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Phosphorous availability in Argisols and sufficiency range in sugarcane in the Northeast of Brazil[1]

Daniela Batista da Costa[2], Fernando José Freire[3], Janyelle de Oliveira Lemos[2], Suellen Roberta Vasconcelos da Silva[2], Nathalia Sobral Bezerra[4], Patrícia Karla Batista de Andrade[5], Joel José de Andrade[2]*

ABSTRACT - Phosphorous is a limiting nutrient in sugarcane cultivated in Argisols in the Northeast of Brazil, and understanding its availability in the soil, as well as determining sufficiency ranges in the plants is essential when recommending levels of phosphorus fertiliser. The aim of this study was to: (i) Define classes for interpreting P availability in Argisols of the Northeast using the Mehlich-1 and Anion Exchange Resin (AER) extractors; (ii) Evaluate P extraction by the same extractors; and (iii) Correlate the P content of the soil with the P content of the plants, and establish sufficiency ranges in the plants. Three field trials were carried out in a sandy ($PVAd_1$), medium (PAdx) and clayey ($PVAd_2$) Argisol, applying the following amounts of P: 0, 40, 80, 120, 160 and 200 kg ha^{-1} P_2O_5. The AER extracted more P than did Mehlich-1 from each of the soils. The P content of the classes for interpreting P availability determined by the AER were higher than those determined by Mehlich-1. AER was the best extractor to represent P availability in the Argisol with the clayey texture ($PVAd_2$), and Mehlich-1 in the Argisol with the sandy texture ($PVAd_1$). The ranges of P sufficiency in the leaves of the sugarcane varied between soils, with values of 0.66-0.73 g kg^{-1} in $PVAd_1$, 0.59-0.69 g kg^{-1} in $PVAd_2$ and 0.34-0.47 g kg^{-1} in PAdx. As such, the texture of Argisols cultivated with sugarcane in the Northeast of Brazil should be a criterion for choosing the P extractor used in assessing its availability.

Key words: Soil texture. Phosphate fertilisation. Available P. Mehlich-1. Anion Exchange Resin.

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*Author for correspondence
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[2]Departament of Agronomy, Federal Rural University of Pernambuco (UFRPE), Recife-PE, Brazil, dani_agro@yahoo.com.br (ORCID ID 0000-0001-6113-0413), janyelle_lemos@yahoo.com.br (ORCID ID 0000-0002-7310-7015), suellenrv1@gmail.com (ORCID ID 0000-0002-5702-6661), joel.andrade@ufrpe.br (ORCID ID 0000-0002-5079-7164)
[3]Federal Rural University of Pernambuco (UFRPE), Recife-PE, Brazil, *fernando.freire@ufrpe.br (ORCID ID 0000-0002-3264-712X)
[4]Carpina Experimental Sugar Cane Station (EECAC/UFRPE), Carpina-PE, Brazil, natthalia_sobral@hotmail.com (ORCID ID 0009-0006-7441-2288)
[5]Departament of Rural Technology, Federal Rural University of Pernambuco (UFRPE), Recife-PE, Brazil, patriciapig@hotmail.com (ORCID ID 0000-0002-3036-5719)

INTRODUCTION

Sugarcane is an important source of renewable energy. In 2020, the use of ethanol as a biofuel avoided the emission of 46.8 $MtCO_2eq$ (EPE, 2021) due to the low CO_2 emissions of burning ethanol and the high capacity for CO_2 fixation of sugarcane (PIFFER CARDOZO; BORDONAL; SCALA JR, 2016). It is estimated that the world demand for ethanol will grow by 14% between 2016 and 2026 (ORGANISATION FOR ECONOMIC COOPERATION AND DEVELOPMENT, 2017).

Increasing the supply of biofuel (ethanol) depends, among other factors, on the productivity of the sugarcane plantation, which is affected by the fertility of the soil: low soil fertility limiting sugarcane productivity. In Brazil, P is one of the most limiting nutrients due to the high P sorption capacity of the soil (CHERUBIN *et al*., 2015; FORMANN *et al*., 2020). Phosphate fertilisation is the principal way of meeting the nutritional demand of sugarcane for P. However, fertiliser efficiency is low, on average recovering 20% of the applied P (SOLTANGHEISI *et al*., 2019; ZAMBROSI, 2021). The low efficiency of phosphate fertiliser requires an increase in the amount of P applied to the sugarcane plantation. In this respect, research has been carried out with the aim of establishing techniques for fertiliser recommendations that would improve the yield of phosphate fertiliser, whose reserves are finite, and increase sugarcane productivity (BORGES *et al*., 2019; SOLTANGHEISI *et al*., 2019).

The main criteria used in recommendations for phosphate fertiliser are the nutritional demand of sugarcane based on expected productivity, the balance of nutrients in the soil/plant system, the replacement of P extracted at harvest, and the critical level of P in the soil. The critical level of a nutrient is the minimum content of that element in the soil below which crop response to the fertiliser is reduced (SUCUNZA *et al*., 2018). To determine the critical level, chemical extractors are used that quantify the available fraction of the element in the soil, where their efficiency is expressed by correlating the P extracted from the soil with its absorption by the plant (VALADARES *et al*., 2017).

The extractor must be carefully chosen, as, depending on the type of soil, some can extract fractions of unavailable P (FINK *et al*., 2016; ROGERS; DARI; LEYTEM, 2019). This situation is common in regions where P fixation occurs (ROBERTS; JOHNSTON, 2015). In the Northeast of Brazil, where 10% of the country's sugarcane is harvested (COMPANHIA NACIONAL DE ABATECIMENTO, 2023), the sugarcane is generally grown in Argisols of different textures that can influence P fixation (SIMÕES NETO *et al*., 2015), in addition to other physical, chemical and mineralogical attributes of the soil (KOME *et al*., 2019).

