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# Agronomic and mineral characterization of cactus varieties under different doses of phosphorus

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**Abstract.** The forage cactus stands out in animal feed, as it adapts to the climatic conditions of the semi-arid region and has a high-water content with benefits for animals fed with this forage plant. The objective of this study was to evaluate the agronomic and mineral characteristics of different forage cactus varieties managed under phosphate fertilization. A randomized blocks design was used, with split-plots in the space, the plots being the forage cactus varieties (Giant sweet clone (*Nopalea cochenillifera* (L.) Mill.), Little sweet clone (*Nopalea cochenillifera* (L.) Mill) and Mexicana (*Opuntia tuna* (L.) Mill)) and the subplots the doses of phosphorus (0, 30, 60 and 90 kg P ha$^{-1}$ year), with four repetitions. The evaluations and cuts were performed two years after planting. The data were submitted to analysis of variance with significance level of 5%. In the mean comparison between the forage cactus pear varieties, the Tukey's test was used. Statistical analyzes were performed using the software SISVAR. The variety Mexicana presented higher values of perimeter, width, and green mass per plant. The variety Giant sweet clone obtained higher values of thickness and length. The highest number of cladodes and the shortest length, perimeter and width were observed on the variety Little sweet clone. Regarding the variety Little sweet clone, a quadratic response was observed for the mineral matter, calcium, zinc and manganese contents and linear response for phosphorus and iron contents, in relation to the increase of phosphorus doses. Mexicana and Giant sweet clone varieties presented quadratic response in the doses of phosphorus for calcium, iron, zinc, and manganese contents. Phosphate fertilization promotes important changes in the agronomic characteristics of the cactus pear varieties, especially in the increase of cladodes and yield. The minerals of the cactus pear are affected by the dosage of the phosphate fertilizer and by the genotypic difference of the plant.

***Keywords***: *growth, fertilization, Nopalea* sp.*, Opuntia* sp., yield of forage

## Introduction

Semi-arid regions present an irregular distribution of rainfall throughout the year, and associated to this, the soils present low fertility and low water retention (Jardim *et al.,* 2020). In these regions, pastures may not meet the nutritional requirements of animals (Dubeux Junior *et al.,* 2010). Thus, the productive performance of livestock in semi-arid regions has been limited by the low high efficiency in water use, which justifies their good adaptability to the soil and climate conditions of the semi-arid region (Lucena *et al.,* 2021).

The cactus because of its morphophysiological characteristics that allows adaptation to the soil and climatic conditions of semi-arid regions, has been cultivated on a large scale, becoming one of the main forage plants used in animal feeding in the dry season (Dubeux Junior *et al.,* 2010). On the other hand, considering that the Brazilian northeastern land structure is formed mostly by small properties, the use of fertilization is an important management strategy to increase the efficiency of forage production. In addition, it is important to know the factors that can contribute to a greater efficiency of fertilizer use, providing higher productivity (Goh and Hardter, 2003). Among the nutrients, phosphorus deserves attention, as it is important for the formation, storage and use of energy by plants, acting in the transport of energy and in tropical soils, which are weathered, it is considered a limiting factor in the development of plants (Trindade *et al.,* 2011).

Thus, the objective in this study was to evaluate the growth, production and mineral composition of different forage cactus pear varieties grown under different doses of phosphate fertilization.

## Material and Methods

The study was carried out at the Experimental Farm of the Federal University of Piauí, Professor Cinobelina Elvas Campus, located in Alvorada do Gurgueia, Piauí, Brazil. The city is located at 8° 22’ 30” south and 43° 50’ 48” west, with an altitude of 239 m (Figure 1). The climate of the region is classified as tropical dry (Nunes, 2011). The climate of the region is semi-arid with soil type dystrophic yellow latosol. The climatic data observed during the experimental period were obtained in a meteorological station located in that region (Figure 1).

