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Phosphorus extractors in soil under no-tillage system with 19 years of swine manure applications

Rodrigo Gomes Silva [a], June Faria Scherrer Menezes [a], Mariana Pina da Silva Berti [b], Augusto Matias de Oliveira [a,*], Ivan Mosconi Neto [a], Carlos César Evangelista de Menezes [a], Givanildo Zildo da Silva [a]

[a] *University of Rio Verde, Rio Verde-GO, Brazil*
[b] *State University of Goiás, Ipameri-GO, Brazil*

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ABSTRACT

The objective of this study was to evaluate the availability of phosphorus (P) in a soil under no-tillage system after successive applications of liquid swine manure (LSM) doses in soil samples collected at different depths and to select the most appropriate chemical extractors. It was used soil with LSM applications for 19 years, using doses of 0, 25, 50, 75 and 100 m^3 ha^{-1} and mineral fertilization (350 kg ha^{-1} in formulation 02-20-18), evaluated at the following depths: 0–10, 10–20 and 20–40 cm. The extractors used were Mehlich-1, Mehlich-3, Prem, Olsen, Bray-1 and Resin. Successive fertilizations with LSM, especially with 100 m^3 ha^{-1}, increase the availability of P, especially in the 0–10 cm layer, as well adding P in the deeper layers evaluated (20–40 cm). The organic P content in relation to the total P ranged from 16 to 19 %. Bray-1, Olsen and Resin extractors are more efficient in extracting P in soil under no-tillage cultivation after successive fertilizations with liquid swine manure.

1. Introduction

The increase in world population has required more productive agriculture, and in addition to the challenge of increasing agricultural productivity, there are many aspects related to sustainability [1–3]. To obtain high yields it is necessary to evaluate the nutritional status of the soil. Thus, it is necessary to know the fertility of the soil in order to properly use the correctives and fertilizers [4]. In this way, it is possible to obtain high quality products and guarantee environmental protection, which provides sustainability to the cultivation system. The proper use of fertilizers provides better use of natural resources, economic gain and reduction in negative impact risks on the production process [5].

Physicochemical soil analysis should be performed for proper soil fertility evaluation [6]. To obtain reliability in the results, the importance of research related to this evaluation arises, which covers some processes, from soil sampling, methods of nutrient analysis, techniques for diagnosing the results and the interpretation and recommendation of fertilization [7,8]. All these steps are intended to determine the availability of nutrients and verify the existence of some other factor that may limit the productivity of crops.

In case exist consolidated soil analysis methods, it is important to compare methodologies to keep the soil-plant relationship calibrated according to the nutrients evaluated. For this, studies are carried out using different extraction methods [9,10] and later, the

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[*] Corresponding author.
E-mail address: augusto2013ufpi@gmail.com (A.M. Oliveira).

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comparison of which method correlates better with the soil-plant relationship, that is, how much of the nutrient available in the soil is absorbed and accumulated in the plant. This procedure allows to evaluate the bioavailability [11].

Phosphorus (P) is a nutrient of great interest, since it restricts more than 30 % of the cultivated soils in the world. It is because P presents low efficiency as fertilizers in the soil [12–14]. Another limiting and important factor is that the most studied and easily accessible sources of P are being used in significant proportion, increasing the risk of a possible scarcity of these raw materials [15], making it necessary to search for alternative sources, and the application of swine manure is one of them [16,17].

The determination of P content available in the soil (P-labile) is fundamental for adequate phosphate fertilization recommendation to obtain high crop yields [18]. There are recommendation tables for phosphate fertilization for Cerrado soils, based on the P and clay contents and also on the high retention capacity of the phosphate applied (Phosphorus buffer capacity - CTP), whose doses were based on calibration tests for maximum physical efficiency of the crop and using phosphate mineral fertilizers [19]. However, in regions where applications of organic fertilizers such as swine manure occur in the soil as a source of nutrients, it is introduced beyond inorganic sources, organic sources of nutrients in the soil, P being one of them.

