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Phosphorus fractions in Cerrado Oxisols fertilized with liquid swine wastewater[1]

Frações de fósforo em Latossolos do Cerrado adubados com dejeto líquido de suíno

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HIGHLIGHTS:

In all areas of study, higher percentages of P were found in moderately labile and residual forms.
There is no predominance of more labile P forms over non-labile ones when comparing areas with and without waste use.
The use of swine wastewater did not contribute to the accumulation of P in Cerrado soils.

ABSTRACT: Knowledge of the forms of phosphorus (P) accumulation in soils that received successive applications of swine waste is essential to prevent the potential contamination risk of shallow waters. This study aimed to evaluate the forms of P accumulation in Cerrado Oxisols subjected to successive applications of liquid swine wastewater. Soil samples were collected from areas with and without use history of swine waste in the 0-0.10 and 0.10-0.20 m soil layers in Campo Verde and Nova Mutum, MT, Brazil. A sequential chemical fractionation was performed, determining the total and available P concentrations. The main forms of P accumulated in the 0-0.20 m layer, despite the soil texture and usage or not of swine wastewater, were residual P and moderately labile P. There was no predominance of more available P forms concerning the unavailable forms when comparing areas with and without the use of swine waste.

Key words: organic fertilization, sequential extraction, agro-industrial wastes

RESUMO: O conhecimento das formas de acumulação de fósforo (P) em solos, que receberam sucessivas aplicações de dejetos de suínos é essencial para prevenir o risco potencial de contaminação das águas superficiais. O objetivo deste estudo foi avaliar as formas de acúmulo de P em Oxisols de Cerrado submetidos a sucessivas aplicações de dejeto líquido de suíno. Foram coletadas amostras de solos em áreas com e sem histórico de uso de dejeto suíno, nas camadas de 0-0,10 e 0, 10-0, 20 m em Campo Verde e Nova Mutum, MT, Brasil. Foi realizado o fracionamento químico sequencial e determinados os teores totais e disponíveis de P. As principais formas de P acumuladas na camada de 0-0,20 m, independente da textura do solo e uso ou não de dejeto de suíno, foram o P residual e o P moderadamente lábil. Não houve predominância de formas de P mais disponíveis em relação às formas não disponíveis, quando foram comparadas áreas com e sem uso de dejeto suíno.

Palavras-chave: adubação orgânica, extração sequencial, resíduo agroindustrial

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INTRODUCTION

Swine biofertilizer, popularly known as liquid swine wastewater (LSW), has been employed in soil fertilization for being a nutrient source to the plants (Guardini et al., 2012; De Conti et al., 2015). In some pig farming properties of the state of Mato Grosso, Brazil, the LSW treated in biodigesters is being used in the fertigation of soybean and maize forage crops, promoting mainly in the most superficial layers of the soil, the increase of the nutrient concentrations such as P, K, Ca, and Mg. As a result, there is an improvement in the soil chemical environment for root growth due to increased base saturation (Lourenzi et al., 2013).

However, the layering of LSW on the soil as a nutrient source, if used out of the adequate criteria, such as inadequate doses, without respecting the soil absorption capacity and the crop needs, may contribute to the alteration of the soil quality and shallow waters since the nutrient amount contained in the waste, including phosphorus, may exceed the soil bearing capacity (Silva et al., 2015).

In the soil, phosphorus (P) is adsorbed to the iron and aluminum oxyhydroxides, and for that reason, its mobility and concentration in the soil solution are low. However, when P is added to the soil successively and in high doses, such as in the massive LSW application, there may occur an increment of its total content in the soil (De Conti et al., 2015).

For a better understanding of P dynamics in the soil, it is necessary to know the total and available P concentration and its distribution in the different fractions of soil compartments, which can be obtained through several extractors (Chang & Jackson, 1957; Hedley et al., 1982; Tiessen & Moir, 1993).

Based on the hypothesis that the continuous use of LSW as a nutrient source in the soil can modify the forms and the availability of P, even in tropical soils, this study aimed to evaluate the forms of P accumulation in Cerrado Oxisols subjected to successive applications of liquid swine wastewater.

