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# Morphometry and yield of ‘Gigante’ forage cactus pear under irrigation and different planting densities

# Morfometria e rendimento de palma forrageira 'Gigante' sob irrigação e diferentes densidades de plantio

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**ABSTRACT** - Growing forage cactus pear in semi-arid regions is an alternative when facing current climate changes, and improving its cropping systems is critical to increasing its yields. The objective was to evaluate morphometric characteristics and yield of ‘Gigante’ cactus pear under complementary irrigation with saline water and different planting densities. The research was carried out in the semi-arid region of Bahia during the period from September 2017 to October 2019. 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 per hectare) to subplots, and four irrigation levels (0, 11, 22 and 33% of ETo) to sub-subplots. High-salinity water (2.91 dS $m^{-1}$), classified as C4S1, did not limit the growth and yield of ‘Gigante’ forage cactus pear for two crop cycles. Fresh matter and dry matter yields, fresh matter-based water use efficiency and dry matter-based water use efficiency were highest at planting densities of 61,465 and 67,786 plants $ha^{-1}$, and 61,848 and 69,707 plants $ha^{-1}$, respectively. The use of 33% ETo irrigation level increased morphometric characteristics, fresh matter yield in the first and second cycles, and dry matter yield in the first cycle. Applying increasing irrigation levels promotes reductions in fresh matter- and dry matter-based water use efficiency.

**Keywords**: Forage. Complementary irrigation. *Opuntia ficus-indica*. Semi-arid region. Salinity.

**RESUMO** - O cultivo de palma forrageira no semiárido é uma opção consciente frente às mudanças climáticas atuais, e a melhoria do seu sistema produtivo é fundamental para aumentar seu rendimento. Objetivou-se avaliar as características morfométricas e de rendimento de palma forrageira ‘Gigante’ sob irrigação complementar com água salina e diferentes densidades de plantio. A pesquisa foi realizada no semiárido baiano durante o período de setembro de 2017 a outubro de 2019. O delineamento experimental foi em blocos casualizados com 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 (0, 11, 22 e 33% da ETo). A alta salinidade da água de irrigação (2,91 dS $m^{-1}$), classificada como C4S1, não limitou o crescimento e a produtividade de palma forrageira ‘Gigante’, até o segundo ciclo de produção. As máximas produtividades de matéria verde e seca e de eficiência de uso da água com base nestas produtividades são obtidas com densidades de plantio de 61.465 e 67.786 plantas $ha^{-1}$, e 61.848 e 69.707 plantas $ha^{-1}$, respectivamente. A aplicação da lâmina com 33% da ETo promoveu incremento nas características morfométricas, aumento da produtividade de matéria verde no primeiro e segundo ciclo e da produtividade de matéria seca no primeiro ciclo. A aplicação de lâminas crescentes de irrigação promove redução da eficiência de uso da água com base nas produtividades de matéria verde e de matéria seca.

**Palavras-chave**: Foragem. Irrigação complementar. *Opuntia ficus-indica*. Semiárido. Salinidade.

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## INTRODUCTION

Brazil has the largest area in the world cultivated with forage cactus pear (*Opuntia ficus-indica* Mill) with more than 500,000 hectares planted, concentrated in the Northeast region and with Bahia as the largest producing state (IBGE, 2017).

In the face of current and future climate changes, which may lengthen drought period and increase irregular rainfall distribution in semi-arid regions, growing forage cactus pear is critical for farmers to secure food for livestock. This forage crop has exceptional potential to reduce desertification, contributing to the sustainability of modern agriculture, in favor of food security (IQBAL et al., 2020).

Although cactus pear has morphological and physiological mechanisms of tolerance to extreme stresses, adverse conditions such as severe water deficit and high temperatures constrain its yield and nutritional quality (LIMA et al., 2016). Thus, adopting cultivation technologies is necessary to maximize the yield potential of these plants.

Among practices used in the cultivation of forage cactus pear, irrigation has been shown to improve forage yield (FERRAZ et al., 2019; CASTRO et al., 2020). However, when considering the limitation of water resources in arid and semi-arid environments, where, under global warming conditions, there is an upward trend of occurrence of severe water stresses, it is necessary to evaluate the use of low-quality water, such as saline water, in forage production (FONSECA et al., 2019).

Defining the optimal planting density for any crop can maximize the use of production factors. Several studies have demonstrated the influence of planting density on yields of forage cactus pear (SILVA et al., 2014), associated with organic and chemical fertilization (DUBEUX JÚNIOR et al., 2006; SILVA et al., 2016a) and arrangements that allow mechanization (FONSECA et al., 2020).

However, there is a demand for studies on planting density of cactus pear associated with irrigation with saline water. Temporal changes in the competition among plants combined with the effects of drought may influence the structural, physiological and yield characteristics of the crop (GUO et al., 2020). Increases in planting density up to 65,000 plants per hectare improve yield (FONSECA et al., 2020), which may be further improved by irrigation (FONSECA et al., 2019).

In this context, the objective was to evaluate the morphometric and yield characteristics of ‘Gigante’ forage cactus pear under complementary irrigation with saline water and different planting densities.

## MATERIAL AND METHODS

A field experiment was carried out in an experimental area of the Instituto Federal Baiano, campus of Guanambi, southwestern Bahia state, Brazil (14°13'30"S and 42º46'53”W, and altitude of 525 m). Mean annual rainfall and temperature are 664 mm and 26 ºC, respectively. According to the Köppen classification, the region’s climate is mostly BSwh: hot semi-arid climate with rainy summers and well-defined dry winters.

The soil throughout the experimental area is Latossolo Vermelho-Amarelo (Oxisol). Prior to 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, samples were randomly collected at 0 to 0.20 m deep for chemical testing and textural classification (Table 1).

