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Soil properties and pH of the extractors influence extraction and availability P in alkaline soils from the São Francisco Valley, Brazil

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ABSTRACT: Phosphorus (P) is one of the most used nutrients in agriculture due to its high degree of interaction with the soil. It is susceptible to calcium precipitation in poorly weathered and alkaline soils, such as those in the Brazilian Semi-Arid region. Mehlich-1 is the most used extractor to evaluate P availability in this region. However, there are controversies regarding the efficiency of Mehlich-1 and the anion exchange resin (AER) has been an alternative extractor to evaluate P availability. However, AER has not yet proven its efficiency in this region. Additionally, other extractors such as Mehlich-3 and Olsen need to be evaluated. This study aimed to correlate soil properties in an alkaline environment with the P extracted by Mehlich-1, AER, Mehlich-3 and Olsen extractors and assess the performance of these extractors in predicting P availability for *Urochloa decumbens* in representative soils of the sub-middle São Francisco Valley. An experiment was carried out with samples of six representative soils from productive areas of the sub-middle São Francisco Valley, Brazil. Soils were incubated with increasing P rates and after 30 days, soil samples were collected for P determination by the extractors Mehlich-1, AER, Mehlich-3, and Olsen, relating this extraction to soil properties. Soils were seeded with *U. decumbens* to determine biomass production and P accumulated in plant biomass, correlating this accumulation with the P extraction capacity of the extractors. Exchangeable Ca^{2+} content and soil pH influenced the P extraction rate more than clay and P-rem content. Mehlich-1 extractor overestimated available P. Anion exchange resin was also influenced by soil properties and showed low prediction of P availability. In contrast, Olsen extractor was not influenced by soil properties, but showed low prediction of available P. The pH of Mehlich-3 extracts was little altered during P extraction in the different soils, with the extraction of P influenced by the exchangeable Ca^{2+} contents and pH. However, Mehlich-3 showed high performance in predicting P availability in alkaline environments, suggesting that soil properties such as exchangeable Ca^{2+} and pH should be considered when P availability is evaluated in alkaline soils.

Keywords: chemical extractors, Semi-arid, recovery rate, soil P determination.

INTRODUCTION

A significant fraction of the Brazilian Semi-Arid region has excelled as a great producer of mango and grapes (Lima et al., 2021); however this fruit crop is under soils with alkaline pH, and soil pH is an important factor that determines P species and their solubility (Penn and Camberato, 2019). In alkaline soils, 2:1 calcium minerals and carbonates react with P and reduce its availability (Ara et al., 2018).

In this region, the Mehlich-1 extractor is the most commonly used to evaluate P availability, but it has been inefficient to perform this evaluation, as it is very acidic and its action can wear out, reducing its ability to extract P or solubilize forms of P-Ca, which plants cannot access and absorb. Alternatively, the region has used anion exchange resin (AER), but there is no data in the literature that proves its efficiency to evaluate the availability of P in these alkaline reaction soils. Although Olsen was explicitly developed for alkaline soils (Dari et al., 2019), its use is not common in Brazil, and Mehlich-3 was developed to cover a wide range of soils with different characteristics.

It is important to highlight three important aspects in the performance of these extractors in alkaline soils. First, it is necessary to evaluate the pH of the extract when these extractants come into contact with alkaline soils, especially more acidic extractants and AER. Second, evaluate how these extractors behave in alkaline soils with different characteristics. Mehlich-1 may underestimate or overestimate phosphate fertilizer recommendations depending on soil texture and Ca content, as it can solubilize P-Ca. Mehlich-1 tends to underestimate available P in clayey soils with neutral or alkaline pH, as these soils are highly buffered (Reis et al., 2020). Few studies evaluate soil pH impact on the effectiveness of Mehlich-3 in P extraction (Penn et al., 2018). On the other hand, AER is described as an insensitive method to the P capacity factor (PCF) and P-Ca fractions, being recommended for acidic and alkaline soils (Novais and Smyth, 1999). However, the use of AER in soils with high buffering capacity and rich in P-Ca is questioned (Novais and Smyth, 1999). Third, it is important to integrate these two aspects, correlating what P actually is inside the plant with the P that extractors are extracting.

Our hypothesis is that soil pH and extractor pH influence the extraction of P and the estimate of available P; therefore, extractants with an alkaline or neutral reaction are more suitable for alkaline soils. This study aimed to correlate soil properties in an alkaline environment with P extracted by Mehlich-1, AER, Mehlich-3 and Olsen extractors and evaluate the performance of these extractors in predicting P availability for *Urochloa decumbens* in representative soils of sub-middle São Francisco Valley.

MATERIALS AND METHODS

Six representative soils were collected from productive areas under irrigation in the Submédio São Francisco Valley in the Northeast of Brazil. The region climate is semi-arid of the BSh type according to the Köeppen classification system (Alvarez et al., 2013). Soils were chosen because they represent 72 % of productive soils in the region (Cunha et al., 2008) and, according to pH values, from neutral to alkaline, and classified as: Neossolo Flúvico (RY; Fluvent), Neossolo Quartzarênico (RQ; Quartzipsamment), Argissolo Vermelho-Amarelo (PVA; Ultisol), Latossolo Vermelho-Amarelo (LVA; Oxisol), and Vertissolo (V; Vertisol) (Jacomine et al., 1973, 1979; Soil Survey Staff, 2014) (Figure 1).