The swine manure use is an alternative to complement mineral fertilization since it has a considerable amount of nutrients [20,21]. As pig farms need to give an adequate destination to these residues, its use as fertilizer in agriculture is a reality. In these properties occur constant residue applications, usually on the same area, consequently the amount of P added in the soil might exceed the amount of nutrients needed by the crop and in addition, over time, exceed the soil adsorption capacity. The excessive P content in the soil, in addition to providing nutritional imbalance, may result in its transport to surface and subsurface waters, with a high risk of eutrophication [16,22,23].

Thus, the objective was to evaluate the P availability in a soil under no-tillage system after successive swine manure applications in soil samples collected at different depths and to select the most appropriate chemical extractor(s).

2. Methodology

2.1. Sampling and samples preparation

Deformed samples from an experiment implemented in 2000 at the University of Rio Verde (UniRV), on a Dystroferric Red Latosol (*Oxisol*) [24] with 4 % slope, were used. The physicochemical characteristics of the samples collected at a depth of 0–10 cm, following the methodology described by Silva [25], are presented in Table 1.

The treatments were arranged in a 6 × 3 factorial scheme. One factor consisted of five sources of fertilization (application of liquid swine manure at doses of 25, 50, 75 and 100 m^3 ha^{-1} and mineral fertilization - 350 kg ha^{-1} of formulation 02.20.3318) and a control without fertilization, and the other one consisted of P quantification in soil samples collected at three depths (0–10, 10–20 and 20–40 cm), in a randomized block design, with three blocks, summing up 54 soil samples. The experiment was conducted under no-tillage system (NTS), in an area which received superficially 19 applications of liquid swine manure, before the experiment implantation. The cultivated soybean and corn crops were alternated annually.

Soil sampling took place in February 2019 after soybean cultivation, crop season 2018/2019. Five simple samples were collected using a probe, at the depths of 0–10, 10–20 and 20–40 cm, to create a composed sample which represented the plot (15 m × 10 m).

The soil samples were conducted to Multiuser laboratories at the UniRV for preparation and P quantification. Initially, the soil samples were prepared in fine soil size (2 mm or less) and after homogenization a soil sample of each composed sample was obtained for chemical and physical characterization (Table 1) and P analysis.

The methodologies used for the extraction and P availability determination of P availability were: Mehlich-1 [26], Mehlich-3 [26], Bray-1 [27], Olsen [28], remaining phosphorus [29] and Resin [30]. The extracts were analyzed by colorimetry using the vitamin C

Table 1
Physicochemical characteristics of the soils used in the study (except P contents).

Samples	pH	Ca	Mg	K	Al	(H + Al)	OM
	$CaCl_2$	———	cmolc dm-3	———			g kg^{-1}
Control	6.43	1.22	0.77	0.23	0.55	10.1	47.82
25 m^3 ha^{-1}	6.49	5.07	3.77	1.03	0.05	2.3	52.43
50 m^3 ha^{-1}	6.72	5.01	3.61	1.08	0.05	2.6	46.54
75 m^3 ha^{-1}	6.87	4.25	3.87	1.38	0.05	2.1	55.51
100 m^3 ha^{-1}	6.92	4.40	3.53	1.27	0.05	2.8	47.05
Mineral	6.81	3.81	2.92	1.05	0.05	2.3	49.36
Samples	**m**	**V**	**CEC**	**SB**	**Clay**	**Silt**	**Sand**
	—— % ——		cmolc dm^{-3}		——— g kg^{-1} ———		
Control	19.86	18.07	12.28	2.22	42.63	21.84	35.53
25 m^3 ha^{-1}	0.50	81.03	12.18	9.87	43.43	20.77	35.80
50 m^3 ha^{-1}	0.51	78.61	12.34	9.70	44.24	20.72	35.04
75 m^3 ha^{-1}	0.52	81.60	11.65	9.51	42.93	20.81	36.26
100 m^3 ha^{-1}	0.54	76.64	12.01	9.20	42.43	22.42	35.16
Mineral	0.64	77.12	10.10	7.79	41.52	24.89	33.59

pH: hydrogen potential; Ca: calcium; Mg: magnesium; K: potassium; H + Al: potential acidity; OM: organic matter; m: aluminum saturation; V: base saturation; CEC: cation exchange capacity; SB: sum of bases.

method, modified by Braga and Defelipo [31].

To P-organic and total P-inorganic (P-total) quantification, the Olsen and Sommers extraction method [32] was used, with determination of P-organic and P-total levels in the extracts following the method described by Murphy and Riley [33].

