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Jatropha curcas growth and productivity under phosphorus doses

Crescimento e produtividade de plantas de pinhão manso sob doses de fósforo

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Abstract: Information on the nutritional requirements of *J. Curcas* is extremely important in developing a fertilization manual for the species, and there are no conclusive studies with phosphorus and nutritional demand for this element is still unknown. The objective of the present study was to identify and recommend adequate phosphate fertilization for *J. curcas* growth and productivity. The experiments were conducted in two years using *J. curcas* plants four months old implanted in the spacing of 4 x 2 m. We used the randomized block design in arrangement in a split plot arrangement with five treatments (phosphorus doses of 0; 75; 150; 225 and 300 kg ha^{-1}) in the plots and two years of evaluations (2015 and 2016) in the subplots, four replications and plot of two plants. Triple superphosphate was used as phosphorus source (P_2O_5) and the doses were divided into five monthly applications starting in November in the first year and in October in the second year, shortly after the first rainfall. The results justify the need to pay special attention to phosphate fertilization because it interferes decisively in vegetable growth and grain yield *J. curcas*. The grain yield in *J. curcas* plants is closely related to the foliar concentration of phosphorus. The highest yields were obtained with foliar phosphorus concentrations of 2.81 g kg $^{-1}$ in the 1st year of cultivation and 3.35 g kg $^{-1}$ in the 2nd year of cultivation. It is recommended the doses of 208 kg ha^{-1} of P_2O_5 in the 1st year of cultivation and 214 kg ha^{-1} of P_2O_5 in the 2nd year of cultivation to obtain plants of *J. curcas* with vigorous vegetative growth and maximum yield of grains.

Keywords: vegetable oil, mineral nutrition, biofuel, grain yield

Resumo: As informações sobre as exigências nutricionais de *J. curcas* são extremamente importantes no desenvolvimento do manual de adubação para a espécie, pois não há estudos conclusivos com fósforo e a demanda nutricional para este elemento ainda é desconhecida. O presente estudo teve como objetivo identificar e recomendar a adequada adubação fosfatada para o crescimento e produtividade de plantas de *J. curcas*. Os experimentos foram conduzidos em dois anos utilizando plantas de *J. curcas* com quatro meses de idade implantadas no espaçamento de 4 x 2 m. Utilizou-se o delineamento em blocos casualizados em arranjo Split plot com cinco tratamentos (doses de fósforo iguais a 0, 75, 150, 225 e 300 Kg ha^{-1} de P_2O_5) nas parcelas e anos de avaliações nas sub parcelas, cinco repetições e parcela de duas plantas. O superfosfato triplo foi utilizado como fonte de fósforo (P_2O_5) e as doses foram parceladas em cinco aplicações mensais iniciadas no primeiro ano em novembro e no segundo ano em outubro logo após a primeira chuva. Os resultados justificam a necessidade de atenção especial a adubação fosfatada por interferir decisivamente no vigor e produtividade de grãos de plantas de *J. curcas*. O elevado número de estômatos e vigoroso crescimento vegetativo de plantas de *J. curcas* foram obtidos com adubação nas doses entre 180 e 225 kg ha^{-1} de P_2O_5. Recomenda-se para a planta de *J. curcas* a adubação fosfatada na dose de 208 kg ha^{-1} de P_2O_5 para obtenção de produtividade em torno de 140 kg ha^{-1} de P_2O_5 no 1º ano de cultivo e 214 kg ha^{-1} de P_2O_5 para obtenção de produtividade em torno de 600 kg ha^{-1} de P_2O_5no 2º ano de cultivo.

Palavras-chave: óleo vegetal, nutrição mineral, biodiesel, rendimento de grãos.

Introduction

Deforestation and charcoal production allied to burning fossil fuels and soil uses have reduced carbon hijacking and increased the gases that intensify the greenhouse effect in the Earth´s atmosphere that results from human actions and endangers natural resources. Biofuel production from commercial exploitation of energetic species has become a viable and sustainable option for partial and/or total fossil fuel substitution.

The research and political policies resulting from the creation of the National Program for Biofuel Production (PNPB) have encouraged production of this fuel in Brazil by gradually mixing biofuel with petrodiesel. Law 13.033, September 24, 2014 made it compulsory to add 7% biofuel to the petrodiesel distributed to refineries in Brazil. This program (PNPB) widened national biofuel production so that in 2015, 3.4 billion liters were produced with installed capacity to produce about 7.9 billion liters (Anp, 2015). The national program for production and use of Brazilian biofuel is based on soybean that is outstanding as the main oilseed destined for biofuel production. For greater security in the productive chain and wealth generation, the raw material should be diversified by cultivating a larger number of potential oilseeds such as *Jatropha curcas* L..