The most common extractor for available P used in Brazil is Mehlich-1. Mehlich-1 promotes the acidic dissolution of phosphate compounds that are weakly bound to inorganic colloids, and the forms of P bound to calcium (P-Ca), aluminium (P-Al) and iron (P-Fe) (MEDEIROS *et al*., 2021). Despite being practical, this extractor can under- or overestimate the recommendations for phosphate fertiliser depending on the texture of the soil and on natural or artificially high levels of Ca, as seen by Valadares *et al*. (2017). The authors analysed the efficiency of P extraction by Mehlich-3 and anion exchange resin (AER) compared to Mehlich-1, in Oxisols rich in P-Ca, and concluded that Mehlich-3 and AER show a better correlation with P extracted by the plant than does Mehlich-1, which is sensitive to the presence of P-Ca.

AER promotes the exchange of P for bicarbonate or chloride from the resin, removing the element linked to the colloid, which generates an electrochemical balance between the soil and the AER (SANTOS; GATIBONI; KAMINSKI, 2008). As it causes no acid dissolution, the extractor does not overestimate the P recommendation and is a more versatile method for the different types of soil (Racena, Díaz and Delgado, 2017).

The choice of method used to quantify available P is important for estimating the correct critical levels and establish more-efficient recommendations for phosphate fertiliser (BRITO NETO *et al*., 2017). The aim of this study was to: (i) Define classes for interpreting P availability in Argisols in the Northeast of Brazil using the Mehlich-1 and Anion Exchange Resin (AER) extractors; (ii) Evaluate P extraction by these extractors; and (iii) Correlate the P content of the soil and plants, and establish ranges of P sufficiency in the plants.

MATERIAL AND METHODS

Study area and characterisation of the soil

Three experiments were carried out under field conditions in areas cultivated with sugarcane: 1) the coastal tablelands of Paraíba, where the climate is hot and humid with an average annual rainfall of 1,600 mm and the soil in the experimental area is classified as a dystrophic Red Yellow Argisol of sandy texture ($PVAd_1$); 2) the northern Zona da Mata in Pernambuco, where the climate is hot and humid, with an average annual rainfall of 1,300 mm and soil classified as a distro-cohesive Yellow Argisol of medium texture (PAdx); 3) the southern Zona da Mata of Pernambuco, where the climate is hot and humid, the average annual rainfall is 2,200 mm and the soil is classified as a dystrophic Red Yellow Argisol of clayey texture ($PVAd_2$). The soils were classified as per Santos *et al*. (2018).

According to the Köppen classification, the climate at the three locations is tropical type Am from monsoon areas (ALVAREZ *et al*., 2013). The rainfall and temperature were recorded monthly (Figure 1) at each of the three study sites.

The soil of each experimental area was selected based on particle size, and sampled at a depth of 0.0-0.30 m. Fifteen discrete samples were collected per area to form one composite sample. After collection, the soil samples were air-dried, crushed and passed through a 2-mm mesh sieve to obtain fine air-dried earth (ADFE), which was later characterised using physical, chemical and mineralogical analysis (Table 1).

Figure 1 - Monthly rainfall (mm) and temperature (ºC) during the first plant cane cycle at the different experimental sites: coastal tablelands of Paraíba, dystrophic Red Yellow Argisol of sandy texture ($PVAd_1$); northern Zona da Mata of Pernambuco, distro-cohesive Yellow Argisol of medium texture (PAdx); and southern Zona da Mata of Pernambuco, dystrophic Red Yellow Argisol of clayey texture ($PVAd_2$)

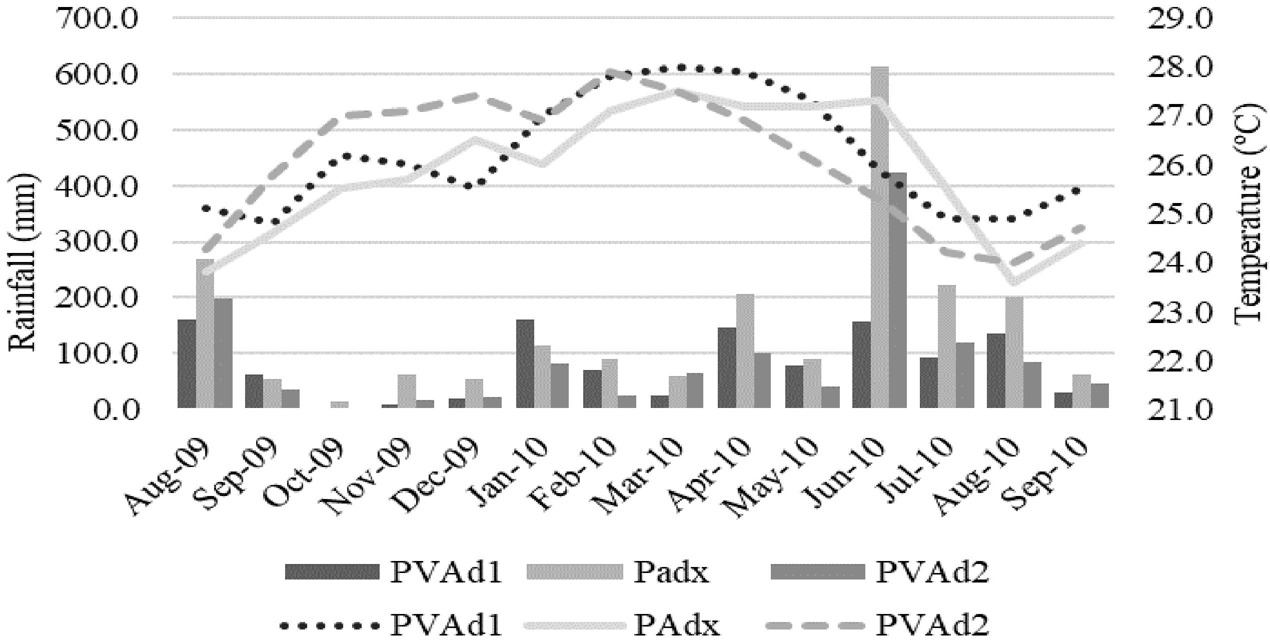


Table 1 - Chemical, physical and mineralogical characteristics of the dystrophic Red Yellow Argisol of sandy texture ($PVAd_1$), distro-cohesive Yellow Argisol of medium texture (PAdx) and dystrophic Red Yellow Argisol of clayey texture ($PVAd_2$)

