Critical phosphorus levels and availability for castor oil plant grown in different soil classes of Brazil

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Abstract

The current study aims to determine critical P levels in different soil classes and their availability for castor bean initial growth. Extraction was done using Mehlich-1 and ion-exchange resin. The experiment was conducted in a greenhouse, in a randomized blocks design with the application of five P doses, which were previously set for each of the four experimental soils (TCo: Chromic Orthic Luvisol; CXbe: Eutrophic Haplic Cambisol; CXve: Typical Eutrophic Cambisol; RY: Fluvic), with four repetitions for 40 days. In the end of the experiment, plants were harvested and shoot dry mass was weighted. At the time plants were collected, samples were gathered to determine soil P availability through Mehlich-1 and ion-exchange resin. Mehlich-1 was more efficient in phosphorus recovery in the following soils: TCo, CXbe and CXve, regardless of applied dose. Critical P levels ranged from 21.33 to 416.64 mg dm^{-3} due to the clay content in Mehlich-1, and from 30.70 to 177.55 mg dm^{-3} in resin. MPAC presented positive coefficients regarding soil clay content. The highest castor bean shoot dry mass production was found in CXve and TCo soils. It ranged from 34.65 to 33.55 g vessel^{-1} in the treatment containing the lowest P dose applications (87.94 mg dm^{-3} and 104.33 mg dm^{-3}, respectively).

Introduction

P is a macronutrient required by plants in lower amounts, despite its importance to plants' growth and development. It is one of the factors that limit yield in most crops (Xie et al., 2014). Suboptimal P fertilizer input may lead to poor growth and malfunctioning in plants, whereas over optimal P input may lead to low P efficiency (Ma et al., 2012). Most Brazilian soils have high weathering degree, large iron and aluminum oxide amounts and clay belonging to the kaolinite minerals group, which is characterized by surface charges presence, varying according to the soil solution reaction (Torres et al., 2016). Thus, soil can work as P source, showing good P input capacity to plants, or as drainer, since it strongly competes for P in the plant and leaves. However, most of the added phosphorus is fixed to soil colloids and unavailable to plants (Pavinatto et al., 2009).

As weathering increases, the soil becomes more electropositive and adsorbs more anions, such as phosphates (Novais and Smyth, 1999). Many of these highly weathered and even less weathered soils, besides having lower total P content, appear to lack P availability. Low solubility, found in most P forms, and/or the strong interaction between phosphate and the soil, in order to form low solubility compounds in different soils, is associated with different combinations of iron, aluminum, calcium, organic matter and other elements (Rolim Neto et al., 2004). To know the P level available in the soil is very important to carry out phosphorus fertilization properly, in order to increase castor oil plant yield, mainly in Brazil's Northeastern region, which is responsible for its largest crops.

Therefore, the current study aims to determine critical P levels in four soil classes and their availability to castor bean plants, through Mehlich-1 and ion-exchange Resin.

Results and Discussion

P concentrations in the soils originally checked (Table 1) are classified depending on their distance from the ground and on high RY in TCo, CXbe and CXve soils. Extraction-recovered P amount was different depending on soil type and extractor used (Table 2). Resins should theoretically work similarly with roots because they adsorb P from the solution and gradually consume the soil labile P, which has different chemical, physical and mineralogical properties (Gatibonni et al., 2005).

Settings

A more linear determination coefficient set the ion-exchange resin by regression equations between the applied P doses and the recovered P amounts by the extractors used. P concentrations used were recovered by extracting the high variability of treatments that were not supplied with P (Table 2), demonstrating the difference among soils and available P reserves. Extractors were somehow influenced by the buffering capacity, which predicts soil nutrient resistance during desorption (Novais and Smyth, 1999).