MATERIAL AND METHODS

Soil samples belonging to the Oxisol class, with different textures and history of use or not of liquid swine wastewater (LSW), were collected in Campo Verde and Nova Mutum, important industrial pig farming poles of the state of Mato Grosso, Brazil. The identification, coordinates, history of use, and time of LSW application are listed in Table 1.

The climate classification of Campo Verde and Nova Mutum is Aw-type according to the Köppen classification. The rainfall regime is well defined, with a dry period, from May to September, and with a rainy period from October to April. In Campo Verde, the average annual precipitation is 1726 mm, and the average annual temperature is 22.3 °C. In Nova Mutum, the annual precipitation is 1934 mm, and the average annual temperature is 24.6 °C.

In each municipality, areas that presented different times of LSW application were chosen to check the accumulation and distribution of phosphorus over the years. In the chosen areas, the swine waste passed through a stabilization pond before

Table 1. Identification, coordinates, history of use, and management of study areas

Areas	Municipality	Location	Soil use	Soil management
CV0	Campo verde	S 15° 34’ 21.03” W 55° 7’ 45.16”	soybean/maize	Area with mineral fertilization. Without liquid swine wastewater. All fertilizations performed in the sowing row. 2017 /2018- Soybean fertilization - 350 kg ha^{-1} of Single Superphosphate + 200 kg ha^{-1} of KCl + 6.5 kg ha^{-1} of Coppergran Cu (10%). Mayze fertilization - 150 kg ha^{-1} Single Superphosphate + 150 kg ha^{-1}; KCl + 10 kg ha^{-1} of Zincodur Zn (25%) + 100 kg ha^{-1} of ammonium sulphate. Minimum soil preparation (minimum cultivation)
CV3	Campo Verde	S 15° 34’ 22.11’’ W 55° 8’ 8.32”	soybean/maize	3-year fertilization with liquid swine wastewater, performed in 3 or 4 months per year, usually before sowing and during the early stages of the crop. Minimum soil preparation (minimum cultivation)
CV5	Campo Verde	S 15° 34’ 24.87” W 55° 8’ 22.19”	soybean/maize	5-year fertilization with liquid swine wastewater, performed in 3 or 4 months per year, usually before sowing and during the early stages of crop. Minimum soil preparation
CV7	Campo Verde	S 15° 33’ 57.72” W 55° 8 16.50”	soybean/maize	7-year fertilization with liquid swine wastewater, performed in 3 or 4 months per year, usually before sowing and during the early stages of the crop. Minimum soil preparation (minimum cultivation)
NM0.0P	Nova Mutum	S 13° 44’ 36.91” W 56° 3’ 52.60”	pasture	Area with mineral fertilization, without use of swine waste. Chemical correction is performed every 3 years with 1.5 t ha^{-1} of dolomitic limestone + fertilization with 100 kg ha^{-1} of Single Superphosphate Forage grass *Brachiaria brizantha* cv. Piatã.
NM3	Nova Mutum	S 13° 44’ 38.75” W 56° 4’ 12.76”	pasture	3-year fertilization with liquid swine wastewater, performed every 6 months. Forage grass *Brachiaria brizantha* cv. Piatã.
0NM00SM	Nova Mutum	S 13° 44’ 38.49” W 56° 0’ 3.74”	soybean/maize	Area with mineral fertilization, without LSW. All fertilizations are performed in the sowing row. 2017/2018 Season - Soybean fertilization - 400 kg ha^{-1} of Triple Superphosphate + 150 kg ha^{-1} KCl. Maize fertilization - 150 kg ha^{-1} of Triple Superphosphate + 150 kg ha^{-1} KCl + 100 kg ha^{-1} of ammonium nitrate (emergence- VE) Minimum soil preparation (minimum cultivation).
NM5	Nova Mutum	S 13° 44’ 39.83” W 56° 0’ 24. 17”	pasture	5-year fertilization with liquid swine wastewater, performed every 5 months. Forage grass *Brachiaria brizantha* cv. Piatã.

Campo Verde and Nova Mutum – Municipalities of Mato Grosso state, Brazil being applied to the soil. Soil samples were collected between June and October 2018.