2.2. Statistical analysis

The P contents extracted by Mehlich-1, Mehlich-3, remaining P (Prem), Resin, Bray-1 and Olsen were submitted to multivariate normality analysis by Doornik and Hansen test [34] ($p < 0.05$) and multivariate analysis of variance by Wilks Lambda, Pillai trace, Hotelling-Lawley trace and Roy maximum root ($p < 0.05$). Then, the treatments were grouped by Ward's method (formation of homogeneous groups by the lowest minimum internal variance), using as reference the Euclidean distance and *Pearson's coefficient*. The canonical discriminant analysis was used to discriminate the treatment groups according to the methods of P extraction, constructing a biplot graph for the first two canonical variables. Ellipses of 95 % confidence were constructed in order to detect statistical differences ($p < 0.05$) between treatment groups. The analyses were performed with the software R version 4.3.1 [35]. The candisc package was used in canonical discriminant analysis [36].

The P-organic and P-total contents were submitted to Durbin-Watson, Shapiro-Wilk, Bartlett and Tukey.1df tests to verify the independence of errors, normality, homogeneity of variances and additivity, respectively, and then analysis of variance. When there were significant differences, the means of the qualitative factor (depth) were grouped by the Scott-Knott test ($p < 0.05$), and those of the quantitative factor (doses) submitted to regression analysis, using the statistical program R [35].

A correlation network between the extraction methods and the levels of P-organic and P-total was constructed, based on Pearson's correlation (threshold set at 0.60), in which the proximity between the nodes is proportional to the values of absolute correlation between the variables. These analyses were performed in the Rbio software [37].

3. Results

By the multivariate tests of Wilks Lambda, Pillai trace, Hotelling-Lawley trace and Roy maximum root, there was a significant difference between vectors of treatment means (Table 2).

The grouping of treatments was strongly influenced by the depth at which the soil samples were collected, and group I (GI) was formed by the P content after the application of 100 m^3 ha^{-1} of liquid swine manure in soil samples collected at a depth of 0–10 cm (D100P10) (Fig. 1). In the second group (GII) were grouped the treatments whose P content was similar after the soil was not fertilized, fertilized with 50 and 75 m^3 ha^{-1} of LSM and with mineral fertilization at a depth of 0–10 cm (D0P10, D50P10, D75P10 and MP10, respectively) and with 100 m^3 ha^{-1} of LSM in soil sample collected at a depth of 10–20 cm (D100P20). The third group (GIII) was composed of treatments with 25, 50 and 75 m^3 ha^{-1} of swine manure and mineral fertilization in soil samples collected at a depth of 20–30 cm (D0P40, D25P40, D50P40, D75P40 and MP40, respectively). And group four (GIV) included treatments with similar P contents after the soil was fertilized with mineral fertilization, without fertilization, application of swine manure at doses of 25, 50 and 75 m^3 ha^{-1} in soil samples collected at a depth of 10–20 cm (MP20, D0P20, D25P20, D50P20 and D75P20, respectively), and fertilized with 25 and 100 m^3 ha^{-1} of LSM at a depth of 0–10 cm (D25P10) and 20–40 cm (D100P40), respectively (Fig. 1).

The treatments with mineral fertilization were always among those that provided the lowest P contents, usually being close to the control treatment or to the treatments with the application of 25 and 50 m^3 ha^{-1} of LSM (Fig. 1). The treatments with 75 and 100 m^3 ha^{-1} of LSM provided higher P contents in the soil.

The first two canonical variables explained 93.68 % of the total variance contained between the extraction methods of P Mehlich-1, Mehlich-3, Prem, Olsen, Bray-1 and Resin (Table 3). The first canonical variable (Can.1) is most strongly correlated with the Mehlich-1, Mehlich-3, Prem, Olsen and Bray-1 methods, explaining 74.98 % of the original variance. The second canonical variable (Can.2) is more strongly correlated with the Resin extraction method, retaining 18.70 % of the original variation (Table 3).

