Phosphate fertilization increases the production and nutritional quality of forage cactus genotypes in a region of semi-arid climate

Bárbara Silveira Leandro de Lima[1], Ricardo Loiola Edvan[2], Carlos Aldrovandi Torreão Marques[3], Jacira Neves da Costa Torreão[4], Marcos Jácome de Araújo[2], Keuven dos Santos Nascimento[2], Rute Ribeiro Marins Mota[2], Francisco Gleyson da Silveira Alves[1*]

[1]Animal Science Department, Federal University of Ceara, UFC, Fortaleza, CE, Brazil.

[2]Animal Science Department, Federal University of Piaui, UFPI, Bom Jesus, PI, Brazil.

[3]Animal Science Department, Federal University of Sergipe, UFS, Campus do Sertão, SE, Brazil.

[4]Federal Institute of Sergipe, IFS, Aracaju, SE, Brazil.

*Correspondent author: gleysonufc54@gmail.com

ABSTRACT

The study aims to evaluate the effect of phosphate fertilization on yield, chemical composition and in situ degradability of cactus pear genotypes under semi-arid climate conditions. A randomized complete block design was adopted, the plots being three cactus pear genotypes [Doce and Baiano (*Nopalea cochenillifera)* and Mexicano (*Opuntia tuna*)] and the subplots four phosphorus application levels in the soil (0; 30; 60 and 90 kg ha^{-1}). The data were subjected to analysis of variance with a significance level of $P<0.05$. For the means comparison between genotypes, the Tukey's test was used and for the phosphate levels a polynomial regression was used aiming to show linear or quadratic effects. There was an isolated effect of the genotypes and phosphorus levels on the TGFM. The highest total green forage mass yield (TGFM) was observed in the genotype Mexicano with 87,830 ± 4,220 kg ha^{-1}, and there was an increase of 34,630 kg ha^{-1} of TGFM when 90 kg of P ha^{-1} was used. The neutral detergent fiber content showed linear response with increase of 0.285 g kg^{-1} for each kg of phosphorus applied. Regarding the genotype Doce, the highest degradation values of fractions "a" (soluble fraction), "b" (potentially degradable fraction) and "c" (incubation time) of the dry matter were observed at the levels 90, 0 and 90 kg P ha^{-1} year, respectively, and of the crude protein at the levels 0; 0 and 60 kg P ha^{-1} year, respectively. Phosphate fertilization increases yield and improves the nutritional value of cactus genotypes in regions of semi-arid climate.

***Keywords*:** chemical composition; degradability; *Nopalea sp*.; *Opuntia sp*.

INTRODUCTION

Semi-arid regions are characterized by irregular rainfall distribution throughout the year, with annual rainfall average of 800 mm year^{-1} (Jardim et al., 2020), causing poor ruminant animal performance due to reduced forage availability in periods of water scarcity

(Dubeux Junior *et al.,* 2010). An alternative to circumvent this situation is to use forage plants adapted to semi-arid conditions, such as those belonging to the *Cactaceae* family. In this family, plants of the genera *Opuntia* and *Nopalea* stand out because they are widely cultivated in semi-arid regions for their high yield and good nutritional quality (Tosto *et al.,* 2007; Nascimento *et al.,* 2011). The cactus pear (genus *Nopalea* and *Opuntia*) presents crassulacean acid metabolism (CAM) and high-water use efficiency, which gives it high green mass yields per hectare under semi-arid climate conditions, with values that can reach 163,00 kg ha^{-1} of green mass yield (Silva et al., 2015).

Proper knowledge of the nutritional needs of cactus pear is highly important to maximize its yield. Among soil nutrients, phosphorus deserves to be highlighted because it is an important element in plant development, especially of the root system, favoring the increase in water absorption (Cavalcante *et al.,* 2014). Moreover, soils from semi-arid regions have low phosphorus content, less of 5 mmol dm^{-3} (Silva et al., 2016a) and since minerals have a strong interaction with the soil, its absorption efficiency by the plants is low (Goedert and Lobato, 1984; Moreira and Malavolta, 2001). Providing adequate phosphorus to the cactus pear is highly important for its development in semi-arid regions. The cactus pear presents high digestibility and soluble carbohydrates content; however, it has low dry matter, crude protein and fiber content, and phosphate fertilization may interfere in these aspects. It is important to note that the nutritional value of the cactus pear may vary according to the soil fertilization management (Dubeux Junior *et al.,* 2010; Gomes *et al.,* 2018).

Thus, the objective in this study was to evaluate the production, chemical composition and *in situ* degradability of different genotypes of cactus pear cultivated under the influence of different levels of phosphate fertilization in a region of semi-arid climate.