Five mini-trenches were opened for soil collection with a square point shovel in each area, from which deformed samples were collected in the 0 to 0.10 m and 0.10 to 0.20 m layers. The soil samples were dried in an oven with forced air circulation at 60 °C. Once dried, the samples were crushed, sieved through a 2.00 mm mesh sieve, and properly stored.

Some chemical (pH and OM) and particle-size attributes (Table 2) of the soils were determined according to the methodologies described in Teixeira et al. (2017). The available and total P were determined according to the methodology of Tedesco et al. (1995).

P fractionation was performed according to adaptations of the methodology proposed by Hedley et al. (1982) and Teixeira et al. (2017), observing the following procedures

Labile fraction - P extraction with $NaHCO_3$ 0.5 mol L^{-1} (pH adjusted to 8.5 with concentrated HCl). For the determination with $NaHCO_{3,}$ 1 g of ADFS (air-dried fine soil) and 40 mL of $NaHCO_3$ were added into 50 mL centrifuge tubes. Afterward, the tubes were agitated for 16 hours at 120 oscillations per min, centrifuged at 4000 rpm for 10 min, and their content was filtered in quantitative filter paper. After filtering, the supernatant was stored in a closed container for later determination of inorganic P (Pi-bi), organic P (Po-bi), and total P (Pt-bi).

Moderately labile fraction - P extraction with NaOH 0.1 mol L^{-1}. In the residues of the extraction with $NaHCO_3$ 0.5 mol L^{-1}, 30 mL of NaOH 0.1 mol L^{-1} was added, and the soil was mechanically dispersed. Afterward, the samples were agitated for 16 hours at 120 oscillations per min, centrifuged at 4000 rpm for 10 min, and filtered in quantitative filter paper. After filtering, the supernatant was stored in a closed container for later determination of inorganic P (Pi-hi 0.1), organic P (Po-hi 0.1), and total P (Pt-hi 0.1).

Non-labile fraction - P extraction with HCl 1 mol L^{-1}. In the residues of the extraction with NaOH 0.1 mol L^{-1}, 30 mL of HCl 1 mol L^{-1} was added, and the soil was mechanically dispersed. Afterward, the samples were agitated for 16 hours at 120 oscillations per min, centrifuged at 4000 rpm for 10 min, and filtered in quantitative filter paper. After filtering, the supernatant was stored in a closed container to determine the inorganic P (Pi-HCl) later.

Table 2. pH, available phosphorus, organic matter, and particle-size in the 0-0.10 m and 0.10-0.20 m soil layers, in Campo Verde and Nova Mutum, MT, Brazil

Areas	pH	pH	P	OM	Clay	Silt	Sand	Texture
	H_2O	$CaCl_2$	(mg dm^3)	(g kg^{-1})				
				0-0.10 m				
CV0	6.70	5.99	26.32	7.42	243	33	724	medium
V3	5.20	4.35	6.83	7.00	243	33	724	medium
CV5	5.98	5.14	29.42	5.06	176	67	757	medium
CV7	5.54	4.72	18.55	4.81	170	33	797	medium
NM0.0P	5.94	4.92	1.57	2.83	43	33	924	sandy
NM3	6.13	4.88	13.88	2.47	77	23	900	sandy
NM00SM	5.73	4.73	7.57	8.55	443	33	524	clayey
NM5	5.74	4.94	7.80	8.67	410	66	524	clayey
				0.10-0.20 m				
CV0	5.81	4.91	9.84	6.63	277	33	690	medium
CV3	5.40	4.44	2.56	6.94	277	33	690	medium
CV5	5.54	4.64	26.10	4.13	177	33	790	medium
CV7	5.67	4.65	14.44	4.46	177	33	790	medium
NM0.0P	5.44	4.14	0.50	1.75	77	33	890	sandy
NM3	5.58	4.37	5.76	1.63	77	33	890	sandy
NM00SM	5.26	4.42	5.00	7.91	410	33	557	clayey
NM5	5.41	4.54	6.11	10.38	410	33	557	clayey