The P contents increased in the soil due to fertilization with liquid swine manure, and the fertilization with 100 m^3 ha^{-1} of LSM provided the largest increase of P in the soil, especially in the 0–10 cm (GI) layer, regardless of the type of extractor used (Fig. 2). At the dose of 100 m^3 ha^{-1} of LSM the average P contents extracted at the depth of 0–10 cm were: 89.44 mg dm^{-3} (Mehlich-3) > 82.77 mg dm^{-3} (Olsen) > 66.54 mg dm^{-3} (Mehlich-1) > 62.18 mg dm^{-3} (Bray-1) > 61.73 mg dm^{-3} (Resin) > 54.59 mg dm^{-3} (Prem).

After the soil samples of the treatment with D100P10 (GI), they were in the soil samples of the treatments of group II (GII), followed by those of the GIV in which more P were obtained (Fig. 2). In the treatments of GIII, which includes mainly those of the samples

Table 2

Multivariate analysis of variance for vectors of mean P contents extracted by Mehlich-1, Mehlich-3, Prem, Olsen, Bray-1 and Resin methods in soil treated with liquid swine manure at doses of 25, 50, 75 and 100 m^3 ha^{-1}, mineral fertilization (350 kg ha^{-1} of the formulation 02.20.18) and without fertilization of soil samples collected at depths of 0–10, 10–20 and 20–40 cm..

Statistics	Value	[1]num Df	[2]den Df	Approx. F	Pr > (F)
Wilks Lambda	0.035	102	183.74	1.447	0.032*
Pillai trace	2.344	102	216	1.358	0.032*
Hotelling-Lawley trace	5.266	102	176	1.514	0.008**
Roy maximum root	2.082	17	36	4.408	9.003e-05 ***

1 num Df: degrees of freedom of the numerator;2 den Df: degrees of freedom of the denominator. '***' 0.001 '**' 0.01 '*' 0.05.

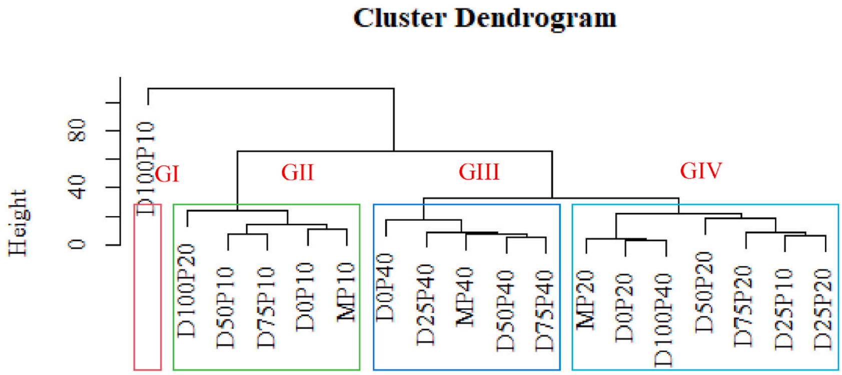

Fig. 1. Grouping of the treatments in a dendrogram with the Euclidean distance considering the methods of extraction of phosphorus Mehlich-1, Mehlich-3, Prem, Resin, Bray-1 and Olsen in soil after the application of liquid swine manure at doses of 25 (D25), 50 (D50), 75 (D75) and 100 (D100) m^3 ha^{-1}, mineral fertilization (M) and without fertilization (D0) of soil samples collected in the depths of 0–10 (P10), 10–20 (P20) and 20–40 (P40) cm.

Table 3

Coefficients, eigenvalues and variance explained by the canonical variables for phosphorus extraction methods as a function of swine manure doses and mineral fertilization and soil depths.

Extraction method	Canonical variables	
	Can 1	Can 2
Mehlich-1	**−0.56**	0.40
Mehlich-3	**−0.70**	0.55
Remaining P (Prem)	**−0.66**	−0.01
Olsen	**−0.87**	0.38
Bray-1	**−0.79**	−0.04
Resin	−0.47	**−0.55**
Eigenvalue	1.57	0.39
Explained variance (%)	74.98	18.70
Cumulative variance (%)	74.98	93.68