The species *J. curcas* is native to Mexico, a country where wide genetic diversity has been reported among materials found naturally (Mancillas et al., 2015). This species can reach 8 m in height and has high capacity to adapt to various climate and soil conditions, resistance to long droughts, pests and diseases (Raffi et al., 2012). The plant grows well in dry tropical regions, wet equatorial zones and arid and stony land.

The *J. curcas* seed contains 30 to 40% oil that can be converted to biofuel (Matos et al., 2018). This species has been used by rural communities for several purposes including soil conservation and a source of decomposed organic matter rich in nitrogen, phosphorus and potassium. Latex extracted from the stem and branches is used for pharmacological purposes because it has a healing effect (Matos et al., 2018). The high potential of the crop caught the attention of researchers and the species expanded rapidly throughout the world. The area planted in 2008 was 900.000 ha which increased to 4.7 million ha in 2010 with the perspective of reaching 12.8 million ha in 2016 (Contran et al., 2013). Increased commercial exploitation depends on clarifying basic agronomic aspects such as fertilization recommendation and harvest uniformity that are not yet available for the species and the developments of management techniques that ensure high yields. Information on nutritional requirements is very scarce and in Brazil fertilization is based on recommendations for *Ricinus communis* (Saikaew et al., 2014).

Research on mineral nutrition in *J. curcas* usually focuses on the element nitrogen that is recommended at about 80 kg ha^{-1} for the first years of commercial production (Laviola and Dias, 2008; Matos et al., 2014), but few conclusive studies have been carried out with phosphorus and the nutritional demand for this element is still unknown (Delima et al., 2016). Information on the nutritional requirements of *J. curcas* is extremely important to elaborate a fertilization manual for the species and determine the quantities of fertilizers to be used (Matos et al., 2014).

Phosphorus is a macronutrient required in large quantities in the meristems and plays a fundamental role in nitrogen fixing, root development, flowering and fructification of vegetable species. It is a component of essential molecules such as adenosine triphosphate, deoxyribonucleic acid, ribonucleic acid and phospholipids that are important for energy storage and cell membrane stability. Phosphorus deficiency results in atrophied plants and reduces *J. curcas* vegetative growth because it limits development of the canopy, root system and absorption of other mineral elements (Delima et al., 2011; Brady and Weil, 2013; Freibeger et al., 2014). Phosphorus is the fifth element most required by *J. curcas* and shortage limits growth, especially in the initial phase of crop establishment in the first years of cropping (Laviola and Dias, 2008). In spite of the key importance of phosphorus for *J. curcas* growth, current research carried out independently by Sousa et al. (2012) and Matos et al. (2014) did not obtain consistent data to recommend phosphorus doses for *J. curcas* plants and reported absence of relationship between phosphorus doses and grain yield.

Phosphorus concentration is low in relation to the other macronutrients in soil solution and generally ranges from 0.001 to 1 g L^{-1}. The oxidic acid soils of the Brazilian Cerrado (Savannah) have high phosphorus fixing with aluminum and iron, that decreases the availability of this mineral to plants (Barbosa et al., 2015). In these conditions the easily soluble organic phosphorus soil fractions are important in supplying this element to the plants in the highly weathered soils (oxisols), even though they have low organic matter contents (Brady and Weil, 2013). In oxidic acid soils, phosphorus applied in a localized manner may minimize the fixing reactions.

In the present study we hypothesized that the demand for phosphorus for vigorous plant growth and maximum grain yield in *J. curcas* in soils with high fixing of this element, such as the Brazilian Cerrado, could be met by supplying phosphorus in quantities higher than the absorption capacity of the plants.

The great potential of the species *J. curcas* for biofuel production raises the need to develop research to elucidate basic agronomic aspects such as mineral element requirement. Given the importance of phosphorus for plant species establishment and productivity, the objective of the present study was to identify and recommend adequate phosphorus fertilization for *J. curcas* plant growth and productivity.

Material and Methods

The experiments were carried in two consecutive years in the experimental field at the State University of Goiás, (17°67'90" S, 48°19'59" and 805 m altitude), Ipameri, Goiás, Brazil. The region has a tropical climate with a dry winter and wet summer (Aw), according to the Köppen classification (Koppen and Geiger, 1928). There are two well-defined seasons: the wet season, from October to April and the dry season from May to September. The soil in the experimental area with 2% slope is classified as oxisol (Santos et al., 2013).

For the soil analysis, a composite sample from five simple samples collected within the zig-zag experimental area was used. Based on the soil analysis result (Table 1), 1.89 mg ha^{-1} lime was applied in 2014. The applied limestone had PRNT of 80% and the application was performed on surface. In 2015 the area was not limed because of base saturation and high Ca+Mg contents. In function of the age of the plants it was decided to apply half the potassium and nitrogen doses recommended by Laviola and Dias (2008) and Matos et al. (2014). In both the years each plant received 25 g potassium and 26 g nitrogen divided into five monthly applications, starting in November in the first year and in October in the second year shortly after the first rainfall. Fertilizer was applied in a semicircle following the canopy projection, 0.20 m from the stem.