CV - Campo Verde; NM - Nova Mutum – Municipalities of Mato Grosso state, Brazil; pH ($CaCl_2$) - (Calcium chloride); OM - Organic matter

Moderately labile fraction - P extraction with NaOH 0.5 mol L^{-1}. In the residues of the extraction with HCl 1 mol L^{-1}, 30 mL of NaOH 0.5 mol L^{-1} was added, and the soil was mechanically dispersed. Afterward, the samples were agitated for 16 hours at 120 oscillations per min, centrifuged at 4000 rpm for 10 min, and filtered in quantitative filter paper. After filtering, the supernatant was stored in a closed container for later determination of the inorganic P (Pi-hi 0.5), organic P (Po-hi 0.5), and total P (Pt-hi 0.1).

Residual fraction (non-labile) - Residual P extraction. The residue (soil) was dried in an oven with forced air circulation. After drying, approximately 0.25 and 0.5 g of soil was weighed in digestion tubes. 1 mL of a saturated $MgCl_2$ solution, 2 mL of H_2SO_4 (1:1), and 2 mL of H_2O_2 were added, proceeding to the digestion for three hours at 200 °C, slowly raising the temperature. After digestion, the samples were transferred to flasks, and the volume was completed up to 50 mL.

The determination of the inorganic P in the alkaline extracts ($NaHCO_3$ and NaOH) and inorganic P in the acid extracts (HCl), as well as the total P, was performed according to the proceeding described in Teixeira et al. (2017). The organic P was obtained through the difference between the total P and the inorganic P.

The P in the fractions was determined through UV-vis spectrophotometry at the wavelength of 882 nm, according to Murphy & Riley (1962).

The data were subjected to the non-parametric test of Kruskal-Wallis, at a $p \leq 0.05$. The principal component analysis was performed to verify the most important variables between the study areas.

RESULTS AND DISCUSSION

Concerning the available P (PA), in Campo Verde, greater P concentrations were observed in areas CV7, CV5, and CV0 (Table 3) in the 0-0.10 m and 0.10-0.20 m layers. No difference was verified between these areas by the Kruskal Wallis test - $p \leq 0.05$.

The area with three years of swine waste application (CV3) presented the lowest concentration of available P (PA) in the 0-0.10 m and 0.10-0.20 m layers, which may be related to its lower pH in comparison with the pH of the other studied areas (Table 2). The pH interferes with the number of positive charges. Consequently, P adsorption should be higher with low pH values, a medium in which Fe and Al oxyhydroxides are generators of these charges and responsible for retaining phosphate ions (Viviani et al., 2010).

Therefore, in the area with the lowest application of liquid swine wastewater, there was no pH increase and larger amounts of available P when compared to the control area, which may have occurred due to the buffer power of the soil and to the mineralization process of organic residues (Maluf et al., 2015).

Table 3. Concentration of inorganic (Pi) and organic phosphorus (Po) (mg dm^{-3}) in the chemical fractions of an Oxisol in Campo Verde and Nova Mutum, MT, Brazil, with the history of liquid swine wastewater application