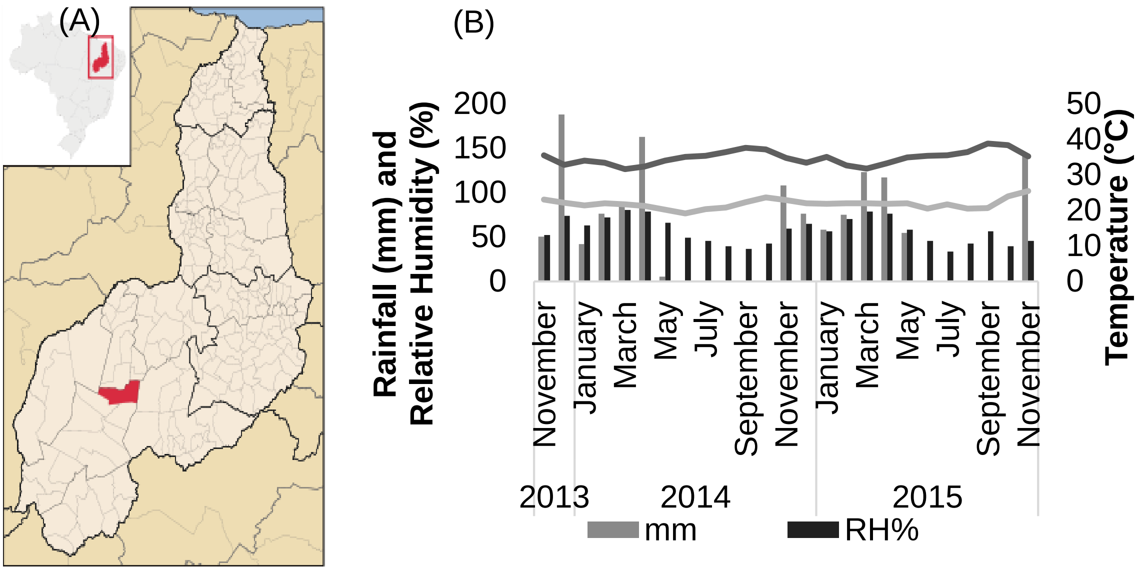


**Figure 1.** Map of the city where the experiment was carried (A) out and Meteorological data of the experimental site, from November 2013 to November 2015 (B).

Before the beginning of the experiment, representative soil samples of the area (0-20-cm-deep layer) were collected for analysis and chemical characterization. Compound samples were sent to the Soil Laboratory of the Federal University of Piauí - Cinobelina Elvas Campus, located in Bom Jesus, Piauí. The values obtained in the soil analyzes were: pH in water = 5.40; phosphorus (P) = 6.6 mg $dm^{-3}$; potassium (K) = 21.19 mg $dm^{-3}$; calcium (Ca) = 2.4 cmol $dm^{-3}$; magnesium (Mg) = 0.6

cmol $dm^{-3}$; aluminum (Al) = 0.0 cmol $dm^{-3}$; hydrogen + aluminum (H + Al) = 3.5 cmol $dm^{-3}$; sum of bases (SB) = 3.1 cmol $dm^{-3}$; Effective CEC (t) = 3.1 cmol $dm^{-3}$; CEC at pH 7.0 (T) = 6.5 cmol $dm^{-3}$; saturation of bases (V) = 46.8%, saturation by aluminum (m) = 0.0% and organic matter (OM) = 0.0%.

It was not necessary to perform soil correction based on the saturation of bases obtained in the soil analysis and according to the requirement of the plant. The base fertilization consisted of the application of 50 kg $ha^{-1}$ of nitrogen (urea with 45% of N) and 50 kg $ha^{-1}$ of potassium (potassium chloride, 48% of $K_2O$) and the source of phosphorus was simple superphosphate (18% $P_2O_5$), where the amount of phosphorus depended on the treatment. Based on the phosphorus content in the soil and the recommendations of Edvan and Carneiro (2019), the phosphorus recommendation would be 15 kg/ha, in the experiment higher doses of phosphorus in the soil were aimed at verifying the effect on plant growth. Fertilizer applications were carried out during the planting and one year after the planting, using the same dosages. In order to determine the growth and yield, a randomized complete blocks design with split-plots in the space was used. The plots consisted of the three forage cactus pear varieties: Giant sweet clone (*Nopalea cochenillifera*), Little sweet clone (*Nopalea cochenillifera*) and Mexicana (*Opuntia tuna*) and subplots the four doses of phosphorus (0, 30, 60 and 90 kg of P $ha^{-1}$ year), with four replications.

The healthy cladodes of the cactus peas varieties were obtained from the National Semiarid Institute, Paraiba, Brazil. The cladodes selected for planting had a healthy appearance, dark green in color, vigorous and free of pests and diseases, and with similar ages and weights according to each genotype, not using very young or very old cladodes. After selection, they remained in a shaded place for healing and 10 days after harvesting. The spacing used for the planting of the cactus pear varieties was 1.5 m x 0.1 allowing a density of 66,133 plants $ha^{-1}$. The plots measured 4.5 m x 5.0 m, spaced from each other by one meter of uncultivated area, with a total of 144 plants, and the subplots measured 4.5 m x 1.2 m with 36 cladodes of cactus pear. Two useful plants, located in the central region of the row in the subplots, were evaluated by subplots which corresponded to the treatment, for growth, yield and mineral analysis. The cultivation was under rainfed conditions.