Table 1. Summary of the chemical analyses of the soil carried out in September in 2014 and 2015

Year/Depth	pH $CaCl_2$	O.M. (g dm^{-3})	P-Mehlich (mg dm^{-3})	Sortive complex (cmol dm^{-3})						V%
				K	Ca	Mg	Al	H+Al	CEC	
2014- 0-20 cm	4.9	33.0	7.4	0.2	3.5	0.9	0.0	5.0	9.61	47.9
2015 -0-20 cm	5.1	46.0	11.6	0.2	4.2	1.6	0.0	3.9	9.91	60.7

O.M. = Organic matter; V% = base saturation

Four-month old *J. curcas* plants were used in a 4 x 2 m spacing. The experiments were set up in 2014 and 2015 and the treatments were repeated in the same plants following a randomized block design in split plot arrangement with five treatments (phosphorus doses of 0, 75, 150, 225 and 300 kg ha^{-1} of P_2O_5) the plot in two years of evaluation in sub plot, four replications and two plants per plot. Triple superphosphate was used as phosphorus source (P_2O_5). In 2014 the plants received 50% of the dose of phosphorus in the planting and the rest of the doses were parceled out in five monthly applications started in November, in the second year in 2015 the plants received 50% of the dose of phosphorus in September and the rest was parceled in five applications started in October, so treatments were implemented in the last months of 2014 and 2015 and evaluations occurred between March and June of the following year in 2015 and 2016. The meteorological data (Figure 1) were obtained at the INMET meteorological station, located in Ipameri, GO, 1200 m away from the experimental area.

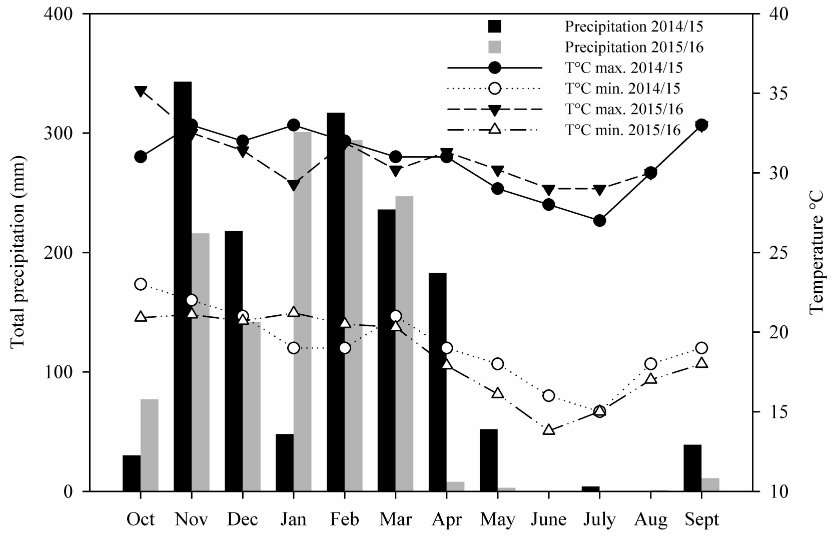

Figure 1. Average weather variables monthly: Total rainfall and minimum and maximum temperatures in Ipameri - GO (Inmet, 2017)

The physiological and nutritional analyses were carried out in april in each year by assessing the following variables: plant height, number of leaves, number of branches, stem diameter, canopy diameter, number of stomata on the abaxial and adaxial epidermis, total chlorophylls, carotenoids, leaf phosphorus content and grain yield. The productive analyses were carried out from March to June 2015 and 2016, because the *J. curcas* plant presents uneven maturity of fruits, being harvested in approximately four months, that is, from March to June.

Physiological and nutritional variables

Plant height and stem diameter were measured with graduated ruler and a digital pachymeter, respectively. The canopy diameter was measured using a graduated measuring tape between the two side extremities. The number of leaves was measured by counting all the leaves on each plant. For chlorophylls (*a* + *b*) and total carotenoids analysis were determined spectrophotometrically from the above extracts according to Lichthenthaler (1987). Leaf chlorophylls and carotenoids concentration was expressed per unit mass.

A replication of the abaxial and adaxial surfaces of the leaves was removed with colorless varnish in the region of the middle third of previously hydrated leaves. The stomata were counted in the replication with the help of an optical microscope equipped with a light chamber. Stomata density was determined by counting the stomata situated in a 1 mm² area, giving the number of stomata/area (Borges et al., 2014).