Ten simple soil samples were collected in the 0.00-0.20 m layer to obtain a representative composite sample of each area. Soil samples were air-dried, crushed, passed through a 5-mesh sieve, homogenized, and stored. A subsample of each soil was separated and passed through a 2.0 mm diameter sieve for characterization analyses (Table 1).

Table 1. Chemical and physical characterization of the soils Fluvent (RY), Quartzipsamment (RQ), Ultisol (PVA1 and PVA2), Oxisol (LVA) and Vertisol (V)

Soil	RY	RQ	PVA1	PVA2	LVA	V
$pH(H_2O)$ (1:2,5)	7.42	7.56	7.09	7.42	7.33	8.50
EC_{se}[(1)] ($dS\ m^{-1}$)	1.00	0.77	3.23	3.96	1.03	0.49
Ca^{2+}_{se} ($mmol_c\ L^{-1}$)	9.33	3.97	21.98	18.00	5.31	5.12
Mg^{2+}_{se} ($mmol_c\ L^{-1}$)	3.56	3.55	23.77	21.53	5.27	0.72
Na^{+}_{se} ($mmol_c\ L^{-1}$)	1.10	0.87	2.73	8.34	1.19	0.71
K^{+}_{se} ($mmol_c\ L^{-1}$)	1.58	1.51	6.01	17.02	2.05	0.18
SAR[(2)] [$(mmol_c\ L^{-1})^{0,5}$]	0.43	0.45	0.57	1.88	0.52	0.41
$Ca^{2+}_{exchangeable}$ ($mmol_c\ dm^{-3}$)	63.95	38.85	61.26	40.91	48.95	255.64
$Mg^{2+}_{exchangeable}$ ($mmol_c\ dm^{-3}$)	11.61	10.98	23.08	26.77	17.09	15.71
$Na^{+}_{exchangeable}$ ($mmol_c\ dm^{-3}$)	3.53	2.29	6.02	10.19	3.50	7.62
$K^{+}_{exchangeable}$ ($mmol_c\ dm^{-3}$)	7.29	5.58	14.42	22.72	7.58	8.82
CEC[(3)] ($mmol_c\ dm^{-3}$)	89.03	58.43	106.88	100.58	79.42	298.58
ESP[(4)] (%)	3.96	4.43	5.63	10.13	4.41	2.55
TOC[(5)] ($dag\ kg^{-1}$)	1.83	1.44	3.17	2.86	2.50	1.43
P-rem[(6)] ($mg\ L^{-1}$)	51.04	55.46	49.48	44.34	47.20	18.92
P Mehlich-1 ($mg\ dm^{-3}$)	83.22	327.73	386.09	222.69	350.49	17.49
P Mehlich-3 ($mg\ dm^{-3}$)	65.16	266.64	323.62	360.63	329.98	7.50
P AER[(7)] ($mg\ dm^{-3}$)	39.56	86.14	156.25	158.59	129.37	3.27
P Olsen ($mg\ dm^{-3}$)	12.71	55.64	62.99	92.03	48.29	3.26
Total sand ($g\ kg^{-1}$)	784.08	903.09	752.45	803.17	866.67	354.73
Coarse sand ($g\ kg^{-1}$)	494.37	642.65	381.29	424.45	452.33	255.30
Fine sand ($g\ kg^{-1}$)	289.71	260.44	371.16	378.73	414.34	99.43
Silt ($g\ kg^{-1}$)	99.52	14.59	101.87	51.53	30.75	209.98
Clay ($g\ kg^{-1}$)	116.40	82.32	145.68	145.30	102.58	435.29
WDC[(8)] ($g\ kg^{-1}$)	75.43	34.31	62.43	75.97	27.32	245.84
Flocculation ($g\ g^{-1}$)	0.33	0.57	0.57	0.40	0.69	0.44
BD[(9)] ($g\ cm^{-3}$)	1.48	1.55	1.39	1.39	1.46	1.29
PD[(10)] ($g\ cm^{-3}$)	2.51	2.59	2.44	2.49	2.57	2.16
PC[(11)] ($g\ g^{-1}$)	0.34	0.30	0.36	0.35	0.37	0.45

[(1)] EC_{se}: electrical conductivity of saturation extract; [(2)] SAR: sodium adsorption ratio; [(3)] CEC: cation exchange capacity; [(4)] ESP: exchangeable sodium percentage; [(5)] TOC: Total organic carbon; [(6)] P-rem: Remaining-P; [(7)] P AER: P extracted by anion exchange resin; [(8)] WDC: Water-dispersible clay; [(9)] BD: Bulk density; [(10)] PD: particle density; [(11)] PC: pot capacity.

