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CROP PRODUCTION

# Morpho-physiology, yield, and water-use efficiency of *Opuntia ficus-indica* irrigated with saline water

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**ABSTRACT.** Forage cactus pear is considered a xerophilic plant, so it is adapted to harsh semiarid conditions and is a forage resource of significant importance for animal production in regions that are subject to food shortage and long dry periods. We aimed to evaluate the morphometric and physiologic characteristics and water-use efficiency of 'Gigante' forage cactus pear under different settings of irrigation depth and irrigation intervals with saline water. The treatments included seven conditions of water application: rainfed, 5 liters of water per linear meter every 15 days; 7% reference evapotranspiration (ETo) with a 15-day irrigation interval; 15% ETo with a 7-day irrigation interval; 33% ETo with a 3-day irrigation interval; 50% ETo with a 2-day irrigation interval; and 100% ETo with daily irrigation. Likewise, the use of saline water (3.6 dS $m^{-1}$) as irrigation water on forage cactus pear did not stress the crop even in the presence of salts. The treatment with saline water and 33% ETo with a 3-day irrigation interval increased the plant height, number of cladodes, cladode area index, green mass and dry matter yields of forage cactus pear.

**Keywords:** semiarid; irrigation management; salinity.

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## Introduction

The Brazilian semiarid region is remarkable for its irregular, short rainy season. This region is characterized by average annual rainfall below 800 mm; an aridness index of up to 0.5, calculated by the water balance equation, which relates the amounts of rain and the potential evapotranspiration, from 1961 to 1990; and drought risk or stretching of the dry season from one year to another of higher than 60% from 1970 and 1990 (Brasil, 2005). It is a troublesome task to raise ruminant livestock during long periods of drought because of the limitation of natural forage production in terms of quantity and nutritional quality to meet the food demand of these animals.

In this situation, the exploitation of species adapted to these conditions is fundamental to ensure food availability to livestock. The future of arid and semiarid regions in the world depends on developing sustainable crops with adequate management (Sales, Leite, & Andrade, 2016), which prompted the conduction of studies to develop highly efficient management techniques for higher yields of forage species adapted to semiarid conditions (Perazzo et al., 2013; Porto, Vitor, Alves, Lima, & Silva, 2014).

The forage cactus pear (*Opuntia ficus-indica*) is considered a xerophilic plant and is adapted to the harshness of semiarid regions. Its physiology is characterized by employing a carbon fixation pathway called crassulacean acid metabolism (CAM), in which there is a reduction in water loss because of daytime stomatal closure and nocturnal stomatal opening and $CO_2$ fixation (Sampaio, 2005); despite its adaptation to semiarid conditions, its yield has been reported as being low, mainly because of the lack of adequate management (Donato et al., 2014).

Despite the relevance of forage cactus pear in semiarid regions as a source of animal feed, its cultivation is seen as being of low economic potential. This is associated with irregularities in yield as a result of the absence of specific management practices for each clone and growing environment and the definition of a production system that encourages the expansion of forage cactus pear fields (Cruz Neto et al., 2017).

Several studies have demonstrated the performance of forage cactus pear with regard to its growth and yield in different regions and using different types of crop management (Cunha et al., 2012; Silva et al., 2013a; Cavalcante, Santos, Silva, Fagundes, & Silva, 2014). Thus, it is important to evaluate new technologies that are able to increase current yields.

Among these technologies, irrigation stands out as a technique that increases crop yields. Knowledge about the water demand of forage cactus pear is insufficient, especially when it is grown under semiarid conditions; hence, it is necessary to determine the water demand with the aim of improving the understanding of the yield response of this crop in local soil and climate (Silva et al., 2014).

However, the water used for irrigation in arid and semiarid regions, especially that from tube wells, often exhibits high salt concentrations, which can be unsafe for growing most crops (Silva et al., 2013b). Because of the limitation of water resources, with increasing demand to meet human and agriculture needs, the addition of low-quality water to the production system becomes a necessary alternative to provide the crop with better conditions and ensure agriculture production. Therefore, we aimed to evaluate the morphometric and physiologic characteristics, yield, and water-use efficiency of 'Gigante' forage cactus pear under combinations of different irrigation depths and intervals using saline water.

## Material and methods

The experiment was carried out at the Instituto Federal de Educação, Ciência e Tecnologia Baiano, campus Guanambi, located in the municipality of Guanambi, southwestern Bahia, Brazil, at 14°17'27''S and 42°46'53''W, 537-m altitude, 680-mm average annual rainfall, and 26°C average annual temperature. The experiment was conducted between October 2014 and October 2016 in a red-yellow Latosol (Oxysol), whose physicochemical characteristics before planting are shown in Table 1.

**Table 1.** Physicochemical characteristics of the soil in the experimental area.

| Parameters | 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 |
| $Mg^{2+}$ | cmol$_c$ 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 |
| t[2] | cmol$_c$ dm$^{-3}$ | 2.4 | 1.9 |
| T[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 |
| CE[5] | dS m$^{-1}$ | 0.7 | 0.8 |
| Textural class | | Sandy clay loam | |

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

Over this period, the main climate elements (Figure 1) were collected from a weather station close to the experimental area.