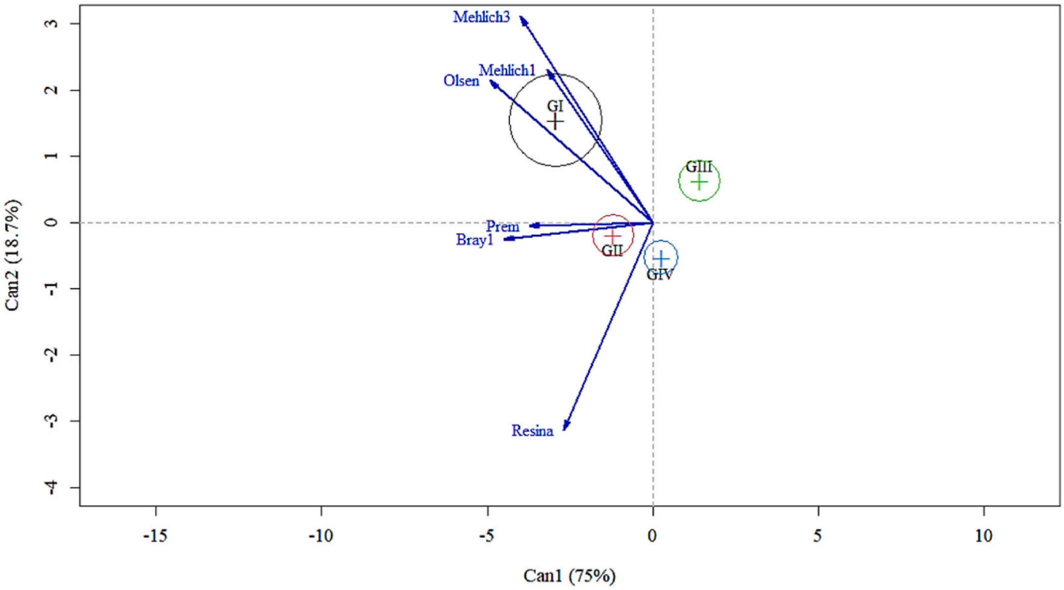

Fig. 2. Canonical discriminant analysis of the methods of extraction of phosphorus Mehlich-1, Mehlich-3, Remaining P (Prem), Resin, Bray-1 and Olsen as a function of the application of liquid swine manure at doses of 25, 50, 75 and 100 m^3 ha^{-1}, mineral fertilization (350 kg ha^{-1} of formulation 02.20.18) and without fertilization of soil samples collected at depths of 0–10, 10–20 and 20–40 cm.

collected at a depth of 20–40 cm, it is where the lowest levels of P were obtained (Fig. 2). In general, the resin extractor was the method that allowed the largest extraction of P, especially after the application of 25, 50 and 75 m^3 ha^{-1} of LSM, being also the most efficient method in the extraction of P in soil samples collected at all depths of 10–20 cm (Figs. 1 and 2). After the Resin extractor, in the soil samples collected at depths of 0–10 and 20–40 cm, the Bray-1 and Olsen extractors were the most efficient in the extraction (Figs. 1 and 2).

In the P-organic and P-total contents there was no significant interaction between the doses of LSM and mineral fertilization with the depth at which the soil samples were collected, but there was an effect of the factors isolated doses and depth (Table 4).

The levels of P-organic and P-total P as a function of the doses of LSM were adjusted to the quadratic polynomial model, with higher levels of total P in the soil samples treated with 75 m^3 ha^{-1} of LSM, followed by the doses of 25 and 50 m^3 ha^{-1} (Fig. 3). The P-organic content was higher in the soil fertilized with 25 m^3 ha^{-1} of LSM, followed by the dose of 75 m^3 ha^{-1} of LSM and mineral fertilization with 350 kg ha-^{1} (Fig. 3). The P-organic content in relation to the P-total was low, with little variation in the P-organic content in relation to the P-total between doses, ranging from 16 to 19 %.

The highest levels of P-organic and P-total were obtained from soil samples collected at a depth of 0–10 cm (1817.23 and 10357.04 mg dm^{-3}, respectively), followed by soil samples collected at a depth of 10–20 cm and after those of 20–40 cm (Fig. 4).

The correlations were all positive and the Mehlich-1 method was significantly correlated with Mehlich-3 (0.92), Olsen (0.86) and Bray-1 (0.71) (Fig. 5). The Mehlich-3 method, in addition to the correlation with Mehlich-1, was significantly correlated with the Olsen (0.93) and Bray-1 (0.75) methods (Fig. 5). The Olsen extractor was also correlated with Bray-1 (0.78). The P-organic content correlated with the P- total content (0.74).