The cut and evaluations of the forage cactus pear varieties occurred two years after the planting. For the evaluation of growth, two plants were used per subplot, where the following variables were measured: number of cladodes; plant height, measured with a metric trace from the soil surface to the apex of the highest cladode; cladode length, measured with a measuring tape (100 cm) from the base to the apex of the cladode; cladode width, measured with a measuring tape (100 cm) in the central region of the cladode; cladode perimeter, measured with a measuring tape (100 cm); and cladode thickness, measured with a digital precision caliper (0.05 cm), all measurements being made in the middle third of the cladodes (Figure 2).


**Figure 2.** Evaluation of non-destructive and destructive characteristics of cactus pear varieties. 1 – planting of forage plasma; 2, 3 and 4 – Evaluation of non-destructive characteristics (plant height, cladode morphometry, etc.); 5, 6, 7, 8, 9 and 10 - Evaluations of destructive characteristics (cutting, production, mineral composition, etc.).

The cut was performed at the junction between the secondary and primary cladodes using a machete (Santos *et al.,* 2010). The material was weighed to obtain the total green forage mass per plant (GFMP). For the calculation of the agronomic efficiency of the applied phosphorus (AEP), the following equation was used: AEP = total forage biomass with fertilization of P (kg) - biomass with lower fertilization of P (kg) / dose of phosphorus (kg); in kg of total forage biomass $kg^{-1}$ of applied phosphorus.

The mineral analyzes were carried out in the soil laboratory of the Federal University of Ceará. Nitrogen (N) was obtained by sulfur digestion, and then quantified by the micro Kjeldahl method. The determination of the minerals potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), phosphorus (P), sulfur (S), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) were done through nitric-perchloric digestion, according to Malavolta *et al.* (1997). In the nitric-perchloric extractor, the contents of K and Na were obtained by flame emission photometry, whereas Ca, Mg, Cu, Fe, Mn and Zn by atomic absorption spectrophotometry. Sulfur was obtained by turbidimetry of barium sulfate, phosphorus by UV-VIS spectrophotometry and Boron was determined by spectrophotometry with H-azemetry (SILVA, 1999).

The data were submitted to analysis of variance with significance level of 5%. In the mean comparison between the forage cactus pear varieties, the Tukey's test was used and for the phosphate doses a polynomial regression was used, seeking to show linear or quadratic effect. Statistical analyzes were performed using the software SISVAR version 5.0 (Ferreira, 2011). The following statistical model was used:

$$Y_{ijkl}=\mu+B_{i+}F_j+D_k+FT_{jk}+\varepsilon_{ijkl}$$

Where $Y_{ijkl}$ is the dependent variable; μ is the general mean associated with all observations; $B_i$ is th effect of the block *i*; $F_j$ is the fixed effect of the cactus pear varieties *j*; $D_k$ is the fixed effect of phosphate doses *k*; FT is the effect of interaction between phosphate doses and phosphate doses, and εijkl is the random error associated with each observation.


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## Results

### *Agronomics parameters*

Regarding the agronomic parameters of the cactus pear there was no interaction ($p>0.05$) between varieties x phosphorus doses. The varieties of forage cactus pear affected all the variables ($p<0.05$) (Table 1), while the phosphorus doses affected only the production of green forage mass per plant (GFMP) and number of cladodes (Figure 3).

**Table 1.** Agronomic characteristics of different varieties of forage cactus pear

| Varibles | Cactus pear varieties | | | | |
|---|---|---|---|---|---|
| | Mexicana | Little sweet clone | Giant sweet clone | MSE | p-value |
| Number of cladodes | 8.81 b | 15.37 a | 5.06 c | 0.91 | <0.001 |
| Thickness (mm) | 13.12 b | 13.05 b | 16.66 a | 0.51 | <0.001 |
| Lengh (cm) | 21.26 b | 16.24 c | 24.46 a | 0.6 | <0.001 |
| Perimeter (cm) | 52.90 a | 36.21 b | 53.01 a | 1.24 | <0.001 |
| Width (cm) | 14.16 a | 7.17 c | 11.27 b | 0.75 | <0.001 |
| Plant height (cm) | 60.84 a | 50.75 b | 52.43 ab | 2.48 | 0.015 |
| GFMP (Kg plant$^{-1}$) | 50.84 a | 33.28 b | 9.20 c | 4.39 | <0.001 |

*GFMP: Green Forage Mass per plant; MSE: mean standard error; Means followed by the same letters in the row do not differ by the Tukey's test at the level of 5% of probability.*