The treatments included seven conditions of water application: rainfed; 5 litters of water per linear meter every 15 days; 7% reference evapotranspiration (ETo) with a 15-day irrigation interval; 15% ETo with a 7-day irrigation interval; 33% ETo with a 3-day irrigation interval; 50% ETo with a 2-day irrigation interval; and 100% ETo with daily irrigation. They were arranged in a randomized block design, with four replicates, totaling 28 experimental units (plots). We chose to use lower irrigation depths with longer irrigation intervals to avoid applying a small fraction of saline water to the soil on a daily basis; otherwise, it could cause salt accumulation in the topsoil. As the root distribution is higher closer to the ground surface, high salt concentrations could compromise the development of the crop; also, the evapotranspiration demand is often high, which causes almost all the applied water to evaporate, leaving the salts in the topsoil.

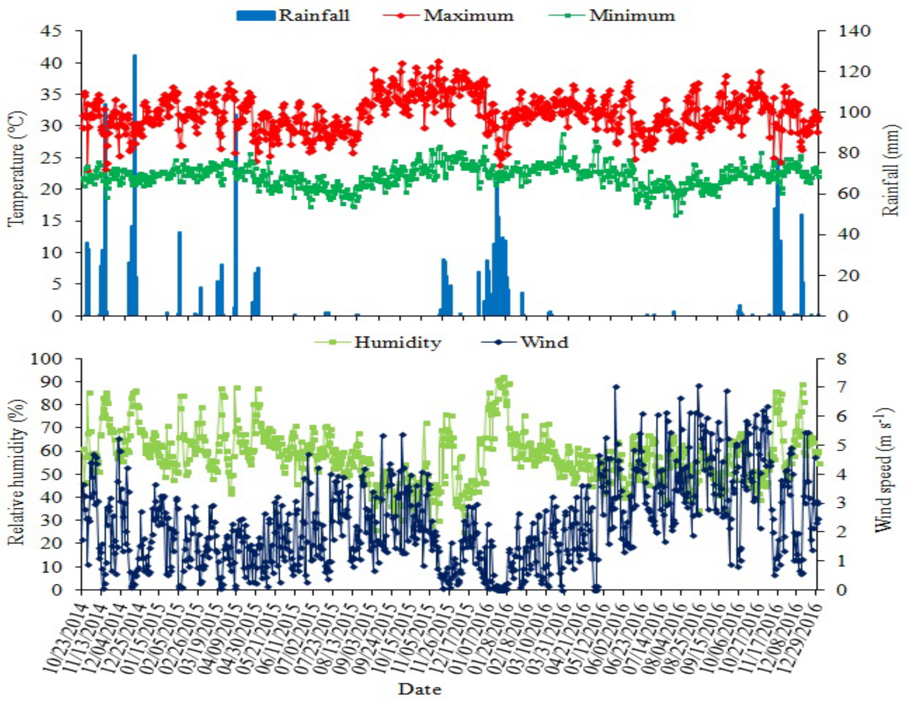


**Figure 1.** Maximum and minimum temperatures, rainfall, relative humidity, and wind speed during the experiment conduction. Data from an automatic weather station installed near the experimental area.

Each plot consisted of three 8-meter-long rows of plants, in which the measured plants were those located in 4-meter-long central portions of each of these three rows, totaling 20 $m^2$.

The 'Gigante' cactus pear (*Opuntia ficus-indica* Mill) was planted on October 23 and 24, 2014, and the crop was grown over two production cycles. Prior to planting, the area had underwent conventional tillage (plowing and harrowing). The furrows in which the cladodes were placed were 0.20 m deep. The spacing was 0.14 m between plants and 1 m between rows of plants, laid out in triplet rows spaced 3.0 m apart.

The ETo data were collected from a weather station near the experimental area. These ETo data were downloaded daily and used to calculate the irrigation run time of each treatment, according to the equation, for continuous wet strips (Santos & Brito, 2016).

The main and sub-main lines were made of PVC with a nominal diameter of 50 mm. The laterals were 16-mm hoses with pre-installed emitters with a flow rate of 4 L $h^{-1}$, spaced out at 0.5 m. As shown in Figure 1, we monitored the accumulated water under different conditions of water application in the two production cycles (Figure 2).