MATERIALS AND METHODS

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

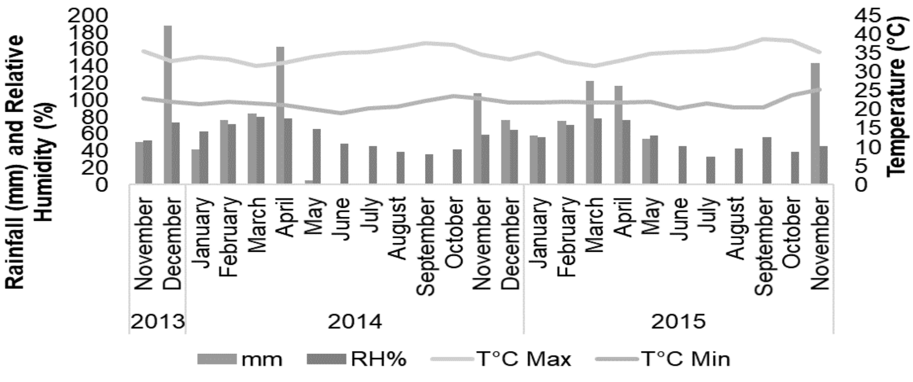

Figure 1. Meteorological data of the experimental site from November 2013 to November 2015.

Prior to the beginning of the experiment, soil samples representing the area of the 0-20 cm layer were collected for analysis and chemical characterization. Composite samples were sent to the Soil Laboratory of the Federal University of Piauí - Campus Cinobelina Elvas (UFPI - CPCE), in Bom Jesus, Piauí. The soil had the following characteristics: Sand: 716 g kg^{-1}, Silt: 34 g kg^{-1}, Clay: 250g kg^{-1}. The values obtained in the soil analysis were: pH in water= 5.40; phosphorus (P)= 9.6 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}; base saturation (V)= 46.8%, aluminum saturation (m) = 0.0% and organic matter (OM) = 0.0%. The soil of the experimental area was classified as Dystrophic Yellow Latosol, according to Raij *et al.* (2001).

It was not necessary to perform soil correction based on the soil base saturation, according to the analysis and plant requirement. The base fertilization consisted of the application of 50 kg ha^{-1} of nitrogen (urea with 45% N) and 50 kg ha^{-1} of potassium (potassium chloride, 48% K_2O), and single superphosphate (18% P_2O_5) was used as the source of phosphorus and the amount of phosphorus depended on the treatment. Fertilizers were applied during the planting (November 2013) and one year after planting (November 2014) using the same levels.

A randomized complete block design with plots subdivided in the space was adopted. The plots were the three cactus pear genotypes [Doce (*Nopalea cochenillifera*), Baiano (*Nopalea cochenillifera*) and Mexicano (*Opuntia tuna*)] and the subplots were the four levels of phosphorus (0, 30, 60 and 90 kg ha^{-1} year), with four replications.

The healthy cladodes of the cactus pear genotypes were obtained from the National Institute of Semi-arid (INSA), Paraíba, Brazil. The spacing used for planting was 1.5 m x 0.1 m allowing a density of 66,666 plants ha^{-1}. The plots measured 4.5 m x 5.0 m, spaced between them 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 cactus pear cladodes. Two useful plants were evaluated by subplot corresponding to the treatment.

The evaluations and cutting of the plants occurred two years after planting in November 2015. The cut was made at the junction between the secondary and the primary cladode using a machete (Santos *et al.,* 2010). The material was weighed in order to obtain the total green forage mass (TGFM).

Regarding the chemical composition analysis, the samples were collected, weighed and dried in a 55 °C forced ventilation oven until reaching constant weight (72 hours) and weighed again. The samples were ground in Wiley mills using 1-mm screen sieve. The chemical composition analyses were performed in the Animal Nutrition Laboratory of the Federal University of Piauí - UFPI / CPCE. The contents of dry matter (DM; Method INCT-CA G-003/1), mineral matter (MM; Method INCT-CA M-001/1), crude protein (CP; Method INCT-CA N-001/1), ether extract (EE; Method INCT-CA G-004/1), hemicellulose, cellulose and lignin by acid hydrolysis (INCT-CA, 2012; Method F-005/1), neutral detergent fiber (NDF; Method INCT-CA F-002/1) and acid detergent fiber (ADF; Method INCT-CA F-004/1) were obtained according to the methodologies described by Detmann *et al.* (2012).

To estimate total carbohydrates (TCHO), it was used the equation proposed by Sniffen *et al.* (1992): TCHO = 100 - (%CP + %EE + %MM), and, for the estimation of non-fibrous carbohydrates (NFC), the equation recommended by Hall (2003): NFC = %TCHO - %NDF.

For the evaluation of *in situ* degradability it was not possible to evaluate the genotype Baiano, since there was not enough material for the analyses, then prioritizing the analyses of chemical and mineral composition. A completely randomized design with a 4 x 2 factorial arrangement was adopted, with two cactus pear genotypes (Doce and Mexicano) and four levels of phosphate fertilization (0, 30, 60 and 90 kg P ha^{-1}).

Three Santa Inês sheep, approximately 36 months old and with an average weight of 40 kg, with permanent ruminal cannulas were used. The animals used in the experiment belong to the Small Ruminant Research Unit of the Bom Jesus Technical School, located at CPCE / UFPI. The animals were housed in individual stalls, 1.10-m wide and 2.10-m long, with cemented floor and provided with trough and feeder. All animals had free access to water and mineral salt.