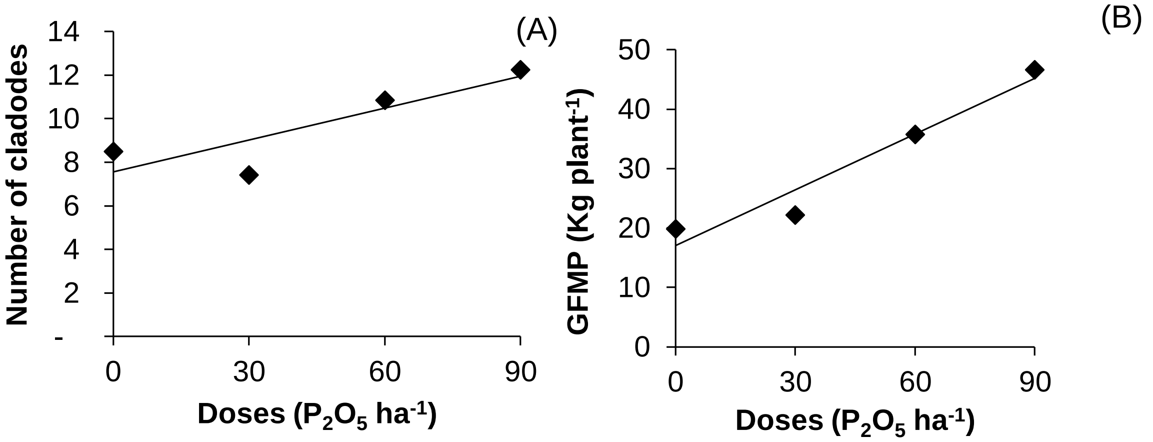


**Figure 3.** Number of cladodes per plant (A) and green forage mass per plant (GFMP)of cactus pear varieties (B) under different doses of phosphate fertilization. *significative at 5% of probability.

The highest number of cladodes and the shortest length, perimeter and width were observed on the variety Little sweet clone (Table 1). The variety Giant sweet clone presented higher results for the thickness and length of cladodes. The perimeter was similar to the variety Mexicana and both were superior to the variety Little sweet clone (Table 1). Regarding the variable width, higher values were found in the variety Mexicana and smaller in the Little sweet clone (Table 1).

The variety Mexicana presented superior height when compared to Little sweet clone, and the variety Giant sweet clone was similar to the other varieties (Table 1). The highest GFMP value was observed in the variety Mexicana and lowest in the Giant sweet clone (Table 1).

It is observed in Figure 3 that there was an effect ($p<0.05$) of the doses of phosphate on the variables number of cladodes per plant and green forage mass per plant (GFMP). The number of cladodes per plant showed a positive linear response, with increment of 1.47 cladodes for each unit of phosphorus added. The GFMP showed an increasing linear response, with an increase of 9.38 kg plant$^{-1}$ for each unit of phosphorus applied (Figure 3).

Regarding the agronomic efficiency, a quadratic response was found for the varieties Giant sweet clone and Little sweet clone (Figure 4). For the variety Little sweet clone the maximum point of agronomic efficiency was observed at the dose 64.09 kg $ha^{-1}$ of P, this implies that for each kg $ha^{-1}$ of P applied to the soil there was an increment of forage mass of 777.40 kg with the mentioned dosage.