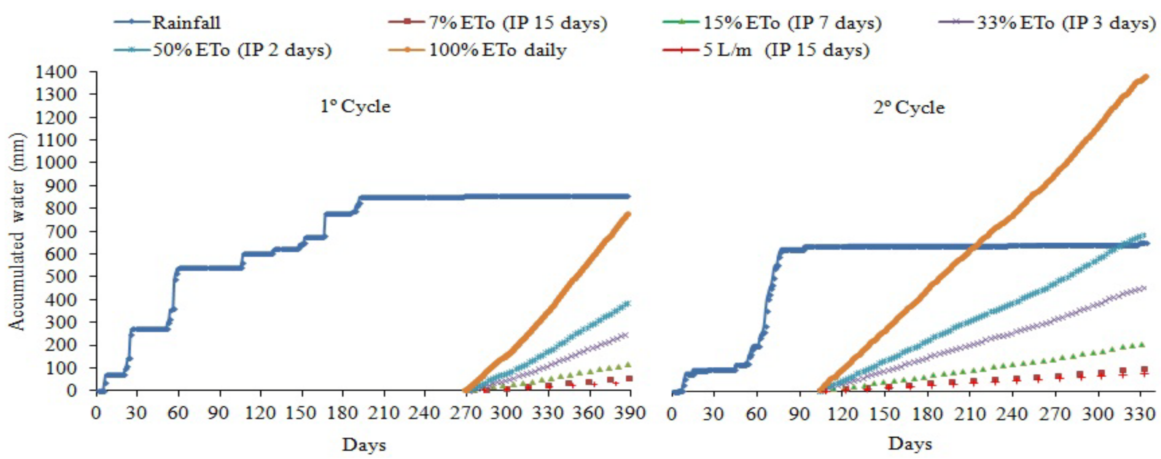


**Figure 2.** Water accumulation in the first and second production cycles of 'Gigante' forage cactus pear.

The water used in the treatment with the application of 5 liters of water per linear meter every 15 days had an electric conductivity of 0.75 dS $m^{-1}$, classified as C2S1. For the remaining irrigated treatments, the irrigation water was from a tube well with the following characteristics: pH 6.4; electric conductivity, 3.6 dS $m^{-1}$; calcium, 11.90 mg $L^{-1}$; magnesium, 9.54 mg $L^{-1}$; potassium, 0.48 mg $L^{-1}$; sodium, 30.40 mg $L^{-1}$; carbonate, 0.00 mg $L^{-1}$; bicarbonate, 4.10 mg $L^{-1}$; and chloride, 34.80 mg $L^{-1}$. It was classified as C2S1 in accordance with Ayers and Westcot (1985).

Organic fertilization was performed with 30 Mg $ha^{-1}$ cattle manure applied at planting. Topdressing was performed after planting with 60 Mg $ha^{-1}$, totaling 90 Mg $ha^{-1}$ cattle manure in the crop cycle. At planting, chemical fertilization was also performed, with application of 300 kg $ha^{-1}$ $K_2O$ (source, potassium chloride) and 150 kg $ha^{-1}$ $P_2O_5$ (source, simple superphosphate). After the harvest of the first production cycle and beginning of the second production cycle, other organic and chemical fertilizations were performed using the same application rate used at planting. During the experiment, all crop practices were performed so that ideal conditions could be provided for plant development. Weed control was performed by hoeing or by using the herbicide glyphosate with an application rate of 200 mL 20 $L^{-1}$ water, which was applied during the rainy season of each cycle.

The application of the treatments began 266 days after planting (DAP), during which the rainy season occurred, and it was necessary for the crop to establish. The assessments of the first cycle were performed on the 120$^{th}$ day after the onset of the experiment (treatment application) and before the rainy season. At the end of the harvest, the application of the treatments was suspended for 102 days due to the rainy season. After that, at the beginning of the dry season, the application of the treatments was restarted, and the evaluations of the second cycles were performed 230 days after the restart of the applications.

To verify the soil salinity level under different conditions of water application, soil samples were collected at depths of 0-0.20 m and 0.20-0.40 m, 0.20 m away from the plant. The sampling was performed in three periods: at the end of the first crop cycle, at the end of the second crop cycle, and one week after the rainy season. We picked these periods to check on the soil salinity level immediately after the end of each cycle and the effect of the rain on salt accumulation in the soil. The salinity was determined from the saturated paste extract, which was prepared by adding distilled water and letting it rest for 24 h, and then, through vacuum suction, the saturated extract was obtained with which the electric conductivity was read according to the methodology described by Richards (1954).

Chlorophyll fluorescence reading was performed using a pulse-modulated fluorometer, model OS1-FL, OPTI-Science®, in three plants within the plot. The PAR (photosynthetically active radiation) clips used to measure the *a* chlorophyll fluorescence were positioned on the middle third of the cladode, to which there two more cladodes were attached. The measurement was performed after five minutes of adaptation of the sample to the dark, followed by a pulse of saturated light for 0.3 s at a frequency of 0.6 kHz. Right then, the minimum, maximal, and variable fluorescences (F0, Fm, Fv, respectively) and the photochemical efficiency (Fv/Fm) were measured. During the measurements, we used a PAR clip to adapt the chloroplasts to the dark so all the reaction centers of the photosystem irrigation interval (PSII) were open and the heat loss would be kept to a minimum (Strauss, Krüger, Strasser, & Van Heerden, 2006).

Readings on light-adapted cladodes were also performed, and saturating pulses were applied to determine the chlorophyll under steady state (Fs), maximal and variable fluorescences with actinic illumination (Fms and Fvs, respectively), and quantum photosynthetic yield of the photosystem irrigation interval (Yield). Three readings on dark-adapted samples and one reading on light-adapted samples were performed on each identified plant.

The morphometric characteristics we evaluated were plant height, number of cladodes per plant, length and width of cladodes, and cladode area index. Six plants, located in a 4-meter-long central portion of the plot, were randomly selected for assessment. To determine the plant height and the width and length of cladodes, we used a measuring tape. The plant height was measured from the ground surface to the very top of the plant. For the length and width of cladodes, we considered the longest straight line across the cladode, using every cladode of the plant.

The cladode area index was estimated from the length and width of cladodes. First, the area of the cladode was determined according to the methodology used by Donato et al. (2014). As a function of the area of cladodes of the plant, the cladode area index was calculated (AIC). The AIC is a measure of the total area of cladodes of the plant, considering both sides of the cladode and dividing it by the area the plant covers ($m^2$ of cladode area / $m^2$ of ground); then, the photosynthetically active area of the plant can be determined.