4. Discussion

The grouping of doses according to the depth at which the samples were collected (Fig. 1) is due to the greater accumulation of P in the most superficial layers of the soil due to the addition of P in large quantities via LSM in the long term. Phosphate forms internal sphere complexes with functional groups of inorganic reactive soil particles, this causes its mobility to be low and increases its concentration, mainly by addition on the soil surface and without turning, respecting the SPD [18].

According to Lourenzi et al. [38] successive applications of swine manure in soils under no-tillage can increase the nutrient contents in their surface layers and also part of the nutrients can be transferred to the deeper layers, as observed with the P content in the present study (Figs. 1 and 4). The aforementioned authors also observed that LSM applications during eight years promoted migration of P-total up to the depth of 30 cm and available P to the deepest layer analyzed (50–60 cm).

The application of 100 m^3 ha^{-}1 of LSM provided higher levels of P in the 0–10 cm layer of the soil (Figs. 1 and 2). Similar results were obtained by Scherer et al. [39], in which high P contents were observed in the 0–5 cm layer in soils that received swine manure for more than 20 years. Something remarkable is that application of 100 m^3 ha^{-1} of LSM is able to provide a P content in the layer of 10–20 cm similar to that provided by mineral fertilization with 350 kg ha^{-1} and with 50 and 75 m^3 ha^{-1} of LSM in the layer of 0–10 cm (Fig. 1). This is due to the fact of leaching [40], because although the manure is applied to the surface, part of the nutrients is leached to deeper regions of the soil and the amount of P present in the dose of 100 m^3 ha^{-1} of LSM is higher than that of the doses of 50 and 75 m^3 ha-^{1} of LSM.

The difference between the P contents extracted by the extractors (Fig. 2) may have occurred due to having different chemical reagents and also extracting different forms of P. The extractors Mehlich-1, Mehlich-3 and Remaining P are among those that extracted the lowest amount of P (Fig. 2). The Mehlich-1 extractor is easy to perform, but with some limitations due to the sensitivity to the phosphorus buffer capacity, and overestimates the extractable P content in soils with application of natural phosphates and has low extraction capacity in clayey soils [10,41]. The extraction of P with Mehlich-3 was higher than with Mehlich-1 (Fig. 2), showing that Mehlich-3 has greater extraction power on soils fertilized with organic sources than the Mehlich-1 extractor. This result may be due to the higher acidity of the Mehlich-3 extractor, which provides greater dissolution of the P available in the soil. In the soils evaluated, the recovery value of Mehlich-3 was 1.6 times more than the P recovered by Mehlich-1. This result was similar to those of Tran et al. [42], who found that in acidic soils the recovered P had a value of 1.3 times more than the P recovered by the Mehlich-1 extractor. According to Beegle [43] the fact that the Mehlich-3 extractor extracts higher P content is partly due to its chemical characteristics in which it preferentially extracts the P bound to the Fe and Al and, to a lesser extent, the P bound to Ca. The calibration of the Mehlich-3 extractor

Table 4
Analysis of variance for organic phosphorus and total phosphorus content of soil samples after application of liquid swine manure at doses of 25, 50, 75 and 100 m^3 ha^{-1}, mineral fertilization (350 kg ha^{-1} of formulation 02.20.18) and without fertilization for 19 years of samples collected at depths of 0–10, 10–20 and 20–40 cm.

Source of variation	DF	P-organic	P-total
Doses (D)	5	849868**	26340882 **
Depth (P)	2	2993343**	52401318**
D x P	10	240736 ^{ns}	3574680 ^{ns}
Residue	34	613528	8750654
Block	2	350252	1712986
CV (%)		8.69	5.5

DF: Degree of freedom; CV: Coefficient of variation; ** and * Significant at 1 and 5 % probability, respectively; ^{ns} Not significant.