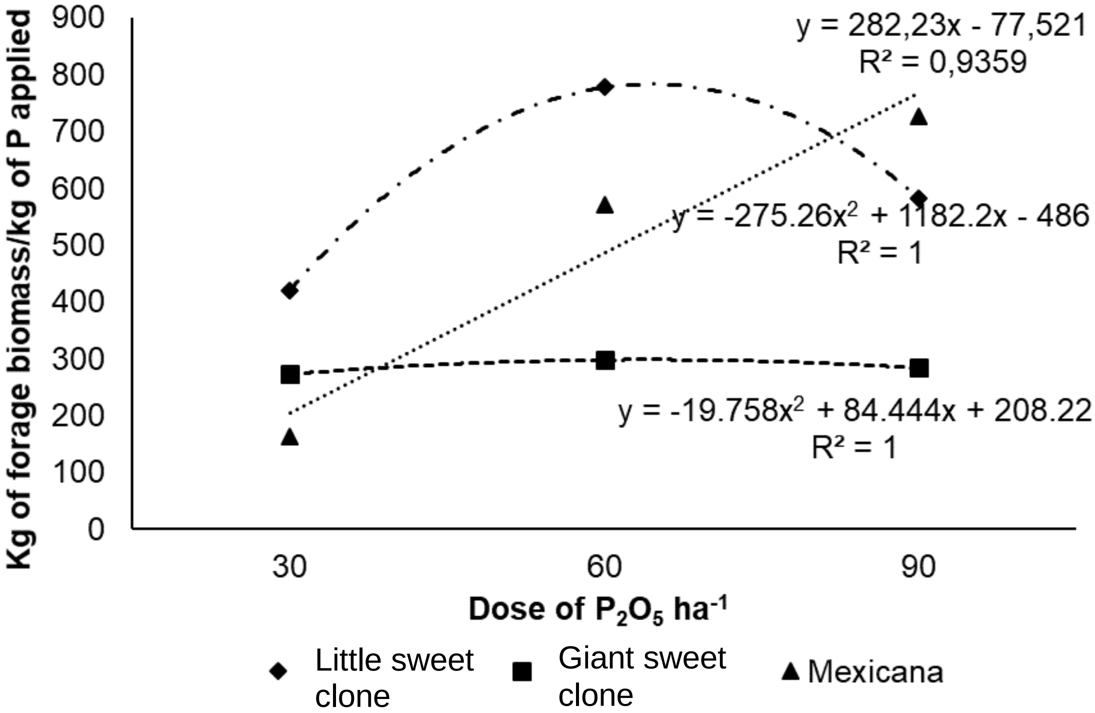


**Figure 4.** Agronomic efficiency of phosphorus doses in different varieties of forage cactus pear, Giant sweet clone and Little sweet clone *Nopalea cochenillifera* and Mexicana *Opuntia tuna*.

The variety Giant sweet clone did not present a positive agronomic efficiency in relation to the increase in P dosage in the soil. For the variety Mexicana, a positive linear response was observed, with an increase in efficiency of 282.23 kg for each unit of phosphorus added, and at the maximum dosage (90 kg $ha^{-1}$ of P) there was an increment in forage mass of 726.5 kg $ha^{-1}$ for each kg of P applied to the soil (Figure 4).

### *Mineral composition*

Regarding the mineral composition, there was effect of the interaction between varieties and phosphorus doses ($p<0.05$) on the contents of phosphorus (P), calcium (Ca), iron (Fe), zinc (Zn) and manganese (Mn) (Table 2). There was effect of the doses ($p<0.05$) on the contents of sulfur (S), copper (Cu) and Boron (B). And there was an effect of the varieties ($p<0.05$) on the contents of nitrogen (N), sulfur (S), potassium (K) and copper (Cu) (Table 3).

**Table 2.** Contents of phosphorus (P), calcium (Ca), iron (Fe), zinc (Zn) and manganese (Mn) in different varieties of cactus pear under doses of phosphate fertilization

| **Varieties** | **Doses of P (kg ha$^{-1}$)** | | | | **Regression equation** |
|---|---|---|---|---|---|
| | **0** | **30** | **60** | **90** | |
| P (g kg$^{-1}$) | | | | | |
| Little sweet clone | 1.1B | 1.5A | 1.5A | 1.6A | $\hat{Y}$= 1.2330+0.0047x $R^2$=0.73 |
| Giant sweet clone | 1.4A | 1.4A | 1.3B | 1.5A | $\hat{Y}$=1.482-0.006x+0.0007x$^2$ $R^2$=0.84 |
| Mexicana | 1.1B | 1.4A | 1.4A | 1.5A | $\hat{Y}$=1.2115+0.0040x $R^2$=0.86 |
| MSE | 0.04 | | | | |
| p-value | <0.001 | | | | |
| Ca (g kg$^{-1}$) | | | | | |
| Little sweet clone | 29.6B | 30.9B | 30.3B | 36.6A | $\hat{Y}$=30.076-0.056x+0.001x$^2$ $R^2$=0.87 |
| Giant sweet clone | 33.5B | 32.7B | 33.7A | 38.6A | $\hat{Y}$=33.616-0.087x+0.001x$^2$ $R^2$=0.98 |
| Mexicana | 37.7A | 38.9A | 28.6B | 34.5A | $\hat{Y}$=39.115-0.185x+0.001x$^2$ $R^2$=0.39 |
| MSE | 1.18 | | | | |
| p-value | <0.001 | | | | |
| Fe (mg kg$^{-1}$) | | | | | |
| Little sweet clone | 116B | 118B | 135B | 161A | $\hat{Y}$=110.249+0.507x $R^2$=0.87 |
| Giant sweet clone | 163A | 131B | 161A | 161A | $\hat{Y}$=158.653-0.714x+0.008x$^2$ $R^2$=0.40 |
| Mexicana | 114B | 166A | 129B | 130B | $\hat{Y}$=121.248+1.287x-0.013x$^2$ $R^2$=0.43 |
| MSE | 5.8 | | | | |
| p-value | <0.001 | | | | |
| Zn (mg kg$^{-1}$) | | | | | |
| Little sweet clone | 35.9A | 45.5A | 25.0B | 20.2A | $\hat{Y}$=39.271-0.165x+0.001x$^2$ $R^2$=0.47 |
| Giant sweet clone | 39.0A | 40.6A | 54.7A | 29.3A | $\hat{Y}$=36.450+0.623x-0.007x$^2$ $R^2$=0.58 |
| Mexicana | 40.7A | 36.5A | 41.1A | 48.5A | $\hat{Y}$=40.404-0.196x+0.003x$^2$ $R^2$=0.97 |
| MSE | 5.0 | | | | |
| p-value | 0.020 | | | | |
| Mn (mg kg$^{-1}$) | | | | | |
| Little sweet clone | 121A | 125A | 129A | 120A | $\hat{Y}$=124.011+0.757x-0.009x$^2$ $R^2$=0.74 |
| Giant sweet clone | 111A | 121B | 119A | 118A | $\hat{Y}$=110.492+0.636x-0.005x$^2$ $R^2$=0.92 |
| Mexicana | 118A | 113B | 126A | 130A | $\hat{Y}$=116.914-0.063x+0.002x$^2$ $R^2$=0.79 |
| MSE | 3.8 | | | | |
| p-value | 0.004 | | | | |