At harvest time, all measured plants were harvested with the aid of a knife, cutting off all the cladodes except the 'mother' (cladode used at planting). The cut was performed at the joint between cladodes to avoid harming the remaining cladode. All cladodes removed from the plot were placed in containers for weighing; then, green mass yield was determined (Mg $ha^{-1}$).

The water-use efficiency (WUE) was determined by the result of the division between the crop yield and the total volume of water applied to the different treatments, in addition to the rain that fell during the crop cycle. The WUE is defined as the commercial production per unit of water that is effectively used by the crop as evapotranspiration (Jensen, 2007; Simsek, Tonkaz, Kaçira, Çomlekçoglu, & Dogan, 2004, and Zhang, Kendy, Qiang, Changming, & Hongyong, 2004) or the relation between yield and irrigation + rainfall (Aujla, Thind, & Buttar, 2005), or both (Sousa, Coelho, Andrade Junior, Folegantti, & Frizzone, 2000).

The water-use efficiency was also determined based on the division between yield and gross depth, considering only the depth applied to each irrigated treatment. Two water-use efficiencies were considered: one for green mass yield and the other for dry matter yield.

The data we collected were subjected to analysis of variance as we adopted 0.05 as the critical significance level for the Type I error. The means were divided into groups using the Scott-Knott criterion at a significance level of 5%. Statistical analysis was performed with the statistical software 'R' (R Development Core Team, 2012).

## Results and discussion

At the depth of 0 to 0.20 m, at the end of the first cycle, the highest values of electric conductivity were those under the following conditions: 7% ETo with a 15-day irrigation interval; 15% ETo with a 7-day irrigation interval; 33% ETo with a 3-day irrigation interval; 50% ETo with a 2-day irrigation interval; and 100% ETo with daily irrigation. These differed from the remaining conditions (Table 2). At the end of the second cycle, the conditions of 33% ETo with a 3-day irrigation interval, 50% ETo with a 2-day irrigation interval and 100% ETo with daily irrigation were those with the highest means, differing from the remaining conditions. There was an increase of 3.93 dS $m^{-1}$ in salinity when comparing that of the initial soil (prior to applying the treatments) to the highest value, 4.63 dS $m^{-1}$, recorded under the condition 33% ETo with a 3-day irrigation interval. After the rainy season, there was no significant difference in soil salinity among the different conditions of water application, exhibiting a mean value of 0.52 dS $m^{-1}$.

**Table 2.** Mean values of electric conductivity in the soil cultivated with 'Gigante' forage cactus under different irrigation depths and irrigation intervals

| Treatments | Electric conductivity (dS $m^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | End of 1st cycle | | End of 2nd cycle | | After rainy season | |
| | 0-0.20 m | 0.20-0.40 m | 0-0.20 m | 0.20-0.40 m | 0-0.20 m | 0.20-0.40 m |
| Rainfed condition | 0.93 B | 1.28 B | 1.11 B | 1.28 B | 0.52 A | 0.91 B |
| 5 L $m^{-1}$ every 15 days | 0.55 B | 0.84 B | 1.07 B | 1.28 B | 0.49 A | 0.70 B |
| 7% ETo (15-day II) | 2.37 A | 1.54 B | 2.17 B | 2.60 A | 0.48 A | 0.70 B |
| 15% ETo (7-day II) | 2.65 A | 2.23 A | 2.44 B | 1.97 A | 0.42 A | 0.98 B |
| 33% ETo (3-day II) | 2.21 A | 1.99 A | 4.63 A | 2.49 A | 0.68 A | 1.19 A |
| 50% ETo (2-day II) | 1.72 A | 1.62 B | 4.06 A | 2.36 A | 0.49 A | 1.31 A |
| 100% ETo (daily) | 2.52 A | 2.88 A | 3.67 A | 2.16 A | 0.55 A | 1.27 A |
| Mean | 1.85 | 1.77 | 2.74 | 2.02 | 0.52 | 1.01 |
| CV (%) | 34.53 | 38.19 | 43.72 | 21.53 | 44.56 | 27.08 |

Means followed by the same uppercase letter in the column belong to the same group by the Scott-Knott criterion at significance level 5%. II – Irrigation interval.

At depths of 0.20 and 0.40 m, at the end of the first cycle, the soil exhibited the highest values of electric conductivity under the following conditions: 15% ETo with a 7-day irrigation interval; 33% ETo with a 3-day irrigation interval; and 100% ETo with daily irrigation. These differed from the remaining conditions. At the end of the second cycle, the conditions that were grouped and differed from the remaining conditions were as follows: 7% ETo with a 15-day irrigation interval; 15% ETo with a 7-day irrigation interval; 33% ETo with a 3-day irrigation interval; 50% ETo with a 2-day irrigation interval; and 100% ETo with daily irrigation.

There was an increase of 1.69 dS m$^{-1}$ in the salinity of the initial soil in relation to the highest value, 2.49 dS m$^{-1}$, under the conditions 33% ETo with a 3-day irrigation interval. After the rainy season, the highest values of electric conductivity were clustered with the following conditions: 33% ETo with a 3-day irrigation interval; 50% ETo with a 2-day irrigation interval; and 100% ETo with daily irrigation. These differed from the remaining conditions.

The mean value of salinity at the depth 0.00 – 0.20 m (0.52 dS m$^{-1}$) was lower than that of the initial soil (0.70 dS m$^{-1}$), which indicated that after the rainy season, the soil returned to its initial condition in regard to salinity. The amount of rain that occurred after the end of the experiment (Figure 1) was enough to promote leaching of salts that had accumulated over the application of the treatments.