The phosphorus contents were determined on fully open healthy leaves without pest or disease attacks, located between the fourth and fifth pair of leaves below the inflorescence. The vegetable material sampled was placed in a forced air circulation chamber at 60 °C until constant mass. After drying, the samples were weighed, ground and submitted to chemical analysis following recommendations by Silva (2009).

The *J. curcas* fruits were harvested by hand when they presented dark brown coloring. After harvesting, they were peeled and dried until they reached 13% moisture when they were finally weighed.

Statistical procedure

The experiments were set up in in split plot arrangement with five treatments (phosphorus doses of 0, 75, 150. 225 and 300 Kg ha^{-1} of P_2O_5) the plot in two years of evaluation (2015 and 2016) in sub plot, four replications and two plants per plot. The results were submitted to variance and regression analysis at 5% probability. Principles components analysis was carried out using all the variables analyzed and the broken stick criterion was adopted to select the axes. Permutational multivariate analysis of variance (Permanova –Anderson, 2001) was used to assess the difference between the groups formed. All the statistical analyses were carried out using the R software (R core team, 2016).

Results

Summaries of variance analysis for all variables are shown in Tables 2 and 3. The height of plant, number of leaves, stem diameter, canopy diameter, number of branches, carotenoids, chlorophylls *a* and *b* ratio, total chlorophylls, leaf phosphorus content, stomata density in abaxial and plant productivity were higher in the 2nd year of cultivation and significantly different from 1 year of cultivation. The variables that were adjusted to the regression curcas are shown in Figure 2 and 3.

Table 2. Analysis of variance and mean test for height, number of leaves, stem diameter (SD), canopy diameter (CD), number of branches (NR) and leaf phosphorus content in *J. curcas* plants evaluated in two years (2015 and 2016), fertilized with different phosphorus doses (0; 75; 150; 225 and 300 kg ha^{-1} of P_2O_5)

		Mean squares					
Variation source	DF	Height (cm)	Nº Leaf	SD (cm)	CD (m)	NB	Content of P (g kg^{-1})
Block	3	103.57^{ns}	2823^{ns}	11.06^{ns}	13.66^{ns}	13.35^{ns}	0.071^{ns}
Year (Y)	1	89491**	166422**	21918**	184416**	25452**	0.53*
Erro 1	3	22.95	1568.9	23.03	246.8	14.4	0.01
Doses (D)	4	1315**	30271**	204.9**	514.47**	189.2**	0.66**
Y x D	4	45.74**	11781**	137.2**	603.4**	130**	0.005^{ns}
Error 2	24	58.49	1626.53	24.4	81.3	21.4	0.03
CV 1 (%)		2.28	15.59	6.83	7.65	10.91	9.63
CV 2 (%)		3.65	15.88	7.03	4.39	13.31	14.24
Year		Averages					
1º		162.37b	189.5b	46.8b	137.4b	9.6b	1.28b
2º		256.97a	318.5a	93.68a	273.2a	60.05a	1.51a

*significant at 5% and at **1% probability; ns = not significant by F test. Averages followed by the same small letter in the column do not differ at 5% probability by Newman-Keuls test

Table 3. Analysis of variance and mean test for chlorophylls *a* e *b* ratio (Chl*a*/Chl*b*), total chlorophylls (Chl), carotenoids (Car), stomata density in abaxial (SDAB), Stomata density in adaxial (SDAD) and grain yield (GY) of *Jatropha curcas* evaluated in two years (2015and 2016), fertilized with different phosphorus doses (0; 75; 150; 225 and 300 kg ha^{-1})

		Mean squares					
Variation source	GL	Chl*a*/Chl*b* (g kg^{-1})	Chl (g kg^{-1})	Car (g kg^{-1})	SDAB (mm^2)	SDAD (mm^2)	GY
Block	3	0.007^{ns}	0.09^{ns}	0.008^{ns}	11977^{ns}	100.4^{ns}	683.4^{ns}
Year (Y)	1	0.33*	16.43*	0.103*	46987.8*	0.55^{ns}	17.10**
Erro 1	3	0.01	0.75	0.008	2500.4	111.65	3569.2
Doses (D)	4	0.006^{ns}	0.44^{ns}	0.006^{ns}	8473.8*	279.09**	21425**
Y x D	4	0.009^{ns}	0.21^{ns}	0.006	1633^{ns}	45.35^{ns}	11372**
Error 2	24	0.65	0.29	0.025	2967.6	24.22	2593.08
CV 1 (%)		15.60	17.59	9.59	22.80	33.02	17.61
CV 2 (%)		20.45	11.02	16.75	24.84	15.38	15.01
Year		Averages					
1º		0.71b	4.30b	0.89b	184.9b	31.88a	132.8b
2º		0.89a	5.58a	1.00a	253.5a	32.11a	545.8a