Areas	PA	Pt	Pi-bi	Po-bi	Pi-hi 0.1	Po-hi 0.1	Pi-hi 0.5	Po-hi 0.5	Pi HCl	Pr
0-0.10 (m)										
CV0	26.32 a	374.20 a	24.44 ab	11.56 a	63.15 a	11.45 a	17.03 a	22.08 a	15.52 a	61.94 a
CV3	6.83 b	207.24 b	10.59 b	8.94 a	39.30 b	3.91 a	6.60 b	13.45 ab	10.33 a	71.41 a
CV5	29.42 a	322.20 ab	32.35 a	6.65 a	57.73 ab	12.83 a	11.38 ab	8.27 ab	17.85 a	72.85 a
CV7	18.55 ab	254.93 ab	21.25 ab	7.73 a	46.87 ab	10.15 a	13.65 ab	6.52 b	10.51 a	71.23 a
0.10-0.20 (m)										
CV0	9.84 ab	297.82 a	18.71 ab	10.21 a	47.47 a	14.01 a	12.61 a	15.19 a	7.41 a	69.95 a
CV3	2.56 b	189.30 a	5.51 b	9.43 ab	27.13 b	4.75 a	5.13 b	13.19 a	6.36 a	65.03 a
CV5	26.10 a	267.08 a	25.76 a	4.68 b	37.45 ab	3.31 a	6.96 ab	9.70 ab	10.91 a	50.59 a
CV7	14.44 ab	212.02 a	17.63 ab	11.11 ab	37.40 ab	4.70 a	11.03 ab	5.03 b	6.50 a	75.39 a
0-0.10 (m)										
NM0.0P	1.57 b	235.98 b	3.83 b	9.70 a	15.62 b	25.99 a	5.59 b	10.39 a	5.89 a	126.42 a
NM3	13.88 a	324.66 ab	28.24 a	8.22 a	37.38 ab	16.81 a	7.75 b	8.59 a	8.46 a	148.46 a
NM00SM	7.57 ab	458.10 a	20.64 ab	6.45 a	140.00 a	19.57 a	42.22 a	3.00 b	5.32 a	140.53 a
NM5	7.80 ab	424.23 a	8.93 ab	9.51 a	53.21 ab	38.64 a	28.67 ab	8.64 a	4.99 a	139.35 a
0.10-0.20 (m)										
NM0.0P	0.50 b	209.98 b	2.27 b	9.45 a	10.29 b	24.90 a	3.72 b	7.88 a	6.47 a	111.20 a
NM3	5.76 a	257.54 ab	7.86 ab	11.93 a	18.52 ab	23.44 a	4.75 ab	8.14 a	5.99 a	135.70 a
NM00SM	5.00 ab	433.84 ab	13.82 a	10.23 a	121.70 a	21.28 a	36.77 a	2.72 a	4.79 a	160.22 a
NM5	6.11 a	392.32 ab	15.93 a	11.65 a	91.91 a	37.23 a	33.73 a	7.47 a	6.29 a	124.30 a

See Table 1 for the description of the areas; Campo Verde (CV) and Nova Mutum (NM) – Mato Grosso state, Brazil; PA - Mehlich-1 available phosphorus; Pt - Total phosphorus; Pi-bi and Po-bi - Inorganic and organic phosphorus extracted with NaHCO$_3$; Pi-hi and Po-hi 0.1 - Inorganic and organic phosphorus extracted with NaOH 0.1 mol L^{-1}; Pi-hi and Po-hi 0.5 - Inorganic and organic phosphorus extracted with NaOH 0.5 mol L^{-1}; P - HCl- Non-labile fraction extraction with HCl 1 mol L^{-1} Pr - Residual phosphorus; Means followed by the same lowercase letters in the column are equal at a $p \leq 0.05$ by the Kruskal-Wallis test

Higher values of available P in the area without swine waste (CV0) concerning area CV3 (Table 3) in the 0-0.10 m layer might have been due to the application of single superphosphate (Table 1) in the first area (CV0) since according to Herrera et al. (2016), the increase of available P in the soil is the consequence of the consecutive addition of fertilizers on the superficial layer and absence of soil turning.

In the samples collected from Nova Mutum, it was verified that the concentration of available P in the control area (NM0.0P) was lower in comparison with the area that received three years of LSW application (Table 3), both presenting the same texture and soil use (pasture), which is due to the amounts of P added in the control area (100 kg ha^{-1} of simple superphosphate every three years) (Table 1).

However, no difference was verified between the areas with swine waste application for three and five years ago and the control area, even if these areas presented different textures, which may be due to soil management in these areas (Table 1).

When analyzing the concentrations of available P in the soil layers, it was observed that they decreased with depth in all studied areas. Factors such as the non-revolving of the soil, implemented by minimum cultivation management (Table 1), which according to Guareschi et al. (2012), favors the maintenance of organic matter, and a low mineralization rate can justify this greater P concentration in the 0-0.10 m layer.

The maximum concentrations of available P were observed in the area with five years of LSW application in the 0-0.10 m layer (29.42 mg dm^{-3}), a concentration considered adequate for all Cerrado soils since, according to the fertility interpretation table of Sousa & Lobato (2004), the adequate concentration is between 20.1 and 30.0 mg dm^{-3}.