The experimental ration was iso-protein formulated according to the NRC (2007). The animals were submitted to an adaptation period of 15 days. During the experimental period, the animals received a diet consisting of the cactus pear genotypes to be evaluated, fresh elephant grass (*Pennisetum purpureum*) and concentrate ration of corn meal, soybean meal and mineral supplement in a roughage:concentrate ratio of 60:40, provided two times a day (8 h and 18 h) in sufficient amount to allow 15% of leftovers.

For *in situ* incubation, after drying under forced ventilation (55 ºC) and processed in a knife mill (2 mm), the samples of the different genotypes were put in non-woven bags (TNT, 100 g/m^2), measuring 5 x 7 cm. The samples were conditioned following the ratio of 20 mg of DM per square centimeter of surface.

The sample bags were incubated in quintuplicate for each incubation time in the animal's rumen. After weighing, the bags were placed in a phyllo bag attached to a nylon thread, and then deposited in the ventral region of the rumen, where they remained during the following incubation times: 0, 2, 4, 6, 12, 24, 48, 72 and 96 hours. The bags were arranged in reverse order for incubation times to be removed simultaneously and then rinsed under running water to prevent the degradation activity of rumen microorganisms from continuing. The bags were then placed in a 55 °C forced ventilation oven for 72 hours and then cooled in a desiccator and weighed.

To estimate the kinetic parameters of *in situ* degradability of the DM and CP, the model proposed by Sampaio (1995) was used, based on the simplification of the exponential model proposed by McDonald (1981): $PD = a + b(1-e^{-ct})$; where PD is the potential ruminal degradability of the feed; "a" is the soluble fraction; "b" is the potentially degradable fraction of the insoluble fraction that would be degraded at a rate "c"; "c" is the degradation rate of fraction "b"; and "t" is the incubation time in hours. To estimate the effective degradability (ED), the following mathematical model was used: $ED = a + [(b * c) / (c + K)]$; where K is the rumen passage rate of solids, defined here as 2, 5 and 8% h^{-1}, which can be attributed to low, medium and high feed intake.

The data were subjected to analysis of variance with a significance level of $P<0.05$. To verify the premises of normality was used the test of Shapiro-Wilk. For the means comparison between the cactus pear genotypes, the Tukey's test was used and for the phosphate levels a polynomial regression was used aiming to show linear or quadratic effects. The statistical analyses were performed using the software SISVAR version 5.0 (FERREIRA, 2011).

RESULTS AND DISCUSSION

Total green forage mass yield

Regarding the total green forage mass (TGFM) there was no effect ($P>0.05$) of the interaction between genotypes and phosphorus levels. However, there was an isolated effect ($P<0.001$) of the genotypes and phosphorus levels on the TGFM (Table 1). The highest TGFM value was observed in the genotype Mexicano and the lowest in Baiano.

Table 1. Total green forage mass yield (kg ha^{-1}) of cactus pear genotypes under different levels of phosphorus fertilization.

P Levels (kg ha^{-1})				SEM	P-Value
0	30	60	90		
36,080	43,230	54,770	70,710	422	<0.001
$\hat{Y}=33,884.2 + 384.8^{*}x$ $R^2= 0.95$					
Doce		Baiano	Mexicano		
48,710b		17,040c	87,830a		

*SEM: standard error of the mean; Means followed by different lowercase letters on the row are different (P<0.05) by the Tukey's test. *: significant difference (P<0.05).*

A linear increasing response was observed for TGFM with the increase of soil phosphorus level, with an increment of 34,630 ± 422 t ha^{-1} when 90 kg of P ha^{-1} was used. P fertilization provided an increase of 384.8 kg ha^{-1} for each kg of phosphorus added.

The higher TGFM value observed in the genotype Mexicano can be explained by the larger cladode size observed in this genotype when compared to genotype Baiano, giving the genotype Mexicano a greater water storage capacity in the chlorenchyma tissue (Goldstein *et al.,* 1991).

The low productivity of genotype Baiano may be related to the higher difficulty of establishment and the lower adaptation to the conditions of the semi-arid climate region (Leite, 2009; Sales *et al.,* 2009). In a study carried out by Silva *et al.* (2015), under rainfed conditions, the green mass yield values were 124,300, 117,500 and 163,000 kg ha^{-1} for Baiano, Doce and Mexicano respectively, which are higher than the ones found in the present study. This difference in yield, especially for genotypes of the genus *Nopalea*, is explained by the lower adaptation to the climatic conditions of the area where the present study was carried out, since there was a high mortality of the plants in the field, probably due to the high temperatures associated with the low air relative humidity (Figure 1), especially at night, where temperatures above 30 °C associated with air relative humidity lower than 20% were recorded. It was observed that the increase in phosphorus levels contributed to a better genotype development.

Climatic factors, especially temperature and air relative humidity, are fundamental to increase cactus productivity. For Silva and Sampaio (2016), the good yield of cactus pear is climatically related to the area with 750 mm of annual rainfall, air relative humidity above 40%, daytime temperature of 25 ºC, and nighttime temperature of 15 ºC. Thus, it is possible to state that there was climatic restriction, since the average annual rainfall, maximum and minimum temperature and air relative humidity were 500 mm, 39 ºC ± 4 ºC, 23 ºC ± 2 ºC and 34% ± 14.78, respectively (Figure 1).