*significant at 5% and at **1% probability; ns = not significant by F test. Averages followed by the same small letter in the column do not differ at 5% probability by Newman-Keuls test

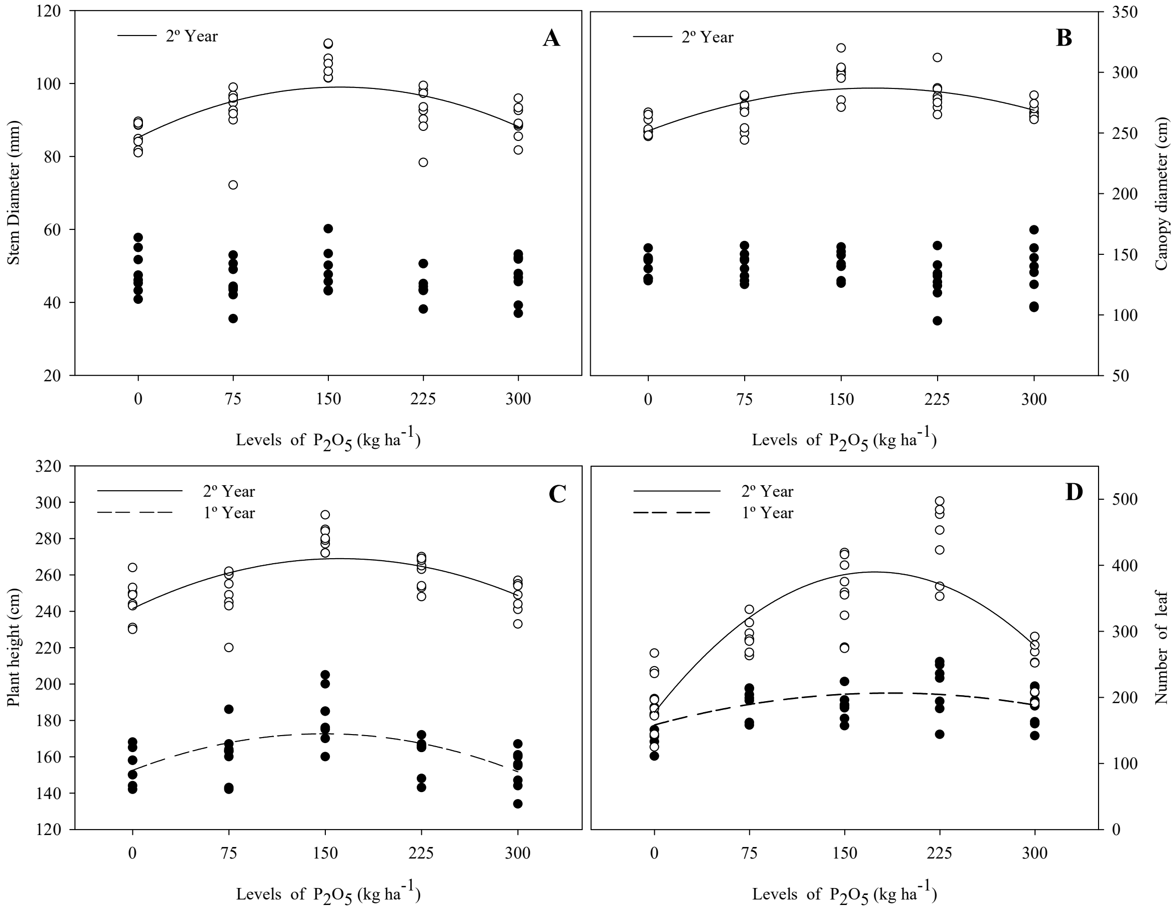

Figure 2. Regression equations for stem diameter assessed in the second cropping year($Y= 84.80 + 0.21x - 0.0007x^2$, $R^2 = 0.99^{**}$) (A), canopy diameter assessed in the second year ($Y= 251.67 + 0.41x - 0.0012x^2$, $R^2 = 0.997^{**}$) (B), plant height assessed in the first year ($Y= 152.58 + 0.27x - 0.0009x^2$, $R^2= 0.99^{**}$) and in the second year ($Y= 241.53 + 0.341x - 0.0011x^2$, $R^2= 0.99^{**}$) (C) and number of leaves assessed in the first year ($Y= 154.54 + 0.56x - 0.0014x^2$, $R^2= 0.98^{**}$) and second year ($Y= 174.88 + 2.48x - 0.0068x^2$, $R^2= 0.96^{**}$) (D) in *J. curcas* plants fertilized with different doses (0; 75; 150; 225 and 300 kg ha^{-1}) P_2O_5. **Significant at 1% probability

The results of stem diameter and canopy diameter fitted the regression curve only in the second cropping year, and in the first year there was no linear or quadratic fit. The biggest stem diameters (100 mm) and canopy diameters (288 cm) were obtained with 151 and 169 kg ha^{-1} P_2O_5, respectively. Plant height and number of leaves fitted the quadratic regression model for the two assessment years. The largest plant heights (173 cm e 268 cm) were obtained with 150 and 159 kg ha^{-1} P_2O_5 in the first and second years, respectively, and the maximum number of leaves (211 e 395) was with 198 and 214 kg ha^{-1} P_2O_5 in the first and second years, respectively.