Characteristic	Soil		
	$PVAd_1$	PAd_x	$PVAd_2$
pH (H_2O)	6.5	6.0	4.4
(H + Al) ($cmol_c$ dm^{-3})	5.1	7.9	7.6
Al^{3+} ($cmol_c$ dm^{-3})	0.00	0.00	1.20
Ca^{+2} ($cmol_c$ dm^{-3})	1.00	2.53	0.50
Mg2+ ($cmol_c$ dm^{-3})	0.90	1.55	0.50
Na^+ ($cmol_c$ dm^{-3})	0.02	0.03	0.03
K^+ ($cmol_c$ dm^{-3})	0.04	0.15	0.06
P (mg dm^{-3})	7.00	13.6	4.02
MPAC (mg cm^{-3})	0.26	0.52	0.90
P-rem (mg L^{-1})	40.67	34.72	11.99
OM (%)	1.21	2.6	5.79
Fe (mg dm^{-3})	29.70	101.1	186.6

Continuation Table 1

Cu (mg dm^{-3})	0.90	0.50	0.40
Zn (mg dm^{-3})	5.30	8.70	4.90
Mn (mg dm^{-3})	1.80	10.3	0.80
CTC_{total} ($cmol_c$ dm^{-3})	7.06	12.16	8.69
$CTC_{effective}$ ($cmol_c$ dm^{-3})	1.96	4.26	2.29
m (%)	0.00	0.00	52.4
V (%)	27.76	35.03	12.54
Ds (g cm^{-3})	1.50	1.36	1.08
Dp (g cm^{-3})	2.67	2.56	2.53
CC (Mg Mg^{-1})	0.044	0.115	0.221
PWP (Mg Mg^{-1})	0.028	0.067	0.163
Sand (g kg^{-1})	887	704	474
Silt (g kg^{-1})	35	80	70
Clay (g kg^{-1})	78	216	456
Ko (cm h-1)	39.12	58.78	19.52
Porosity (%)	43.82	46.87	57.31
Textural class	Sandy	Sandy Loam	Sandy Clay
Feo (g kg^{-1})	0.18	2.79	2.65
Fed (g kg^{-1})	13.81	18.15	18.98
Feo/Fed	0.01	0.15	0.14
Minerals	Kt, Gt, Hm, An, Rt, Qz	Kt, Gb, Gt, An, Qz	Kt, Gb, Qz

MPAC= Maximum P Adsorption Capacity; P-rem= Remaining P; Kt=kaolinite; Gt=Goethite; Hm=hematite; An=Anorthite; Rt=Rutile; Qz=Quartz; Gb=Gibbsite

The soils were physically characterised using the methods described by Teixeira *et al*. (2017) to determine particle size, soil density, particle density, field capacity, permanent wilting point and saturated hydraulic conductivity. Chemically, the soils were characterised for pH (H_2O), Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}, (H+Al), P, Fe, Cu, Zn, Mn, Remaining P (P-rem) and Maximum P Adsorption Capacity (MPAC). Ca^{2+}, Mg^{2+}, Na^+ and Al^{3+} were extracted using 1.0 mol L^{-1} KCl; Fe, Cu, Zn, Mn, P and K by Mehlich-1; and H+Al by 0.5 mol L^{-1} calcium acetate. $Ca2^+$, $Mg2^+$, Fe, Cu, Zn and Mn were determined by atomic absorption spectrophotometry, K^+ and Na^+ by flame photometry, P by colorimetry, and $Al3^+$ and (H+Al) by volumetry analysis, following the methodology described by Teixeira *et al*. (2017).

P-rem was determined as per Alvarez V. *et al*. (2017). To determine the MPAC, the soil samples received P doses based on the value of P-rem. ADFE samples from each soil were saturated with increasing concentrations of P in 0.01 mmol L^{-1} $CaCl_2$ solution. The Langmuir isotherm was adopted to estimate the MPAC.

Mineralogical characterisation of the clay fraction was carried out using X-ray diffraction (MOORE; REYNOLDS, 1997). Sample readings were taken by a diffractometer equipped with a copper tube, using CuKα radiation, and operated at 20 mA and 40 kV. Oxides in the ADFE were determined by sulphuric attack (Al_2O_3 and Fe_2O_3 by digestion with H_2SO_4 1:1, followed by alkaline dissolution to determine the SiO_2), as per the methodology described by Inda and Fink (2017).

The free forms of Fe and Al were extracted with citrate-bicarbonate-dithionite (CBD). Ammonium acid oxalate was used to extract the poorly crystallised Fe and Al oxides. The crystalline forms of Fe and Al were obtained by difference between the forms extracted by the CBD and by the oxalate. All the analyses were carried out as per Cornell and Schwertmann (2003).

Conducting the experiment

The treatments comprised six doses of P (0, 40, 80, 120, 160 and 200 kg ha^{-1} P_2O_5) applied to the plant cane at the bottom of the planting furrow together with the nitrogen and potassium fertilisers. The dose of 120 kg ha^{-1} P_2O_5 was defined as the reference dose based on the Manual of Fertiliser Recommendations for the state of Pernambuco (IPA, 2008), the value recommended for soils with a low P content. The other doses were defined as 1/3 and 2/3 below and above the reference dose. The source of P was triple superphosphate and the variety of sugarcane used was RB 92579. The experimental design was of randomised blocks with four replications, giving a total of 24 experimental plots, which consisted of seven furrows of ten metres. The working area included the three central rows, disregarding one metre at the end of each plot.

