 and 1.87 g kg^{-1} in N, P, Ca, and Mg concentrations

Table 5. Mean values of phosphorus and calcium (g kg^{-1}) and iron (mg kg^{-1}) concentrations in the cladode tissue of 'Gigante' cactus pear as a function of irrigation intervals and planting densities

Nutrient	Irrigation interval (days)	Planting density (plants ha^{-1})				CV (%)
		20,000	40,000	60,000	80,000	
P (1st cycle)	7	1.26 a	1.04 b	1.07 a	1.15 a	24.01
	14	1.08 b	1.42 a	1.18 a	1.17 a	
Ca (2nd cycle)	7	43.97 a	38.66 a	41.90 a	39.12 b	18.72
	14	39.47 b	37.40 a	37.56 b	44.96 a	
Fe (1st cycle)	7	113.79 a	88.25 b	91.63 a	120.52 a	37.74
	14	96.37 b	114.46 a	94.94 a	101.32 b	

Means followed by different letters in the column differ by F test at $p \leq 0.05$; CV - Coefficient of variation in cladode tissues for each 11% increase in ETo, respectively, and these nutrient levels increase by 25.26, 69.10, 70.47 and 43.74%, respectively, when the rainfed condition is compared to the largest irrigation level (33% of ETo).

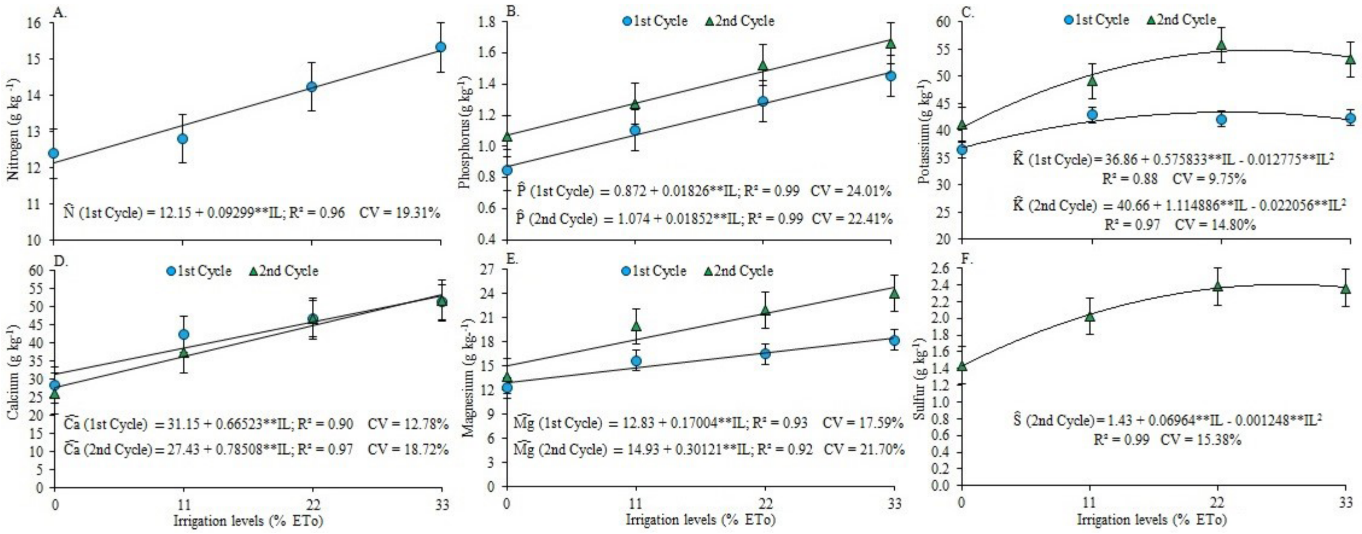
In the second cycle, an increasing linear model was fitted to the effect of irrigation levels on cladode concentrations of P, Ca, and Mg (Figures 3B, D and E). The model estimates increments of 0.20, 8.64, and 3.31 g kg^{-1}, respectively, in the levels of P, Ca, and Mg in cladode tissues, for each 11% increase in ETo and increases of 56.91, 94.45, and 66.58% from the rainfed treatment to the largest irrigation level (33% of ETo).