The results for number of branches did not fit the regression curve in the first cropping year but presented a quadratic fit in the second year with maximum number of branches (68) at the 173 kg ha^{-1} P_2O_5 dose. The P_2O_5 leaf concentrations showed linear fit in the first and second cropping years. The stomata density in the abaxial epidermis fitted quadratically with maximum stomata density points (208 and 272 stomata) at the doses of 207 and 192 kg ha^{-1} P_2O_5 in the first and second year, respectively. The maximum number of stomata in the adaxial epidermis occurred with 225 kg ha^{-1} P_2O_5.

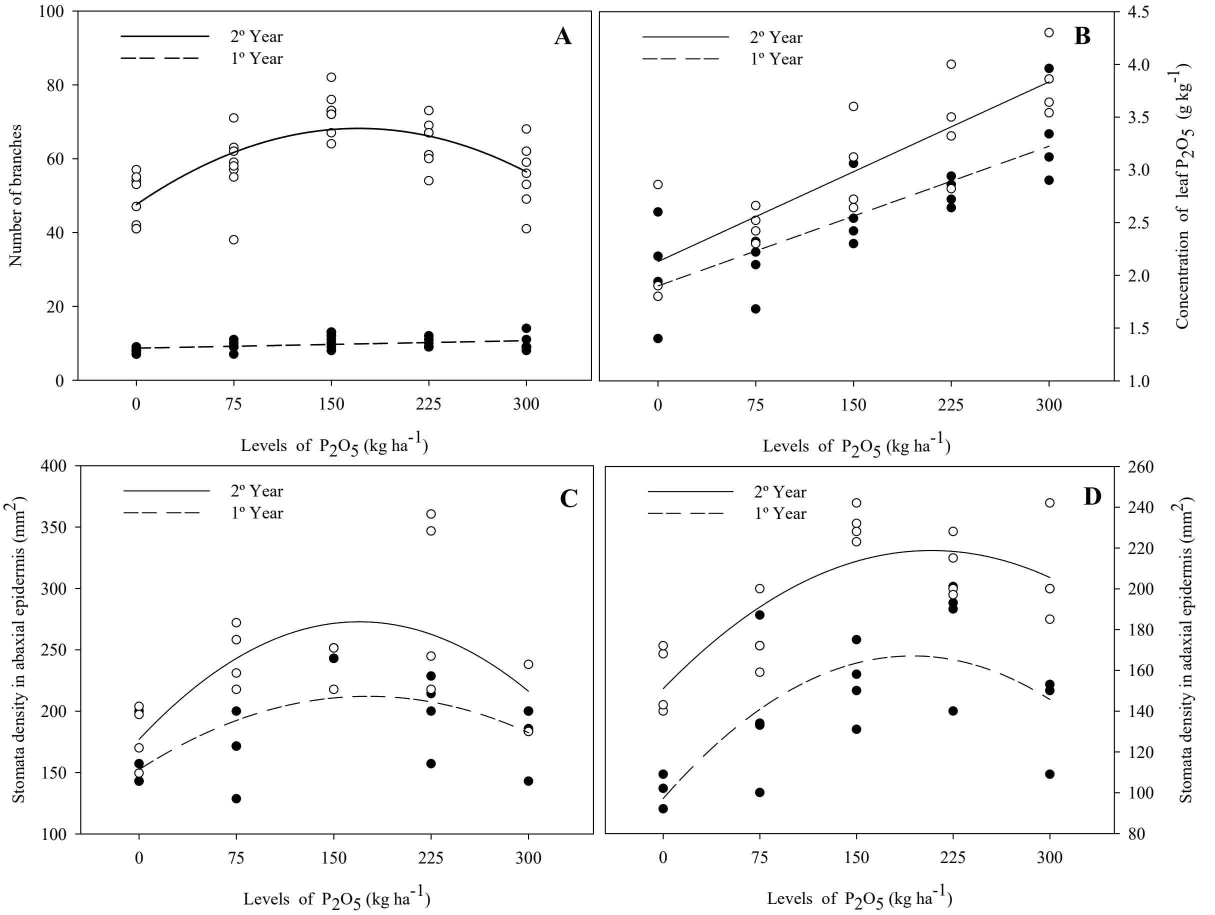

Figure 3. Regression equations for the number of branches assessed in the second cropping year ($Y= 47.58 + 0.24x - 0.0007x^2$, $R^2= 0.98^{**}$) (A), P_2O_5 leaf concentration assessed in the first year ($Y= 1.9 + 0.0044x$ $R^2= 0.98^{**}$) and second year ($Y= 2.26 + 0.0051x$, $R^2= 0.98^{**}$) (B), stomata density in the abaxial leaf epidermis assessed in the first year ($Y= 152.42 + 0.68x - 0.0019x^2$, $R^2= 0.97^*$) and second year ($Y= 177.0 + 1.13x - 0.0033x^2$, $R^2= 0.98^{**}$) (C) and stomata density in the adaxial leaf epidermis of *J. curcas* plants average of the two years of evaluation ($Y=123,6250 + 0.7295x - 0.0019x^2$, $R^2= 0.90^{**}$) (D) in *J. curcas* plants fertilized with different doses (0; 75; 150; 225 and 300 kg ha^{-1}) P_2O_5. **Significant at 1% probability