The increase in the cactus pear green mass yield with the increasing addition of phosphate fertilizer can be explained by the higher development of genotypes, improving their performance in the semi-arid climate. Phosphorus acts on the participation of compounds and on important reactions to plant growth and development (Malavolta, 2006). The P is an integral component of important compounds of plant cells, including phosphate-sugars, intermediates respiration and photosynthesis, as well as phospholipids which are part of plant membranes (Taiz et al., 2017). A characteristic of phosphate fertilization in cactus pear is the increase in the appearance of cladodes of different orders, which contributes directly to the increase of production. Phosphorus promotes a stimulation on the appearance and development of areolas on both sides of the cladodes as photosynthetic radiation reaches the areolas providing a higher generation of new cladodes (Lopes, 2016).

Chemical composition

Regarding the chemical composition, there was effect ($P<0.05$) of the interaction between the factors (genotype × phosphorus level) on all of the evaluated variables, except for the ether extract (EE) (Table 2). The EE was affected ($P<0.001$) only by the cactus pear genotypes.

The highest DM contents were found in the genotype Doce regardless of the phosphorus level (Table 2). The genotypes Mexicano and Baiano showed quadratic response. The genotype Mexicano obtained a maximum value of 91 ± 12 g kg^{-1} at the level 45.31 kg P ha^{-1} and Baiano obtained the lowest value of 82 ± 12 g kg^{-1} at the level 47 kg P ha^{-1}. The higher DM content found in the genotype Doce may be related to the fact that the other genotypes had a higher growth and thus a better osmotic balance, presenting lower amount of non-fibrous carbohydrates. It is noteworthy that regardless of genotype, the cactus pear presented low percentage of DM, which may compromise meeting the animal's DM requirement and promote digestive disorders when supplied in large quantities or as exclusive feed (Costa *et al.,* 2012). On the other hand, this characteristic of the cactus pear, regardless of the genotype, represents a large supply of water, a limiting factor in the most part of the year in semi-arid conditions.

A quadratic response was observed for all genotypes regarding the MM content (Table 2). The genotypes Doce and Mexicano revealed minimum values of 102 ± 31 and 90 ± 31 g kg^{-1} at the levels 42.21 and 50.58 kg P ha^{-1}, respectively. Whereas genotype Baiano presented maximum value of 127 ± 31 g kg^{-1} at the level 43.33 kg P ha^{-1}. Regarding the OM content, genotypes Mexicano and Baiano presented a quadratic response, the opposite of what was observed in MM, with maximum value of 909 ± 31 g kg^{-1} for Mexicano at the level 50.58 kg P ha^{-1} and minimum value of

872 ± 31 g kg^{-1} for Baiano at the level 43.33 kg P ha^{-1}. The responses observed for MM and OM may be related to the DM content of the plant, since according to Silva *et al.* (2013), with lower DM content there is a decrease in MM and OM contents due to a dilution of mineral and organic composition of plant structures.

Regarding the CP content, the genotype Doce presented a decreasing linear response, with a reduction of 0.087 g kg^{-1} for each unit of phosphorus added (Table 2). The CP content of the genotype Mexicano was higher than Doce and Baiano at the level 60 kg P ha^{-1}. The decreasing response in the CP content of genotype Doce is due to the dilution of this nutrient in the plant because of the number of cladodes in comparison to the other genotypes. In the present study for all genotypes, regardless of the phosphorus level applied, the CP levels would limit the rumen microbial activity, since levels below 70 g kg^{-1} decrease digestion due to non-compliance of nitrogen to the rumen microbiota, impairing digestibility and DM intake, and consequently animal performance (Van Soest, 1964).

The NFC presented quadratic response in the genotype Mexicano, with maximum value of 415 ± 60 g kg^{-1} DM at the level 45.55 kg P ha^{-1} (Table 2). The genotype Doce presented the highest NFC values in all phosphorus levels used, when compared to the genotypes Mexicano and Baiano. Regarding the TCHO content, genotypes Mexicano and Baiano showed quadratic response (Table 2). The genotype Mexicano presented maximum value of 844 ± 37 g kg^{-1} DM at the level 48.10 kg P ha^{-1} and genotype Baiano presented minimum value of 813 ± 37 g kg^{-1} DM at the level 46.92 kg P ha^{-1}. Probably, the genotype Doce, due to its smaller size and lighter cladodes, required fewer structural components to support the weight, which justifies the lower NFC concentration in this genotype. The variation in the quality of NFC and TCHO fractions may interfere with the energy availability for the animal due to the greater participation of plant structure constituents, affecting animal productivity (Balsalobre *et al.,* 2003).

Table 2. Chemical composition of cactus pear genotypes in relation to phosphorus levels.