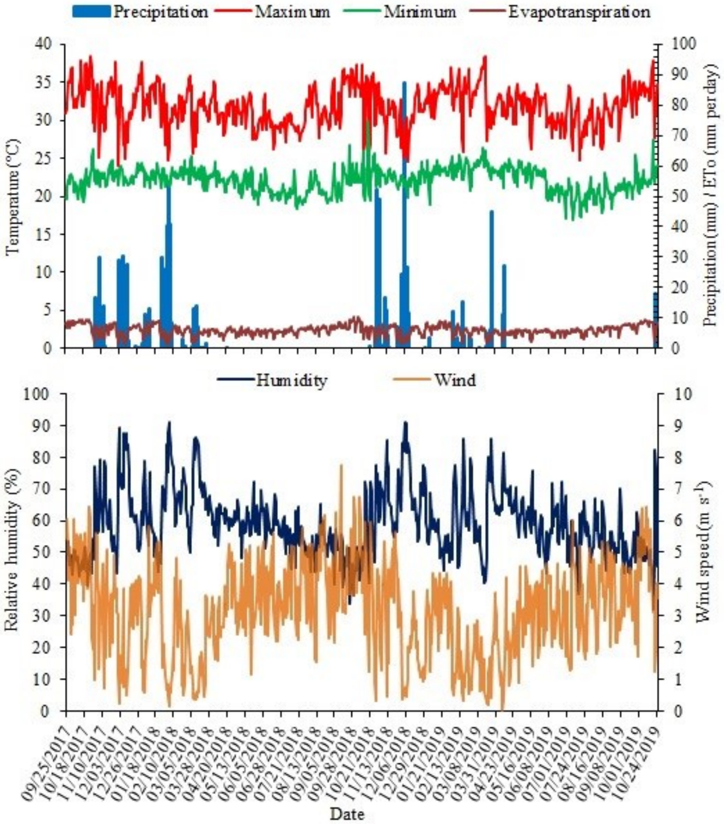
**Table 1**. Chemical attributes and textural class of soil in the experimental area before planting.

| Properties | Unit | Areas | |
|---|---|---|---|
| | | With prior cultivation | Without prior 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 | 3.4 |
| 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 |
| 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.

Despite the different land-use histories, the fertility of both areas is comparable according to the sufficiency range established by Donato et al. (2017b), 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 raised the chloride content in the soil.

The experiment was conducted from September 2017 to October 2019. In this period, an automatic weather station located close to the experimental area collected the meteorological data (Figure 1). In the period from September 25, 2017, to October 22, 2018, referring to the first production cycle, there was an accumulated precipitation of 533.29 mm, while between November 23, 2018, and October 26, 2019, referring to the second cycle, there was 581.20 mm of precipitation.



Data collected from an automatic weather station installed close to the experimental area

**Figure 1**. Data on maximum and minimum temperatures, reference evapotranspiration, precipitation, relative humidity, and wind speed collected during the experiment.

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 per hectare) 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 scheduling was based on reference evapotranspiration (ETo) data provided by a weather station. Evapotranspiration was calculated using the Penman-Monteith method. Irrigation run time for each treatment was determined using an equation for continuous wet strip (SANTOS; BRITO, 2016). The drip irrigation system consisted of PVC main and derivation 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 0.3 m apart.

High-salinity irrigation water came from a tubular well, and its chemical characteristics and classification are shown in Table 2. The water is classified as C4S1 by the classification of 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).

The cladodes of forage cactus pear (*Opuntia ficus-indica* Mill), cultivar Gigante, were planted between September 25 and October 1, 2017. The land was plowed and harrowed before planting. The cladodes, collected from healthy plants, were planted in 0.2-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.

**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 | | |
| SARco | (mmol$_c$ L$^{-1}$)$^{1/2}$ | 3.13 | | |
| SAR ≤ 18.87-4.44 log ECiw | | 16.82 | | |
| Classification[1] | - | C4S1 (High salinity) | | |

[1]Classification of Richards (1954). meq L$^{-1}$ = mmol$_c$ L$^{-1}$. ECiw - Electrical conductivity of irrigation water.

**Table 3**. Total applied water and amounts of elements supplied by each irrigation level and irrigation interval.

| Irrigation levels | Irrigation interval | Total Applied Water (mm) | $Ca^{++}$ | $Mg^{++}$ | $K^{+}$ | $Na^{+}$ | $HCO_3^{-}$ | $Cl^{-}$ |
|---|---|---|---|---|---|---|---|---|
| | | | 1st crop cycle (kg ha$^{-1}$) | | | | | |
| 11% of ETo | 7 | 137.96 | 445.53 | 153.17 | 15.10 | 261.99 | 437.69 | 1,290.45 |
| 22% of ETo | 7 | 275.93 | 891.06 | 306.34 | 30.21 | 523.98 | 875.39 | 2,580.90 |
| 33% of ETo | 7 | 413.89 | 1,336.59 | 459.51 | 45.31 | 785.97 | 1,313.08 | 3,871.35 |
| 11% of ETo | 14 | 141.83 | 458.01 | 157.46 | 15.53 | 269.33 | 449.95 | 1,326.59 |
| 22% of ETo | 14 | 283.66 | 916.02 | 314.92 | 31.05 | 538.66 | 899.90 | 2,653.18 |
| 33% of ETo | 14 | 425.48 | 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 | 150.25 | 485.22 | 166.81 | 16.45 | 285.33 | 476.68 | 1,405.41 |
| 22% of ETo | 7 | 300.51 | 970.44 | 333.63 | 32.90 | 570.66 | 953.37 | 2,810.81 |
| 33% of ETo | 7 | 450.76 | 1,455.66 | 500.44 | 49.35 | 855.99 | 1,430.05 | 4,216.22 |
| 11% of ETo | 14 | 146.35 | 472.62 | 162.48 | 16.02 | 277.92 | 464.30 | 1,368.90 |
| 22% of ETo | 14 | 292.70 | 945.23 | 324.96 | 32.05 | 555.83 | 928.61 | 2,737.80 |
| 33% of ETo | 14 | 439.05 | 1,417.85 | 487.44 | 48.07 | 833.75 | 1,392.91 | 4,106.70 |

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. (2017b) 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. Seventy days after planting, 300 kg ha$^{-1}$ of $K_2O$ was topdressed with KCl as a source, split in two applications. After harvesting the first cycle and beginning of the second, 60 Mg ha$^{-1}$ of goat manure and 300 kg ha$^{-1}$ of $K_2O$ were applied, the latter split in two. The manure used in fertilization has the same composition as that used in the work of Donato et al. (2017a).