The principal component analysis showed that by the broken stick criterion only Axel 1 explained the separation of the groups formed and that the stem and canopy diameters, plant height, number of branches, total chlorophyll and yield were determinant variables for separating the groups (Figure 4). The total grain yield presented maximum points at the doses of 208 and 214 kg ha^{-1} of P_2O_5 n in the first and second cropping years, respectively.

The Table 4 refers to the recommendation of phosphate fertilization based on grain yield and leaf nutrient concentration. The maximum productivity was obtained with foliar concentration of 2.81 g kg^{-1} of P in the 1st year of cultivation and 3.35 g kg^{-1} of P in the 2nd year of cultivation.

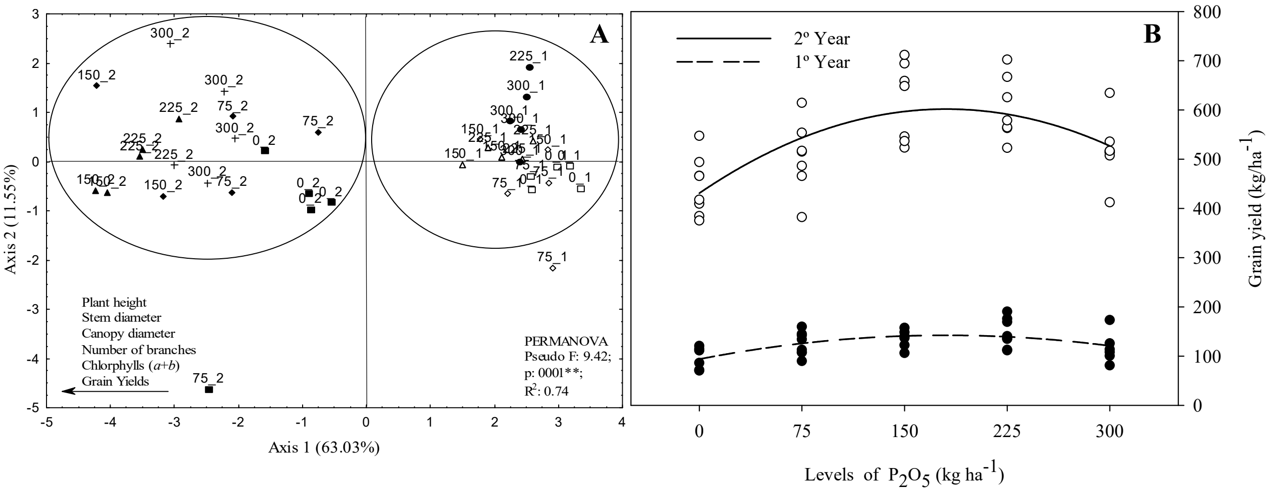

Figure 4. Principal component analysis for all the variables analyzed (A) and regression equation for grain yield assessed in the first year ($Y= 94.8 + 0.52x - 0.0013x^2$, $R^2= 0.96^{**}$) and second year ($Y= 417.62 + 2.22x - 0.0061x^2$, $R^2= 0.98^{**}$) (B) in *J. curcas* plants fertilized with different doses (0; 75; 150; 225 and 300 kg ha^{-1}) P_2O_5. **Significant at 1% probability

Table 4. Recommendation of phosphate fertilization based on foliar phosphorus concentration and grain yield of *Jatropha curcas* evaluated in two years (2015 and 2016), fertilized with different phosphorus doses (0; 75; 150; 225 and 300 kg ha^{-1}).