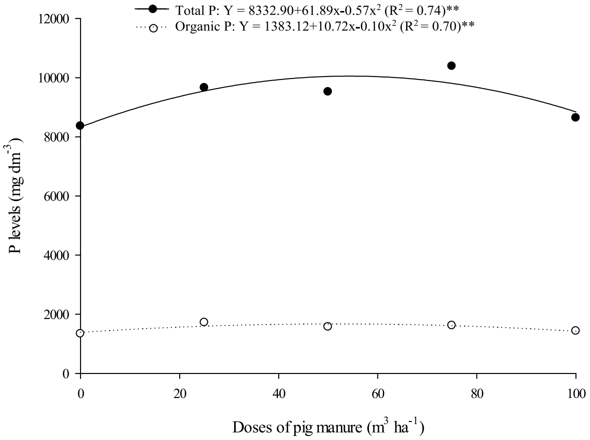

Fig. 3. Organic phosphorus and total phosphorus contents due to the application of liquid swine manure and mineral fertilization. Mean P contents of samples fertilized with 350 kg ha^{-1} of mineral fertilizer of formulation 02.20.18: P-total = 8744 mg dm^{-3}; P-organic = 1608.77 mg dm^{-3} ** Significant at 1 %.

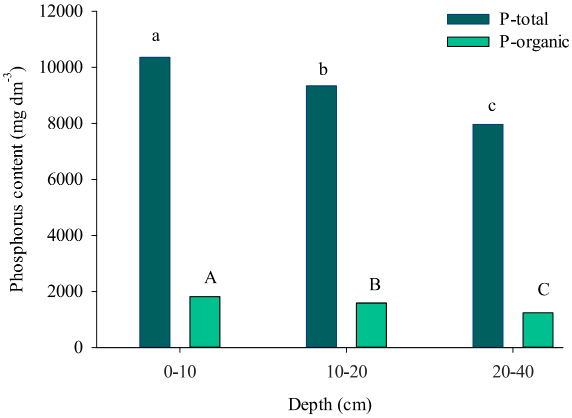

Fig. 4. Total phosphorus and organic phosphorus soil samples collected at different depths. Means followed by the same lowercase and capital letters do not differ for total and organic phosphorus content at different depths, respectively, using the Skott-Knott test at 5 % probability.

is less affected by the fertilizer source used than that of Mehlich-1 [44]. The Mehlich-1 extractor extracts a low amount of P in soils with a predominance of kaolinite and Fe and Al oxides [45], so the amounts of P extracted by this method are usually lower than those extracted by the Mehlich-3 and Resin methods, corroborating the results of this study.

The P contents extracted by Resin had great variation between treatments and at depths (Fig. 2). These results can be explained by the fact that the Resin has greater sensitivity when fixing and extracting the available P. The Resin has an excellent efficiency and this is allied to the method itself, which because it does not have chemical composition makes the transfer only of the P-labile of the soil in aqueous medium [46]. In clayey soils the Resin method extracts more P than in sandy soils and the extraction is even greater in soils with high P contents [45].

The Bray-1 extractor had a good performance in the extraction of P in soils fertilized with swine manure for 19 years, because with the increase of LSM doses there was an increase in the P content, showing that with the increase of the applications of the residues, high residual contents of P were detected in the soil (residual P). These contents above the nutritional requirement in P of plants. The extractors Bray-1, Olsen and Resin were more efficient in the extraction of P (Fig. 2). The results obtained by the Olsen extractor are probably related to the greater release of P by the substitution of P from the colloid adsorption sites by the anions of the extractor solution in conditions where the soil pH is not so acidic, since Olsen is an extractor of alkaline solution ($NaHCO_3$ 0.5 mol L^{-1}) developed for limestone soils [28]. According to Malavolta et al. [47], the Olsen extractor has the ability to extract higher P contents than other extractors because in addition to extracting the soluble forms of P it also has the ability to break bonds between P and the colloids of the soil and thus extract non-labile forms of phosphorus, such as organic P. The P content in the soil according to Olsen's methodology can be low (<15 mg dm^{-3}), medium (15–22.5 mg dm^{-3}), high (22.5–30 mg dm^{-3}) and extremely high (>30 mg dm^{-3}) [48]. The P contents obtained with the Olsen extractor are mostly shown at high to extremely high levels. As there was an increase in the doses of swine manure, there was also an increase in the P content in the soils, especially at the depth of 0–10 cm.