*Means followed by the same uppercase letters in the column do not differ by the Tukey's test at the level of 5% of probability. MSE: mean square error.*



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**Table 3.** Contents of sulfur (S), copper (Cu) and boron (B) in different doses of phosphorus and contents of nitrogen (N), sulfur (S), potassium (K) and copper (Cu) in different varieties of cactus pear

| **Minerals** | **Doses of P (kg ha$^{-1}$)** | | | | **MSE** | **p-Value** |
|---|---|---|---|---|---|---|
| | 0 | 30 | 60 | 90 | | |
| S (g kg$^{-1}$) | 1.2 | 1.2 | 1.1 | 1.0 | 0.02 | <0.001 |
| | $\hat{Y}$=1.2545-0.0020x $R^2$= 0.93 | | | | | |
| Cu (mg kg$^{-1}$) | 5.9 | 6.6 | 6.9 | 6.8 | 0.02 | 0.021 |
| | $\hat{Y}$=5.9502+0.0289x-0.0002$x^2$ $R^2$= 0.9833 | | | | | |
| B (mg kg$^{-1}$) | 28.7 | 37.9 | 37.9 | 41.6 | 1.21 | <0.001 |
| | $\hat{Y}$=30.7672+0.1291x $R^2$= 0.8270 | | | | | |
| **Minerals** | **Little sweet clone** | | **Giant sweet clone** | **Mexicana** | **MSE** | **p-Value** |
| N (g kg$^{-1}$) | 7.1B | | 7.3B | 8.1A | 0.18 | 0.007 |
| S (g kg$^{-1}$) | 1.1B | | 1.1B | 1.2A | 0.02 | 0.065 |
| K (g kg$^{-1}$) | 11.0B | | 13.4A | 14.0A | 0.53 | <0.001 |
| Cu (mg kg$^{-1}$) | 6.9A | | 6.2B | 6.4B | 0.17 | 0.042 |

*Means followed by the same uppercase letters in the column do not differ by the Tukey's test at the level of 5% of probability. MSE: mean square error.*

The P content showed an increasing linear response in the varieties Little sweet clone and Mexicana, obtaining an increment of 0.0047 and 0.0040 g kg$^{-1}$ for each unit of phosphorus added, respectively (Table 2). For the variety Giant sweet clone, a quadratic response was observed, with the lowest content (1.35 g kg$^{-1}$) found at the dose 42.86 kg ha$^{-1}$.

Regarding the Ca content, all varieties showed a negative quadratic response (Table 2). For Little sweet clone, Giant sweet clone and Mexicana, the minimum values of 29.51; 32.42 and 32.53 g kg$^{-1}$ were found at doses 20.07; 27.31 and 71.23 kg ha$^{-1}$, respectively.

The variety Little sweet clone showed a positive linear response for Fe, where for each unit of phosphorus added there was an increase of 0.5071 mg kg$^{-1}$ of this mineral. The variety Giant sweet clone presented a quadratic response with minimum value (144.29 mg kg$^{-1}$) observed at the dose 40.16 kg ha$^{-1}$. Whereas the variety Mexicana presented quadratic response with maximum value of 144.64 mg kg$^{-1}$ at the dose 46.31 kg ha$^{-1}$ (Table 2).

In all varieties, Zn showed quadratic response (Table 3). The varieties Little sweet clone and Mexicana presented the lowest values of 34.97 and 37.37 mg kg$^{-1}$ at doses 51.81 and 30.77 kg ha$^{-1}$, respectively. Whereas the variety Giant sweet clone presented quadratic response with the highest value (49.39 mg kg$^{-1}$) at the dose 41.55 kg ha$^{-1}$.

Regarding the Mn content, all varieties studied showed a quadratic response as the doses of phosphorus increased (Table 2). For the varieties Little sweet clone and Giant sweet clone, maximum values of 139.62 and 127.83 mg kg$^{-1}$ were found at the doses 41.19 and 53.96 kg ha$^{-1}$, respectively. Mexicana presented quadratic response with the lowest value (110.52 mg kg$^{-1}$) at the dose 12.15 kg ha$^{-1}$.