Extractors used

Among extractors used, Mehlich-1 was the one that have recovered more P, regardless of the dose applied to TCo, CXbe and CXve soils (Table 2). Such behavior can be explained by the fact that these soils presented low acidity, favoring the formation of compounds such as poorly soluble calcium phosphate (P-Ca), which probably occurred in these soils due to its high Ca level and pH value close to neutrality. Thus, Mehlich-1-recovered P levels may have been overestimated because the extractor can displace P bound to Ca, Fe and Al oxides, which are unavailable forms to plants. According to Torres et al., (2016), acid extractors predominantly dissolve P when it is attached to Ca. Small P amounts bound to Fe and Al, depending on phosphates solubility features, allowing for inferring whether extractors are less suitable acids for humid tropical region soils, which have kaolinite, iron and aluminum oxides prevalence in the soil clay fraction. However, the anion exchange resin Q in RY extracted more Mehlich-1 (Table 2). It is likely that this behavior is related to high pH and high clay content, which probably caused Mehlich-1 wear. It did not occur with the Resin due to the soil Resin solution stirring period (Alcântara et al., 2008).

According to Novais and Smyth (1999), soils with higher clay content and high acidity buffering capacity rapidly increased the initial Mehlich-1 pH to values close to those of the soil. As the SO_4^{2-} found in the extractor worked in exchange with the adsorbed P, it was quickly adsorbed by the adsorption sites, which were not occupied by P. Thus, the combined action performed by these phenomena was responsible for Mehlich-1 decreased P extraction power. The P possibly added to the soils was preferentially adsorbed by soil colloids, in order to form P-Al and P-Fe and precipitate with calcium found in the soil, which formed P-Ca

Mehlich-1 extracted larger P amounts than those of Resin, and the extraction was inversely proportional to the clay content. Torres et al., (2016) found higher Mehlich-1 efficiency in comparison to that of the Resin when they evaluated Hapludox with 800 g kg^{-1} clay. The ion-exchange Resin was poorly influenced by the soil buffering capacity and showed no extractor wear. Stress got worse as clay content increased (especially kaolinite and Fe and Al oxides); it multiplied the specific surface potentially attacked by the chemical agents used in the extractors.

Soil P Availability

Table 2 presents P recovered levels regression equations associated with the amount applied for each extractor. The obtained correlation coefficients were above 82%, indicating that both extractors were efficient in predicting soil P availability. P extracted by Mehlich-1 from CXbe, RY and CXve soils provided adjusted equations that were able to explain more than 85% variation in P extracted levels. More than 95% variation in ion-exchange Resin P concentrations were explained by the adjusted equations for CXve and CXbe soils, but not for RY. According to Silva and Raij (1999), in theory, the ion-exchange Resin extracted soil phosphorus similarly to plant absorption, and it explains the best result found with this extractor. Büll et al. (1998) demonstrated this method's good ability of predicting P availability in soils from different cultures.

Overall, critical P levels varied due to clay content, which ranged from 21.33 to 416.64 mg dm^{-3} in the Mehlich-1 experiment, and from 30.70 to 177.55 mg dm^{-3} in the ion-exchange Resin experiment (Table 3). Such variation is probably related to chemical, physical and mineralogical soil variability in each study. According to Alvarez et al. (1990), the critical level corresponds to the element content in the plant or in the soil. Growth or production rate significantly decreased below such level, indicating the need for supplementary fertilization. The critical level of an element is related to the element concentration in the soil, being responsible for 90% or 100% of its production. Thus, higher critical level is expected in soils with low maximum P adsorption capacity (MPAC). Therefore, the lesser P is absorbed by the soil, the more it is available to plants. The results of the current study show that the critical P level in the soil was lower in clayey soils, as it was observed in RY, which has 330 g kg^{-1} clay and consequently higher FCP (Table 3), a fact that corroborates with the results found in the literature.

Critical phosphorus levels in soils

CXve and TCo soils were less clayey (125.4 g 1 kg and 135.6 g kg^{-1}, respectively), and critical levels increase appeared to be highly critical; CXbe had 254.9 g kg^{-1} clay and consequently the highest P adsorption capacity (Table 3). In addition, the natural clay content interfered in soil critical P levels, as it was reported by Boem et al. (2011). Overall, such results demonstrate that soil critical P levels are higher in less clayey soils. Knowledge on critical nutrition levels in the soil and plant tissues enables a more precise recommendation on the fertilizer amount to be applied. According to Novais and Smyth (1999), competition between the plant and P-treated soil makes the plant adjust and use the available P more efficiently. Thus, when P is the only limiting factor to production, besides variations resulting from species or cultivars and plant tissues age, nutrient interaction among nutrients, environmental conditions and soil properties reflect P capacity. Therefore, they should also be taken under consideration in the interpretation of critical P levels in plants (Simões Neto et al., 2011).