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.

Complementary irrigation was 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 carried out 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 resumed. Evaluations in the second cycle were carried out 368 days after the harvest of the first cycle.

At the end of each cycle, soil salinity, number of dead plants, morphometric characteristics (plant height and length, and number, length, width and thickness of cladodes), cladode area index, dry matter content, dry matter yield, fresh matter yield, and water use efficiency were evaluated.

To assess how irrigation with high-salinity water affected soil salinity, samples were randomly collected for every treatment, at depths of 0 – 0.20 m and 0.20 – 0.40 m, and at 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). Soil samples were collected in all combinations of irrigation levels and irrigation intervals at the lowest and highest planting density.

The number of dead plants was determined by direct counting. To determine the morphometric characteristics, four observational plants were randomly collected from each plot. Plant height, cladode length and cladode width were determined with a measuring tape. Cladode thickness was measured using a digital caliper. The length and width of cladodes were used to estimate the cladode area index, and cladode area was determined through the methodology used by Donato et al. (2014).

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., 2016b; DONATO et al., 2017a) for determining dry matter content.

To determine dry matter yield, fresh matter yield was determined first by harvesting all observational plants in the plot. Harvests consisted in cutting all the cladodes, leaving behind the "mother" cladode (cladode used in planting). All cladodes collected in the plot were placed in boxes for weighing, so that fresh matter yield (FMY) (Mg ha$^{-1}$) could be estimated. Dry matter yield (DMY) (Mg ha$^{-1}$) was the product of dry matter content (DM) of the treatment and fresh matter yield (FMY).

Water use efficiency (WUE) was the quotient of crop yield by the total amount of water applied to each treatment plus the precipitation recorded over the crop cycle. Water use efficiency was calculated based on fresh and dry matter contents.

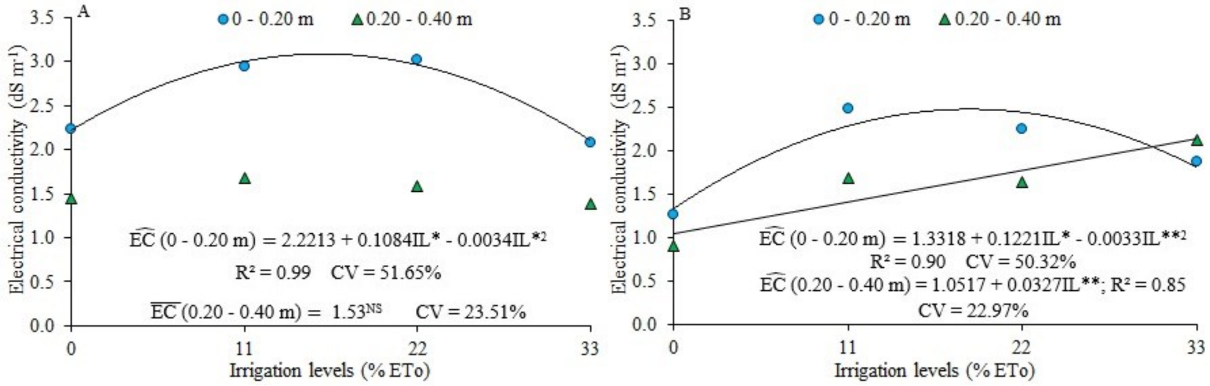
Data were tested for normality and by analysis of variance at 0.05 significance level for type I error. Significant interactions were studied. Single effects of irrigation level and planting density were described by regression models. Models were chosen based on the significance of beta coefficient of t-test and mean square of regression, coefficient of determination, and how well the model fitted the biological phenomenon under study.

## RESULTS AND DISCUSSION

The evaluated characteristics were not influenced by the interactions between the studied factors ($P > 0.05$). The single effect of irrigation interval was not significant ($p > 0.05$) for any evaluated characteristic. Planting densities had no effect ($P > 0.05$) on soil electrical conductivity at the two depths (0-20 and 20-40 cm) and in the two crop cycles.

After the first cycle, a quadratic model was fitted to the response of electrical conductivity at 0 – 0.20 m deep to irrigation levels (Figure 2A). The model estimated the highest electrical conductivity value (3.09 dS m$^{-1}$) at 16% ETo irrigation level, which corresponds to the maximum point of the equation. After this level, electrical conductivity decreased by 32.07% with irrigation equivalent to 33% of ETo. No model was fitted to soil electrical conductivity at depth of 0.20 – 0.40 m as a function of the irrigation levels after the first cycle.

After the second cycle, quadratic effect was obtained for the response of soil electrical conductivity at depth of 0 – 0.20 m to irrigation levels, while an increasing linear effect was obtained for electrical conductivity at depth of 0.20 – 0.40 m as affected by irrigation levels (Figure 2B). At 0 – 0.20 m depth, the highest electrical conductivity (2.46 dS m$^{-1}$) was estimated at the 19% ETo irrigation level. From there on, electrical conductivity dropped by 28.19% at the largest irrigation level (33% of ETo). The electrical conductivity at depth of 0.20 – 0.40 m increased by 102.61% when comparing the treatment without irrigation with the replacement of 33% of ETo.