The S content showed negative linear response, with a reduction of 0.0020 g kg$^{-1}$ for each unit of phosphorus applied (Table 3). A quadratic response was observed for the Cu content, with a maximum value of 7.00 mg kg$^{-1}$ at the dose 72.25 kg ha$^{-1}$ (Table 3). The B content responded in


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an increasing linear way, showing increment of 0.1921 mg $kg^{-1}$ for each unit of phosphorus applied (Table 3).

The variety Mexicana presented the highest values of N, S and K, and the K content was similar to the one presented by Giant sweet clone. The variety Little sweet clone presented the highest concentration of Cu (Table 3).

## Discussion

### *Agronomics parameters*

The superiority of the cultivar Little sweet clone in the number of cladodes may be related to the morphophysiological characteristics of the genus *Nopalea* and the small values of length, perimeter and width are related to the smaller size of the cladodes of this cultivar (Silva *et al.,* 2014b). Although the variety Giant sweet clone did not present a large number of cladodes, the semi-open growing habit of this cultivar allows its plants to have a greater use of the solar radiation incident on the cladodes, inducing their growth. Silva *et al.* (2015b), studying three varieties of cactus pear (IPA Sertânia, little sweet clone and Mexicana) reported that the cultivar Little sweet clone presented a higher number of cladodes per plant.

The greater length and thickness of the cladodes of Giant sweet clone may be due to the semi-open growth form, which causes less shading and, consequently, a greater uptake of sunlight, favoring a higher photosynthetic rate by the plant. Moreover, the variety Giant sweet clone may have prioritized the thickness and length of the cladodes as a way of storing a greater amount of water, increasing the water reserve per plant (Silva *et al.,* 2014a). The superiority in width of the variety Mexicana is related to the oval anatomical shape of the cladodes of this variety, which allows greater growth in width in comparison to the other varieties (Silva *et al.,* 2015a).

Usually, the plants of the genus *Nopalea* are shorter the ones of the genus *Opuntia*. The lower height of the variety Little sweet clone is due to the smaller length, perimeter and width of the cladodes, considering that these parameters directly influence the size of the plant. Cavalcante *et al.* (2014) and Silva *et al.* (2015b), when evaluating different cactus pear varieties, also found lower heights for the variety Little sweet clone.

The highest GFMP value in the variety Mexicana and lowest in the Giant sweet clone might be due to the higher number of cladodes and width of Mexicana when compared to Giant sweet clone, conferring to Mexicana a greater magnitude in the cladode area index and the bigger the cladode area the greater is the storage of water in the collenchyma tissue (Goldstein *et al.,* 1991).

Although the variety Little sweet clone presented low values of length, thickness, width and height, it showed a higher green mass production than the variety Giant sweet clone, and this is due to the greater number of cladodes. The low productivity of Giant sweet clone may be related to the higher difficulty of establishment and the lesser adaptation to the climatic conditions of the region (Sales *et al.,* 2009). The difference in productivity, especially for the varieties of the genus *Nopalea*, is explained by the lower adaptation to the climatic conditions of the area where the present study was carried out, as there was a high mortality of the plants in the field, probably due to the high temperatures associated to the high air relative humidity (Figure 1).

The climatic factors, mainly, temperature and air relative humidity are fundamental to increase the productivity of C*actaceae.* For Silva and Sampaio (2015), the good yield of forage cactus pear is climatically related to an area with 750 mm of annual rainfall, air relative humidity above 40%, and daytime temperature of 25 °C, and nighttime of 15 °C. Thus, it is possible to state that there was a climate restriction, since the average annual rainfall, maximum and minimum temperature and air relative humidity were 500 mm (allied to poor distribution), 39 ± 4 ºC, 23 ºC ± 2 ºC and 34% ± 14.78, respectively (Figure 1).

The increase in green mass production of forage cactus pear with the increasing addition of phosphate fertilization was due to the stimulating effect of this nutrient on the number of cladodes per plant. Considering that, with the greater number of cladodes it is expected a higher production of green mass. The response of the number of cladodes per plant is due to the favorable effect of phosphorus on the appearance of cladodes of different orders, through the stimulation of this nutrient on the appearance and development of the areolas of both faces of the cladodes and as the photosynthetic radiation reached the areolas there was a greater possibility of generating new cladodes (Lopes, 2016).

***Mineral composition***

The high phosphorus content found in the present study may be related to the greater availability of this mineral in the soil, providing the transportation of this nutrient in the soil and greater absorption by the roots of the forage cactus pear, leading to an increase in the plant tissues (Silva *et al.,* 2012).

The high content of Ca in the forage cactus pear may be due to the accumulation of this mineral in the form of oxalate. Moreover, the more acidic pH of the soil may have impaired the uptake of Ca by the plants, since more alkaline soils allow a higher concentration of Ca in the plants' tissues (Galizzi *et al.,* 2004). According to Collier and Tibbitts (1982), factors such as drought, strong winds, high temperatures and air humidity can cause a reduction in the roots' pressure, which reduces the absorption of Ca by them.

