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ROOT DISTRIBUTION, NUTRIENT CONCENTRATION AND ACCUMULATION IN 'GIGANTE' CACTUS PEAR IRRIGATED WITH SALINE WATER[1]

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ABSTRACT - In semiarid regions with greater climatic variability, including prolonged droughts and delayed rainy seasons, supplemental irrigation is critical to ensuring yields of forage cactus pear. The objective was to evaluate root distribution and nutrient concentration and accumulation in 'Gigante' forage cactus pear subjected to different irrigation regimes. Seven irrigation regimes were tested: no irrigation (rainfed); five liters of medium-salinity water, with an electrical conductivity (EC) of 0.75 dS m^{-1}, applied per linear meter every 15 days; 7% reference evapotranspiration (ETo) with a 15-d irrigation interval (II); 15% ETo with a 7-d II; 33% ETo with a 3-d II; 50% ETo with a 2-d II; and 100% ETo, irrigated daily - high-salinity water, EC of 3.6 dS m^{-1}, was used in the last five treatments. The treatments were laid out in a randomized block design with four replicates. Roots developed best in plants irrigated at 50% ETo with a 7-d II. Applying high-salinity water at 15% ETo with a 7-d irrigation interval promotes higher concentrations of P, Ca, Mg and S in cladodes of cactus pear. Applying high-salinity water at 33% ETo with a 3-d II promotes higher uptake/accumulation of P, Ca, Mg, S and Zn in cladodes of 'Gigante' forage cactus pear.

Keywords: *Opuntia ficus-indica*. Salinity. Nutrition.

DISTRIBUIÇÃO RADICULAR, TEOR E EXPORTAÇÃO DE NUTRIENTES EM PALMA FORRAGEIRA 'GIGANTE' IRRIGADA COM ÁGUA SALOBRA

RESUMO - Em regiões semiáridas com maior variabilidade climática, mais eventos de seca e retardo das estações chuvosas, a suplementação hídrica favorece a segurança produtiva do cultivo da palma forrageira. Objetivou-se avaliar a distribuição radicular, o teor e a exportação de nutrientes em palma forrageira 'Gigante' submetida a diferentes condições de aplicação de água. Os tratamentos foram constituídos por sete condições: sem irrigação; cinco litros de água por metro linear a cada 15 dias, com água de condutividade elétrica (CEa) de 0,75 dS m^{-1}; 7% da evapotranspiração de referência (ETo) com turno de rega (TR) de 15 dias; 15% da ETo com TR de sete dias; 33% da ETo com TR de três dias; 50% da ETo com TR de dois dias e 100% da ETo irrigado diariamente, sendo as cinco últimas condições com água de CEa de 3,6 dS m^{-1}, dispostos em delineamento em blocos casualizados, com quatro repetições. O maior desenvolvimento de raízes é obtido na condição de 50% da ETo com TR de dois dias. Aplicação de água com salinidade muito alta, CE 3,6 dS m^{-1}, a 15% da ETo com TR de sete dias proporciona maiores teores dos nutrientes P, Ca, Mg e S nos cladódios de palma. Aplicação de água com salinidade muito alta, CE 3,6 dS m^{-1}, a 33% da ETo com turno de rega de três dias proporciona maiores valores de extração/exportação de P, Ca, Mg, S e Zn nos cladódios de palma forrageira 'Gigante'.

Palavras-chaves: *Opuntia ficus-indica*. Salinidade. Nutrição.

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INTRODUCTION

In the past few years, considerable technological advancements have been made in the cultivation of forage cactus pear (*Opuntia ficus-indica* Mill) by refining farming techniques including organic (DONATO et al., 2017a) and mineral fertilizers (SILVA et al., 2016), planting configuration (LÉDO et al., 2020) and increased crop density (SILVA et al., 2014). Using these techniques not only increases cactus pear productivity, but also improves sustainability of smallholder farms in semiarid regions (DUBEUX JUNIOR et al., 2015).

Morphological and physiological features of forage cactus pear lessen negative effects of drought on crop productivity; however, longer periods of drought may significantly hinder plant growth and yield (PEREIRA et al., 2015). Drought and heat stresses reduce photosynthetic capacity of forage cactus pear (BRITO et al., 2018), which, in turn, leads to an underutilization of available resources to reach the crop's yield potential. Thus, irrigation practices have been studied to address drought-induced losses of productivity of forage cactus pear (QUEIROZ et al., 2015; LIMA et al., 2016).

Supplemental irrigation can be used to alleviate stress factors imposed by the semiarid climate on this crop, particularly in scenarios of increased climate variability (IPCC, 2014), in which drought periods become longer as rainy seasons delay. Furthermore, water scarcity strongly affects semiarid regions around the world, which tends to worsen as agricultural activity needs to increase to meet the demand of a growing population (SOLIZ et al., 2011). Therefore, in these regions, the use of low -quality water for irrigation, e.g. saline water, (AYERS; WESTCOT, 1985), plays an important role in global food security. Fonseca et al. (2019) reported positive physiological, morphological and yield responses of 'Gigante' forage cactus pear to saline water irrigation.

Improved fertilizer application and planting spacing have been shown to increase nutrient uptake and accumulation in cladodes of forage cactus pear (SILVA et al., 2016; DONATO et al., 2017a; LÉDO et al., 2020). However, there is little information on the influence of saline water irrigation on these processes.

Assessing the plant nutritional status is essential in sustaining a balanced nutrient supply to plants, thereby increasing yields while maintaining soil fertility (BLANCO-MACÍAS et al., 2009). Knowing how much nutrient forage crops remove from the soil is critical to enhancing fertilizer application and thus maintaining adequate long-term soil fertility.

Therefore, the objective was to evaluate root distribution, nutrient content, and nutrient uptake/ accumulation of 'Gigante' forage cactus pear under different irrigation regimes.

MATERIAL AND METHODS

A field experiment was carried out from 2014 to 2016 in an experimental area at the Instituto Federal Baiano, campus of Guanambi, southwestern Bahia, Brazil (14°17'27''S, 42°46'53'' W, and altitude of 537 m). Mean annual precipitation is 680 mm and mean annual temperature is 26 °C.