Planting was carried out in 2009: August in $PVAd_2$, September in PAdx, and October in $PVAd_1$. The nitrogen and potassium fertilisers were applied based on the Manual of Fertiliser Recommendations for the state of Pernambuco (IPA, 2008) using urea and KCl as the source, at doses of 60 and 80 kg ha^{-1} N and K_2O, respectively. Soil correction was carried out in $PVAd_2$ before planting, as per the Manual of Fertiliser Recommendations for the State of Pernambuco (IPA, 2008), using 2 Mg ha^{-1} dolomitic limestone and 1 Mg ha^{-1} gypsum. There was no need for correction in the $PVAd_1$ or PAdx soils.

Soil samples were collected at a depth of 0.0-0.30 m prior to planting to determine the available P as a function of the doses of P applied to the soils. The soils were incubated with the same doses of P applied in the field, together with N and K in amounts equal to those used in the field. The samples were kept at field capacity and incubated for 30 days. After the incubation period, the samples were air-dried, crushed and passed through a 2-mm sieve to determine the available P using the Mehlich-1 and AER extractors.

Harvesting was carried out 14 months after planting, in October, November and December 2010 in $PVAd_2$, PAdx and $PVAd_1$, respectively. Twelve plants were removed from each plot at the end of the plant cane cycle, four from each central row. The plants were separated into leaf, tip and stem, which were weighed to obtain the fresh weight. The samples were then oven-dried at 60 ºC to constant weight, ground and sent for nitric perchloric digestion to determine the P content using the colorimetric method (EMBRAPA, 2009). The P content of the plants per compartment was determined by multiplying the P content in the respective compartment by its biomass, and the results estimated by area (kg ha^{-1}).

Statistical analysis

The data for each variable were submitted to analysis of variance by F-test ($p < 0.05$) following the tests of normality (Shapiro-Wilk, $p < 0.05$) and homoscedasticity (Levene, $p < 0.05$). Regressions were carried out between the P content determined by the Mehlich-1 and AER extractors as a function of the amounts of P applied to the soils. Correlations were then made between the levels of P available in the soil and the levels of P in the different compartments of the plant (tip, leaf and stem).

Using the first derivative of the regression equation for agricultural productivity as a function of the applied doses, the P dose that afforded 90% and 100% production was calculated. From the equations between the P content determined by Mehlich-1 and AER as a function of the applied doses of P, classes for interpreting P availability in the soil (Low, Medium and High) were estimated. The ‘Low’ Class was defined as the level of P available in the soil corresponding to the dose that afforded an agricultural production of less than 90%. The ‘Medium’ Class was defined as the available P content in the soil that afforded an agricultural production between 90% and 100%. The ‘High’ Class was defined as the available P content in the soil that afforded an agricultural production of more than 100%.

The P content of the leaves as a function of the P doses applied to the soils was submitted to regression analysis. Based on these equations, the range of P sufficiency in sugarcane leaves was established. The sufficiency range was defined as the P content of the leaf that afforded an agricultural production of between 90% and 100%.

RESULTS AND DISCUSSION

Evaluating the extractors of available P in the Argisols

The P content extracted by Mehlich-1 and AER increased in line with the dose of P applied to the soils cultivated with sugarcane, adjusting to linear models with high coefficients of determination (Figure 2). In general, the highest value for P extraction was obtained with the AER, a fact that has been verified in various studies bearing in mind the ability of the extractor to recover labile P regardless of soil buffering (CAMÊLO *et al*., 2015; CARDOSO *et al*., 2020; MUMBACH *et al*., 2020; RACENA; DÍAZ; DELGADO, 2017).

Even inserted in the same pedological class (Argisol), the different physical, chemical and mineralogical attributes of the soils (Table 1) influenced P availability. The P content determined by Mehlich-1 was higher in the $PVAd_1$ soil, followed by $PVAd_2$ and PAdx (Figure 2). A similar result was obtained by Reis *et al*. (2020), who found lower values for P extraction with an increase in the phosphate buffering power of the soil. The lower P extraction in soils with a high clay content and high MPAC may be related to the sensitivity of Mehlich-1 to the buffering capacity of the soil, since in more-buffered soils, the extraction capacity is reduced due to the higher proportion of P-fixating clay minerals, such as the oxides and hydroxides of Fe and Al (MUMBACH *et al*., 2018; SANTOS *et al*., 2016). However, the lowest P extraction by Mehlich-1 was in the PAdx soil that includes Fe and Al oxides and hydroxides, in addition to higher levels of amorphous Fe compared to the $PVAd_2$ soil (Table 1).

The AER extracted more P from the clayey soil ($PVAd_2$) than from the sandy ($PVAd_1$) and medium-textured soils (PAdx) (Figure 2). Greater P extraction by the AER was also seen in more-clayey soils by Brito Neto *et al*. (2017). During extraction, AER promotes chemical balance in the soil through the exchange of anions between the P adsorbed on the AER and the P in the soil solution. When the P concentration in solution decreases, it is replaced by more labile forms of P. This dynamic explains why more P is extracted from soils with greater buffering capacity, such as the $PVAd_2$ soil, and shows that the buffering power of the soil does not affect the ability of AER to extract labile P (SIMÕES NETO *et al*., 2015).

In the search for an extractor that can better evaluate P availability in Argisols of differing characteristics, the P absorbed and accumulated in the plant was correlated with the available P content determined by Mehlich-1 and AER (Table 2). The P content determined by Mehlich-1 and AER in the different soils correlated positively with the P content of each compartment of the aerial part of the plant. However, the ability of these extractors to represent the available P was different for each type of soil.

In the sandy-textured soil ($PVAd_1$), the correlation coefficients were positive and significant for Mehlich-1 (Table 2), generally with higher values than those found in the PAdx and $PVAd_2$ soils, corroborating the results of Souza, Pegoraro and Reis (2017). The greater ability of Mehlich-1 to predict available P in the sandier soil compared to the more clayey soil, can be attributed to the occurrence of a smaller number of phosphate adsorption sites in sandy soils compared to clayey soils (BRENNER *et al*., 2019; ESLAMIAN; QI; QIAN, 2021; LEMOS *et al*., 2022).