Correlation coefficients

Linear correlation analysis was performed to verify the relationship between the critical P level in the soil by Mehlich-1 anion exchange Resin extractors and soil attributes (Table 4). There was significant and positive correlation between MPAC and clay content, and high correlation coefficient. The clay fraction (iron and aluminum oxides and kaolinite) is responsible for the specific P adsorption phenomenon, establishing a direct relationship with MPAC. There was significant and negative coefficient for the most critical P level in the soil by Mehlich-1 extraction with MPAC, despite the low correlation coefficient between soil critical P levels by the extractors studied. Therefore, the

Table 1. Soil Physicochemical features.

Features	Soils			
	TCo	CXbe	RY	CXve
pH H_2O (1:2,5)	6.8	6.6	6.8	6.5
Ca^{+2} ($mmol_c\ dm^{-3}$)	76.9	182.1	145.3	31.0
Mg^{+2} ($mmol_c\ dm^{-3}$)	29.5	39.3	63.5	20.5
Na^+ ($mmol_c\ dm^{-3}$)	1.1	0.7	1.1	0.5
K^+ ($mmol_c\ dm^{-3}$)	5.1	13.5	4.8	6.2
SB ($mmol_c\ dm^{-3}$)	112.6	235.6	214.7	58.2
H+Al ($mmol_c\ dm^{-3}$)	12.4	38.0	28.1	12.4
T ($mmol_c\ dm^{-3}$)	125.0	273.6	242.8	70.6
V (%)	90	86	88	82
Al^{+3} $mmol_c\ dm^{-3}$	0.5	0.5	0.5	0.5
P $mg\ dm^{-3}$ (Mehlich 1)	296.2	286.8	8.90	22.5
P $mg\ dm^{-3}$ (Resin)	75.0	130.5	10.5	18.0
M.O ($g\ kg^{-1}$)	11.2	28.8	20.9	10.2
Rem-P ($mg\ L^{-1}$)	43.73	16.28	27.34	41.34
MPAC ($mg\ g^{-1}$)	0.279	0.297	0.395	0.293
Sand ($g\ kg^{-1}$)	726.4	716.8	450.1	726.6
Silt ($g\ kg^{-1}$)	138.0	28.3	234.8	148.0
Clay ($g\ kg^{-1}$)	135.6	254.9	330.0	125.4

TCo: Chromic Orthic Luvisol; CXbe: Eutrophic Haplic Cambisol; RY: Fluvic; CXve: Typical Eutrophic Cambisol. SB: sum of bases; T: cation exchange capacity; V (%): base saturation; Rem-P: remaining phosphorus; MPAC: maximum phosphorus adsorption capacity.
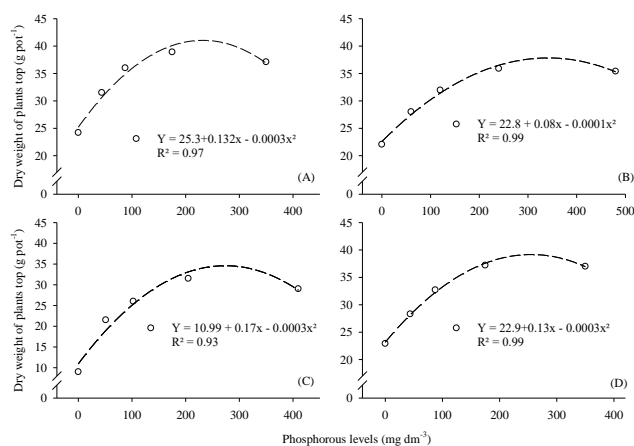
Fig 1. P rates estimated for 90% of maximum shoot dry mass for TCo (A), CXbe (B), RY (C) and CXve (D) soils.

Table 2. Regression equation estimators for P recovered by Mehlich-1 and Resin, depending on the P doses applied to the four soil classes.