The soil at the study site is Latossolo Vermelho-Amarelo (Oxisol). Before setting up the experiment, soil samples were randomly collected throughout the area, at 0.00-0.20 m and 0.20-0.40 m deep, to chemically and texturally characterize the soil (Table 1).

The experiment lasted from Oct 2014 to Oct 2016. During this period, an automatic weather station installed close to the experimental area measured the following data: maximum temperature, minimum temperature, mean relative humidity, mean wind speed and precipitation (Figure 1).

Seven treatments were tested: no irrigation (rainfed); five liters of medium-salinity water, with an electrical conductivity (EC) of 0.75 dS m^{-1}, applied per linear meter every 15 days; 7% of reference evapotranspiration (ETo) with a 15-d irrigation interval (II); 15% ETo with a 7-d II; 33% ETo with a 3-d II; 50% ETo and 2-d II; and 100% ETo, irrigated daily — high-salinity water, EC of 3.6 dS m^{-1}, was used in the last five treatments. The treatments were laid out in a randomized block design and replicated four times, totaling 28 experimental units. The waters came from tube wells and their chemical characteristics and classification are presented in Table 2.

Each experimental unit consisted of three 8-m -long plant rows. The plants used for measurement were those located on the 4-m-long core of each row (20 m^2).

Cactus pear (*Opuntia ficus-indica* Mill) cv. Gigante was planted on October 23 and 24, 2014. The experiment comprised two production cycles. Prior to planting, the area was conventionally tilled. Cladodes were placed in 20-cm-deep furrows spaced 1.0 m apart and arranged in a triple-row pattern spaced 3.0 m apart. Within the row, plants were 0.14 m away from one another.

Table 1. Soil chemical properties and textural class at the experimental area before planting.

Parameter	Unit	Depth	
		0.00 – 0.20 m	0.20 – 0.40 m
pH (H_2O)		5.7	5.3
P	mg dm^{-3}	23.5	5.8
K^+	mg dm^{-3}	108.0	104.0
Na^+	$cmol_c$ dm^{-3}	0.1	0.1
Ca^{2+}	$cmol_c$ dm^{-3}	1.4	1.2
Mg^{2+}	$cmlo_c$ dm^{-3}	0.6	0.4
Al^{3+}	$cmol_c$ dm^{-3}	0.0	0.0
H+Al	$cmol_c$ dm^{-3}	1.7	1.5
S.B.[1]	$cmol_c$ dm^{-3}	2.4	1.9
ECEC[2]	$cmol_c$ dm^{-3}	2.4	1.9
CEC[3]	$cmol_c$ dm^{-3}	4.1	3.5
V[4]	%	58.0	56.0
B	mg dm^{-3}	0.3	0.2
Cu	mg dm^{-3}	0.4	0.2
Fe	mg dm^{-3}	16.0	17.9
Mn	mg dm^{-3}	32.5	21.8
Zn	mg dm^{-3}	2.1	1.2
EC[5]	dS m^{-1}	0.7	0.8
Textural class		Sandy clay loam	

[1]Sum of bases; [2]effective cation exchange capacity; [3]cation exchange capacity at pH 7.0; [4]base saturation; [5]electrical conductivity.

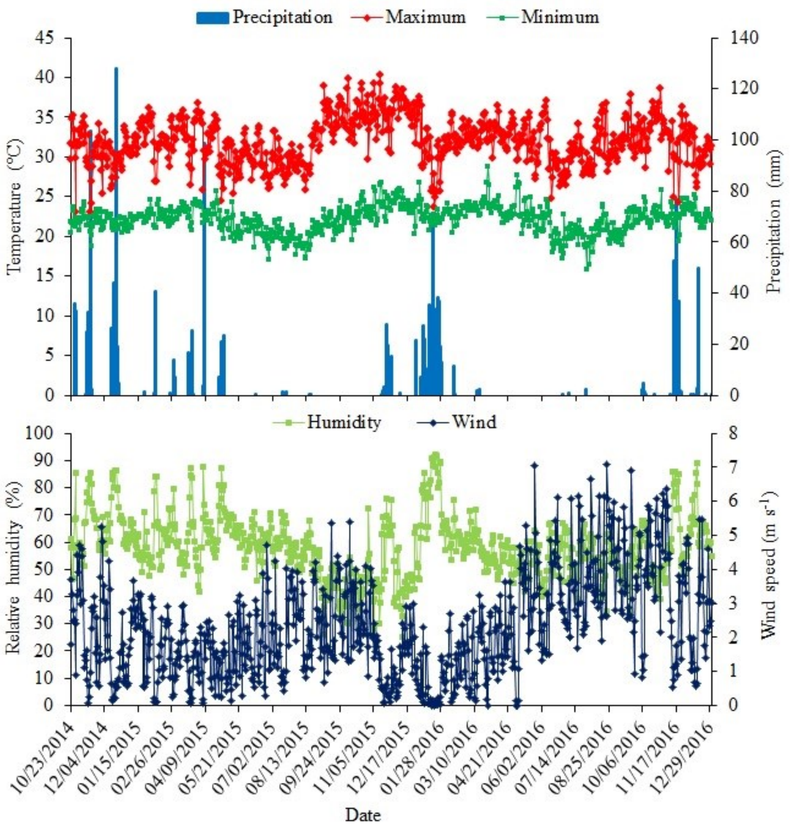


Figure 1. Maximum and minimum temperature, relative humidity, wind speed and precipitation recorded during the experimental period. Data collected from an automatic weather station installed close to the experimental area of the Instituto Federal Baiano.

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

Characteristic	Unit	Well 1	Well 2
pH	-	6.60	6.40
Electrical Conductivity (EC)	dS m^{-1}	0.75	3.60
Calcium (Ca)	mg L^{-1}	3.53	11.90
Magnesium (Mg)	mg L^{-1}	2.23	9.54
Potassium (K)	mg L^{-1}	0.15	0.48
Sodium (Na)	mg L^{-1}	3.48	30.40
Carbonate (CO_3)	mg L^{-1}	0.00	0.00
Bicarbonate (HCO_3)	mg L^{-1}	4.00	4.10
Chloride (Cl)	mg L^{-1}	5.20	34.80
Classification[1]	-	C2S1 (medium salinity)	C4S1 (High salinity)

[1]Ayers and Westcot, 1985.