At a depth of 0.20 - 0.40 m, the highest values of salinity found under the conditions with higher application of saline water were related to the higher accumulation of salts at the end of the second cycle and to the absence of complete leaching of the soil profile. It is worth mentioning that the salinity found at this depth was not considered elevated, and at the moment of measurement, all the annual rainfall had not yet occurred in the region, as the following rains could have boosted the leaching of salts from the depth 0.20 - 0.40 m. These results suggest that after the rainy season, the salts that accumulated due to the application of saline water in two production cycles leached. Resende, Amorim, Cruz, and Meneses (2014), studying the natural leaching of salts in the soil under semiarid conditions, concluded that during the rainy season, intense leaching of salts occurs, which significantly reduces the salinity on the topsoil.

The Fo measured in ‘Gigante’ forage cactus pear exhibited the highest value under rainfed conditions, differing from the remaining conditions of water application. The Fv/Fm exhibited the lowest value (0.68 electrons quantum$^{-1}$) under rainfed conditions, differing from the remaining conditions (Table 3).

The Fs exhibited the highest values under the following conditions: rainfed condition; 5 L m$^{-1}$ every 15 days and 7% ETo with a 15-day irrigation interval. These differed from the remaining conditions of water application. The Fms exhibited the highest values under the conditions with water application of 5 L m$^{-1}$ every 15 days and 7% ETo with a 15-day irrigation interval, deferring from the remaining conditions. The Fvs and the quantum yield of the photosystem irrigation interval exhibited the lowest values under rainfed conditions, differing from the remaining conditions of water application.

**Table 3.** Mean values from the evaluations of chlorophyll fluorescence in ‘Gigante’ forage cactus pear under different irrigation depths and irrigation intervals.

| Treatments | Fo | Fm | Fv | Fv/Fm | Fs | Fms | Fvs | Yield |
|---|---|---|---|---|---|---|---|---|
| Rainfed condition | 307.7 A | 1044.5 A | 736.8 B | 0.68 B | 346.9 A | 864.8 B | 517.8 B | 0.56 B |
| 5 L m$^{-1}$ every 15 days | 239.3 B | 1152.0 A | 912.7 A | 0.79 A | 325.4 A | 1417.2 A | 1091.8 A | 0.77 A |
| 7% ETo (15-day II) | 251.3 B | 1148.2 A | 896.9 A | 0.78 A | 327.6 A | 1356.8 A | 1029.3 A | 0.74 A |
| 15% ETo (7-day II) | 229.2 B | 1001.1 A | 771.9 B | 0.76 A | 288.0 B | 1160.3 B | 872.3 A | 0.73 A |
| 33% ETo (3-day II) | 222.0 B | 957.8 A | 735.7 B | 0.75 A | 280.4 B | 1149.0 B | 868.6 A | 0.74 A |
| 50% ETo (2-day II) | 235.4 B | 1083.3 A | 847.9 A | 0.78 A | 275.6 B | 1122.2 B | 846.7 A | 0.72 A |
| 100% ETo (daily) | 227.2 B | 963.4 A | 736.3 B | 0.74 A | 270.3 B | 1064.5 B | 794.2 A | 0.72 A |
| Mean | 244.59 | 1050.05 | 805.46 | 0.75 | 302.03 | 1162.10 | 860.07 | 0.71 |
| CV (%) | 5.32 | 9.79 | 12.38 | 3.63 | 9.66 | 16.47 | 20.05 | 4.79 |

Means followed by the same uppercase letters in the column belong to the same grouping by the Scott-Knott criterion at significance level 5%. Fo - Minimum fluorescence; Fm – Maximal fluorescence; Fv – Variable fluorescence; Fv/Fm – Maximum photochemical efficiency; Fs – Fluorescence under steady state conditions; Fms - Maximal fluorescence with actinic illumination; Fvs – Variable fluorescence with actinic illumination; and Yield - Quantum photosynthetic yield of photosystem II.

When the photosynthetic apparatus is intact, the values of Fv/Fm vary from 0.75 to 0.85 electrons quantum$^{-1}$ (Suassuna et al., 2010). The lowest value of the Fv/Fm relationship indicates that the photochemical system of cactus plants was altered. This reduction is a defense mechanism because it reduces the absorption of light energy and, as a consequence, decreases the electron flow to the electron transport chain (Willadino, Oliveira Filho, Silva Junior, Gouveia Neto, & Camara, 2011). This suggests that the amount of photochemical energy received by the leaf is higher than the capacity of using this energy for the photosynthetic process. This results in decreases in Fv/Fm, which lead to greater dissipation of non-photochemical energy. The observed change under rainfed conditions is related to the water stress status of the plant, which suggests that the salinity of the water used for irrigation was not a limiting factor for the plant.

The quantum photosynthetic yield of photosystem II is the most important variable to know because it has a direct relationship with plant performance when subjected to limiting conditions (Tatagiba, Moraes, Nascimento, & Peloso, 2014). The water stress on the plant is evidenced under rainfed conditions, which exhibited a quantum yield value below those of the remaining conditions of water application. This reaffirms that the salinity of the irrigation water was not a limiting factor for the crop.