On soil characterization, $pH(H_2O)$ was determined in the soil:water ratio 1:2.5 (Teixeira et al., 2017). Saturation paste extract (USSL Staff, 1954) was prepared to measure electrical conductivity (EC) and pH; and to determine soluble cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}). Exchangeable cations were extracted by ammonium acetate ($1.0\ mol\ L^{-1}$); cation exchange capacity (CEC) was determined by the sodium acetate/ammonium acetate method (USSL Staff, 1954). Soluble and exchangeable Ca^{2+} and Mg^{2+} contents were measured by atomic absorption spectrophotometry, and Na^+ and K^+ by flame emission photometry. Sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) were calculated using the results of the analyses of soluble and exchangeable cations, respectively, according to USSL Staff (1954).

Phosphorus content in the soil was extracted by Mehlich-1 (Mehlich, 1978), Mehlich-3 (Mehlich, 1984), anion exchange resin (AER) (Tedesco et al., 1995) and Olsen (Olsen et al., 1954). The P-rem was obtained by Alvarez V et al. (2000). Total organic carbon (TOC) was determined by the wet oxidation method (Mendonça and Matos, 2005).

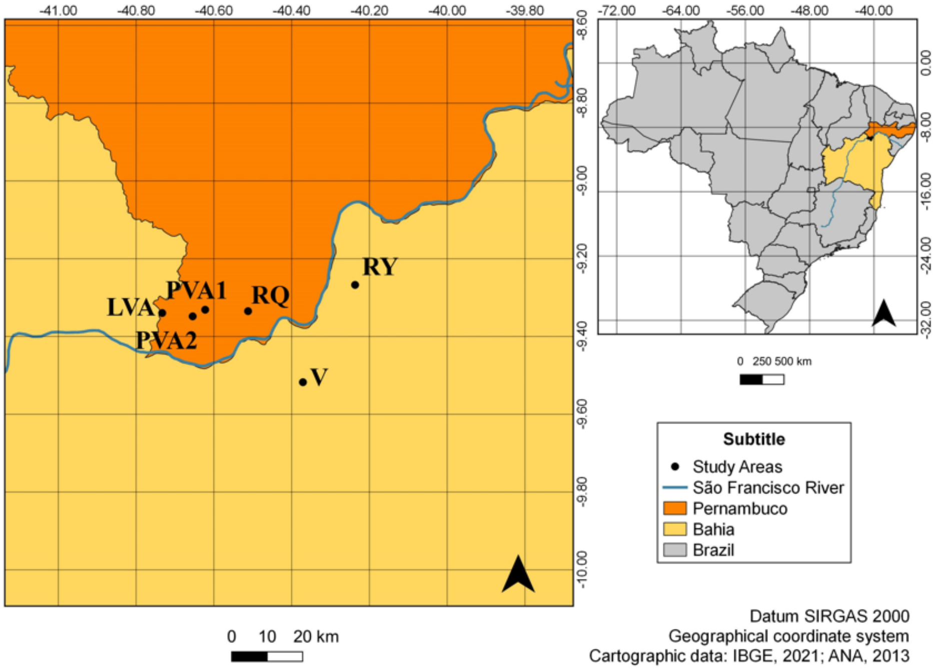

Figure 1. Location of the soils (LVA – Oxisol, PVA1 and PVA2 – Ultisol, RQ – Quartzipsamment, RY – Fluvent, V – Vertisol) collected along the São Francisco River in the semi-arid region of Brazil.

Particle size and water-dispersed clay (WDC) analyses were performed by the pipette method (Teixeira et al., 2017), bulk density (BD) by volumetric cylinder method, particle density (PD) by volumetric flask method (Teixeira et al., 2017), and pot capacity (PC) by direct gravimetric method (Souza et al., 2000).

Amplitude range of P doses was estimated according to Alvarez V and Fonseca (1990), based on P-rem result of each soil. The interval established was 0-770 mg dm^{-3} for Vertissol and 0-370 mg dm^{-3} for the other soils. Phosphorus rates were defined as 0, 10, 20, 40, 70, and 100 % of the maximum rate for each soil.

Phosphorus sources used were monopotassium phosphate (KH_2PO_4) and monobasic ammonium phosphate ($NH_4H_2PO_4$). KH_2PO_4 was applied until the K rate reached 200 mg dm^{-3}. Phosphorus rate was supplemented by $NH_4H_2PO_4$. Potassium and N were provided by potassium chloride (KCl) and ammonium sulfate $(NH_4)_2SO_4$, respectively, in all treatments to balance with the highest rates.

The experiment was carried out in a greenhouse. Treatments were arranged in a 6 × 6 factorial scheme, with six soils, six P rates, and four replications, totaling 144 experimental units. Experiment was arranged in a randomized block design. The plots consisted of pots with 1.7 dm^3 of soil, with their respective P rates added and homogenized in the total soil volume. Moisture content was maintained between 70 and 50 % of the PC during soil incubation with P rates for 30 days.

After incubation for 30 days, the pot content was put into a tray and homogenized. Subsamples of 60 cm^3 of soil were taken for P determination by the extractors Mehlich-1, Mehlich-3, AER, and Olsen. The pH in the extracts of the acid extractants Mehlich-1 and Mehlich-3 from each soil was measured to assess whether there would be changes in the pH of the extractant and the extracts in the different soils.