Irrigations were performed based on daily ETo data recorded by the weather station. Irrigation run times were calculated for each treatment using the equation for a continuous wet strip (SANTOS; BRITO, 2016).

PVC pipes with a 50-cm diameter were used for both main and submain lines. Lateral lines were 16-mm diameter hoses with turbulent-flow in-line emitters that had a discharge rate of 4 L h^{-1} and were spaced 0.5 m apart.

Basal fertilization consisted of 30 Mg ha^{-1} of cattle manure and 150 kg P_2O_5 ha^{-1} using single superphosphate. After planting, 60 Mg ha^{-1} of manure and 300 kg K_2O ha^{-1} were top dressed. Potassium chloride was the source of K_2O and the K rate was split into two applications. This procedure was redone following the harvest of the first cycle into the second cycle. Weed control was performed using hoes.

The application of the treatments began at 266 days after planting (DAP). This period corresponded to the rainy season and to the time needed for the crop to establish. To determine macro - and micronutrient concentrations in cladodes, tissue samples were collected from different locations on the plant at 386 DAP before the upcoming rainy season, when the production cycle ended. After tissue sampling, treatments were suspended for 102 days due to rains occurring during this period. At the beginning of the dry season, treatment application was resumed. Tissue sampling in the second production cycle was performed 230 days after resuming treatment application, at the end of the cycle. Samples were collected using a hole saw (5.00 cm in diameter and 4.00 cm deep) coupled with a cordless drill (SILVA et al., 2016; DONATO et al., 2017a).

Cladode tissue samples were sliced, placed in a forced air oven at 65 °C and kept for 72 h. Then, the dried samples were ground using a Wiley mill with a 1.0-mm-mesh sieve. The ground samples were placed in identifiable plastic bags and taken to a laboratory to determine tissue concentrations of nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg), expressed as g kg^{-1}; and boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and sodium (Na) expressed as mg kg^{-1}. Analytical determinations followed Malavolta, Vitti and Oliveira (1997): N, Kjeldahl digestion method; P, K, S, Ca, Mg, Cu, Fe, Mn, Zn and Na, nitric-per-chloric acid digestion; and B, dry digestion.

Following cladode tissue sampling in each production cycle, cladodes were harvested, leaving behind only the ones used for planting ('mother' cladode). Harvested cladodes were weighed to determine green matter yield (GMY) (Mg ha^{-1}). Dry matter yield (DMY) (Mg ha^{-1}) was determined by multiplying the dry matter content (DM) of plants composing a plot by GMY. The amount of nutrients extracted from the soil, exported and accumulated in the harvested tissues (kg ha^{-1}) was determined using DMY and nutrient concentrations of cladodes.

At the end of each production cycle, soil samples were randomly collected from each plot, at a depth of 0.00-0.20 m and a distance of 0.20 m from plants harvested, to determine the treatment effect on soil chemical properties.

Following the harvest of the second production cycle, roots of three plants per plot were sampled perpendicularly to plant rows. Sampling was conducted from the center of a plant row to the next. Samples were collected at the distances of 0.00, 0.15, 0.30, 0.50, 0.70, 0.85 and 1.00 m from the row and at the depths of 0.00–0.10, 0.10–0.20, 0.20–0.30 and 0.30–0.40 m. Each sample was a 10-cm-high soil core corresponding to a sample volume of 311.725 cm^3 (Vr).

After washing the soil off the roots with water, the roots were scanned into a computer as Tagged Image File Format (TIFF). The images were processed and analyzed using the application Rootedge (KASPAR; EWING, 1997) to determine root length (Lr – cm). Root length density (RLD – cm cm^{-3}) was the product of Lr and Vr.

The analysis of RLD values was based on the following categories: very fine roots (diameter below 0.55 mm), fine roots (diameter between 0.55 and 2.05 mm) and small roots (diameter between 2.05 and 5.05 mm); in addition to total roots, which included all diameters (SANTOS et al., 2014).

Analysis of variance was conducted for cladode nutrient concentrations. The significance level was set at 0.05 for type I error. Similar means were clustered using the Scott-Knott test at 5% significance level.

To test the treatment effect on root distribution, a 7 x 7 x 4 factorial was used: seven irrigation regimes, seven sampling distances and four sampling depths. These were arranged in a randomized block design. Data of RLD were tested by analysis of variance and interactions were analyzed according to their significance; the Scott-Knott test was used for the clustering of the means of irrigation regime, while regression analysis was performed for sampling distance and depth. To select suitable models, we considered the significance of beta coefficients of t-tests, coefficient of determination and how well the model fits the data. All data were analyzed using R statistical computing software (R DEVELOPMENT CORE TEAM, 2012).

RESULTS AND DISCUSSION

Table 3 shows the chemical characteristics of the soil at the end of each production cycle of cactus pear. The main changes were recorded under the condition of greater application of high-salinity water, including increased soil pH, Ca and Mg contents, sum of bases, effective cation exchange capacity, cation exchange capacity at pH 7, base saturation, and electrical conductivity.

Table 3. Chemical properties of the soil cultivated with 'Gigante' forage cactus pear following treatment application in the first and second production cycles.