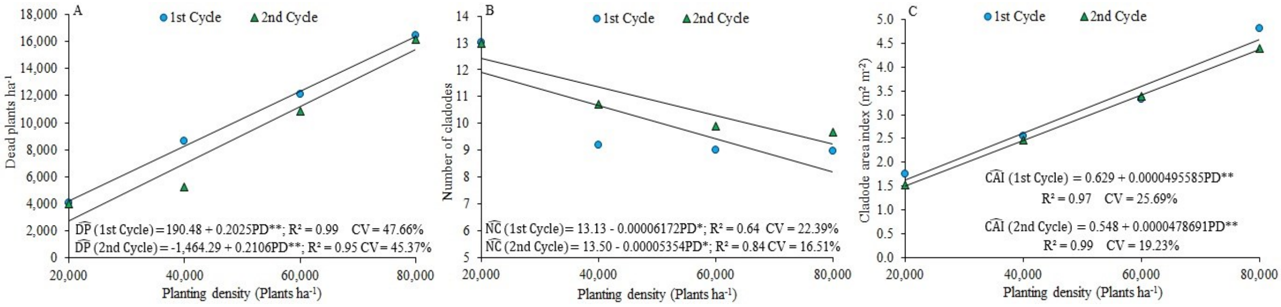
R² - Coefficient of determination; CV - Coefficient of variation. NS - not significant, * significant at 5% by t test, ** significant at 1% by t test.

**Figure 2**. Soil electrical conductivity at depths of 0 – 0.20 m and 0.20 – 0.40 m after the first (A) and second (B) crop cycle as a function of irrigation levels.

The higher salinity at depth of 0 – 0.20 m, with the application of intermediate irrigation levels, may be associated with the accumulation of salts in the superficial portion of the soil. The low salinity values at the lowest irrigation depths are related to the lower volume of water applied and, consequently, the lower input of salts to the soil. Conversely, the reduction in salinity with the highest irrigation levels is associated with the leaching of salts from superficial to deeper layers (0.20 – 0.40 m) in the second crop cycle with 33% ETo irrigation (Figure 2B).

There was no effect (P>0.05) of planting densities on the characters plant height, cladode length, cladode width, cladode thickness, in the two crop cycles.

Increasing linear models were obtained for the number of dead plants in both cycles as a function of planting densities (Figure 3A). Estimates show that, for each increase of 20,000 plants ha$^{-1}$, 4,050 and 4,212 dead plants ha$^{-1}$ for the first and second cycle, respectively. This represents, respectively, stand reduction of 286.52 and 459.88% from the lowest (20,000 plants ha$^{-1}$) to the highest planting density (80,000 plants ha$^{-1}$).



R² - Coefficient of determination; CV - Coefficient of variation. NS - not significant, * significant at 5% by t test, ** significant at 1% by t test.

**Figure 3**. Number of dead plants (A), number of cladodes (B), and cladode area index (C) of 'Gigante' forage cactus pear as a function of planting density.

The high mortality with increasing planting density is related to the competition for space and light during plant establishment and growth. At higher densities, plants end up limiting each other's development and decreasing overall yield per area (FONSECA et al., 2020). Under extreme conditions, larger plants can shade smaller ones, causing them to die. Additionally, higher densities may be associated with a higher probability of spreading inter-root contamination by *Fusarium* and *Pectobacterium* (DIAS; JESUS, 2020), leading to further losses in the field.

Decreasing linear models were fitted to the number of cladodes as a function of planting densities in the first and second cycles (Figure 3B). The models estimate reductions of 31.13 and 25.85% in the number of cladodes, respectively, for the first and second cycle, from the lowest (20,000 plants ha$^{-1}$) to the highest planting density (80,000 plants ha$^{-1}$). The reduction in the number of cladodes at higher planting densities is possibly related to competition between plants for nutrients, which limited the production of cladodes under these conditions. These results agree with those reported Fonseca et al. (2020) and Cavalcante et al. (2014), who found a reduction in the number and size of cladodes with increasing planting density up to 80,000 plants ha$^{-1}$.

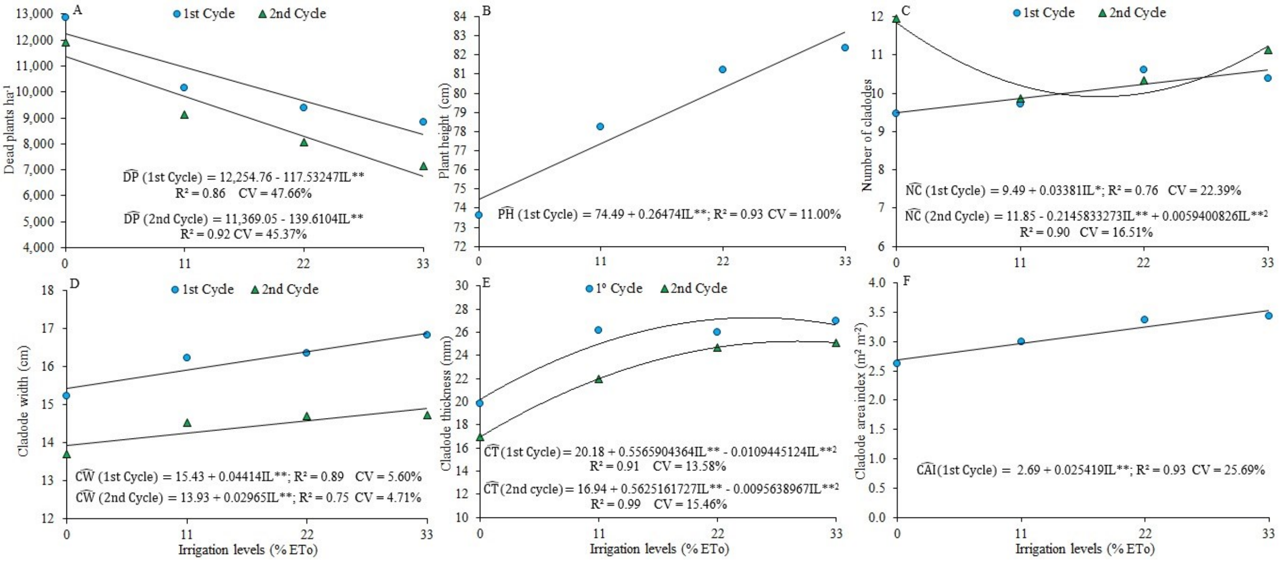
For both cycles, increasing linear models were fitted to cladode area index (CAI) as a function of planting densities (Figure 3C). The models estimate increments of 0.99 and 0.96 m$^2$ m$^{-2}$ in CAI for each increase of 20,000 plants. Cladode area index increased by 183.53 and 190.79% in the first and second cycle, respectively, from the lowest (20,000 plants ha$^{-1}$) to the highest planting density (80,000 plants ha$^{-1}$).