After sampling, 5 cm^3 of *Urochloa decumbens* cv. Basilisk seeds were sown in each pot. Thinning was performed one week after seedling emergence to maintain approximately 10 individuals per pot. Moisture content was maintained at 80 % PC of each soil. Water was replenished daily by weighing the pots.

The first cut of *Urochloa* was carried out 30 days after seedling emergence. Aerial biomass of the plants was weighed and stored in paper bags. Plant leaf biomass was dried in an oven at 60 °C to constant weight, weighed again to obtain the results of dry matter production, and ground in a knife mill. Plants were kept in the pots for the second cycle without adding fertilizer under the same soil moisture management until the second cut, performed 30 days after the first one. Plants were collected using the same procedure adopted in the first cut. Plant dry matter was digested in H_2O_2 and H_2SO_4 to determine P content by the Adler and Wilcox method (Adler and Wilcox, 1985). Total P extracted by the plants in each pot in the two cycles was estimated from P content and dry matter production data.

Equations were adjusted by P recovered values for each extractor as a function of the P applied rates. Coefficients of the equations obtained were the P recovered rates for each extractor in each soil (P-RR). Linear correlations were tested between these coefficients and some of the main attributes of the soils, such as exchangeable Ca^{2+}, P-rem, clay content and pH. Linear correlations were tested between P content in *Urochloa decumbens* in the first and second cuts and P-RR obtained by the extractors for all soils, to select the best extractor to predict P availability in alkaline soils. Regression equations of plant dry matter production were also adjusted as a function of applied P rates. The maximum yield point ($\hat{Y}$) was calculated to obtain $0.9\hat{Y}_{maximum}$ for each equation. Recommended P rate (RPR) was calculated by replacing the maximum dry matter production at $\hat{Y}$ in the equation.

RESULTS AND DISCUSSION

Recovered P varied among different extractors and soils because of the diverse characteristics of these soils. Linear models were the best for fitting the data enabling the definition of equations for recovered P as a function of the applied P rates and P recovery rate (P-RR) for each extractor in the six evaluated soils (Table 2).

Mehlich-1 showed high P-RR values, except for V (Table 2). The V had the highest pH value and clay content, high CEC, and high exchangeable Ca^{2+} content (Table 1). The V has 2:1 clay mineral with a high degree of permanent charges and acidity buffering power, which reduces the extraction capacity of Mehlich-1. The highest pH of V among the six evaluated soils (8.50) may have altered the extraction capacity of the extractors. Also, the formation of low solubility compounds between P and exchangeable Ca^{2+} may have hindered the P extraction in this soil. It can be proven by the P-rem value of V, the lowest among the soils studied (Table 1), which caused the P rates calculated and applied in this soil to be higher than in the other soils.

Mehlich-1 may underestimate or overestimate P availability in soils, depending on the texture and high calcium contents (Santos et al., 2008). Although Mehlich-1 is widely used to estimate available P in soils in Brazil, it is not the most suitable extractor for clayey soils with neutral or alkaline pH values, because Mehlich-1 tends to underestimate the available P in heavily buffered soils. However, in poorly buffered soils, it is common for Mehlich-1 to overestimate the available P, as happened with RY, RQ, PVA1, and PVA2 (Table 2). The AER and Olsen are not part of the acid dissolution group like Mehlich-1 and Mehlich-3. Therefore, AER and Olsen act differently and some authors describe them as more suitable for higher pH soils (Dari et al., 2019; Medeiros et al., 2021).

Calheiros et al. (2012) reported a higher P extraction capacity of Mehlich-1 in a Neossolo Flúvico (Fluvent) in the semi-arid of Pernambuco, an alkaline (pH = 7.63) poorly developed soil. These authors compared Mehlich-1, Mehlich-3, Bray-1, and Olsen and justified the greater extraction of Mehlich-1 by the solubilization of calcium phosphates. Thus, in neutral and alkaline soils, Mehlich-1 tends to overestimate P availability because P-Ca may not be available to plants. In our study, Mehlich-1 overestimated P availability in most soils, except for LVA and V (Table 2). Although soil V has the highest exchangeable Ca^{2+} content, Mehlich-1 underestimated the available P due to its high buffering power.

Table 2. Equations for recovered P content (ŷ, mg dm^{-3}) by the extractors depending on applied P rates (x, mg dm^{-3}) in each soil and P recovery rate (P-RR) for each extractor