Genotypes	P Levels (kg ha^{-1})				Regression Equation
	0	30	60	90	
			Dry Matter (g kg^{-1})		
Doce	101A	105A	101A	108A	$\hat{Y}=104^{ns}$
Baiano	94B	89B	87B	90B	$\hat{Y}=93.13-0.47x+0.050^{*}x^2$ $R^2=0.70$
Mexicano	74C	89B	86B	71C	$\hat{Y}=74.82+0.72x-0.000^{*}x^2$ $R^2=0.99$
SEM	12				
P-value (genotype × P level)				<0.001	
			Mineral Matter (g kg^{-1} of DM)		
Doce	115B	103B	107A	121A	$\hat{Y}=115.17-0.59x+0.000^{*}x^2$ $R^2=0.98$
Baiano	97B	121B	117A	97B	$\hat{Y}=99.79+0.130x-0.001^{*}x^2$ $R^2=0.90$
Mexicano	147A	116AB	91C	137A	$\hat{Y}=152.06-0.242x+0.002^{*}x^2$ $R^2=0.81$
SEM	31				
P-value (genotype × P level)				<0.001	
			Organic Matter (g kg^{-1} of DM)		
Doce	884 A	896A	892B	878B	$\hat{Y}=888^{ns}$

Baiano	902A	878B	882B	902A	$\hat{Y}=900.20-0.130x+0.001^{*}x^2$ $R^2=0.90$
Mexicano	852B	883AB	919A	862B	$\hat{Y}=847.90+0.242x-0.002^{*}x^2$ $R^2=0.81$
SEM		31			
P-value (genotype × P level)				<0.001	
Crude Protein (g kg^{-1} of DM)					
Doce	53A	52A	47B	46B	$\hat{Y}=54.185-0.087^{*}x$ $R^2=88.28$
Baiano	54A	51A	46B	54A	$\hat{Y}=57^{ns}$
Mexicano	57A	49A	62 A	61A	$\hat{Y}=51^{ns}$
SEM	13				
P-value (genotype × P level)				0.030	
Non-fibrous Carbohydrates (g kg^{-1} of DM)					
Doce	460A	403A	472A	430A	$\hat{Y}=44^{ns}$
Baiano	401B	359A	365B	369B	$\hat{Y}=37^{ns}$
Mexicano	300C	405A	389B	305C	$\hat{Y}=302.86+0.473x-0.005^{*}x^2$ $R^2=0.98$
SEM		60			
P-value (genotype × P level)			<0.001		
Total Carbohydrates (g kg^{-1} of DM)					
Doce	814B	828A	830A	820A	$\hat{Y}=82.5^{ns}$
Baiano	841A	822A	820A	835A	$\hat{Y}=78.391+0.250x-0.002^{*}x^2$ $R^2=0.93$
Mexicano	786B	826A	830A	780B	$\hat{Y}=83.997-0.112x+0.001^{*}x^2$ $R^2=0.91$
SEM		37			
P-value (genotype × P level)			0.002		
Ether Extract (g kg^{-1} of DM)					
	Doce	Baiano	Mexicano		
	15a	13a	6b		
SEM		1.0			
P-value (genotype)			<0.001		

*Means followed by different lowercase letters in the row and different uppercase letters in the column are different ($P<0.05$) by the Tukey's test; *: significant difference ($P<0.05$) for linear or quadratic effect; ^{ns}: not significant ($P>0.05$) for linear or quadratic effect.*

Regarding the EE contents, the genotype Doce presented the highest value, 15 ± 1.0 g kg^{-1} DM, twice the value presented by genotype Mexicano. The fact that genotype Doce has higher EE content when compared to the genotype Mexicano can be explained by the difference in cladode size of these genotypes, and the genotype Doce presents smaller cladodes when compared to the genotype Mexicano. Thus, the smaller cladodes of the cactus pear Doce may have concentrated the EE content more than in the cladodes of the genotype Mexicano. Moreover, the genotype Doce presented higher DM content than the genotype Mexicano, contributing to the higher concentration of EE in g kg^{-1} of DM. The dilution effect of EE can also be explained in terms of total biomass (DM) produced per unit area: genotype Mexicano had 7026 kg/ha vs 5054 kg/ha in genotype Doce.

In regard to the cell wall components, there was effect ($P<0.001$) of the interaction between the cactus pear genotypes and phosphorus levels on acid detergent digestible fiber (ADF), hemicellulose, lignin and cellulose (Table 3). Whereas neutral detergent digestible fiber (NDF) was affected ($P<0.005$) by the phosphorus levels.

Table 3. Cell wall components of cactus pear genotypes in relation to phosphorus levels.