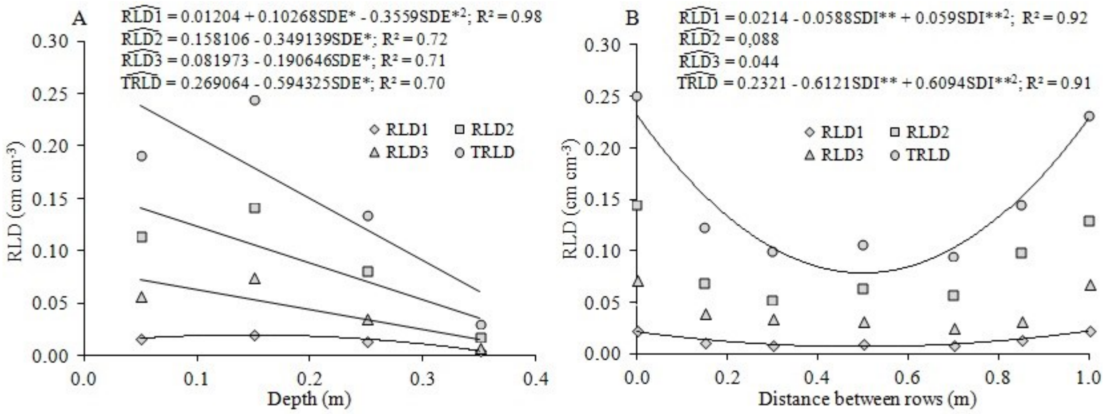
Parameter	Unit	Treatments – 1st production cycle						
		T1	T2	T3	T4	T5	T6	T7
pH (H_2O)	-	5.75	5.83	5.85	5.40	5.98	6.83	7.20
P	mg dm^{-3}	97.45	121.80	50.85	58.15	54.13	120.50	78.87
K^+	mg dm^{-3}	287.00	152.50	92.50	118.50	111.50	83.75	73.50
Na^+	cmol$_c$ dm^{-3}	0.10	0.10	0.10	0.13	0.15	0.10	0.10
Ca^{2+}	cmol$_c$ dm^{-3}	2.10	3.10	2.15	2.05	2.40	3.58	3.35
Mg^{2+}	cmol$_c$ dm^{-3}	1.05	1.38	1.13	1.10	1.53	1.78	1.85
H+Al	cmol$_c$ dm^{-3}	2.50	2.58	2.48	3.75	2.48	1.45	1.68
S.B.[1]	cmol$_c$ dm^{-3}	3.93	4.90	3.60	3.58	4.38	5.65	5.50
ECEC[2]	cmol$_c$ dm^{-3}	3.93	4.90	3.60	3.58	4.38	5.65	5.50
CEC[3]	cmol$_c$ dm^{-3}	6.48	6.73	6.08	7.33	6.85	7.13	7.18
V[4]	%	60.50	66.75	59.00	48.50	63.00	79.00	76.25
B	mg dm^{-3}	0.43	0.38	0.28	0.35	0.28	0.25	0.28
Cu	mg dm^{-3}	0.43	0.58	0.30	0.38	0.45	0.53	0.40
Fe	mg dm^{-3}	18.48	15.30	17.83	25.35	20.35	18.73	18.90
Mn	mg dm^{-3}	73.83	76.55	53.13	52.40	55.30	64.40	64.08
Zn	mg dm^{-3}	4.65	5.78	3.50	3.55	3.35	5.90	4.05
EC[5]	dS m^{-1}	0.93	0.55	2.37	2.65	2.21	1.72	2.52
		Treatments – 2nd production cycle						
pH (H_2O)	-	6.25	6.38	6.63	7.08	7.05	7.10	7.53
P	mg dm^{-3}	92.78	94.15	79.38	89.53	90.88	91.70	80.35
K^+	mg dm^{-3}	232.00	252.50	136.75	145.75	122.50	84.25	87.00
Na^+	cmol$_c$ dm^{-3}	0.10	0.10	0.10	0.10	0.13	0.10	0.10
Ca^{2+}	cmol$_c$ dm^{-3}	1.88	2.08	2.23	2.58	2.95	2.78	3.08
Mg^{2+}	cmol$_c$ dm^{-3}	0.75	0.85	1.08	1.35	1.40	1.30	1.58
H+Al	cmol$_c$ dm^{-3}	1.45	1.60	1.23	1.03	0.98	1.00	0.83
S.B.[1]	cmol$_c$ dm^{-3}	3.30	3.70	3.80	4.43	4.78	4.40	5.00
ECEC[2]	cmol$_c$ dm^{-3}	3.30	3.70	3.80	4.43	4.78	4.40	5.00
CEC[3]	cmol$_c$ dm^{-3}	4.75	5.35	5.03	5.45	5.75	5.43	5.88
V[4]	%	69.50	68.75	74.75	81.50	82.75	80.25	85.25
B	mg dm^{-3}	0.75	0.68	0.65	0.50	0.65	0.50	0.35
Cu	mg dm^{-3}	0.43	0.58	0.40	0.50	0.53	0.68	0.50
Fe	mg dm^{-3}	15.10	13.30	14.33	14.00	16.05	15.33	15.48
Mn	mg dm^{-3}	67.65	69.50	55.53	63.28	71.65	69.33	65.53
Zn	mg dm^{-3}	6.45	8.28	5.65	17.40	11.70	10.55	5.85
EC[5]	dS m^{-1}	1.11	1.07	2.17	2.44	4.63	4.06	3.67

[1]Sum of bases; [2]effective cation exchange capacity; [3]cation exchange capacity at pH 7.0; [4]base saturation; [5]electrical conductivity. T1 – rainfed; T2 – 5 L m^{-1} of water with an electrical conductivity (ECw) of 0.75 dS m^{-1} every 15 days; T3 – 7% ETo with a 15-d irrigation interval (II); T4 – 15% ETo with a 7-d II; T5 – 33% ETo with a 3-d II; T6 – 50% ETo with a 2-d II; and T7 – 100% ETo, irrigated daily; the water used in T3, T4, T5, T6 and T7 had an ECw of 3.6 dS m^{-1}.

Interactions were not significant ($p>0.05$). Within the different root length density (RLD) categories, decreasing linear models were fitted to fine roots, small roots and total roots, while quadratic models were fitted to very fine roots — all of which as a function of increasing sampling depth (Figure 2). The models predict decreases of 0.35, 0.19 and 0.59 cm cm^{-3} in fine, small and total roots for each cm in depth, and, in terms of percentage, reductions of 74.47, 78.85, and 74.49% from the depth of 0.00–0.10 m to 0.30–0.40 m, respectively. For very fine roots, the model estimates the highest RDL as 0.019 cm cm^{-3} at 0.14 m deep.

Among the models tested, no model could be fitted to fine and small roots as a function of sampling distance from the plant row. Quadratic models were fitted to very fine roots and total roots as a function of sampling distance. The models estimate the lowest RLD as 0.0067 cm cm^{-3} for very fine roots and as 0.0784 cm cm^{-3} for total roots, both at 0.50 m from the plant row. These results are consistent because the distance of 0.50 m falls half way between two plant rows, where a lower number of roots are expected, whereas both shorter and longer distances are closer to a plant row, where roots are more numerous.