As CAI is the ratio of the total area of cladodes to the area occupied by the plant on the soil and the number of cladodes decreased, the increase in CAI with increasing planting density is related to the smaller area occupied by the plant at higher planting densities. These results corroborate those reported by Fonseca et al. (2020), who found increases in CAI of up to 95,000 plants ha$^{-1}$ under similar environmental conditions.

No model was fitted to the response of plant height and cladode area to irrigation levels in the second cycle and to cladode length in the two crop cycles.

Decreasing linear models were fitted to the number of dead plants as affected by irrigation levels in the two crop cycles (Figure 4A). The models allow estimation of 1,293 and 1,536 dead plants per hectare, respectively, for each 11% ETo increase in irrigation level, resulting in decreases of 31.65 and 40.52% in plant mortality rate, for the first and second cycle, respectively, when comparing the rainfed condition to the highest irrigation level (33% of ETo).

The decrease in plant mortality with increasing irrigation levels is associated with the water supply for maintaining the plant's metabolic processes and shows the competitive advantage of irrigated systems, especially in years with greater climatic variability (FONSECA et al., 2019; SANTOS; DONATO; COTRIM JÚNIOR, 2020). Conditions of water restriction, especially in the first cycle, impair the establishment of plants, as they need to accumulate reserves to maintain growth and ensure survival.



$R^2$ - Coefficient of determination; CV - Coefficient of variation. NS - not significant, * significant at 5% by t test, ** significant at 1% by t test.

**Figure 4**. Number of dead plants (A), plant height (B), number of cladodes (C), cladode width (D), cladode thickness (E), and cladode area index (F) of 'Gigante' forage cactus pear as a function of irrigation levels.

An increasing linear model was fitted to plant height as affected by irrigation levels in the first cycle (Figure 4B), allowing estimation of increments of 2.91 cm in plant height for each 11% ETo replacement. Plants were 11.73% taller when comparing the treatment without irrigation with the highest irrigation level (33% of ETo).

In the first production cycle, 11.76% more cladodes were produced per plant in the irrigated system with 33% of ETo (Figure 4C) than in the rainfed system. In the second cycle, the lower number of cladodes (9.91) was estimated by the model at 18% ETo; after this irrigation level, the number of cladodes continued increasing to 13.37% at the highest irrigation level (33% of ETo).

When relating cladode width to irrigation levels (Figure 4D), increases of 0.49 and 0.33 cm in width were estimated, respectively, for the first and second cycles, for each 11% ETo replacement. The cladode width increases by 9.44 and 7.03%, respectively, in treatments without irrigation and with 33% of ETo replacement.

In the second cycle, the lower number of cladodes from the non-irrigated treatment when compared with the treatment of 18% ETo irrigation may be related to the fact that the plant, under water stress, uses the reserves stored during the period with favorable growth conditions (rainy season) to produce new cladodes, even if the new cladodes are smaller and thinner (Figures 4D and 4E).

The characteristics plant height, cladode width and number of cladodes correlate with one another. This is because the cladodes overlap on the plant; therefore, the greater the number, length and width of cladodes, the taller and wider the plants. The increase in water availability to the plant enables the production of new cladodes, which reach larger dimensions and, consequently, greater height and width of the plant, agreeing with the results reported by Fonseca et al. (2019), who observed higher values for plant height, number of cladodes and cladode length with greater water supply, especially in the second production cycle.

As for the response of cladode thickness to irrigation levels (Figure 4E), the highest values, 27.26 and 25.21 mm, were estimated with 25 and 29% of ETo replacement for the first and the second cycle, respectively, which represented increases of 35.07 and 48.83% in comparison with the values obtained in the treatment without irrigation.

The lower values of cladode thickness recorded in the treatment without irrigation suggest that the plant used the water stored in its tissues to maintain metabolic activities. The water stress tolerance mechanism of forage cactus pear is associated with having large vacuoles for water storage, so cladode thickness reflects the plant's water status. As noted by Fonseca et al. (2019), the greater water supply led to thicker cladodes, suggesting greater water storage per unit area (SANTOS; DONATO; COTRIM JÚNIOR, 2020) and lower dry matter percentage in irrigated plants (FONSECA et al., 2019).

In the first production cycle, there were increments of 0.28 $m^2$ $m^{-2}$ in the cladode area index (CAI) for each 11% ETo replacement, and an increase of 31.18% up to the treatment with 33% of ETo replacement (Figure 4F).