The dynamics of Fe in the plant tissues occurred due to the effect of fertilization and edaphoclimatic conditions on the balance of this nutrient in the soil. For Nunes *et al.* (2004), factors such as low humidity, P excess and high pH can decrease the uptake of Fe by the plants due to the reduction in the movement of this element in the soil, leading to an iron deficiency in the crop. It is worth mentioning that interactions with other metals such as molybdenum, Cu and Mn might reduce the absorption of this nutrient (Malavolta, 2006). It is important to note that the Fe values found in the present study are above the range considered adequate (50.0 to 100.0 mg $kg^{-1}$) by Malavolta (2006).

Regarding the Zn, Lopes (2016) reports that fertilization with phosphorus may increase or decrease Zn uptake depending on the interaction with other nutrients as well as on the edaphoclimatic factors, which lead to changes in Zn concentration in the plant's tissues. To the Mn, it is worth mentioning that factors such as pH, organic matter and Fe, Ca and magnesium concentrations in the soil can affect the availability of Mn, decreasing the absorption by the plant and, consequently, its content in the tissues (Prado, 2008). According to Mortvedt (2001), for each increase of a soil pH unit there is a reduction of approximately 100 times in the concentration of Mn available in the soil.

The response observed to the S content can be explained by the relation between the growth rate of the crop and the nutrient absorption, where fertilizations that can potentiate the increase in biomass cause a dilution of the nutrient in the plant's tissues (Silva *et al.,* 2012; Lopes, 2016). To


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the Cu, the presence of metal ions in the soil may have led to a reduction in Cu uptake by the plant (Aref, 2011), which may lead to a decrease in Cu content in plants fertilized with high doses of phosphorus.

According to Abreu *et al.* (2007), the absorption of B depends on the pH of the soil, with higher availability in the range of pH 5.0 to 7.0. For Dubeux Júnior and Santos (2005), boron is an important micronutrient for forage cactus pear plants because it is related to their growth.

The highest value of N presented by Mexicana was related to the larger size of the cladodes, which probably had a higher content of chlorophyll allowing a greater photosynthetic efficiency of the plants. Moreover, the higher growth of the plants of the variety Mexicana may have provided a greater root growth and thus favor the absorption of these nutrients from the soil (Lopes, 2016). The similar concentration of K in the varieties Mexicana and Giant sweet clone may have been due to the greatest root growth of these two varieties, allowing higher absorption by these plants, a fact that may not have happened in the plants of the variety Little sweet clone. The higher concentration of Cu in the cactus pear Little sweet clone was related to the size of the cladodes, which allowed a higher concentration of this nutrient in their tissues.

## Conclusion

Phosphate fertilization promotes important changes in the agronomic characteristics of the cactus pear varieties Giant sweet clone, Little sweet clone and Mexicana, especially in the green forage mass per plant and number of cladodes. The minerals of the cactus pear are affected by the dosage of the phosphate fertilizer and by the genotypic difference of the plant.

## AVAILABILITY OF SUPPORTING DATA

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## COMPETING INTERESTS

The authors declare that they have no competing interests.

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## AUTHOR CONTRIBUTIONS

Conceptualization: Bárbara Silveira Leandro de Lima, Ricardo Loiola Edvan and Carlos Aldrovandi Torreão Marques; methodology: Bárbara Silveira Leandro de Lima, Ricardo Loiola Edvan, Leilson Rocha Bezerra; investigation: Bárbara Silveira Leandro de Lima, Ricardo Loiola Edvan, Romilda Rodrigues do Nascimento and Francisco Gleyson da Silveira Alves; resources: Ricardo Loiola Edvan, Carlos Aldrovandi Torreão Marques and Jucilene Silva Araújo; data curation: Ricardo Loiola Edvan, Carlos Aldrovandi Torreão Marques, Marcos Jácome de Araújo and Júlio César Azevedo Nóbrega; writing-original draft preparation: Francisco Gleyson da Silveira Alves, Bárbara Silveira Leandro de Lima, Romilda Rodrigues do Nascimento and Ricardo Loiola Edvan; writing-review and editing: Carlos Aldrovandi Torreão Marques, Leilson Rocha Bezerra, Jucilene Silva Araújo, Marcos Jácome de Araújo and Júlio César Azevedo Nóbrega; visualization: Ricardo Lola Edvan and Francisco Gleyson da Silveira Alves.

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**ETHICS STATEMENT**

Not applicable.

**CONSENT FOR PUBLICATION**

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**AVAILABILITY OF SUPPORTING DATA**

All data generated or analyzed during this study are included in this published article.

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