	1st Year		2nd Year	
Doses	Leaf Concentration P_2O_5 (g kg^{-1})	Productivity (kg ha^{-1})	Leaf Concentration P_2O_5 (g kg^{-1})	Productivity (kg ha^{-1})
0	1.90	94.75	2.26	417.62
75	2.23	126.33	2.64	550.12
150	2.56	143.29	3.02	614.00
225	2.89	145.62	3.40	609.25
300	3.22	133.33	3.79	535.88
Recomendation	**P_2O_5 208 kg ha^{-1}**		**P_2O_5 214 kg ha^{-1}**	
	2.81	146.37	3.35	614.25

Discussion

The results presented justify the need to pay special attention to phosphate fertilization because it interferes decisively in *J. curcas* plant vigor. *J. curcas* vegetable growth and grain yield were maximized in response to phosphate fertilization. The present study elucidated agronomic aspects lacking in the literature and recommended, with scientific consistency, the correct P_2O_5 dose to increase grain yield.

The results show differences in practically all the variables analyzed between the evaluation years and indicate intense vegetative growth and fast establishment of plants of *J. curcas*. The number of branches and grain yield showed the highest percentage differences between the evaluated years. The number of branches is the vegetative variable that shows the highest correlation with grain yield in *J. curcas* plants, because the inflorescences and fruits appear at the apex of the branches. Some studies with this species indicate that grain production is closely dependent on the number of branches (Fey et al., 2014; Oliveira et al., 2016).

Phosphate fertilization interfered decisively in *J. curcas* vegetative growth by increasing significantly plant height, stem and canopy diameters, number of leaves and branches. The *J. curcas* plant begins grain production in the first cropping year and competition for mineral nutrients is intense at the initial growth stage between the vegetative and reproductive stages. This the greater phosphorus availability may have increased the root system development, absorption of other mineral nutrients, especially nitrogen and increased the photosynthetic capacity of the plant. The higher production of assimilates minimized the effects of competition, allowing intense growth and high grain yield (Delima et al., 2011). According to Laviola and Dias (2008) phosphorus is important especially in the crop establishment stage for root and vegetative organ development. In some research results with young *J. curcas* plants, positive growth effects were observed in response to phosphate fertilization (Delima et al., 2011; Delima et al., 2015; Dos Santos et al., 2015).

The increase in the number of stomata in the adaxial and abaxial leaf epidermis is related to the need for greater CO_2 inflow because of the increase in leaf capacity. The intense vegetative growth and grain yield increase augment the drain force and more sucrose must have been produced at the cost of greater phosphorus use as triose phosphate exchanger between cytosol and chloroplast as reported for this, more phosphorus was stored in the foliar machinery and made available as demonstrated by the increase in foliar phosphorus concentration in relation to the applied doses. The results corroborate those found in other studies (De Lima et al., 2015; Dos Santos et al., 2015) and the absolute values are similar to those found by Laviola e Dias, (2008) of around 2.8 g kg^{-1} leaf dry matter for a potential 500 kg ha^{-1} grain yield. The increase in soil availability and phosphorus content in plants is a result of correct pH supply and correction. The liming elevates soil pH by hydroxyl production, promoting exchangeable Fe and Al precipitation, reducing P precipitation with these two metals, increasing availability.

The grain yield obtained in the present study (614 kg ha^{-1}) surpasses the productive estimate of 500 kg ha^{-1} reported by Laviola and Dias, (2008) in the second cropping year. De Souza et al. (2013) reported increase in grain yield in *J. curcas* with higher phosphorus doses. Results of the present study do not corroborate those found by Negussie et al. (2016) who concluded that there was no effect of different phosphorus doses on *J. curcas* grain yield. Sousa et al. (2012) used doses of 135 and 200 kg ha^{-1} P_2O_5 in a single cropping year and reported absence of effect on vegetative growth.

The principal component analysis separated the treatments into two large groups differentiated by cropping year. This result was due to the fact that all the variables that correlated with axis 1 presented larger maximum points in the second cropping year compared to the first year. According to Laviola and Dias (2008), phosphorus applied to *J. curcas* at the initial growth stage should always be in a higher quantity than that extracted by the plant and in the present study carried out in soils of the Brazilian Cerrado characterized by high phosphorus fixing rate with aluminum and iron, the high phosphorus doses applied in the first cropping year may have occupied the fixing sites in the soil. In the second year, with a supply of the same doses, a greater quantity phosphorus was made available to the plants. In addition, it should be noted that the maximum vegetative growth was obtained with doses of phosphorus lower than necessary for maximum grain yield. These results indicate that the grains of *J. curcas* are strong phosphorus-importing drains.

Conclusions

The highest yields were obtained with foliar phosphorus concentrations of 2.81 g kg^{-1} in the 1st year of cultivation and 3.35 g kg^{-1} in the 2nd year of cultivation.

It is recommended the doses of 208 kg ha^{-1} of P_2O_5 in the 1st year of cultivation and 214 kg ha^{-1} of P_2O_5 in the 2nd year of cultivation to obtain plants of *J. curcas*.

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