In the first cycle, the highest means of plant height were found under the conditions of water application with 15% ETo with a 7-day irrigation interval; 50% ETo with a 2-day irrigation interval; and 100% ETo with daily irrigation. They were clustered separately from the other conditions of water application (Table 4). In the second cycle, the highest means of plant height were found under the conditions of water application with 33% ETo with a 3-day irrigation interval, 50% ETo with a 2-day irrigation interval, and 100% ETo with daily irrigation, which formed a different group from the remaining treatments (Table 5). The plant height increased 15.72 and 47.73% under the rainfed conditions in comparison with the highest value, for the first and second cycles, respectively. In the first cycle, the number of cladodes exhibited the highest means under the conditions of water application with 7% ETo with a 15-day irrigation interval, 50% ETo with a 2-day irrigation interval, and 100% ETo with daily irrigation, which clustered into a different grouping by the Scott Knott criterion (Table 4). For the second cycle (Table 5), the highest mean values were observed under the conditions 33% ETo with a 3-day irrigation interval, 50% ETo with a 2-day irrigation interval, and 100% ETo with daily irrigation, which were clustered into a group that differed from the remaining treatments. The increase in the number of cladodes of ‘Gigante’ forage cactus pear under the rainfed condition for the highest value was 21.01 and 49.38% for the first and second production cycles, respectively.

**Table 4.** Average morphometric characteristics of ‘Gigante’ forage cactus pear under different irrigation depths associated with different irrigation intervals.

| Treatments | Morphometric characteristics- 1st cycle | | | | |
|---|---|---|---|---|---|
| | HEI (cm) | NC (Unit.) | CL (cm) | CW (cm) | CAI ($m^2$ $m^{-2}$) |
| Rainfed condition | 72.84 B | 9.33 B | 22.03 A | 11.88 A | 1.61 B |
| 5 L $m^{-1}$ every 15 days | 71.00 B | 8.63 B | 23.42 A | 12.90 A | 1.58 B |
| 7% ETo (15-day II) | 72.21 B | 10.25 A | 23.82 A | 12.58 A | 1.85 B |
| 15% ETo (7-day II) | 80.63 A | 9.08 B | 24.78 A | 13.38 A | 1.79 B |
| 33% ETo (3-day II) | 75.84 B | 9.75 B | 24.31 A | 13.18 A | 1.86 B |
| 50% ETo (2-day II) | 84.29 A | 11.25 A | 24.16 A | 13.31 A | 2.29 A |
| 100% ETo (daily) | 84.00 A | 11.29 A | 25.09 A | 13.42 A | 2.47 A |
| Mean | 77.26 | 9.94 | 23.94 | 12.95 | 1.92 |
| CV (%) | 7.08 | 11.80 | 8.41 | 7.53 | 21.30 |

HEI – Plant height; NC – number of cladodes; CL – Cladode length; CW – Cladode width; and CAI – Cladode area index. Means followed by the same uppercase letters in the columns belong to the same grouping by Scott-Knott criterion at significance level 5%.

In the second cycle, the cladode length means clustered into a group with the highest means for the conditions 5 L $m^{-1}$ every 15 days, 15% ETo with a 7-day irrigation interval, 33% ETo with a 3-day irrigation interval, 50% of ETo with a 2-day irrigation interval, and 100% ETo with daily irrigation, which differed from the remaining conditions (Table 5). The cladode widths under 15% ETo with a 7-day irrigation interval, 33% ETo with a 3-day irrigation interval, 50% of ETo with 2-day irrigation interval, and 100% of ETo with daily irrigation formed a group with the highest mean values, which differed from the remaining conditions.

The cladode area index of ‘Gigante’ forage cactus pear in the first cycle clustered into two groupings in which the highest means were observed under the conditions 50% ETo with a 2-day irrigation interval and 100% ETo with daily irrigation, which differed from the remaining conditions (Table 4). In the second cycle, the water application conditions 33% ETo with a 3-day irrigation interval, 50% ETo with a 2-day irrigation interval, and 100% ETo with daily irrigation generated the highest means values for cladode area index, which formed a grouping that differed from the remaining conditions (Table 5). There was an increase of 53.42 and 126.26% in the cladode area index from the rainfed treatment to the highest observed means for the first and second cycles, respectively.

**Table 5.** Mean morphometric characteristics of 'Gigante' forage cactus pear under different irrigation depths associated with different irrigation intervals.

| Treatments | Morphometric characteristics – 2nd cycle | | | | |
|---|---|---|---|---|---|
| | HEI (cm) | NC (Unit.) | CL (cm) | CW (cm) | CAI ($m^2$ $m^{-2}$) |
| Rainfed condition | 66.96 B | 10.63 B | 24.84 B | 11.87 B | 1.98 B |
| 5 L $m^{-1}$ every 15 days | 73.62 B | 10.63 B | 27.52 A | 13.97 B | 2.51 B |
| 7% ETo (15-day II) | 68.75 B | 9.58 B | 25.24 B | 13.12 B | 1.93 B |
| 15% ETo (7-day II) | 81.08 B | 12.21 B | 27.06 A | 14.73 A | 2.97 B |
| 33% ETo (3-day II) | 86.92 A | 12.79 A | 28.47 A | 15.32 A | 3.39 A |
| 50% ETo (2-day II) | 97.63 A | 13.92 A | 29.34 A | 15.76 A | 3.89 A |
| 100% ETo (daily) | 98.92 A | 15.88 A | 29.84 A | 16.02 A | 4.48 A |
| Mean | 81.98 | 12.23 | 27.47 | 14.39 | 3.02 |
| CV (%) | 10.82 | 17.26 | 6.34 | 7.71 | 24.81 |

HEI – Plant height; NC – Number of cladodes; CL – Cladode length; CW – Cladode width; and CAI – Cladode area index. Means followed by the same uppercase letters in the columns belong to the same grouping by Scott-Knott criterion at significance level 5%.