Genotypes	P Levels (kg ha^{-1})				Regression Equation
	0	30	60	90	
	Acid detergent digestible fiber (g kg^{-1} of DM)				
Doce	174B	203A	143B	186A	$\hat{Y}=177^{ns}$
Baiano	205A	110C	207A	202A	$\hat{Y}=198^{ns}$
Mexicano	204A	166B	204A	204A	$\hat{Y}=181^{ns}$
SEM	2.4				
P-value (genotype x P level)				<0.001	
	Hemicellulose (g kg^{-1} of DM)				
Doce	179A	121B	217A	206A	$\hat{Y}=181^{ns}$
Baiano	134A	247A	147B	163A	$\hat{Y}=166^{ns}$
Mexicano	181A	154B	151B	178A	$\hat{Y}=172^{ns}$
SEM	6.4				
P-value (genotype x P level)				<0.001	
	Lignin (g kg^{-1} of DM)				
Doce	43AB	47A	42A	48A	$\hat{Y}=45^{ns}$
Baiano	48A	55A	40A	27B	$\hat{Y}=42^{ns}$
Mexicano	30B	51A	21B	25B	$\hat{Y}=32^{ns}$
SEM	2.2				
P-value (genotype x P level)				0.03	
	Cellulose (g kg^{-1} of DM)				
Doce	131A	156 A	99B	138C	$\hat{Y}=131^{ns}$
Baiano	190B	114 B	198A	225A	$\hat{Y}=182^{ns}$
Mexicano	155A	154 C	166A	175B	$\hat{Y}= 163^{ns}$
SEM	4.4				
P-value (genotype x P level)				<0.001	
	Neutral detergent digestible fiber (g kg^{-1} of DM)				
	359	332	357	380	$\hat{Y}=344.803+0.285^{*}x$ $R^2=0.32$
SEM	6.1				
P-value (genotype x P level)			0.005		

*Means followed by different uppercase letters in the column are different ($P<0.05$) by the Tukey's test; *: significant difference ($P<0.05$) for linear or quadratic effect; ^{ns}: not significant ($P>0.05$) for linear or quadratic effect.*

The lowest ADF content was observed in the genotype Doce (Table 3) at levels 0 and 60 kg P ha^{-1}. Genotypes Mexicano and Baiano presented higher ADF content than genotype Doce, but at the highest level applied there was no difference between the studied genotypes. Probably the climatic conditions of the region may have influenced the ADF values found in the genotypes, as the high temperature influences the reduction of cell content metabolites causing photosynthesis products to be converted into structural components of the plant (Van Soest, 1964; Simioni et al., 2014).

Regarding the hemicellulose, an effect was observed only at levels 30 and 60 Kg P ha^{-1}, with the highest values for Baiano and Doce, respectively (Table 2). Cellulose presented difference between genotypes in all levels of phosphate fertilization (Table 2), where in the level 0 the genotypes Doce and Mexicano were similar and in the highest level the genotype Baiano presented the highest content (225 ± 4.4g kg^{-1} of DM). For the lignin content, the highest value was found in the genotype Doce and only at the level 30 kg P ha^{-1} there was no difference between genotypes (Table 3). The higher lignin content in the genotype Doce may be explained by the larger number and smaller size of cladodes observed in this genotype, which may have increased the concentration. Corroborating with Cunha *et al.* (2012), who stated that the variation of nutrients in the plant is due to the characteristics of cladodes development and growth.

A linear effect of the addition of P in the soil was observed ($P<0.005$) on NDF in the cactus pear genotypes, showing an increment of 0.285 g kg^{-1} of DM for each kg of phosphorus added to the soil in cactus pear cultivation. The positive effect of phosphate fertilization on the increase of NDF content is due to the positive effect of P on plant growth, which favored the plants to reach maturity faster and, consequently, there was an increase in the NDF content of plants as it is a structural component of the plant cell wall. In the case of cactus pear this fact is beneficial for animal feed since the fiber content in this plant is low (Jardim et al., 2020).

In situ degradability

The highest disappearance rate of fraction “a” of the DM (g kg^{-1} of DM) was found at the level 90 kg P ha^{-1} in both genotypes (Table 4). Whereas for the fraction “a” of CP, it was observed that the genotype Doce presented higher values at the level 0 and Mexican at the level 90 kg P ha^{-1} year. By representing time 0 the fraction “a” may be related to the solubilization of soluble compounds such as sugars and nitrogen compounds. This similar result at the beginning of degradation is due to the lag time phase, which corresponds to the phase prior to the beginning of ruminal degradation of the material and the beginning of microbial colonization (Swinnen *et al.,* 2004). In addition, Bushinelli *et al.* (2012) reported that higher initial disappearance may be associated with greater presence of water-soluble compounds.

Table 4. *In situ* degradability of cactus pear genotypes under different phosphorus levels.

P Level€	a£	b£	c¥	PD£	Effective Degradability¥		
					2	5	8
			Dry matter				
Doce							
0	213C	664A	0.58A	878	709A	572A	494A
30	186D	520B	0.41C	870	646D	494C	417D
60	241B	484D	0.43B	853	661C	526B	457C
90	280A	543C	0.34D	918	683B	540B	471B
Mexicano							
0	626B	355C	0.26A	951	686B	548B	488B
30	444B	536A	0.20C	939	626B	489B	434B
60	479B	487B	0.26B	892	601C	450B	384B
90	744A	293D	0.19D	955	752A	667A	636A

Crude Protein							
Doce							
0	528A	626A	0.47A	936	814A	726A	679A
30	446B	444C	0.38B	966	789B	673A	616A
60	468A	479C	0.29D	952	757B	648C	598B
90	280C	543B	0.34C	933	775B	658B	595B
Mexicano							
0	407C	355B	0.20C	981	832B	753B	717B
30	520B	536A	0.23B	981	736C	617B	567C
60	484C	487A	0.28A	966	765D	656B	607C
90	543A	293B	0.15D	938	873A	814A	792A

€: kg ha^{-1}; £: values expressed as g kg^{-1} of DM; ¥: values expressed as g kg^{-1} h^{-1}; a: Soluble fraction; b: Slowly degraded fraction; c: degradation rate; PD: Potential degradability. Means followed by different uppercase letters in the column are different (P<0.05) by the Tukey's test.