Figure 2 - Regression equations that estimate the P extracted by Mehlich-1 (A) and Anion Exchange Resin (AER) (B) as a function of the P dose applied in the different soils: dystrophic Red Yellow Argisol of sandy texture ($PVAd_1$), distro-cohesive Yellow Argisol of medium texture (PAdx) and dystrophic Red Yellow Argisol of clayey texture ($PVAd_2$)

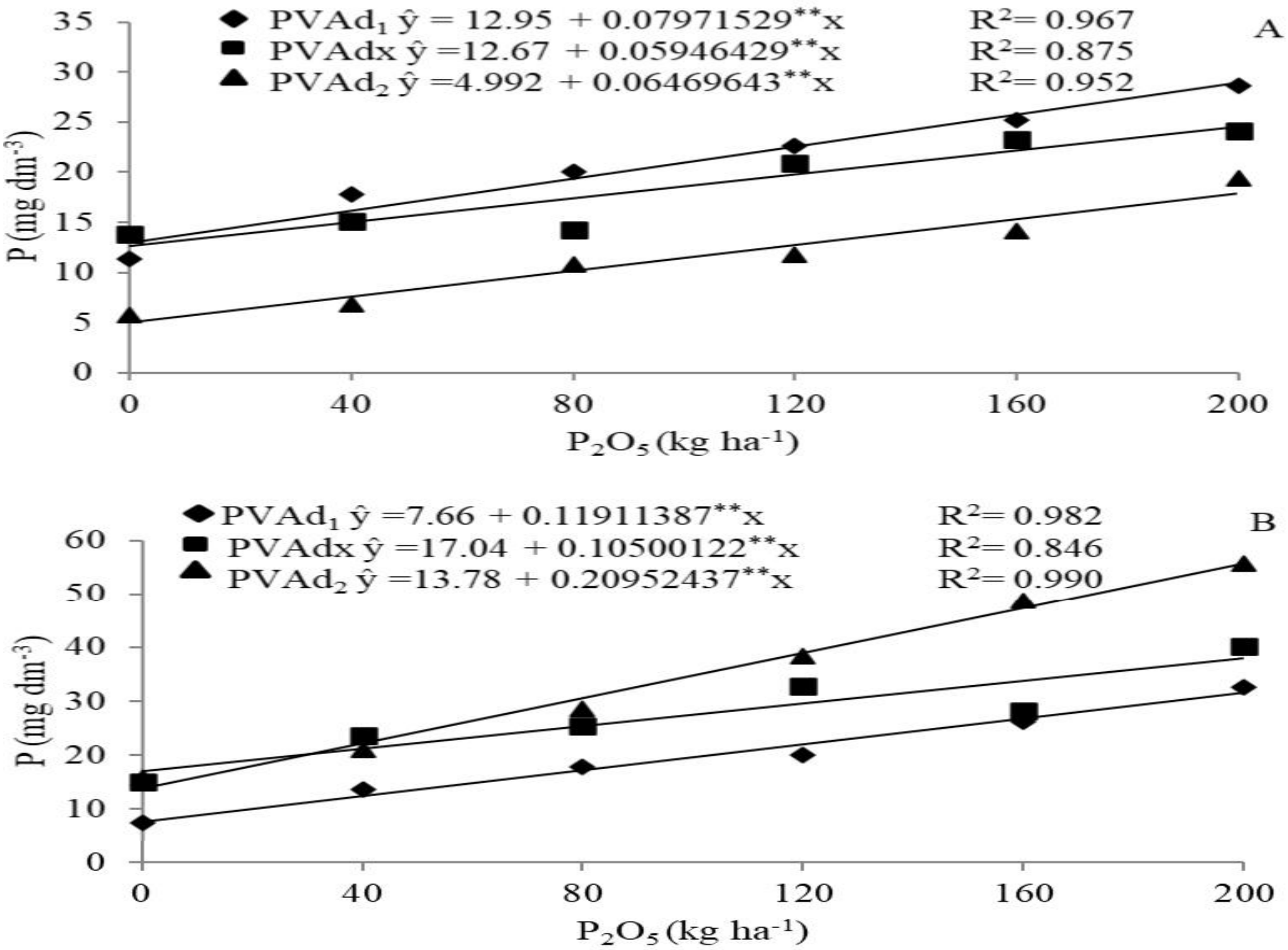


Table 2 - Simple correlation coefficients between the P content of each compartment of the aerial part of the plant and the available phosphorus content of the soils, determined by Mehlich-1 and Anion Exchange Resin (AER)

Compartment	Extractor	
	Mehlich-1	Resin
	Dystrophic Red Yellow Argisol ($PVAd_1$)	
Tip	0.92*	0.84^{ns}
Leaf	0.96**	0.89^{ns}
Stem	0.94*	0.88^{ns}
Total	0.90*	0.81^{ns}
	Distro-cohesive Yellow Argisol (PAd_x)	
Tip	0.96**	0.91*
Leaf	0.54^{ns}	0.99*
Stem	0.53^{ns}	0.40^{ns}
Total	0.80^{ns}	0.70^{ns}
	Dystrophic Red Yellow Argisol ($PVAd_2$)	
Tip	0.34^{ns}	0.45^{ns}
Leaf	0.92*	0.94*
Stem	0.97*	0.98*
Total	0.92^{ns}	0.96*

*, ** significant at p < 0,01 and p < 0,05, respectively; ns not significant

On the other hand, correlations in the soil of medium texture (PAdx) and of clayey texture ($PVAd_2$) were more significant for the AER (Table 2), showing that the AER extractor better evaluated P availability in these soils. This is consistent with the ability of the resin to extract labile P regardless of soil buffering, as found by Camêlo *et al*. (2015) and Simões Neto *et al.* (2015), in soils from the midwestern and northeastern regions of Brazil, respectively. It is likely that increases in the clay content of these soils (Table 1) contributed to Mehlich-1 being less significant, since, when in contact with soil with a high buffering capacity, the acidity of the extractor is consumed, reducing its power of extraction.