Plant height and number of cladodes are associated with each other due to cladode placement on the plant, on which one cladode is attached to the top of another cladode, and consequently, the greater the number of cladodes, the taller is the plant. The greater number of cladodes indicates a relationship between water availability to the crop and the higher sprouting of buds by the plant. The forage cactus pear, when grown under conditions of water availability, functions as a C3 plant. The PEP carboxylase enzyme becomes inactive during the daytime, and the nocturnal stomatal opening is no longer advantageous. Crassulacean acid metabolism (CAM), under severe abiotic stress, exhibits a higher intensity of expression (Taiz, Zeiger, Møller, & Murphy, 2017); however, changes in crop management may enhance the radiation use and nutritional status of the plant with a consequent increase in photosynthetic rates, growth, yield, and nutritional composition (Silva et al., 2013a; Donato et al., 2014).

The significant increase in the cladode area index with saline irrigation water in comparison with rainfed conditions is linked to the increase in the number of cladodes in the first cycle and to the increase in the number, length, and width of cladodes in the second cycle. A higher cladode area index is an important characteristic from a plant physiology standpoint, as it means a higher area to capture the photosynthetic active radiation and, therefore, higher crop yields.

The highest means of the morphometric characteristics of cactus pear under the conditions of higher water availability indicate that even with the use of saline water, irrigation gives better conditions for crop development, perhaps due to the increase in photosynthetic rates and, as a consequence, greater plant growth.

**Table 6.** Mean yield values of 'Gigante' forage cactus pear under different irrigation depths with different irrigation intervals.

| Treatments | Yield (Mg $ha^{-1}$) | | | |
|---|---|---|---|---|
| | --------- 1st cycle -------- | | -------- 2nd cycle -------- | |
| | GMY | DMY | GMY | DMY |
| Rainfed condition | 55.81 B | 4.59 A | 78.53 B | 5.76 B |
| 5 L $m^{-1}$ every 15 days | 61.00 B | 3.69 A | 103.75 B | 5.34 B |
| 7% ETo (15-day II) | 63.88 B | 5.02 A | 116.43 B | 6.33 B |
| 15% ETo (7-day II) | 66.46 B | 4.93 A | 142.27 B | 6.29 B |
| 33% ETo (3-day II) | 96.19 A | 6.07 A | 187.43 A | 8.76 A |
| 50% ETo (2-day II) | 107.69 A | 7.73 A | 198.50 A | 10.26 A |
| 100% ETo (daily) | 117.88 A | 6.91 A | 218.20 A | 10.57 A |
| Mean | 81.27 | 5.56 | 149.30 | 7.61 |
| CV (%) | 35.90 | 34.21 | 23.32 | 21.62 |

Means followed by the same uppercase letters in the columns belong to the same grouping by Scott-Knott criterion at significance level 5%. GMY – Green mass yield; DMY – Dry matter yield.

The green mass yield of 'Gigante' forage cactus in the first cycle (Table 6) exhibited the highest values under the conditions of water application of 33% ETo with a 3-day irrigation interval, 50% ETo with a 2-day irrigation interval, and 100% ETo with daily irrigation, which clustered into a grouping that differed from the remaining conditions. In the first cycle, comparing the highest observed value with that of the rainfed treatment, there was an increase of 111.22% in green mass yield.

In the second cycle, the green mass yield behaved in a similar way, as the highest means clustered under the conditions of water application of 33% ETo with a 3-day irrigation interval, 50% ETo with a 2-day irrigation interval, and 100% ETo with daily irrigation, which differed from the remaining conditions. When comparing the highest observed value with that of the rainfed treatments, there was an increase of 177.87% in green mass yield.

The dry matter yield of 'Gigante' forage cactus pear in the second cycle formed a grouping in which the highest values were under the conditions of water application of 33% ETo with a 3-day irrigation interval, 50% ETo with a 2-day irrigation interval, and 100% ETo with daily irrigation, which differed from the remaining conditions. When comparing the highest observed value with that of the rainfed treatment, the increase in dry matter yield was 85.51%.

The results we obtained imply that irrigation with saline water promoted no reduction in yield for forage cactus pear. This may be because of the storage of ions in large vacuoles of the cactus pear as well as the accumulation of organic solutes in these vacuoles. There are some mechanisms of ionic balance in plants, such as ion allocation in the vacuoles, regulation of ion concentration by increasing the succulence of the tissues, production and accumulation of organic composts to promote osmotic adjustment between the cytoplasm and different cellular compartments (Larcher, 2000).

Considering the sustainability of agricultural production, using the condition of saline water application with 33% ETo and a 3-day irrigation interval significantly increases the forage cactus pear yield in comparison with rainfed conditions. The highest values of the evaluated characteristics found in the second production cycle are linked to the longer period of application of the treatments (230 days), whereas in the first production cycle, the period was shorter (120 days).