For both crop cycles, a quadratic model was fitted to the response of cladode K content to irrigation levels (Figure 3C). The highest K concentrations, 43.35 and 54.75 g kg^{-1}, recorded in the first and second cycles, respectively, were obtained under 23 and 25% of ETo, which represent increases of 17.60 and 34.65% when compared to those recorded in the treatment without irrigation. The highest levels of K in cladodes of irrigated forage cactus pear might be the result of an improved mineral nutrient flow in the soil with greater moisture, enhancing nutrient uptake by roots (Novais & Mello, 2007).

In the first cycle, there was no adjustment of regression models for the S concentrations as a function of irrigation levels, attested by the non-significance of the regression coefficients (S 1st Cycle = $1.50 + 0.0341^{ns}IL - 0.0009^{ns}IL^2$; $R^2 = 0.43$).

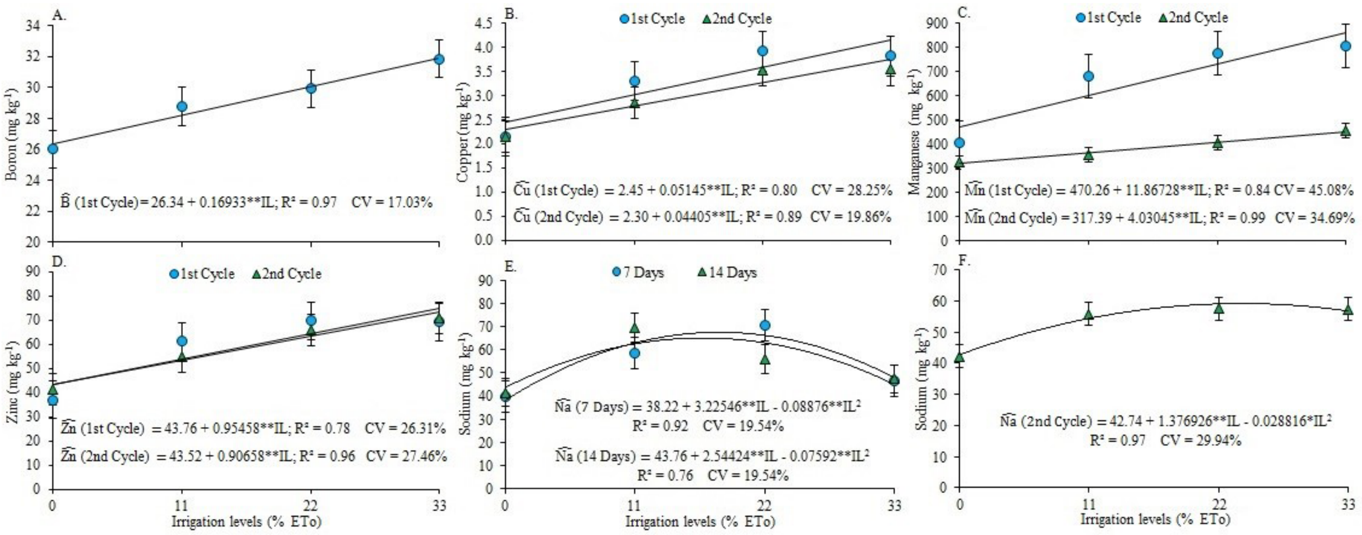
In the second cycle, cladode S concentrations changed in a quadratic fashion as a function of irrigation levels (Figure 3F). The highest content of S (2.40 g kg^{-1}) was obtained under 28% ETo irrigation level, which represented an increase of 67.94% in comparison with that recorded for the rainfed treatment.

In the first cycle, an increasing linear model was fitted to the effect of irrigation levels on cladode concentrations of B, Cu, Mn, and Zn (Figures 4A, B, C and D). The model estimates increments of 1.86, 0.57, 130.54, and 10.50 mg kg^{-1} in cladode tissue concentrations of B, Cu, Mn, and Zn for each 11% increase in ETo, respectively. In comparing the rainfed condition to plants under the largest irrigation level (33%



** - Significant at p ≤ 0.01 and * - Significant at p ≤ 0.05 by the t test

Figure 3. Concentrations of N (A), P (B), K (C), Ca (D), Mg (E), and S (F) in cladode tissues of 'Gigante' cactus pear as a function of irrigation levels



** - Significant at p ≤ 0.01 and * - Significant at p ≤ 0.05 by the t test

Figure 4. Concentrations of B (A), Cu (B), Mn (C), Zn (D), and Na (E) for the first cycle and Na for the second cycle (F) in cladodes of 'Gigante' cactus pear as a function of irrigation levels

ETo), the model estimates increases of 21.21, 69.30, 83.28, and 71.99% for B, Cu, Mn, and Zn, respectively.