Soil	Extractor	Applied Phosphorus ($mg\ dm^{-3}$)					Equations	R^2
		0.0	43.75	87.5	175	350		
		Recovered phosphorus ($mg\ dm^{-3}$)						
TCo	Mehlich-1	296.2	389.5	447.89	532.40	580.55	y= 350.34+0.754*x	0.85
	Resin	75.00	85.25	98.50	110.25	125.25	y = 75.93+0.215*x	0.99
		Applied Phosphorus ($mg\ dm^{-3}$)						
		0.0	60.0	120	240	480		
		Recovered phosphorus ($mg\ dm^{-3}$)						
CXbe	Mehlich-1	286.8	356.96	384.09	395	471	y=319.40+0.329*x	0.88
	Resin	130.5	148.75	165.0	222.0	316.0	y=125.30+0.395*x	0.99
		Applied phosphorus ($mg\ dm^{-3}$)						
		0	51.25	102.5	205	410		
		Recovered phosphorus ($mg\ dm^{-3}$)						
RY	Mehlich-1	8.90	11.43	20.69	37.18	41.43	y= 10.87+ 0.084*x	0.86
	Resin	10.50	17.00	22.75	47.00	83.00	y= 8.018+0.182*x	0.99
		Applied phosphorus ($mg\ dm^{-3}$)						
		0	43.75	87.5	175	350		
		Recovered phosphorus ($mg\ dm^{-3}$)						
CXve	Mehlich-1	22.50	44.88	145.2	193.53	231.44	y= 48.89+0.599*x	0.82
	Resin	18.00	24.75	56.50	77.50	16.00	y= 19.48+0.312*x	0.97

TCo: Chromic Orthic Luvisol; CXbe: Eutrophic Haplic Cambisol; RY: Fluvic; CXve: Typical Eutrophic Cambisol.*Significant at 5% probability level.

Table 3. Soil critical P levels by Mehlich-1 and ion-exchange Resin in order to obtain 90% of maximum production.

Soil	Clay	Prem	Soil critical P level	
			Mehlich-1	Resin
	----g kg^{-1}----	-----mg L^{-1}-----	-------------mg dm^{-3}--------------	
TCo	135.6	43.73	416.64	94.83
CXbe	254.9	16.28	362.28	177.51
RY	330.0	27.34	21.33	30.70
CXve	125.4	41.34	111.33	52.03

Table 4. Simple linear correlation coefficients between soil critical P levels by Mehlich-1 and anion exchange Resin, showing soil chemical properties.

Variables	MPAC[1]	EL[2]	FCPm[3]	Prem[4]	Clay[5]	NCM[6]	NCR[7]
MPAC		-0.77**	-0.08ns	-0.33ns	0.83**	-0.71**	-0.49*
EL			0.62**	0.30ns	-0.91**	0.17ns	-0.05ns
FCPm				0.05ns	-0.33ns	-0.58*	-0.56ns
Rem-P					0.36ns	0.14ns	-0.02ns
Clay						-0.38ns	0.03ns

(1) Soil critical P level by resin extraction, (2) Soil critical P level in the soil by Mehlich-1 extraction, (3) Soil clay content (g kg^{-1}), (4) Remaining phosphorus (Alvarez V. et al., 2000), (5) P capacity factor, (6) Binding energy, (7) P maximum adsorption capacity.

higher the clay content, the lower the critical level. It is common to find significant and positive correlations between soil clay content and MPAC in the literature (Valladares et al., 2003; Falcão and Silva, 2004).

Although adsorption energy is not correlated to critical P levels by the studied extractors, there was significant negative correlation between FCPm and the critical P level by Mehlich-1extraction; however, there was no correlation between Prem, clay content and critical P level in the two extractors tested (Table 4).

Shoot maximum dry matter yield

Response curves used to explain castor bean shoot dry mass production resulting from P rates applied to TCo, CXbe, RY and CXve are presented in Figure 1. P rate applications led to shoot dry mass production increase, which was adjusted to high determination coefficient quadratic models. There was shoot dry mass production variation from 34.65 to 33.55 g vessel^{-1}, respectively, (Figure 1A and 1D) in TCo and CXve soils. P input increased plant height, stem diameter and leaf area in castor oil plants (Brito Neto et al., 2014). These soils were responsible for higher shoot dry mass production due to the application of lower P doses (87.94 mg dm^{-3} and 104.33 mg dm^{-3}, respectively). Such production was directly related to the low clay content of these soils and, consequently, to their lower phosphate adsorption capacity and greater P availability to plants.