Soil	Equation	R^2	P-RR
	Mehlich-1		
RY	$\hat{y}$ = 190.77808 + 1.33658*** x	0.9906	1.33658
RQ	$\hat{y}$ = 560.25571 + 1.65269*** x	0.8941	1.65269
PVA1	$\hat{y}$ = 832.88707 + 1.79720*** x	0.9394	1.79720
PVA2	$\hat{y}$ = 474.42602 + 1.40128*** x	0.9745	1.40128
LVA	$\hat{y}$ = 840.45737 + 1.01692*** x	0.7378	1.01692
v	$\hat{y}$= 2.14004 + 0.24848*** x	0.9865	0.24848
	Mehlich-3		
RY	$\hat{y}$ = 54.61838 + 0.97418*** x	0.9795	0.97418
RQ	$\hat{y}$ = 316.07918 + 0.83191*** x	0.7991	0.83191
PVA1	$\hat{y}$ = 342.64452 + 1.05252*** x	0.8317	1.05252
PVA2	$\hat{y}$ = 361.76922 + 1.26053*** x	0.9589	1.26053
LVA	$\hat{y}$ = 411.21026 + 1.10559*** x	0.8411	1.10559
V	$\hat{y}$ = 10.56103 + 0.40016*** x	0.9806	0.40016
	Anion Exchange Resin		
RY	$\hat{y}$ = 36.04680 + 0.84780*** x	0.9652	0.84780
RQ	$\hat{y}$ = 113.12757 + 0.82785*** x	0.8727	0.82785
PVA1	$\hat{y}$ = 110.95156 + 0.77919*** x	0.9570	0.77919
PVA2	$\hat{y}$ = 200.34068 + 0.64773*** x	0.8518	0.64773
LVA	$\hat{y}$ = 158.35448 + 0.57707*** x	0.7593	0.57707
V	$\hat{y}$ = 7.21992 + 0.03992*** x	0.8467	0.03992
	Olsen		
RY	$\hat{y}$ = 40.96825 + 0.39383*** x	0.9879	0.39383
RQ	$\hat{y}$ = 57.95944 + 0.73108*** x	0.9773	0.73108
PVA1	$\hat{y}$ = 70.78391 + 0.84478*** x	0.9621	0.84478
PVA2	$\hat{y}$ = 109.96995 + 1.06846*** x	0.9696	1.06846
LVA	$\hat{y}$ = 71.40775 + 0.76813*** x	0.9612	0.76813
V	$\hat{y}$ = 9.21238 + 0.10889*** x	0.9788	0.10889

RY: Fluvent; RQ: Quartzipsamment; PVA1 and PVA2: Ultisol; LVA: Oxisol; and V: Vertisol. *** Significant at 0.1 % of probability.

Reis et al. (2020) found higher values of P-RR with Mehlich-1 and lower values with AER, even in more weathered soils (Ferralsol and Acrisol) with pH between 5.14 and 6.92. In our study, AER and Olsen showed lower P-RR values (Table 2). The AER is described as not sensitive to PCF or to P-Ca presence; therefore, it is the appropriate method for soils in a wide pH range, from acidic to alkaline (Novais and Smyth, 1999; Santos et al., 2008).

Olsen generally had lower P-RR values than those of the acid extractors and higher values than the AER. Ara et al. (2018) also found that Olsen has a lower ability to extract P from acidic and alkaline soils than acid extractors. Olsen is recommended for high pH soils worldwide, but its use is uncommon in Brazilian laboratories. Comparing Mehlich-1, Mehlich-3, Bray-1, and Olsen in Neossolo Flúvico (Fluvent) from semi-arid region of Brazil, Calheiros et al. (2012) observed similar values of P-RR among Olsen (0.6131 mg dm^{-3}/mg dm^{-3}), Mehlich-1 (0.6216 mg dm^{-3}/mg dm^{-3}), and Mehlich-3 (0.5966 mg dm^{-3}/mg dm^{-3}). Although the soil used by these authors is alkaline (pH = 7.63), there were no major differences among the extractors evaluated, possibly due to the lower clay content and pH in relation to the V soil in our study.

The P-RR value above 1.0 means that the extractor is recovering more P than was provided by fertilization, since the pre-existing P levels in the soil are also added to the equation, estimated by the intercept. In these soils, part of the P released by the extractors may be less soluble P compounds, especially calcium phosphates. This is quite common, especially in soils fertilized with natural phosphate and evaluated by Mehlich-1 (Reis et al., 2020). In addition, in our study, pH values of the soils are between 7.09 and 8.50 and exchangeable calcium contents between 38.85 and 255.64 $mmol_c$ dm^{-3} (Table 1), values quite different from most Brazilian tropical soils. The AER was the only extractor that had P-RR values below 1.0 for all soils.

The V was the only soil in which the P-RR of Mehlich-1 was lower than 1.0 because V is the soil with the highest clay content and lowest P-rem in the study (Table 1). Furthermore, V has the highest pH, which may have resulted in greater wear of the extractor. Although Mehlich-3 is another extractor from the acid dissolution group evaluated in this study, its wear due to pH was less expressive.

To prove this, we measured the pH of the extracts obtained from each soil with acid extractors (Mehlich-1 and Mehlich-3) (Table 3). As the initial pH of these extractors was 1.2 and 2.5 for Mehlich-1 and Mehlich-3, respectively, the change in pH was clear in the Mehlich-1 extract in V. Possibly, Mehlich-1 solubilized precipitated compounds in this soil, releasing hydroxyls in high proportion, resulting in a high pH value in the extract (8.27). This proves the wear theory of the Mehlich-1 extractor, especially in higher pH soils such as V.

Although the wear of Mehlich-3 is lower than Mehlich-1, its P extraction capacity may be influenced by the increase in soil pH, due to the reduction of P-Al and P-Fe dissolution and the desorption of P from Fe and Al oxides (Penn et al., 2018). For neutral pH soils, Penn et al. (2018) found a significant positive correlation between soil pH and the pH of the Mehlich-3 extractor solution after reaction. They also found a significant negative correlation between the pH of the extractor solution after reaction and the P extracted by Mehlich-3, confirming that the P extraction capacity of Mehlich-3 decreases in high pH soils.