In a study on root growth of forage cactus pear, clone IPA 20, Edvan et al. (2013) reported a decrease of 89.09% in root biomass from the depth of 0.00-0.10 m to the depth of 0.30-0.40 m and higher root densities close to the plant. Castro et al. (2021) also found a higher concentration of all classes of ‘Gigante’ and ‘Miuda’ forage cactus pear’s roots at a distance of up to 0.20 m from the base of the plant and at a depth of 0.10 to 0.25 m. The results of these authors corroborate those obtained in the present study, with the concentration of the cactus pear root system in the first 0.15 m deep and at shorter distances from the plant. This consolidates the technical recommendations for the crop, such as applying fertilizers close to the plant to increase nutrient-use efficiency by improving nutrient uptake and utilization by plants.



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

Figure 2. Root length density (RLD) in ‘Gigante’ forage cactus pear subjected to different irrigation regimes as a function of root sampling depth (A) and root sampling distance (B). RLD1 – root length density of very fine roots; RLD2 – Root length density of fine roots; RLD3 – Root length density of small roots; and TRLD – Total root length density.

Irrigation regimes had no effect on RLD of fine roots, small roots and total roots ($p>0.05$). The highest RDL values for very fine roots in plots irrigated with high-salinity water at 33% ETo with a 3-d II and at 50% ETo with a 2-d II formed a group, while the remaining treatments were grouped with lower RDL values (Table 4).

Castro et al. (2021) also found no differences in RLD of small root class with an increase in the percentage of soil water replacement level; however, they found an increase in RLD of very fine and fine root classes up to the irrigation level of 75% of ETo.

Figure 3 depicts the root distribution profile represented by RDL of different root diameter categories. It can be seen that fine roots predominated with 60.46% of the total, while very fine and small roots represented 9.51 and 30.03% of the total, respectively. The greater number of fine roots is associated with high drought tolerance of cactus pear, with constant production of new roots under water availability conditions allowing water uptake (DONATO et al., 2017c).

Nutrient concentrations of N, K, B, Fe, Mn Zn, and Na in cladodes of ‘Gigante’ forage cactus pear were not influenced ($p>0.05$) by different irrigation regimes in the first production cycle. Mean macronutrient concentrations of N and K were 16.35 and 41.73 g kg^{-3}, respectively. Mean micronutrient concentrations of B, Fe, Mn, Zn and Na were 31.99, 123.73, 463.11, 56.79, and 49.66 mg kg^{-1}, respectively.

It should be noted that Na is considered an essential element in plants employing the crassulacean acid metabolism (BROADLEY et al., 2012).

Table 4. Root length density in ‘Gigante’ forage cactus pear as a function of different irrigation regimes.

Treatment	Root length density - RLD (cm cm^{-3})			
	RLD1	RLD2	RLD3	TRLD
No irrigation (rainfed)	0.006853 B	0.072800 A	0.031770 A	0.113750 A
5 L m^{-1} every 15 days	0.006373 B	0.033067 A	0.035217 A	0.087117 A
7% of ETo (II of 15 days)	0.013233 B	0.097247 A	0.050533 A	0.164463 A
15% of ETo (II of 7 days)	0.011407 B	0.050700 A	0.032003 A	0.096440 A
33% of ETo (II of 3 days)	0.020823 A	0.127187 A	0.046803 A	0.197297 A
50% of ETo (II of 2 days)	0.024893 A	0.156603 A	0.075050 A	0.259287 A
100% of ETo (daily)	0.013620 B	0.080347 A	0.035520 A	0.133047 A
Mean	0.0138862	0.0882786	0.0438424	0.1502000
CV (%)	38.59	52.10	53.60	49.28

Means followed by the same uppercase letters in the columns belong to the same group as determined by Scott-Knott test at 5% significance level. RLD1 – Root length density of very fine roots; RLD2 – Root length density of fine roots; RLD3 – Root length density of small roots; TRLD – total root length density.

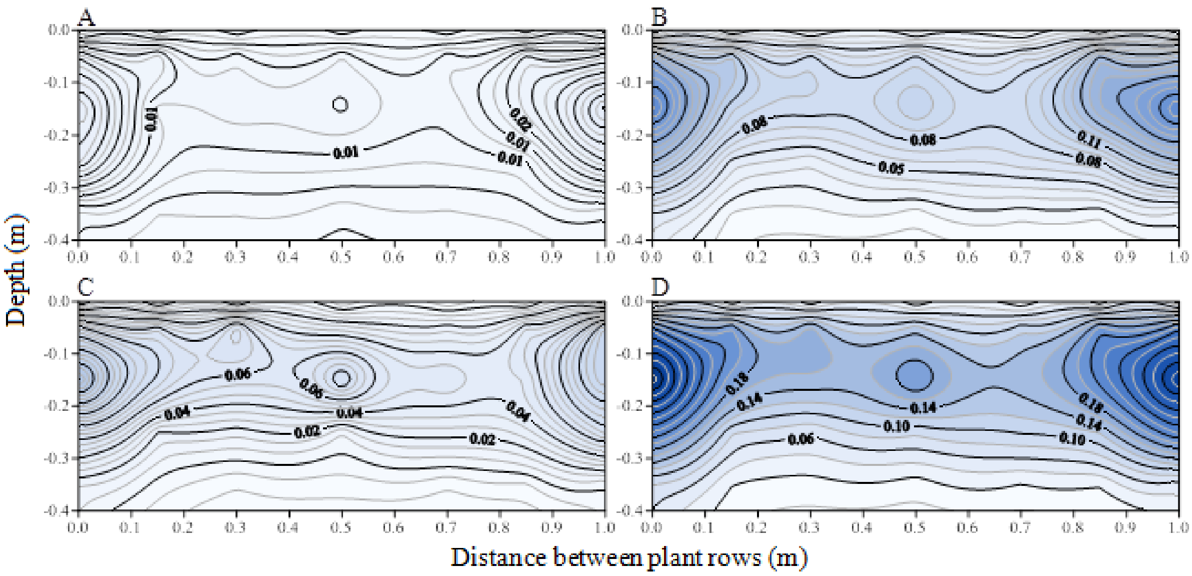


Figure 3. Root length density (cm cm^{-3}) in ‘Gigante’ forage cactus pear subjected to different irrigation regimes. Very fine roots (A), fine roots (B), small roots (C) and total roots (D).