The lower significance of Mehlich-1 compared to AER in the PAdx soil (Table 2) can also be attributed to the presence of P-Ca, seeing that the highest Ca content (2.53 $cmol_c\ dm^{-3}$) was found in this soil (Table 1). The ability of Mehlich-1 to solubilise calcium phosphates means this extractor is not recommended for soils where the phosphate is present, as it extracts the P fraction that is not accessible by the plant (P-Ca), overestimating the levels of the element, as seen by Souza, Pegoraro and Reis (2017) in soils of limestone origin in the state of Minas Gerais, and by Medeiros *et al.* (2021) in soils of the northeastern semi-arid region. Valadares *et al*. (2017), analysing the efficiency of extractors in quantifying P in highly weathered soils with levels of P-Ca, found that Mehlich-3 and AER are more efficient than Mehlich-1.

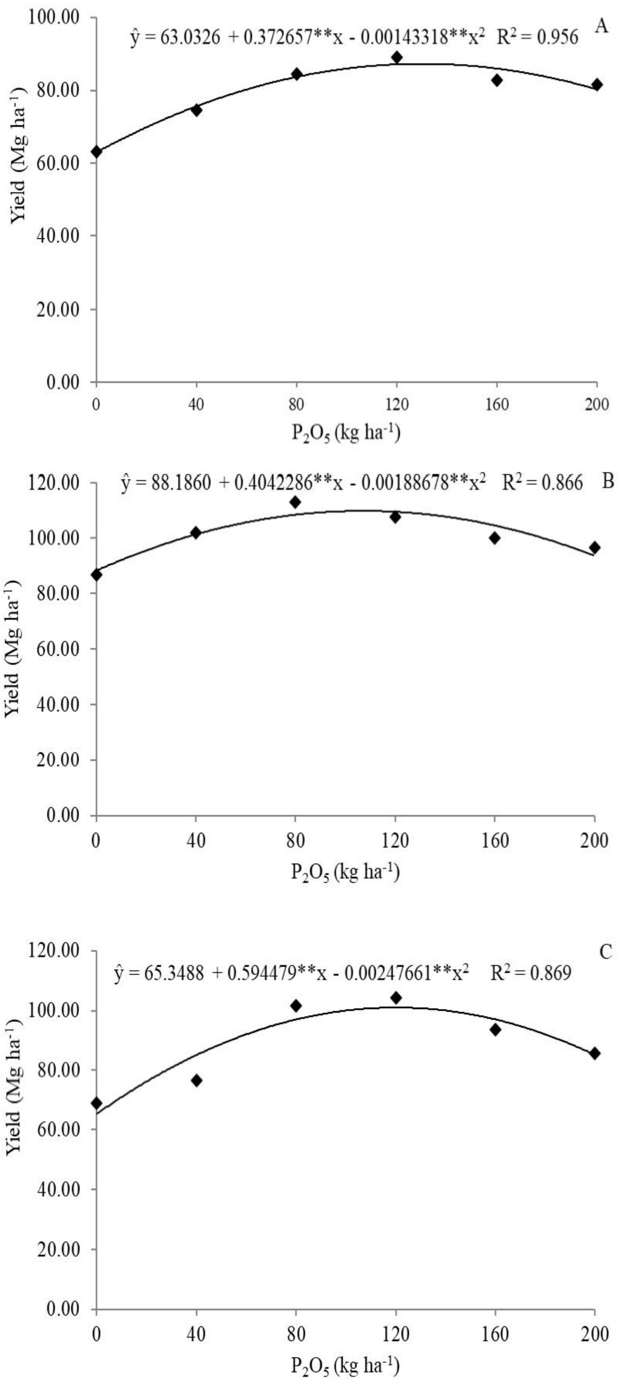
Agricultural productivity and P levels in plants as a function of phosphorus fertilisation

The plant cane production data as a function of phosphorus fertilisation adjusted to a curvilinear model for the three soils (Figure 3).

The recommended dose of P to reach 100% production in the $PVAd_1$ soil is 130 kg ha^{-1}, which is higher than the recommended dose for the PAdx and $PVAd_2$ soils, of 107 kg ha^{-1} and 120 kg ha^{-1}, respectively (Figure 3). The P_2O_5 doses for 100% production found in this study were higher than those found by Simões Neto *et al*. (2011) in Argisols cultivated with sugarcane in the state of Pernambuco, of 93 and 150 kg ha^{-1}.

The high dose necessary for 100% production found in the $PVAd_1$ soil (130 kg ha^{-1}), and the lower levels of production seen in this soil can be attributed to its low CEC in relation to other soils and to its low water retention capacity (Table 1). Soil water retention is fundamental for the supply of P to the plant, since P moves primarily by diffusion in the soil (VOLF; ROSOLEM, 2021; ZHAO; LI; YANG, 2021). On the other hand, the high initial fertility of the PAdx soil afforded higher yields for a smaller dose of P (Figure 3).

Figure 3 - Sugarcane productivity during the first crop cycle (plant cane) for increasing doses of P_2O_5 (0, 40, 80, 120, 160 and 200 kg ha^{-1}) in a dystrophic Red Yellow Argisol of sandy texture ($PVAd_1$) (A), distro-cohesive Yellow Argisol of medium texture (PAdx) (B), and dystrophic Yellow Red Argisol of clayey texture ($PVAd_2$) (C)



The highest dose required to reach 100% production in the $PVAd_2$ soil compared to the PAdx soil may be related to the high clay content (456 g kg^{-1}) and high levels of Fe and Al (186.6 mg dm^{-3} and 1.20 cmol$_c$ dm^{-3}, respectively) in the $PVAd_2$ soil (Table 1), demonstrating its character as a P fixer, as found in a study carried out in soils cultivated with sugarcane in Pernambuco (SIMÕES NETO *et al*., 2012, 2015). Under such conditions, P tends to precipitate in solution with the ionic forms of Fe and Al, becoming unavailable to plants and increasing their demand in order to achieve higher productivity (JOHAN *et al*., 2021).