In regard to the fraction "b" of DM and CP (g kg^{-1} of DM), it was observed that in genotype Doce the highest rates were found at the level 0, and in Mexicano at the level 30 kg P ha^{-1}, respectively (Table 4). The non-degradable fraction in the rumen, represented by the fraction "c" of DM (g kg^{-1} h^{-1}) was smaller in both genotypes at the level 90 kg P ha^{-1} (Table 4). As for the fraction "c" of CP, the genotype Doce presented the lowest value at the level 60 kg P ha^{-1} year and genotype Mexicano at the level 90 kg P ha^{-1} year.

A higher degradation rate of fraction "b" represents a better use by the rumen microbiota. The lower degradation rate of the potentially soluble fraction is related to the chemical composition of the cell wall, which is composed mainly of NDF, ADF and lignin (Sniffen *et al.* 1992). For Pires *et al.* (2006), the differences found in CP degradation are probably due to differences in specific protein characteristics or enzyme access in these proteins. The response observed in fraction "c" may have been due to the higher rate of degradation of the soluble fraction had happened at the same level.

The highest potential degradation values of DM (g kg^{-1} of DM) were found at the highest level applied in both genotypes, where genotype Mexicano presented higher values than the Doce. The highest potential effective degradation of DM and CP (g kg^{-1} of DM) in genotype Doce was observed in all passage rates, in the plants that did not receive fertilization. In the genotype Mexicano, the same was observed for the highest P level, respectively.

The highest potential degradation of genotypes at the highest level is due to the higher degradation rate of the soluble fraction also at the highest level. The fact that the genotype Mexicano has a greater potential degradation than genotype Doce is due to the degradation of fraction "a" being higher for Mexicano when compared to Doce. According to Benevides *et al.* (2007), the lower passage rate may provide the increase in effective degradability, while those feeds that may have a fast passage rate may not suffer adequate degradation, reducing degradability. Moreover, if the passage rate is not considered, the degradability may be overestimated, since feed particles may pass into the next compartment of the gastrointestinal tract without being completely degraded (Ladeira *et al.,* 2001).

Both genotypes presented the same response regarding the ruminal degradability of the dry matter (DM). However, the genotype Doce presented lower averages when compared to genotype Mexicano, showing a peak at 6 hours and stability after 12 hours (Figure 2). It can be observed that plants of the genotype Mexicano that received the highest level of phosphate fertilizer showed higher DM disappearance rate between 0 and 6 hours of incubation. Regarding the ruminal degradability of crude protein (CP) as a function of the incubation times, both genotypes presented the same response, with a peak at 6 hours and stability after 12 hours (Figure 3). The plants of the genotype Mexicano that received the highest level of phosphate fertilizer presented higher CP disappearance rate between 0 and 6 hours.

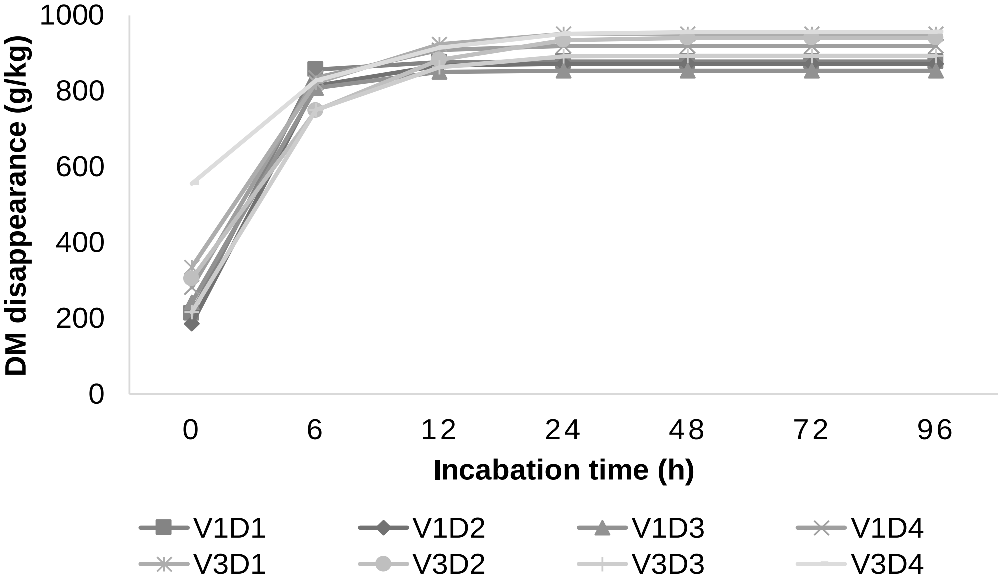

Figure 2. Potential degradability of the dry matter as a function of the time inside the rumen (h). (V1D1 - Doce and 0 kg P ha^{-1}; V1D2 - Doce and 30 kg P ha^{-1}; V1D3 - Doce and 60 kg P ha^{-1}; V1D4 - Doce and 90 kg P ha^{-1}; V3D1 - Mexicano and 0 kg P ha^{-1}; V3D2 - Mexicano and 30 kg P ha^{-1}; V3D3 - Mexicano and 60 kg P ha^{-1}; V3D4 - Mexicano and 90 kg P ha^{-1}).