The concentrations of total P can be observed in Table 3, with the highest value being registered in the control area (CV0 = 374.2 mg P-total dm^{-3}) in the 0-0.10 m layer in Campo Verde. The highest concentration of total P in the control area may have occurred due to the P amounts added as fertilizers, which might have been greater than those exported by the grains, as observed by Pandolfo & Veiga (2016). However, there was no difference (Table 3) between the areas of Nova Mutum, where textures are the same (NM5 and NM00SM) and (NM3 and NM0.0P).

Higher concentrations of total P were observed in the 0-0.10 m layer in all studied areas. This occurs as a consequence of the non-incorporation of fertilizers added to the surface, the lower erosion losses, and also by the recycling provided by the plants, which absorb the available P in the deepest layers, bringing it onto the surface after the decomposition of their residues (Guareschi et al., 2012).

As for the phosphorus fractions for both municipalities, their results are presented in Table 3. It was verified that there was no difference in the concentration of labile P (Pi-bi) (Table 3) of the control area (CV0 = mineral fertilization) in comparison with the areas that received swine waste (CV7, CV5, and CV3) in Campo Verde in the 0-0.10 m and 0.10-0.20 m layers. The lowest concentrations of this fraction were observed in area CV3, which was only different from CV5. Smaller concentrations of labile P in area CV3 may have occurred due to the mineralization of organic waste (Maluf et al., 2015).

No difference was verified between the areas in the 0-0.10 m layer in Campo Verde with relation to Po-bi. Also, this fraction was found in lower concentrations concerning Pi-bi in all study areas, which may be related to the fast decomposition of this fraction in the soil. According to Couto et al. (2017), the Po-bi fraction little accumulates in the soil for being related to organic compounds of easy decomposition, which are regulated by the microbial biomass of the soil.

In the areas of Nova Mutum (Table 3), lower Pi-bi concentrations were observed in the control area (NM0.0P), being different from the area with three years (NM3) of LSW application in the 0-0.10 m soil layer. Therefore, the use of DLS may have increased the amounts of P more readily available in the soil, as these soils (NM0.0P and NM3) are of the same texture and use. However, in the areas NM00SM and NM5, there was no difference.

No difference was verified between areas in the 0-0.10 m and 0.10-0.20 m layers regarding the Po-bi. Higher Po-bi amounts compared to Pi-bi were observed in the areas NM5 and NM0.0P. Therefore, in these areas, the mineralization of organic compounds may have been slower, occurring accumulation of P in Po-bi forms. Although this accumulation is agronomically desired, it increases the risk of environmental contamination (Couto et al., 2017).

The Pi and Po-bi forms were higher in the 0-0.10 m layer, which may have occurred due to the minimum soil preparation in the studied areas. Also, as De Conti et al. (2015) observed, P is an element with low mobility in the soil, so surface applications favor P increments in the first layers.

The inorganic and organic P fractions extracted with NaOH 0.1 mol L^{-1} (Po and Pi hi 0.1) and NaOH 0.5 mol L^{-1} (Po and Pi hi 0.5) represent the inorganic P absorbed by oxides and clays with intermediate binding energy as well as the organic P found in moderately labile forms (Guardini et al., 2012). In all evaluated areas, the Pi and Po hid in NaOH 0.1 mol L^{-1} were more representative of P accumulation when compared to fractions Pi and Po hid 0.5 in the 0-0.20 m layer (Figure 1).

This result may indicate that the inorganic colloids of the studied soils did not present high P affinity since, according to Couto et al. (2017), in other types of soil and especially in those that present a high amount of iron oxide, greater amounts of moderately labile P are found in the Pi-hi 0.5 fraction as a function of the high absorbing power of the soil.

The concentrations of P in the moderately labile fraction (P-hi) were greater than in the labile fraction (P-bi) in the 0-0.20 m soil layer (Figure 1). Although the P-hid fractions are considered of low availability to the plants, in soils of tropical regions, they are relatively dynamic since the moderately labile fraction can act as either a source or drain of available P depending on the amount of P that is added to the soil (Couto et al., 2015). Therefore, greater P amounts in this fraction can be of great importance for plant absorption.