The data on the P content of leaves of plant cane as a function of phosphorus fertilisation in the different argisols showed that in $PVAd_1$ and $PVAd_2$ the data adjusted to the linear model, while in the PAdx soil they adjusted to the quadratic model (Figure 4).

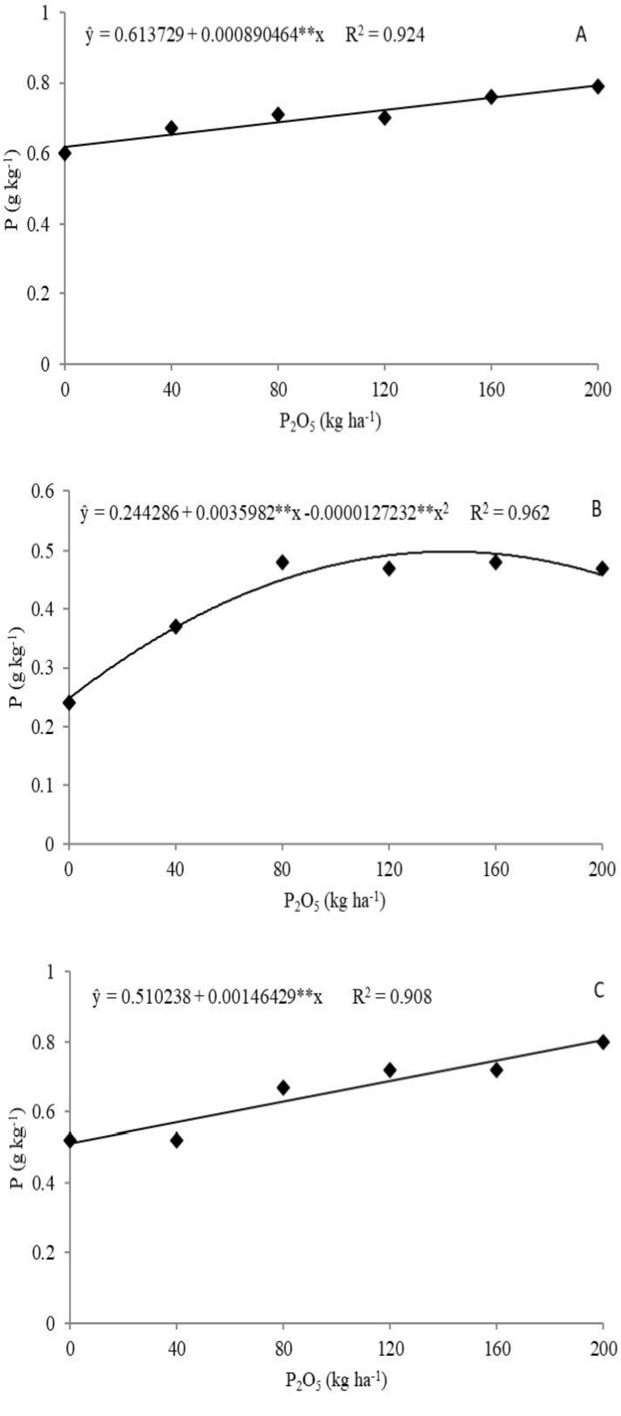
There was greater P absorption in the soil with the lowest P buffering capacity, as was the case of $PVAd_1$ (Figure 4). In environments where there is little restriction on P availability, plants absorb more, but are less efficient in converting P into biomass (NETO *et al*., 2016), as seen in $PVAd_1$, which was less productive than the other soils (Figure 3). The PVAdx soil, despite not having any indicators of high buffering power (Table 1), showed high P fixation, since the plants had the lowest levels of P in the leaves (Figure 4). This may have been due to the mineralogy of the soil, which presented both Fe (goethite) and Al (gibbsite) oxides in addition to kaolinite, unlike the other soils, which contained only goethite or gibbsite (Table 1). In addition, the PVAdx soil presented the highest Ca content, which was 1.5 times greater than $PVAd_1$ and five times greater than $PVAd_2$ (Table 1); this may have influenced P precipitation, increasing the fixation capacity of the soil.

Classes of P availability in the soil and P sufficiency ranges in plant cane

The critical levels of P using the Mehlich-1 extractor were 17.10, 14.53 and 8.64 mg dm^{-3} in $PVAd_1$, PAdx and $PVAd_2$, respectively (Table 3). Using AER as the extractor, the respective critical levels were 13.85, 20.33 and 25.60 mg dm^{-3} (Table 3). A variation in critical level was found between the extractors and the soils. For the difference in the critical levels of P between extractors, the highest values were found using AER, where the most obvious difference was in $PVAd_2$, where the value was three times greater than that found with Mehlich -1 (Table 3). A similar result was found by Brito Neto *et al*. (2017). The fact that the resin extracted greater levels of P is consistent with its ability to recover available forms of P regardless of the characteristics of the soil, reflecting in critical levels of higher value.

With the Mehlich-1 extractor, the $PVAd_1$ soil presented the highest critical level (Table 3), consistent with its lower buffering power (Table 1). Although this soil presented Fe oxide, such as goethite, considered one of the main components of the clay fraction responsible for P adsorption in the soil (FINK *et al*., 2016), the low clay content resulted in a lower phosphate buffering capacity, which reflected in a higher critical level using Mehlich-1.