Irrigation regimes influenced cladode nutrient concentrations of P, Ca, Mg and S ($p \leq 0.01$), and of Cu ($p \leq 0.05$).

The irrigation regimes 15% ETo with a 7-d II, 33% ETo with a 3-d II, 50% ETo with a 2-d II, and 100% ETo irrigated daily — all of which irrigated with high-salinity water — were grouped with the highest cladode concentrations of P and Mg (Table 5). The lowest concentrations of these two elements were found in a group containing the rainfed treatment, 5 L m^{-1} of medium-salinity water applied every 15 days, and 7% ETo of high-salinity water with a 15-d II. For plants irrigated with 50% ETo of high-salinity water with a 2-d II, P and Mg concentrations were, respectively, 82.43 and 37.57% higher than for rainfed plants.

Treatments irrigated with high-salinity water at 33% ETo with a 3-d II, 50% ETo with 2-d II, and 100% ETo irrigated daily led to the highest Ca and Cu concentrations in cladodes; these treatments formed a group separated from the remaining treatments, which had lower values. From the lowest level, measured in rainfed plants, to the highest level, measured in plants irrigated at 33% ETo with a 3-d II, the cladode Ca concentrations increased by 45.77%. Cladode Cu concentration increased by 111.79% when comparing rainfed plants with those irrigated at 50% ETo and II of two days.

The treatments irrigated at 15% ETo with a 7-d II, 33% ETo with a 3-d II, and 50% ETo with a 2-d II fell into one group for having the highest cladode S concentrations. The remaining treatments formed another group with lower values. From the lowest S level, measured in rainfed plants, to the highest S levels, measured in plants irrigated with 33% ETo every two days, cladode S concentration increased by 33%.

Table 5. Mean nutrient concentrations in cladodes of 'Gigante' forage cactus pear subjected to different irrigation regimes in the first and second production cycles.

Treatment	Nutrient level										
	1st cycle					2nd cycle					
	P	Ca	Mg	S	Cu	P	K	Ca	Mg	S	Cu
	g kg^{-1}				mg kg^{-1}	g kg^{-1}					mg kg^{-1}
No irrigation (rainfed)	1.48 B	30.15 B	16.05 B	1.70 B	2.12 B	1.08 C	38.75 B	17.38 C	5.75 C	1.40 C	2.69 B
5 L m^{-1} every 15 days	1.75 B	30.68 B	16.25 B	1.90 B	2.47 B	1.50 B	56.33 A	35.45 B	11.28 B	2.73 A	3.35 B
7% ETo (II of 15 days)	1.73 B	29.70 B	16.20 B	1.73 B	2.81 B	1.55 B	57.75 A	40.83 A	11.23 B	2.13 B	5.06 A
15% ETo (II of 7 days)	2.28 A	34.25 B	19.15 A	2.03 A	2.68 B	2.23 A	59.53 A	41.98 A	15.73 A	2.13 B	5.86 A
33% ETo (II of 3 days)	2.55 A	43.95 A	21.83 A	2.10 A	3.78 A	2.38 A	42.58 B	44.48 A	17.23 A	2.03 B	5.69 A
50% ETo (II of 2 days)	2.70 A	43.13 A	22.08 A	2.10 A	4.49 A	2.50 A	40.13 B	44.35 A	16.15 A	2.00 B	5.48 A
100% ETo daily	2.53 A	42.58 A	21.53 A	1.90 B	3.77 A	2.52 A	38.33 B	43.05 A	18.05 A	1.98 B	5.35 A
Mean	2.14	36.35	19.01	1.92	3.16	1.96	47.63	38.21	13.63	2.05	4.78
CV (%)	19.58	11.34	11.99	8.39	28.73	12.95	17.76	8.29	15.78	15.88	17.58

Means followed by the same uppercase letters in the columns belong to the same grouping by Scott-Knott test at 5% significance level.

Alves et al. (2019a, 2019b) established sufficiency ranges for 'Gigante' cactus pear grown under semiarid conditions. Accordingly, in the first cycle P, Ca and Mg concentrations of cladode tissues were either sufficient or high under lower water supply and too high under greater high-salinity water supply. Sulfur and Cu concentrations were sufficient under lower water supply and high under greater high-salinity water supply.

In the second cycle, mean concentrations of N, B, Fe, Mn, Zn and Na in cladodes of 'Gigante' forage cactus pear were not influenced ($p>0.05$) by irrigation regimes. Mean N concentration was 13.30 g kg^{-1}, while mean micronutrient concentrations of B, Fe, Mn, Zn and Na were, respectively, 40.09, 107.09, 316.09, 316.09, 85.23 and 59.04 mg kg^{-1}.

Mean concentrations of P, K, Ca, Mg, S and Cu in cladodes were significantly different ($p\leq0.01$) as a result of different irrigation regimes. Mean P and Mg concentrations were separated into three groups (Table 5). The first group was composed of the highest values obtained in plots where high-salinity water was supplied at 15% ETo with a 7-d II, 33% ETo with a 3-d II, 50% ETo with a 2-d II and 100% ETo irrigated daily (fully irrigated plants). The second group contained intermediate values measured in plants irrigated with 5 L m^{-1} of medium-salinity water every 15 days and 7% ETo of high-salinity water with a 15-d II. The third group had only the rainfed condition with the lowest P and Mg concentrations.

When comparing rainfed plants with fully irrigated plants, P and Mg concentrations increased by 133.33 and 213.91%, respectively. This shows the contribution of the water (Table 2) to meeting the plant's demand for nutrients, so it should be taken into consideration in fertilizer recommendations, particularly for irrigated areas.