The increase in CAI resulted from the fact that irrigation is related to the increase in the number and width of cladodes in the first cycle. Higher values of CAI are associated with increased yield potential of forage cactus pear because larger areas intercept more photosynthetically active radiation (NOBEL, 2001). These results are in line with Fonseca et al. (2019), who reported higher CAI as a result of increased water supply.

No model could be fitted to the effect of planting density on dry matter content.

There was a quadratic relationship between yield and plant population. The highest fresh matter yields (FMY), 188.88 and 183.29 Mg ha$^{-1}$, were obtained at planting densities of 67,786 and 62,467 plants ha$^{-1}$, in the first and second cycles, respectively (Figure 5A). Lower yields were recorded in the other populations of plants evaluated. A similar behavior was found for dry matter yields.

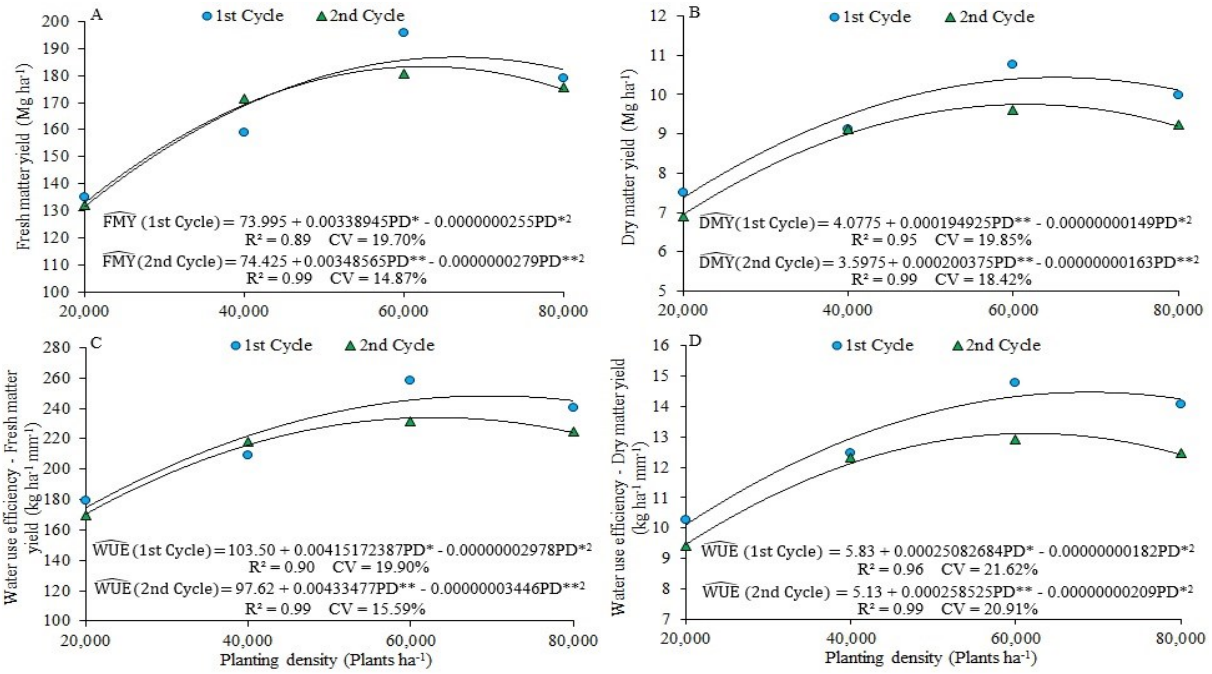
The highest values of dry matter yield (DMY), 10.45 and 9.76 Mg ha$^{-1}$, were obtained at planting densities of 65,411 and 61,465 plants ha$^{-1}$, in the first and second cycles, respectively (Figure 5B).

These results corroborate those of Fonseca et al. (2020), who tested planting densities and patterns for mechanization of ‘Gigante’ forage cactus pear and reported the maximum yield of fresh and dry matter at populations of 69,111.79 and 64,445.91 plants ha$^{-1}$, respectively.

There is a strong relationship between yield components and the number of dead plants and number of cladodes. The lack of positive response of yield of forage cactus pear to higher planting densities is related to the competition among plants for space, light and nutrients. This is evidenced by the increase in the number of dead plants and decrease in the number of cladodes with increasing planting density up to 80,000 plants ha$^{-1}$.

Nobel (2001) reports that CAI values between 4 and 5 m$^2$ m$^{-2}$ promote maximum yield. In our study, at the highest planting density (80,000 plants ha$^{-1}$), CAI values of 4.59 and 4.38 m$^2$ m$^{-2}$ were found in the first and second cycles, respectively (Figure 3C). However, it is worth mentioning that these CAI values are due to the smaller spacing between plants, thus individual plants had less space to grow and there was more competition for nutrients and light with neighboring plants. Increased plant population density intensifies competition for nutrients, especially for more mobile ones, or when the roots of two neighboring plants encounter immobile nutrients (NOVAIS; MELLO, 2007). In addition to being consistent with Fonseca et al. (2020), fresh matter and dry matter yields peak at plant populations between 60,000 and 70,000 plants ha$^{-1}$. This finding suggests that self-shading increases mortality rates (Figure 4A) and limits yield if plant population density is higher than 70,000 plants ha$^{-1}$; therefore, one should not increase planting density of cactus pear beyond that limit. In addition, the use of very high planting densities for forage cactus pear, with regard to the purchase of plantlets, becomes excessively costly (DONATO et al., 2020).

Brito et al. (2018), studying plant spacing in ‘Gigante’ forage cactus pear, found higher values of quantum efficiency and quantum yield of photosystem II at a less shaded spacing. Because these parameters indicate the functioning of photosystem II (PSII), which represents the efficiency with which plants use photochemical radiation to assimilate carbon, the higher planting densities cause less accumulation of reserves in the plant, and, consequently, decreased yield.