Lower amounts of Pi-hi 0.1 and Pi-hi 0.5 were observed in the area CV3 in the 0-0.10 m and 0.10-0.20 m layers, with the only difference being found between areas the CV3 and CV0. With relation to Po-hi 0.1, no difference was verified between the areas.

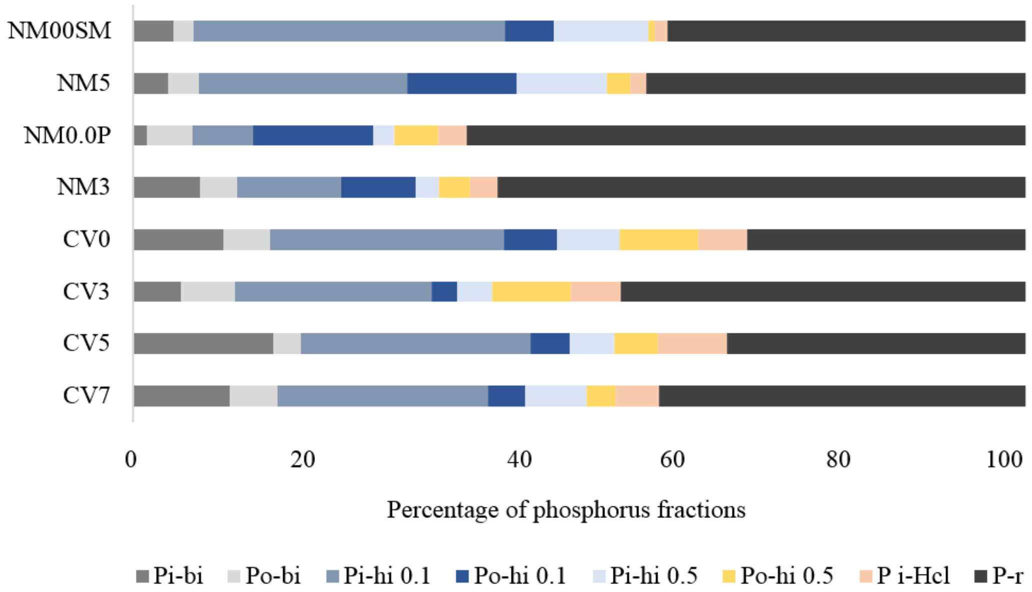
In the Pi-hi 0.5 fraction, no difference was verified between the areas of Nova Mutum, either with or without swine waste in the 0-10 cm layer. As for Po-hi 0.5, there was no difference between areas.

There was no difference between the studied areas for the non-labile P fraction extracted by the HCl 1 mol L^{-1} (Pi HCl) solution. This fraction is present in the P forms related to calcium (Cross & Schlesinger, 1995) and residual P. It was observed that the fraction extracted with HCl had little participation in the total P (1.38 a 7.78%) (Figure 1).

Guardini et al. (2012), using swine waste for an extended period in a Ultisol, verified a P increase in the HCl fraction, especially in the upper soil layers. The authors explain that, generally, more than 60% of the P contained in the waste applied to the soil is found bound to calcium in the inorganic fraction.

Therefore, the increase in the P-HCl will depend on the composition of the swine waste and the soil since the HCl extract preferentially extracts the P forms bound to Ca (Cross & Schlesinger, 1995).

The most recalcitrant fraction of P in the soil is the residual fraction, which is not easily accessed by selective chemical extractors used in soil fractionation. This fraction can



See Table 1 for the description of the areas; Campo Verde and Nova Mutum – Mato Grosso state, Brazil; Pi-bi and Po-bi - Inorganic and organic phosphorus extracted with $NaHCO_3$; Pi-hi 0.1 and Po-hi 0.1 - Inorganic and organic phosphorus extracted with NaOH 0.1 mol L^{-1}; Pi-hi 0.5 and Po-hi 0.5 - Inorganic and organic phosphorus extracted with NaOH 0.5 mol L^{-1}; P- HCl - Non-labile fraction extraction with HCl 1 mol L^{-1}; Pr - Residual phosphorus

Figure 1. P forms and their proportions in the 0-0.20 m soil layer in Campo Verde (CV) and Nova Mutum (NM), MT, Brazil

contribute to plant nutrition only in situations of P deficiency (Guardini et al., 2012).