In the second cycle, there was no adjustment of regression models for the B concentrations as a function of irrigation levels, attested by the non-significance of the regression coefficients (B 2nd Cycle = 25.087 + 0.1075^{ns}IL; R^2 = 0.42).

In the second cycle, an increasing linear model was fitted to the response of Cu, Mn, and Zn concentrations to irrigation levels (Figures 4B, C, and D). The model allows estimation of increments of 0.48, 44.33, and 9.97 mg kg^{-1} in the cladode concentrations of Cu, Mn, and Zn for each 11% increase in ETo and increases of 63.20, 41.91, and 69.74% when comparing the rainfed treatment to that under the largest irrigation level (33% of ETo).

In the first cycle, quadratic models were fitted to the responses of Na concentrations to irrigation levels at 7 and 14 days irrigation intervals (Figure 4E). The highest Na values, 67.52 and 65.08 mg kg^{-1}, at 7 and 14 days irrigation intervals were obtained with the application of 18 and 17% of ETo, which allowed increases of 76.67 and 48.71% compared to those observed in rainfed treatments, respectively.

Cladode Na concentrations in the first cycle differed between irrigation intervals at 11 and 22% ETo (Figure 4E). At 11% ETo level, the highest Na content (69.52 mg kg^{-1}) was obtained with 14 days irrigation interval and showed an increase of 18.76% in comparison with the lowest content (58.54 mg kg^{-1}) recorded with 7 days interval. At 22% ETo, the highest Na content (70.65 mg kg^{-1}) was observed with 7 days interval and showed an increase of 26.07% compared to the lowest content (56.04 mg kg^{-1}) with 14 days irrigation interval.

In the second cycle, a quadratic model was fitted to Na content as a function of irrigation levels (Figure 4F). The highest Na content, 59.19 mg kg^{-1}, was obtained with the application of 24% ETo irrigation level and allowed an increase of 38.49% when compared to the values obtained in rainfed treatment. The amounts of Na supplied by 33% ETo irrigation level every 14 days in the first and second cycles were, respectively, 807.98 and 833.75 kg ha^{-1} (Table 3). This suggests the need for frequent monitoring of Na levels in the soil cultivated with saline water-irrigated forage cactus pear to avoid environmental impacts because high accumulation of Na in the soil causes soil dispersion, resulting in decreased water infiltration and nutrient flow in the soil.

The increase in levels of N, P, Ca, Mg, B, Cu, Mn, and Zn in cladode as high-salinity irrigation water levels increase is associated with a greater soil water availability, improving soil-root transport (Novais & Mello, 2007) and nutrient uptake by forage cactus pear. The contact of mineral nutrients to root surface enables plant nutrient uptake, and nutrient uptake is directly related to nutrient concentration in the soil solution; therefore, moisture may have the greatest influence on the nutrient transport and absorption (Meurer, 2007).

The effect of soil moisture on plant growth was also reported by Donato et al. (2017b). The authors determined growth curves for 'Gigante' forage cactus pear and verified that rainy periods at initial and final plant development stages improve growth rates due to greater water availability and nutrient flow in the soil. In the present study, the availability of saline water during dry season was essential as it maintains nutrient uptake and stabilizes plant growth. Fonseca et al. (2019) found a positive response of 'Gigante' cactus pear with higher values of plant height, number, length and width of cladodes and cladode area index when applying an irrigation depth of 33% of ETo with saline water (3.6 dS m^{-1}). This result shows the maintenance of plant growth promoted by the improvement in water and nutrient availability in the soil.