Growth and plant dry matter production differed among soils and the two cuts. Equations were obtained for each soil in the first and second cuts of the plants, with significant coefficients and high R^2 values. In the first cut, there was a significant increase in dry matter production of U. decumbens as a function of the P rates applied to the soils, except for PVA1 (Table 4). On the other hand, the increase was significant for all soils in the second cut, indicating that the time between sowing and the first cut may not have been sufficient for the plants of each treatment to express differences in plant biomass production in a significant way.

The PVA1 was one of the soils with the highest available P concentrations and had the highest TOC content (Table 1). Organic matter adsorbs P by complexation reaction and provides P to the plants, thus it is also a P source in the soil. This is another reason why P fertilization did not have much influence on dry matter production in PVA1 in the first cut.

Table 3 Mean pH values of extracts obtained for the determination of P rates in the soils Fluvent (RY), Quartzipsamment (RQ), Ultisol (PVA1 and PVA2), Oxisol (LVA) and Vertisol (V)

Extractor		RY	RQ	PVA1	PVA2	LVA	V
				pH			
Mehlich-1	1.2	1.45	1.51	1.79	1.57	1.55	8.27
Mehlich-3	2.5	2.91	2.94	3.17	3.27	2.91	3.58

Table 4. Equations of dry matter production ($\hat{y}$, g pot^{-1}) of *Urochloa decumbens* in the first and second cuts as a function of P rates (x, mg dm^{-3}) applied in each soil, 90 % of the maximum yield (0.9-$\hat{y}_{max}$), and recommended P rates (RPR)

Soil	Equation	R^2	0.9-$\hat{Y}_{max}$	RPR
	First cut		g pot^{-1}	mg dm^{-3}
RY	$\hat{y}$ = 9.270733 + 0.015111** x - 0.000024548* x^2	0.97	10.44	90.45
RQ	$\hat{y}$ = 4.592011 + 0.030104** x - 0.000055403** x^2	0.98	7.81	146.50
PVA1	$\hat{y} = \bar{y}$ = 6.23	-	6.23	0.00
PVA2	$\hat{y}$ = 0.80598 + 0.02576** x - 0.00004696** x^2	0.99	3.90	101.50
LVA	$\hat{y}$ = 7.175909 + 0.015723** x - 0.000025169* x^2	0.97	8.67	116.73
V	$\hat{y}$ = 0.50802 + 0.00243* x	0.74	2.14	672.09
	Second cut			
RY	$\hat{y}$ = 10.613718 + 0.030097** x - 0.000078283** x^2	0.97	12.16	60.88
RQ	$\hat{y}$ = 11.056975 + 0.016156** x - 0.000023239* x^2	0.97	12.48	103.35
PVA1	$\hat{y}$ = 11.346670 + 0.018828** x - 0.000053664** x^2	0.97	11.70	5.70
PVA2	$\hat{y}$ = 3.427243 + 0.040888** x - 0.000066567** x^2	0.98	8.73	186.37
LVA	$\hat{y}$ = 11.200212 + 0.035397** x - 0.000082987** x^2	0.96	13.48	78.94
V	$\hat{y}$ = 1.430041 + 0.006906** x - 0.000005438* x^2	0.99	3.26	376.87

RY: Fluvent; RQ: Quartzipsamment; PVA1 and PVA2: Ultisol; LVA: Oxisol; and V: Vertisol. *, ** significant at 5 and 1 % probability, respectively.

Quadratic models were the ones that best fit the data, except for V in the first cut, which was linear (Table 4). Plant dry matter production in V was much lower than in other soils, although the P rates in V were higher than those in RY, RQ, PVA1, PVA2, and LVA. In addition to having the lowest P-rem among the soils studied, it is possible that the formation of low solubility compounds occurred since V characterization shows the highest exchangeable Ca^{2+} content among all soils evaluated, the highest pH value, and the lowest available P contents by the extractors (Table 1). Furthermore, P content estimated by the P rate of 770 mg dm^{-3} in V with any chemical extractor of the experiment (Table 1) was lower or similar to the P content of the other soils without P addition (rate 0 mg dm^{-3}).

In general, the highest values of dry matter production were in the second cut. After the first cut, the plants already had a well-developed root system and only needed to recover the aerial part. Thus, recommended P rates were lower in the second cut due to the lower demand for P (Table 4). Increase in dry matter production is shown in figure 2, where the difference between the soils and the two cuts evaluated is clear. The two Entisols, RY (Fluvent, Figure 2a), and RQ (Quartzipsamment, Figure 2b) had similar productions in the second cut. However, in the first cut, dry matter production in RQ was lower than in RY. The PVA1 and PVA2 belong to the same soil class and have similar characteristics (Table 1), but the dry matter production of PVA2 was lower than PVA1 (Figures 2c and 2d). It is possible that the plants had other growth limitations in PVA2, such as 10 % PST, which may have affected the physical properties and limited root development of the plants. The LVA (Figure 2e) was the soil in which the plants had the highest dry matter production, in contrast to V (Figure 2f). The LVA has lower pH and clay content and higher P-rem than soil V (Table 1), providing better conditions for plant development in this study, with good responses to P rates (Figures 2e and 2f).