Although the applications of LSM increase the P content in the soil it is necessary to be cautious with the applications, because

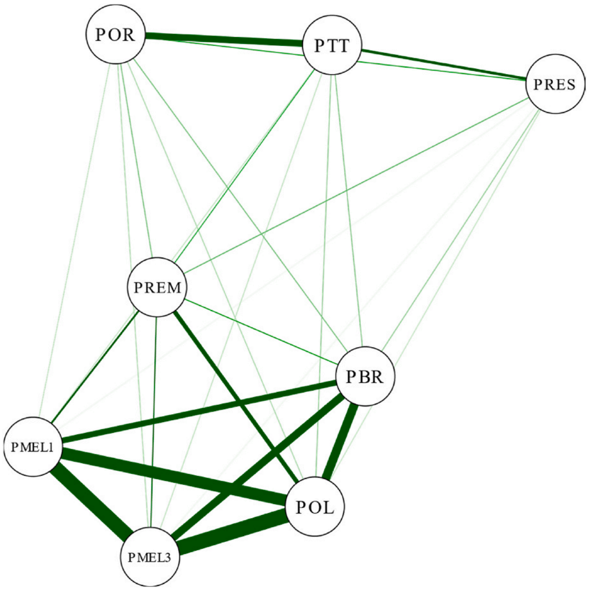

Fig. 5. Correlation network illustrating *Pearson's* correlations between the extraction methods of P Mehlich-1 (PMEL1), Mehlich-3 (PMEL3), Remaining P (PREM), Olsen (POL), Bray-1 (PBR) and Resin (PRES) and P-organic (POR) and P-total (PTT) contents after P extraction in soils treated with liquid swine manure at doses of 25, 50, 75 and 100 m^3 ha^{-1}, mineral fertilization (350 kg ha^{-1} of formulation 02.20.18) and without fertilization of soil samples collected at depths of 0–10, 10–20 and 20–40 cm. The thicker, greener lines represent the highest positive correlations.

although there is an increase in the levels of P available to plants with the accumulation of labile forms of P in the soil, the risk of this P contaminating surface and groundwater is also increased, causing environmental problems such as eutrophication [16,49,50].

Corrales [51] in his work obtained a P-total content higher than 2.000 mg dm^{-3} in three types of soils in Costa Rica, unlike the soils under study in which the P-total contents were above 8.000 mg dm^{-3} (Fig. 3). High levels of total P-total are justified by the addition of high doses of waste that provided much of this P. However, the increase in the P-total content did not increase the P-organic content, since the highest amount of P-total was obtained with the application of 75 m^3 ha^{-1} of LSM, while that of P-organic was obtained with the application of 25 m^3 ha^{-1} of LSM (Fig. 3).

Extractors that have correlation coefficients above 0.70 are considered adequate to measure the availability of P in the soil [52]. Thus, it can be stated that the Olsen and Bray-1 extractors are efficient and could replace the Mehlich-1, Mehlich-3 and Remaining P methods for determining the available P of the soil (Fig. 5). Although the Resin extractor did not correlate with the others, along with the Bray-1 and Olsen extractors, they were the most efficient in the extraction of P, corroborating the results of Barbosa et al. [52] in which the Bray-1 and Resin extractors were the most indicated for the determination of the P available in soils of Brazilian state of Amazonas.

5. Conclusions

Successive liquid swine manure applications of, especially doses of 75 and 100 m^3 ha^{-1}, in soils under no-tillage crops increased the soil P contents down to the layer of 20–40 cm. The increase in liquid swine manure doses promote increase in the P-total content, but there is no increase in the P-organic content. The maximum content of P-organic was achieved with 25 m^3 ha^{-1} of LSM application. The Bray-1, Olsen and Resin extractors are more efficient in extracting P in soil under no-tillage after successive fertilizations with LSM.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Rodrigo Gomes Silva: Writing - original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **June Faria Scherrer Menezes:** Writing - review & editing, Writing - original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Mariana Pina da Silva Berti:** Writing - original draft, Visualization, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Augusto Matias de Oliveira:** Writing - review & editing, Writing - original draft, Validation, Software, Investigation, Formal analysis, Conceptualization. **Ivan Mosconi Neto:** Writing - original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Carlos César Evangelista de Menezes:** Writing -

original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Givanildo Zildo da Silva:** Writing - review & editing, Visualization, Validation, Software, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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