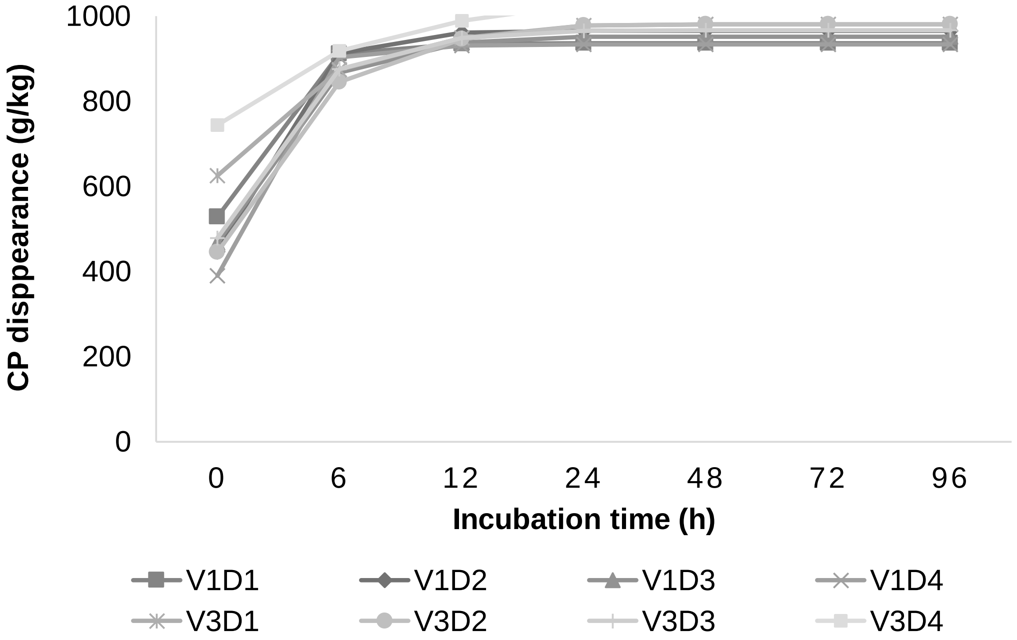

Figure 3. Potential degradability of the crude protein as a function of the time inside the rumen (h). (V1D1 - Doce and 0 kg P ha^{-1}; V1D2 - Doce and 30 kg P ha^{-1}; V1D3 - Doce and 60 kg P ha^{-1}; V1D4 - Doce and 90 kg P ha^{-1}; V3D1 - Mexicano and 0 kg P ha^{-1}; V3D2 - Mexicano and 30 kg P ha^{-1}; V3D3 - Mexicano and 60 kg P ha^{-1}; V3D4 - Mexicano and 90 kg P ha^{-1}).

The highest DM disappearance rate for the genotype Mexicano that received the highest phosphate fertilizer level was due to the higher presence of the fastest degradation fraction (Cavalcante *et al.,* 2012). Probably, the higher disappearance of the CP in the genotype Mexicano is due to the fact that these plants presented larger rumen rapidly degradable protein fractions (Cavalcante *et al.,* 2012).

CONCLUSION

Phosphate fertilization increases the production of cactus genotypes in semi-arid climate region and promotes important changes in the nutritional value, mainly in the levels of neutral detergent digestible fiber, crude protein and dry matter.

ETHICS STATEMENT

The evaluations using animals were carried out in accordance with the Guide of the National Council for Animal Experimentation Control (CONCEA), and the ethics committee of the Federal University of Piauí approved the protocol of this study under registration No. 016/14.

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.

FUNDING

Not aplicable.

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, Marcos Jácome de Araújo; investigation: Bárbara Silveira Leandro de Lima, Keuven dos Santos Nascimento, Rute Ribeiro Marins Mota and Francisco Gleyson da Silveira Alves; resources: Ricardo Loiola Edvan, Carlos Aldrovandi Torreão Marques and Jacira Neves da Costa Torreão; data curation: Ricardo Loiola Edvan, Carlos Aldrovandi Torreão Marques and Jacira Neves da Costa Torreão; writing-original draft preparation: Francisco Gleyson da Silveira Alves, Bárbara Silveira Leandro de Lima, Keuven dos Santos Nascimento and Ricardo Loiola Edvan; writing-review and editing: Carlos Aldrovandi Torreão Marques, Jacira Neves da Costa Torreão, Marcos Jácome de Araújo and Rute Ribeiro Marins Mota; visualization: Ricardo Lola Edvan and Francisco Gleyson da Silveira Alves.

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