Furthermore, water availability positively affects plant root growth, resulting in greater soil exploration and nutrient uptake. Castro et al. (2021), in a study with 'Gigante' and 'Miuda' forage cactus pear under different water replacement levels, verified an increase of 196.88% in the length density of very fine roots (< 0.5 mm) when comparing the treatment without irrigation with the one with the highest level of water replacement (75% of ETo). As very fine roots account for most nutrient absorption, the contribution of greater root growth obtained with increased irrigation depths can be associated with increased nutrient concentration in cladodes.

In addition to the effect of soil moisture, increased Ca and Mg levels in the soil are strongly associated with the supply of these nutrients by high-salinity irrigation water (Table 3). The amounts of Ca and Mg at 33% ETo level at 14 days irrigation interval were 1,374.02 and 472.38 kg ha^{-1} in the first cycle and 1,417.85 and 487.44 kg ha^{-1} in the second cycle, respectively. These values are higher than the export of these nutrients measured in rainfed 'Gigante' forage cactus pear (Silva et al., 2016; Donato et al., 2017a; Lédo et al., 2021).

The highest K levels recorded at intermediate irrigation levels (23 and 25% of ETo) and subsequent reduction until the highest irrigation level (33% of ETo) might be explained by the competitive effect resulted from the increase in the concentrations of Ca and Mg in the soil solution due to saline water irrigation. A study on the effect of Ca/Mg ratio on the nutritional status of soybeans reported that the decrease in K levels is due to the competition between bivalent Ca ions, which increase in the soil solution and plant tissue, and monovalent K ions (Silva et al., 2012). Additionally, the greater irrigation depth may have increased leaching of K to deeper soil layers.

Although the irrigation levels caused nutrient concentrations in cladode tissues to vary considerably, plants showed no deficiency symptoms for any nutrient. According to values established by Alves et al. (2019a, 2019b), N and P concentrations in cladode tissues went up from marginal levels in the absence of irrigation to sufficient levels with irrigation. The levels of K, Ca, and Mg went up from sufficient in rainfed plants to good or very good in irrigated plants. The levels of S and B were sufficient, those of Cu and Na were sufficient or good, and those of Mn and Zn were sufficient, good or very good in irrigated plants.

Saline water application resulted in increases in nutrient concentrations in cladode tissues to higher sufficiency ranges. This indicates that using this type of water in the production system of forage cactus pear can provide plants with good availability of water and nutrients, ensuring growth and yields of this crop. Fonseca et al. (2019) reported no change in the functioning of the photosynthetic apparatus and maintenance of metabolic activities of forage cactus pear plants when irrigated with saline water (3.6 dS m^{-1}), which reinforces the positive results of the use of saline water, including improved nutrition and maintenance of plant growth.

The absence of nutrient deficiencies in cactus pear plants, even without irrigation, shows how well fertilized plants were, as organic and chemical fertilization followed standard recommended rates in the two crop cycles, with applications carried out in the rainy season.

Finally, despite the lack of evaluations on cladode Cl concentrations, it is worth speculating the effect of this element in high-salinity water-irrigated 'Gigante' cactus pear. The amounts of Cl supplied by 33% ETo irrigation level at 14 days irrigation interval in the first and second cycles were, respectively, 3,979.77 and 4,106.70 kg ha^{-1} (Table 3). Soil electrical conductivities in rainfed and irrigated areas (33% ETo) were, respectively, 0.91 and 2.13 dS m^{-1} (Table 4). This indicates that in soils cultivated with forage cactus irrigated with high-salinity water, the K fertilizer source must be potassium sulfate instead of potassium chloride to reduce risks of soil salinization as the former has lower salt index than the latter. It is also suggested to monitor the electrical conductivity of soil continuously.

Conclusions

1. Intermediate planting densities (43,002 and 54,687 plants ha^{-1}) promote lower concentrations of P, Ca, and Fe in cladode tissues of forage cactus pear.

2. Irrigation of 'Gigante' forage cactus pear with saline water (electrical conductivity of 2.91 dS m^{-1}) up to 33% of ETo increases concentrations of N, P, Ca, Mg, B, Cu, Mn, and Zn in cladode tissues.

3. Irrigation levels between 16 and 25% of ETo with saline water result in the highest concentrations of K, S, and Na in cladode tissues.

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