This result confirms the inefficiency of Mehlich-1 for alkaline soils with high Ca^{2+} concentrations, overestimating P availability in these soils (Novais et al., 2007). In addition, the most clayey soils showed the lowest correlation coefficients with Mehlich-1, whether significant or not. It also shows the lower extraction power of Mehlich-1 in very clayey soils.

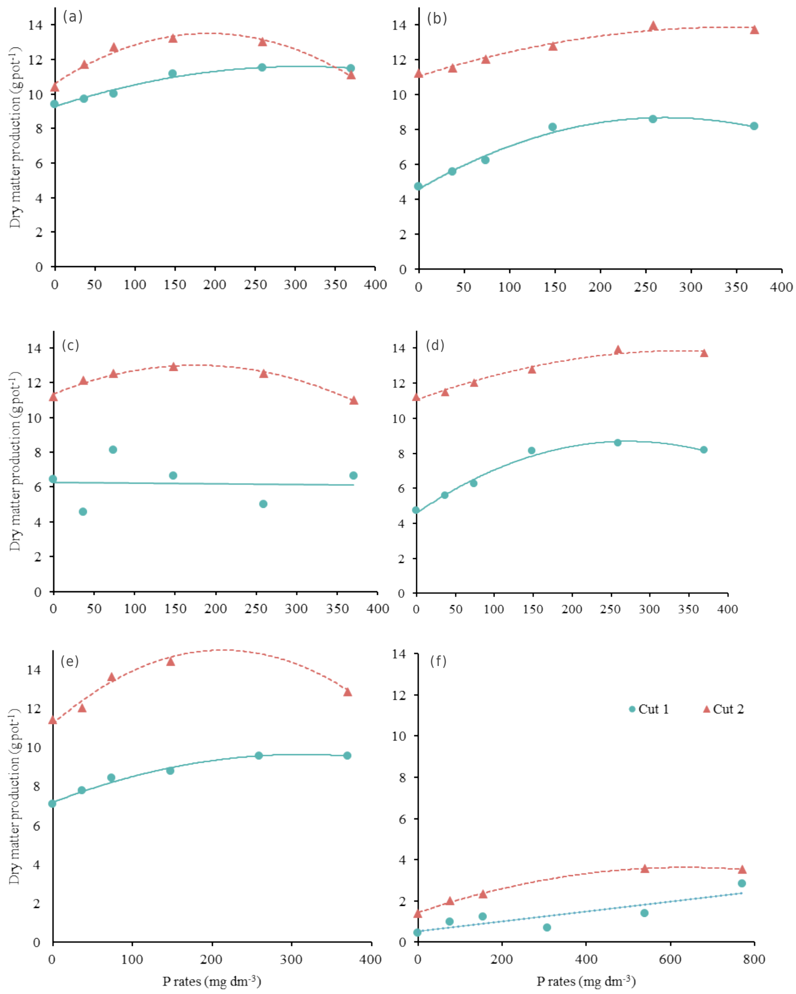

Figure 2. Dry matter production (g pot^{-1}) of aerial part of Urochloa decumbens in first and second cuts, cultivated in Fluvent-RY (a), Quartzipsamment-RQ (b), Ultisol 1-PVA1 (c), Ultisol 2-PVA2 (d), Oxisol-LVA (e), and Vertisol-V (f) as a function of P rates (mg dm^{-3}).

Calheiros et al. (2012) showed an opposite result, which Mehlich-1 was the second extractor with the highest correlation with P content in the aerial part of corn grown in a Neossolo Flúvico (Fluvent). However, the soil in Calheiros et al. (2012) had a lower mean concentration of Ca^{2+} (28.2 mmol$_c$ dm^{-3}) than that of our study (84.9 mmol$_c$ dm^{-3}), which may have influenced the better fit of Mehlich-1 in the authors' work.

Mehlich-3 was the only extractor with a significant correlation in all soils and cuts. It confirms its versatility, encompassing neutral and alkaline soils with various chemical and physical properties, fulfilling the Mehlich-3 development proposal (Penn et al., 2018).

There was a significant inverse correlation between exchangeable Ca^{2+} contents and P-RR by all chemical extractors evaluated (Figure 3). Thus, the higher the exchangeable Ca^{2+} content in the soil, the lower the P-RR of the extractor. There was also a significant inverse correlation with soil pH for all chemical extractors except Olsen, which can be explained by the high pH of this extractor (8.5). It also proves that pH does not interfere with P-RR by the Olsen extractor and can be used for soils in a wide pH range. Mehlich-1 correlates with clay, P-rem, and exchangeable Ca^{2+}, showing that it is not a versatile extractor for different soil types.

Figure 3 shows different results for AER in neutral and alkaline soils. AER usually does not correlate significantly with P-rem or clay content in acidic soils as reported by Simões Neto et al. (2009). These authors used more weathered soils, with pH between 4.10

and 5.55, with Mehlich-1, Mehlich-3, and AER extractors. However, in our study, AER correlated with P-rem, clay content, exchangeable Ca^{2+}, and soil pH, which are important properties for soil P availability. This indicates that AER is not the most indicated extractor for soils with a wide pH range. In our study, when the P recovered by the extractors was correlated with P-rem and clay content, there was significant correlation at 5 % only between Mehlich-3 and P-rem.