The highest K concentrations in cladodes fell into a group containing plants irrigated with 5 L m^{-1} of medium-salinity water every 15 days, 7% ETo with a 15-d II and 15% ETo with a 7-d II the last two irrigated with high-salinity water. The lowest K concentrations formed a group containing the rainfed treatment and the treatments irrigated with high-salinity water at 33% ETo with a 3-d II, 50% ETo with a 2-d II and 100% ETo irrigated daily. Potassium concentration increased by 53.63% when comparing the rainfed condition with the condition where high-salinity water was supplied at 15% ETo with a 7-d II. The high-salinity water contains three times more K than the medium-salinity water; nevertheless, results varied not only because of the different K contents in each water, but also because of how much and how often water had been supplied. Lower K concentrations were measured in plants irrigated more frequently than in those irrigated less frequently and with more water. As K generally moves in the soil driven by the concentration gradient (NOVAIS; MELLO, 2007), applying more water less frequently allows a greater accumulation of K around the roots. This leads to an increased diffusive flow of K from the soil to the plant's roots, so more K is absorbed and accumulated in plant tissues.

Mean Ca concentrations were separated into three groups. The first group was composed of the treatments having the highest means: 7% ETo with a 15-d II, 15% ETo with a 7-d II, 33% ETo with a 3-d II, 50% ETo with a 2-d II, and 100% ETo irrigated daily all of which irrigated with high-salinity water. The second group, with intermediate values, contained only the treatment 5 L m^{-1} of medium-salinity water every 15 days. The third group contained the lowest mean measured in exclusively rainfed plants. The increase in cladode Ca concentration from rainfed plants to plants irrigated at 33% ETo with a 3-d II was equal to 155.93%. Calcium content in high-salinity water was three times higher than in medium-salinity water (Table 2).

Mean S concentrations were also split into three groups. The first group was formed by the highest mean value measured in plots where 5 L m^{-1} of medium-salinity water was applied every 15 days.

The second group, with intermediate values, was formed by the high-salinity water irrigated treatments: 7% ETo with a 15-d II, 15% ETo with a 7-d II, 33% ETo with a 3-d II, 50% ETo with a 2-d II and 100% ETo daily irrigated. The third group contained the lowest S concentration measured in rainfed plants. Sulfur concentration measured in plants irrigated with medium-salinity water every 15 days was 95.00% greater than that measured in exclusively rainfed plants.

The highest values of mean Cu concentrations were measured in the treatments irrigated with high-salinity water at 7% ETo with a 15-d II, 15% ETo with a 7-d II, 33% ETo with a 3-d II, 50% ETo with a 2-d II and 100% ETo irrigated daily. The lowest means were found in plants irrigated with 5 L m^{-1} of medium-salinity water every 15 days and rainfed plants. The highest mean Cu concentration, measured in plants irrigated at 15% ETo with a 7-d II, was 117.84% higher than that in rainfed plants.

In the second production cycle, cladode P and Cu concentrations went from sufficient or high in plants supplied with lower rates of high-salinity water to too high in plants supplied with more water. Cladode K concentrations are within a sufficient range in rainfed plants and plants irrigated with more high-salinity water, whereas in plots to which lower amounts of high-salinity water were applied at a lower frequency, cladode K concentrations were too high. Mean cladode S concentration was within the sufficient range in rainfed plants, and either high or too high under the remaining conditions. As for Ca and Mg, their concentrations in cladodes of rainfed plants were within the deficient range while being high or too high under conditions of greater water supply. These classifications are based on sufficiency ranges reported by Alves et al. (2019a, 2019b).

As fertilizers were evenly applied to all plots, the higher concentrations of P, Ca, Mg S and Cu in cladodes of plants irrigated with greater amounts of high-salinity water may be related to a positive effect of soil moisture on nutrient availability in the soil and increased nutrient uptake by plants. Besides, the levels of Ca, Mg and K in the high-salinity water were higher than in the medium-salinity water.

Soil water content plays a major role in plant nutrition. Ions move through the soil dissolved in water as a result of mass flow and diffusion. If soil water levels are insufficient, plants will experience nutrient deficiencies (NOVAIS; MELLO, 2007).

Furthermore, root interception positively affects nutrient transport in the soil. This occurs as a result of an increased distribution of very fine roots (Table 4) and a broader exploration of the soil by roots when soil water content is higher. Root interception has an indirect effect on diffusive flow by shortening the distance between element-containing soil colloids and root surface. This facilitates particularly the diffusion of P, which has the lowest diffusivity. In addition, high-salinity water is an additional source of K.

Concerning cladode Ca and Mg concentrations, the presence of these nutrients in the high-salinity water is also a contributing factor, which, compared to the medium-salinity water, has three times more Ca and four times more Mg, as already shown in this work. This is clearly evidenced by the increase in the concentrations of these elements in the soil at the end of each production cycle (Table 3) in plots irrigated with more high-salinity water.

In the second production cycle, the lower levels of K in cladodes under the condition without irrigation and of greater application of high-salinity water may be associated with the decrease in absorption and availability of this nutrient due to the lack of soil moisture under the condition without irrigation and due to the increased concentration of Ca and Mg in the soil under greater application of saline water, which led to competition of these nutrients with K, as both adsorption by the soil and absorption by the plant decreased. Given that the optimal soil K saturation for 'Gigante' forage cactus pear ranges from 6.99% to 7.72% (DONATO et al., 2017b), the low values of K saturation in the second cycle, 5.46, 3.98 and 3.79% under water application of 33% of ETo with 3-d II, 50% of ETo with 2-d II and 100% of ETo irrigated daily with very-high-salinity water, respectively, indicate a competition of K with Ca and Mg for sites of adsorption in the soil and absorption by plant roots. It is worth mentioning that, despite the reduction in K levels under conditions of greater application of high-salinity water, plants exhibited no K deficiency symptoms because of the greater K input owing to the higher concentration of the element in the high-salinity water. However, the differences are also due to the frequency of irrigation when comparing the same irrigation water.

Supplying plants with high-salinity water had no effect on most cladode micronutrient concentrations. The increase in soil pH, with values reaching up to 7.53, might explain this outcome (Table 3). In employing Diagnosis and Recommendation Integrated System in forage cactus pear, Teixeira et al. (2019) reported that the increase in soil pH leads to the decrease in micronutrient availability and uptake by plants.

Higher cladode P concentrations in plants irrigated with greater amounts of high-salinity water may also be related to the increase in soil pH, which plays a key role in making P available to plants (VON TUCHER; HÖRNDL; SCHMIDHALTER, 2018).