R$^2$ - Coefficient of determination; CV - Coefficient of variation. NS - not significant, * significant at 5% by t test, ** significant at 1% by t test.

**Figure 5**. Fresh matter yield (A), dry matter yield (B), fresh matter-based water use efficiency (C) and dry matter-based water use efficiency (D) of ‘Gigante’ forage cactus pear as a function of planting density.

In the first cycle, the response of fresh matter- and dry matter-based water use efficiencies (WUE) to planting density (Figures 5C and 5D) had the highest values, 248.20 and 14.47 kg ha$^{-1}$ mm$^{-1}$, at planting densities of 69,707 and 68,908 plants ha$^{-1}$, respectively. These represented, respectively, increases of 42.14 and 43.03% compared to the values obtained at the lowest planting density (20,000 plants ha$^{-1}$).

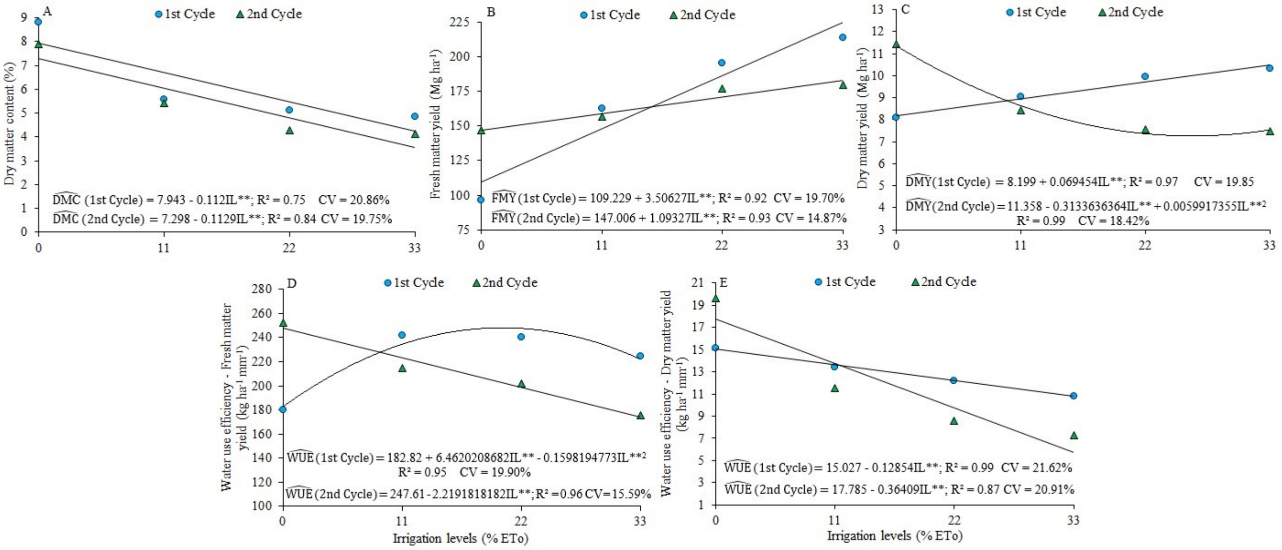
With the highest values of WUE in the first cycle, it appears that cactus pear requires 40.29 and 691.08 L ha$^{-1}$ of water to produce, respectively, 1 kg of fresh and dry matter.

Water use efficiencies were higher, 233.84 and 13.12 kg ha$^{-1}$ mm$^{-1}$, for fresh and dry matter yields recorded in the second cycle as a function of planting density, respectively (Figures 5C and 5D). Considering fresh and dry matter yields, the maximum values were found, respectively, at planting densities of 62,896 and 61,848 plants ha$^{-1}$. Reductions of 4.31 and 5.25% in WUE were obtained when 80,000 plants ha$^{-1}$ were planted.

In the second cycle, plants required 42.75 and 762.19 L ha$^{-1}$ of water to produce, most efficiently, 1 kg of fresh and dry matter, respectively.

Planting densities associated with the highest yields were consistent with the highest WUE. Planting densities above 70,000 plants ha$^{-1}$ do not increase physical yield (FONSECA et al., 2020).

Decreasing linear models were fitted to the response of dry matter content to irrigation levels in both cycles (Figure 6A). Dry matter contents decreased by 46.53 and 51.05%, in the first and second cycles, respectively, from the rainfed condition to 33% of ETo replacement.



R² - Coefficient of determination; CV - Coefficient of variation. NS - not significant, * significant at 5% by t test, ** significant at 1% by t test.

**Figure 6**. Dry matter content (A), fresh matter yield (B), dry matter yield (C), fresh matter-based water use efficiency (D) and dry matter-based water use efficiency (E) of ‘Gigante’ forage cactus pear as a function of irrigation levels.

The reduction in dry matter content with increasing irrigation levels is related to the constant production of cladodes due to increased soil moisture. Under such conditions, cladodes also store greater amounts of water, which is evidenced by thicker, more turgid cladodes (Figure 4E). Similar results were found by Fonseca et al. (2019) and discussed by Santos, Donato and Cotrim Júnior (2020). Under water limiting conditions, cactus pear uses the water stored in large vacuoles to maintain metabolic activities, as evidenced by the thinner cladodes in the treatment without irrigation (Figure 4E). Plants in the rainfed system showed wilted appearance and, consequently, higher dry matter percentage, which agrees with Scalisi et al. (2016), who reported thicker cladodes in irrigated plants than those in non-irrigated ones.

In the two cycles, there was increasing linear effect between irrigation levels and FMY (Figure 6B). Fresh matter yield increased by 105.93 and 24.54% for the first and second crop cycle, respectively, when comparing the treatment without irrigation with 33% of ETo replacement.