Figure 4 - P content of sugarcane leaves during the first crop cycle (plant cane) for increasing doses of P_2O_5 (0, 40, 80, 120, 160 and 200 kg ha^{-1}) in a dystrophic Red Yellow Argisol of sandy texture ($PVAd_1$) (A), distro-cohesive Yellow Argisol of medium texture (PAdx) (B), and dystrophic Red Yellow Argisol of clayey texture ($PVAd_2$) (C)



With the other soils, the lower critical levels determined by Mehlich-1 can be attributed to the effect of their characteristics, such as a higher clay content, lower P-rem, and higher MPAC (Table 1), which are the characteristics that best reflect the P capacity factor. This result is in line with that of Rogeri *et al*. (2016), who found that with an increase in the buffering capacity of the soil there is a reduction in P extraction by Mehlich-1, and a lower value for the critical level of P, offsetting the sensitivity of the extractor to the buffering capacity of the soil.

When the AER extractor was used, the $PVAd_2$ soil presented the highest critical level (Table 3), showing that AER is not influenced by the buffering capacity of the soil since the soil presented the highest MPAC (Table 1). To determine whether the critical level for P in the soil can vary according to the extractor used and the soil characteristics, Simões Neto *et al*. (2011) carried out a correlation analysis between the critical levels obtained by the different extractors and the soil characteristics that reflect the P capacity factor (PCF). From the resulting data, these authors found no significant correlation between the critical levels of P determined by AER and the characteristics of the soil, with the exception of P-rem, which was attributed more to a chance variation than to the consistency of the relationship.

Despite the high clay content of $PAVd_2$ (456 g kg^{-1}), the organic matter content (5.79%) may have helped raise the critical level of P due to organic acids blocking the hydroxyls exposed on the mineral surfaces (Fe and Al oxides), preventing P fixation, as seen by Mumbach *et al*. (2018). Debicka *et al*. (2015) observed a smaller amount of adsorbed P in the subsurface layers of five soils following the removal of organic matter, due to: (i) a break in the bonds of organic matter and P via cation bridges, (ii) clay mineral-organic complexes, and (iii) association of the organic matter with Fe and Al.

The critical levels of P in the leaves varied between soils. $PVAd_1$ presented the highest value (0.66 g kg^{-1}), followed by $PVAd_2$ (0.59 g kg^{-1}) and PAdx (0.34 g kg^{-1}). This shows that the P content of the plant required to reach maximum production is influenced by the characteristics of the soil, particularly those that reflect the ability for P fixation, as seen in various studies (REIS *et al*., 2020; SINGH *et al*., 2019). According to Fonseca *et al*. (2000), in clayey soils, i.e. those with a high PCF value, like $PVAd_2$, the plant shows better use of P in solution, producing more biomass per unit of absorbed P than in soils with a lower PCF, as is the case of $PVAd_1$.

As soils with a higher PCF present a lower critical level for P, it was expected that the plant grown in the clayey soil ($PVAd_2$) would have a lower critical level than when grown in the soil of medium texture (PAdx). However, the good fertility of the PAdx soil

Table 3 - Classes of available P content by the Mehlich-1 and Anion Exchange Resin (AER) extractors in a dystrophic Red Yellow Argisol of sandy texture ($PVAd_1$), distro-cohesive Yellow Argisol of medium texture (PAdx), and dystrophic Red Yellow Argisol of clayey texture ($PVAd_2$), and P sufficiency ranges in sugarcane leaves during the first crop cycle (plant cane) for different expected yields

Soil	Expected productivity (Mg ha^{-1})	Classes of available P content		
		Mehlich-1 (mg dm^{-3})		
		Low	Medium	High
$PVAd_1$	90	< 17.10	17.10-23.31	> 23.31
PAd_x	110	< 14.53	14.53-19.03	> 19.03
$PVAd_2$	100	< 8.64	8.64-12.75	> 12.75
Soil	-	AER (mg dm^{-3})		
$PVAd_1$	-	< 13.85	13.85-23.14	> 23.14
PAd_x	-	< 20.33	20.33-28.27	> 28.27
$PVAd_2$	-	< 25.60	25.60-38.92	> 38.92
Soil	-	Sufficiency ranges (g kg^{-1})		
$PVAd_1$	-	< 0.66	0.66-0.73	> 0.73
PAd_x	-	< 0.34	0.34-0.47	> 0.47
$PVAd_2$	-	< 0.59	0.59-0.69	> 0.69

afforded maximum production with a smaller amount of accumulated P in the plant, which reflected in a lower critical level for P in the leaf.

A knowledge of the critical levels for P, both in the soil and in the plant, is essential for establishing a more accurate recommendation for phosphate fertiliser, especially as sugarcane responds to phosphate fertilisation, and the recovery of P fertiliser by the crop is low, less than 25% (BORGES *et al*., 2019; ZAMBROSI, 2021). Simões Neto *et al*. (2015) highlighted the importance of knowing not only the available levels of P, but also the characteristics of the soil that can predict its PCF. It is therefore possible to understand P dynamics between the soil and the plant, and recommend doses of P that are able to meet the nutritional demand for this nutrient.

CONCLUSIONS

1. The AER extractor best represented P availability in Argisols of medium (PAdx) and clayey texture ($PVAd_2$) during the first sugarcane cycle (plant cane);
2. The available P content determined by the two extractors correlated positively with the P content in the aerial part of the sugarcane during the first crop cycle (plant cane), with the P determined by Mehlich-1 being more representative in the sandy soil ($PVAd_1$) and that determined by AER more representative in the clayey ($PVAd_2$) and medium (PAdx) soils;
3. The P content in the classes for interpreting P availability determined by AER were higher than those determined by Mehlich-1;
4. The P sufficiency ranges in the sugarcane leaves varied between soils: 0.66-0.73 g kg^{-1} in $PVAd_1$, 0.59-0.69 g kg^{-1} in $PVAd_2$, and 0.34-0.47 g kg^{-1} in PAdx;
5. The texture of the Argisols used in sugarcane cultivation in the Northeast of Brazil should be a criterion in choosing the P extractor in order to assess its availability.

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