Linear correlations between P content in the plants and P recovered by the extractors (Figure 4) were significant in all soils in at least one cut for each extractor, except for Mehlich-1, in LVA and V. Mehlich-1 had the lowest number of significant correlations individually with each soil. It shows that Mehlich-1 should not be recommended for alkaline soils with high Ca^{2+} concentration and can overestimate P availability in those soils. Furthermore, the most clayey soils had the lowest correlation coefficients in Mehlich-1, evidencing its low extraction capacity in clayey soils.

Figure 4 shows that Olsen correlated with P content in the plant for all soils except PVA1 and PVA2 in the first cut. Mehlich-3 correlated with P content in the plant for all soils, although it is an acid extractor, indicating that Mehlich-3 is a very versatile extractor for neutral and alkaline soils. AER had a similar result to Olsen, but had lower significance levels of correlation than Olsen in the second cut.

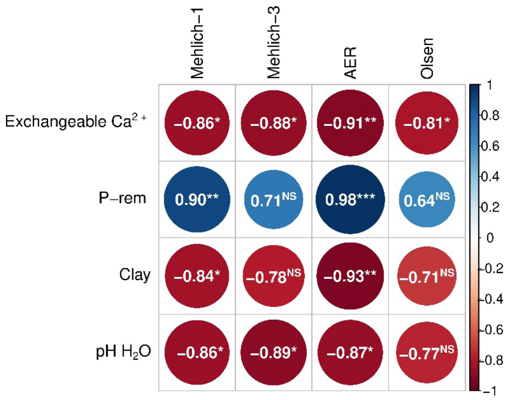

Figure 3. Linear correlation coefficients (r) between P recuperation rates (P-RR) of the extractors and some soil properties. NS, *, **, *** non-significant and significant at 5, 1, and 0.1 %, respectively.

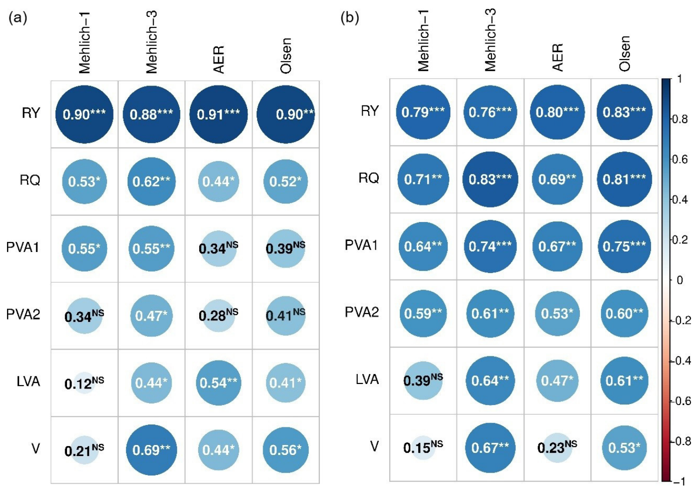

Figure 4. Linear correlation coefficients (r) between P content (mg pot^{-1}) in *Urochloa decumbens*, in the first (a) and second (b) cuts, and recovered P (mg dm^{-3}) by the extractors for soils Fluvent (RY), Quartzipsamment (RQ), Ultisol (PVA1 and PVA2), Oxisol (LVA), and Vertisol (V). NS, *, **, *** non-significant and significant at 5, 1, and 0.1 %, respectively.

This shows the differences in relation to the most appropriate extractor to obtain results that better estimate P availability in neutral and alkaline soils. Despite the predominance of Oxisols and Ultisols in Brazil, there are soils with a lower degree of weathering in many productive areas Usually, these soils have predominance of 2:1 clay minerals and pH values on the alkalinity scale. The use of Mehlich-1 extractor to estimate P availability in those cases may lead to wrong P fertilizer recommendations and should be reviewed.

CONCLUSIONS

Plant dry matter production of *Urochloa decumbens* raised with increasing P doses in poorly developed soils with alkaline pH. Exchangeable Ca content and soil pH influenced the P extraction rate more than the clay and P-rem content and these soil properties should be considered when evaluating P availability in alkaline soils. Mehlich-1 extractor overestimated available P, except in Vertisol, which presented the highest pH and high levels of exchangeable Ca^{2+}. Anion exchange resin was also influenced by soil properties and showed low prediction of P availability. Olsen extractor was influenced only by exchangeable Ca as soil properties and showed low prediction of available P. The pH of the Melhich-3 extracts was little altered during P extraction in these different studied soils and it was influenced by exchangeable Ca contents and pH. Melhich-3 showed high performance in predicting P availability in alkaline environments. Soil properties such as exchangeable Ca^{2+} and pH should be considered when P availability is evaluated in alkaline soils. We suggest that P availability be better studied in environments with high pH, considering soil, extractor and cultivated plant.

DATA AVAILABILITY

The data will be provided upon request.

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