In the first cycle, an increasing linear model and in the second cycle a quadratic model were fitted to the response of DMY to irrigation (Figure 6C). In the first cycle, DMY increased to 27.95% at the irrigation level corresponding to 33% of ETo. The lowest DMY in the second cycle (7.26 Mg ha$^{-1}$) was estimated at 26% ETo replacement, with a reduction of 36.07% when compared to the treatment without irrigation.

The increases in fresh matter yield in both cycles and dry matter yield in the first production cycle as irrigation levels increased are associated with the maintenance of plant growth due to soil water availability, which can also be evidenced by the increased morphometric characteristics as compared to the treatment without irrigation (Figure 4). In addition to water availability, nutrients become more available in the soil as soil moisture increases, with considerable supply of Ca, Mg and K by the application of saline water (Table 3).

The effect of low water availability in the soil for forage cactus pear is evidenced in the study conducted by Silva et al. (2016b), who, in determining growth curves for ‘Gigante’ forage cactus pear as a function of spacing and chemical fertilizers, reported impaired plant growth in the dry period of the year due to lack of water and decreased nutrient uptake.

Environmental factors modulate the extent to which the biochemical and physiological capacities of CAM plants are expressed. Changes in environmental conditions, such as water availability, make plants switch their $CO_2$ uptake pattern, with gradual transition from CAM to C3 photosynthesis (TAIZ et al., 2017). This adaptive mechanism explains the accumulation of reserves and increase in yield of the irrigated cactus pear.

Liguori et al. (2013), when comparing irrigated with non-irrigated forage cactus pear, found that after 60 days of irrigation, net $CO_2$ assimilation rate in irrigated plants doubled, while in non-irrigated plants it remained unchanged; however, the cladodes of irrigated plants became flaccid due to increased water loss to maintain photosynthetic activities. This indicates that drought stress for prolonged periods interferes with the capacity to accumulate reserves, lowering yields.

The reduction in dry matter yield in the second cycle as irrigation levels increased is associated with a lower yield response of cactus pear in the second cycle (24.54% fresh matter) compared to the first cycle (105.93% fresh matter).

Yield results also show that the application of irrigation with high-salinity water caused no stress or limitation on the growth of ‘Gigante’ forage cactus pear. Similarly, in a study on the response of *Opuntia* to saline irrigation, Nadaf et al. (2018) reported the high potential in producing forage using this mechanism.

Fonseca et al. (2019) also reported the absence of stress in plants irrigated with saline water. The authors tested different conditions of water application in ‘Gigante’ forage cactus pear and detected no statistical difference in quantum yield of photosystem II between irrigation conditions with high-salinity water and irrigation conditions with good quality water. However, rainfed plants had the worst results. As quantum yield of photosystem II quantifies the performance of plants, reductions in this parameter indicate stress conditions; therefore, we can infer from these findings that salinity is not a stressing factor to cactus pear, under complementary irrigation.

The absence of salinity stress in forage cactus pear can be explained by a series of ionic adjustment mechanisms, including allocation of ions to vacuoles, regulation of concentration of ions by increasing water content in tissues, and production and accumulation of organic compounds to promote the osmotic balance between the cytoplasm and different cell compartments (WILLADINO; CAMARA, 2010).

Our findings point out that it is possible to use low-quality water, such as saline water, in forage cactus pear, as a form of complementary irrigation, which contributes to the sustainability of agriculture by increasing the availability of forage during drought in semi-arid regions, without competing for the use of better quality water, so necessary for other activities on rural properties.

It is worth noting that the cactus pear cultivar ‘Gigante’, despite being traditional and productive, is susceptible to carmine cochineal (*Dactylopius opuntiae*), so it is not recommended for planting in places where the pest occurs.

A quadratic model was fitted to fresh matter-based WUE as a function of irrigation levels in the first cycle and a decreasing linear model was fitted to fresh matter-based WUE as a function of irrigation levels in the second cycle (Figure 6D). In the first cycle, the highest WUE value (248.14 kg $ha^{-1}$ $mm^{-1}$) was found with the application with 20% ETo replacement, with an increase of 35.73% compared to the treatment without irrigation. In the second cycle, there was a reduction of 29.58% in WUE from the treatment without irrigation to the 33% of ETo replacement.

Decreasing linear models were fitted to the response of dry matter-based WUE to irrigation levels in the first and second cycles (Figure 6E). Water use efficiency dropped by 28.23% and 67.56% for the first and second cycles, respectively, when comparing the rainfed treatment to the highest irrigation level (33% of ETo).

The reduction in fresh matter-based WUE in the second cycle and dry matter-based WUE in the first and second cycles as irrigation levels increased are associated with increased water availability when compared to the increase in yield; as it is a crop with minimal water requirements, the increase in applied volume does not lead to significant increases in production. The increase in fresh matter-based WUE in the first cycle, up to the 20% ETo irrigation level, is related to the high increase in fresh matter yield (105.9%) recorded from the treatment without irrigation to the highest irrigation level (33% ETo). Irrigation levels higher than 20% ETo decreased WUE.

## CONCLUSIONS

The use of high-salinity water in the form of complementary irrigation does not limit growth and yield of ‘Gigante’ forage cactus pear in the first crop cycles. Plant mortality rate decreases with increasing irrigation level and increases with increasing planting density.

In general, 33% ETo replacement with saline water increases morphometric characteristics and fresh matter production in the first production cycle of ‘Gigante’ forage cactus pear.

Under the conditions evaluated, the forage cactus pear ‘Gigante’ presented itself as more productive and more efficient in the use of water at the planting densities between 61.000 and 70.000 plants $ha^{-1}$.

The forage cactus pear ‘Gigante’ reduced its water use efficiency and its dry matter yield when it received supplemental irrigation of up to 33% ETo in the second production cycle.

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