Accumulation of N, K, S, B, Mn, Zn and Na in cladodes harvested at the end of the first cycle of 'Gigante' cactus pear was not affected ($p \leq 0.01$) by different irrigation regimes. Mean nutrient accumulation values in cladodes for N, K, S, B, Fe, Mn, Zn and Na were 88.45, 226.93, 10.24, 0.17, 0.63, 2.72, 0.32 and 0.27 kg ha^{-1}, respectively.

Irrigation regimes had a significant effect on accumulation of P, Ca, Cu ($p \leq 0.01$) and Mg ($p \leq 0.05$).

The highest accumulation values for P, Ca, Mg and Cu formed a group containing irrigation regimes at 33% ETo with 3-d II, 50% ETo with 2-d II, and 100% ETo irrigated daily all of which irrigated with high-salinity water. These were different from the remaining treatments, which had lower values (Table 6). In comparing rainfed plants to fully irrigated plants (100% ETo, daily irrigated with high-salinity water), the latter accumulated more P, Ca and Mg in cladodes, 111.91, 90.08 and 74.32%, respectively. For Cu accumulation, there was a 130.77% increase from rainfed plants to plants irrigated with high-salinity water at 50% ETo with a 2-d II.

Table 6. Mean nutrient accumulation in cladodes of ‘Gigante’ forage cactus pear subjected to different irrigation regimes in the first and second production cycles.

Treatment	Nutrient accumulation (kg ha^{-1})										
	1st cycle				2nd cycle						
	P	Ca	Mg	Cu	P	Ca	S	Mg	B	Cu	Zn
No irrigation (rainfed)	7.39 B	153.47 B	84.90 B	0.013 B	8.85 B	147.13 B	11.60 B	49.77 B	0.28 B	0.023 B	0.61 B
5 L m^{-1} every 15 days	8.09 B	155.68 B	83.91 B	0.013 B	7.86 B	192.57 B	14.46 B	63.34 B	0.25 B	0.018 B	0.36 B
7% ETo (II of 15 days)	8.56 B	142.46 B	77.98 B	0.013 B	9.80 B	257.71 B	13.31 B	70.25 B	0.27 B	0.033 B	0.40 B
15% ETo (II of 7 days)	9.27 B	149.33 B	86.64 B	0.010 B	13.43 B	259.58 B	13.14 B	97.34 B	0.29 B	0.038 B	0.57 B
33% ETo (II of 3 days)	13.51 A	246.61 A	123.98 A	0.020 A	20.65 A	389.29 A	17.71 A	150.10 A	0.31 B	0.048 A	0.80 A
50% ETo (II of 2 days)	15.07 A	260.08 A	135.15 A	0.030 A	24.72 A	457.05 A	19.97 A	161.81 A	0.44 A	0.058 A	0.91 A
100% ETo daily	15.66 A	291.72 A	148.00 A	0.028 A	26.99 A	461.05 A	21.35 A	196.08 A	0.44 A	0.055 A	1.25 A
Mean	11.08	199.91	105.79	0.018	16.04	309.20	15.93	112.67	0.33	0.039	0.70
CV (%)	20.05	31.16	34.34	35.98	29.04	27.02	29.24	33.18	24.18	29.08	41.06

Means followed by the same uppercase letter in the columns belong to the same grouping separated by Scott-Knott test at 5% significance level.

In the second cycle, accumulation of N, K, Fe, Mn and Na was not significantly influenced ($p > 0.05$) by irrigation regimes; mean values were 102.86, 356.72, 0.87, 2.61, and 0.47 kg ha^{-1}, respectively.

Mean accumulation values for P, Ca, Mg, Cu, B and Zn ($p \leq 0.01$), and S ($p \leq 0.05$) were affected by the different irrigation regimes.

Mean macronutrient accumulation values of P, Ca, S and Mg fell into a group composed of the following high-salinity water irrigation regimes: 33% ETo with a 3-d II, 50% ETo with a 2-d II and 100% ETo irrigated daily; these differed from the remaining conditions, which had lower mean accumulation values (Table 6). Mean accumulation values of P, Ca, S and Mg in cladodes of fully irrigated plants (100% ETo daily irrigated with high-salinity water) were, respectively, 204.97, 213.36, 84.05 and 293.97% higher than those of rainfed plants.

For B accumulation in cladodes, a group was formed containing the irrigation regimes 50% ETo with a 2-d II and 100% ETo irrigated daily with high -salinity water, which had mean accumulation values higher than those measured in the remaining treatments. Plants irrigated at 50% ETo with a 2-d II accumulated 57.14% more B than rainfed plants.

The highest mean Cu and Zn accumulations were found in plants supplied with high-salinity water at 33% ETo with a 3-d II, 50% ETo with 2-d II and 100% ETo irrigated daily; this group differed from the other treatments, which accumulated lower amounts of these micronutrients. Plants irrigated with high-salinity water at 50% ETo with a 2-d II accumulated 152.17% more Cu than rainfed plants. As for Zn, plants fully irrigated with high-salinity water accumulated 104.92% more Zn than rainfed plants.

The higher values of nutrient accumulation of plants irrigated with larger amounts of high-salinity water is associated their higher cladode nutrient concentration (Table 5), in addition to accumulating more dry matter, 66.27% more than that of less irrigated plants (FONSECA et al., 2019).

CONCLUSIONS

For plants planted at the beginning of the rainy season and established under rainy conditions in the first months, the highest concentration of roots is found at a depth of 0.10 to 0.20 m and at a distance of 0.15 m from the center of the row of plants, regardless of the condition of water application; however, applying 50% of ETo with a 2-d irrigation interval results in greater root length density of ‘Gigante’ forage cactus pear.

Applying high-salinity water, EC of 3.6 dS m^{-1}, at 15% ETo with a 7-d irrigation interval promotes higher concentrations of P, Ca, Mg and S in cladodes of ‘Gigante’ forage cactus pear.

Applying high-salinity water, EC of 3.6 dS m^{-1}, at 33% ETo with a 3-d irrigation interval promotes higher accumulation of P, Ca, Mg, S and

Zn in cladodes of 'Gigante' forage cactus pear.

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