The water-use efficiency of 'Gigante' forage cactus pear in the first cycle formed three groupings (Table 7). The first grouping was formed by the condition 5 L $m^{-1}$ every 15 days. The second grouping was formed by the condition 7% ETo with a 15-day irrigation interval. The third grouping was formed by the remaining conditions of water application.

In the second cycle, the highest mean values of water-use efficiency clustered into a grouping in which the conditions of water application 5 L $m^{-1}$ every 15 days and 7% ETo with a 15-day irrigation interval differed from the remaining conditions.

**Table 7.** Mean values of water-use efficiency (kg $ha^{-1}$ $mm^{-1}$) for green mass yield of 'Gigante' forage cactus pear under different irrigation depths with different irrigation intervals.

| Treatments | ---------- 1st cycle ---------- | | ---------- 2nd cycle ---------- | |
|---|---|---|---|---|
| | WUE[1] | WUE[2] | WUE[1] | WUE[2] |
| Rainfed condition | 68.32 A | ----------- | 100.47 A | ----------- |
| 5 L $m^{-1}$ every 15 days | 71.19 A | 1533.72 A | 123.26 A | 925.50 A |
| 7% ETo (15-day II) | 72.68 A | 1032.89 B | 136.42 A | 843.28 A |
| 15% ETo (7-day II) | 70.08 A | 505.84 C | 134.89 A | 472.60 B |
| 33% ETo (3-day II) | 87.34 A | 338.25 C | 141.89 A | 303.81 B |
| 50% ETo (2-day II) | 85.55 A | 243.79 C | 124.69 A | 219.04 B |
| 100% ETo (daily) | 69.32 A | 133.43 C | 84.27 A | 116.19 B |
| Mean | 74.93 | 631.32 | 120.84 | 480.07 |
| CV (%) | 30.82 | 47.06 | 33.70 | 45.81 |

Means followed by the same uppercase letters in the columns belong to the same grouping by Scott-Knott criterion at significance level 5%. [1]Water-use efficiency when considering the gross irrigation depth and the rain that occurred in the crop cycle. [2]Water-use efficiency when considering only the gross irrigation depth applied to the irrigated treatments.

The water-use efficiency of 'Gigante' forage cactus pear, when considering only the gross irrigation depth on irrigated treatments (Table 8), clustered into a grouping with the highest means under the conditions of water application 5 L $m^{-1}$ every 15 days and 7% ETo with a 15-day irrigation interval, which differed from the remaining conditions. In the second cycle, the highest values were observed under the conditions of 5 L $m^{-1}$ every 15 days and 7% ETo with a 15-day irrigation interval, which formed a grouping and differed from the remaining conditions.

Water-use efficiency, considering green mass yield in the first cycle and dry matter yield in the second cycle, behaved in a similar way as the highest values grouped in the conditions with higher availability of saline water.

The highest availability of saline water provided an increase in crop yield (Table 6) and, as a consequence, higher WUE. This indicates that the application of saline water improves the uptake of water by forage cactus as a result of higher WUE. The lowest values of WUE under the conditions with lower availability of water to the crop are associated with the lowest values of yield recorded, which are related to the lowest plant growth rates (Tables 4 and 5). Therefore, higher values of WUE of forage cactus pear can be attained under conditions with higher application of saline water.

**Table 8.** Mean values of water-use efficiency (kg $ha^{-1}$ $mm^{-1}$) for dry matter yields of 'Gigante' forage cactus pear under different irrigation depths with different irrigation intervals.

| Treatments | ---------- 1st cycle ---------- | | ---------- 2nd cycle ---------- | |
|---|---|---|---|---|
| | WUE[1] | WUE[2] | WUE[1] | WUE[2] |
| Rainfed condition | 5.61 A | ---------- | 10.58 A | --------- |
| 5 L $m^{-1}$ every 15 days | 4.32 A | 92.94 A | 6.37 A | 47.85 A |
| 7% ETo (15-day II) | 5.71 A | 81.09 A | 7.39 A | 45.69 A |
| 15% ETo (7-day II) | 5.19 A | 37.51 B | 5.83 A | 20.43 B |
| 33% ETo (3-day II) | 5.51 A | 21.34 B | 6.63 A | 14.19 B |
| 50% ETo (2-day II) | 6.14 A | 17.49 B | 6.47 A | 11.37 B |
| 100% ETo (daily) | 4.06 A | 7.82 B | 4.06 A | 5.59 B |
| Mean | 5.22 | 43.03 | 6.76 | 24.19 |
| CV (%) | 30.32 | 39.45 | 34.81 | 46.72 |

Means followed by the same uppercase letters in the columns belong to the same grouping by Scott-Knott criterion at significance level 5%. [1]Water-use efficiency when considering the gross irrigation depth and the rain that occurred in the crop cycle. [2]Water-use efficiency when considering only the gross irrigation depth applied to the irrigated treatments.

## Conclusion

Applying saline water (3.6 dS $m^{-1}$) as irrigation water to 'Gigante' forage cactus pear does not lead to salinization of red-yellow Latosol (Oxisol) after two production years and a rainy season.

Using saline water (3.6 dS $m^{-1}$) to water forage cactus pear does not stress the plant.

The condition of saline water application with 33% ETo with a 3-day irrigation interval promotes increased plant height, number of cladodes, cladode area index, green mass yield, dry matter yield, and water-use efficiency of 'Gigante' forage cactus pear.

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