Soils with high clay content (CXve and RY) showed shoot dry mass production variations from 31.86 to 27.43 g vessel^{-1}, respectively, and such production was related to higher P doses (132.18 mg dm^{-3} and 124.63 mg dm^{-3}). It demonstrates P drain character and the lack of P availability to plants (Figure 1B and 1C, respectively), with higher adsorption. These results demonstrate that it took a higher P dose with higher FCP (CXbe and RY) values for shoot dry mass production, showing the character of these soils.

According to Novais and Smith (1999), data available in the literature show that plants adjust to P increased use in soils with high MPAC and FCP values. Based on the results of this study, the importance of clay to adsorption and of P availability to the plants is evident. Novais and Smyth (1999) reported that, in soils with high FCP values, as is the case of RY and CXbe (Figure 1B and 1C), plants optimize the lowest P concentration in the available solution (intensity factor),

producing more biomass per absorbed P unit than soils with lower FCP values.

Materials and Methods

Experimental site

The experiment was conducted in greenhouse at the National Center for Cotton Research. Climate was tropical wet, according to Köppen classification. Mean annual temperature is 28.6^{o}C.

Samples of four soils with different chemical, physical and mineralogical attributes were collected at 0-30 cm below the soil surface, corresponding to the plow layer. Subsequently, they were taken to the experiment site. Soil samples were grounded, air-dried and sieved through a 2-mm mesh, in order to be physically and chemically characterized (Table 1), according to Embrapa (1997). The experimental design consisted of a completely randomized design comprising 20 treatments (4 soils x 5 phosphorus levels) and four repetitions, totaling 80 experimental units. Each experimental unit consisted of a plastic vessel containing 20 dm^{-3} of soil and BRS Energia castor plant.

Treatments and experimental design

The soil was sieved through a 4-mm mesh after being grounded and air-dried. Subsequently, vessels were packed with 23 kg of soil. Each soil type received five P doses (0.0, 43.75, 87.5, 175, and 350 mg dm^{-3} for TCo and CXve), (0.0, 60, 120, 240 and 480 mg dm^{-3} for CXbe) and (0.0, 51.25, 102.5, 205 and 410 mg dm^{-3} for RY). Triple superphosphate was used as P source, according to the remaining P (Prem), and followed the methodology by Alvarez et al. (2000). Triple superphosphate was applied and homogenized in 100% of the soil volume in each vessel. A nutrient solution was applied (Hoagland and Arnon, 1950); the solution contained all the essential nutrients except for P, which was used as treatment.

Characteristics evaluated

After the soil P levels of each vessel were assessed, samples were incubated for 15 days. Afterwards, distilled water was added to them (70% of field capacity of each soil type). After the incubation period, 0.2 dm^{-3} of soil subsamples were

removed from each vessel to determine P availability by Mehlich-1 (Embrapa, 1997) and anion exchange resin. The vessels were regularly watered with distilled water (the remaining 70% of its field capacity); the water requirement was set by weighing the vessel by weight per block of four vessels.

Three BRS Energia castor seeds were sowed in each vessel; thinning was performed ten days after emergence, making the plants more vigorous. Forty days after germination, plant shoots from each vessel were cut 1 cm from the ground, separating the plant shoot (stem and leaf) from the root. The plant material was washed in running water and then in distilled water. Subsequently, the material was oven-dried under forced air circulation at 65°C until constant weight was obtained. The material was then weighed on an analytical scale, in order to get shoot dry mass.

Data analysis

Regression equations were adjusted to relate shoot dry mass and P dose variation, applied to P contents recovered by Mehlich-1 and ion-exchange Resin. The dose was set on 90% of the maximum value due to the importance of working with maximum economic efficiency doses. This value was replaced in the regression equations by the extraction-recovered P, using the added P amount as a function of the critical P level in the soil. Data were subjected to analysis of variance and polynomial regression, in order to match dependent variables and treatments.

Conclusion

Soil critical P level, determined for 90% of maximum castor bean dry mass production, was 21.33 mg dm^{-3} for RY; as for TCo, application of 87.94 mg dm^{-3} P led to the greatest castor bean shoot dry mass production increase (34.65 g vessel^{-1}).

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