In all studied areas (Table 3), it was verified that there was no difference for the P-r. According to Couto et al. (2015), in soils that are little subject to losses by erosion or removal by harvest, the P-r does not suffer significant alterations.

Most of the total P in the areas NM3 (59%) and NM0.0P (62%) was determined in the residual fraction (Figure 1), which indicates that most of the P in this soil is found in forms of high binding energy with the colloids, that is, with a greater adsorption capacity of phosphates (Cross & Schlesinger, 1995).

In the areas CV7 (41%), CV5 (33%), CV3 (45%), CV0 (31%), NM5 (42%), and NM00SM (40%), the participation of the residual fraction in the total P was lower, being an indication of smaller proportions of iron and aluminum oxides in the clay fraction, in which the added phosphorus tends to preferentially accumulate in labile fractions, with little or no effect over the residual fraction (Couto et al., 2017).

Ceretta et al. (2010) evaluated different wastewater doses in a Ultisol and verified that the residual P was not affected by the addition of swine waste. According to the authors, this occurs because the P added with swine waste accumulates in the soil in less recalcitrant fractions.

It is observed in Figure 1 that in the areas CV7, CV3, NM3, and NM0.0P the preferential P accumulation forms were, in descending order, P-r > P-hi 0.1 > P-hi 0.5, Pbi > P- HCl. Whereas in the areas CV5, CV0, NM5, and NM00SM the preferential forms were: P-hi 0.1 > P-hi 0.5 > P-r > P-bi > P-HCl.

It was observed that despite the use or not of swine wastewater, moderately labile P was found in large quantities in all evaluated areas (Figure 1). The increase in moderately labile P might have occurred due to the increased availability of inorganic P in soils with the use of swine wastewater and the lower concentration of compounds dissolved in the mineral fertilizer of area CV0, once these compounds can be adsorbed in the functional groups of the surface of the mineral components of the solid phase, increasing P desorption (Ceretta et al., 2010; Couto et al., 2017).

The percentages of P in labile (P-bi) and non-labile forms (Pi-hi 0.1 + Pi-hi 0.5 + Pi-HCl + P-r) are presented in Figure 2. There was no predominance of labile P forms over non-labile ones when comparing areas with and without swine wastewater use.

A large amount of labile P in the areas without swine wastewater indicates that the LSW did not increase the concentrations of available P when compared to the area with mineral fertilization, the opposite to the observed by Couto et al. (2017) when comparing different sources of organic residues and mineral fertilization in a Ultisol, verified that the deep swine bedding, the liquid swine wastewater, and the bovine manure favored higher levels of P in the labile fractions (resin + organic $NaHCO_3$ + inorganic $NaHCO_3$) than the mineral fertilization.

It was observed that the largest P reservoirs were moderately labile and residual. Thus, P is in low-loss compartments, remaining for longer periods stored in the studied soils, with no risk of contamination by excess phosphorus.

In the principal components analysis (PCA), two components were extracted, which explained 65.35% of the total variability in the data (Figure 3). The first component (C1) explained 36.81% of the total data variability, and the variables Pi-hi0.5, Pr, and Pt were the most representative. In contrast, the second component was more correlated with the PA and Pi-bi.

The PCA indicated variation in the distribution of the phosphorus forms (Figure 3) and a separation between the studied areas. It was observed that the areas CV0 and CV5 were grouped and related to variables PA and Pi-bi. Therefore, in these areas, the amount of available phosphorus is greater, indicating that swine wastewater does not increase the P concentration compared to the area with mineral fertilization (CV0). The areas NM5 and NM0 were also grouped and related to variables Pi-hi0.5, Pr, and Pt.

It is observed that the PCA did not differentiate the areas with and without the swine wastewater since these areas were grouped, indicating that the change in the distribution of the variables is not related to the use of LSW in the soils.

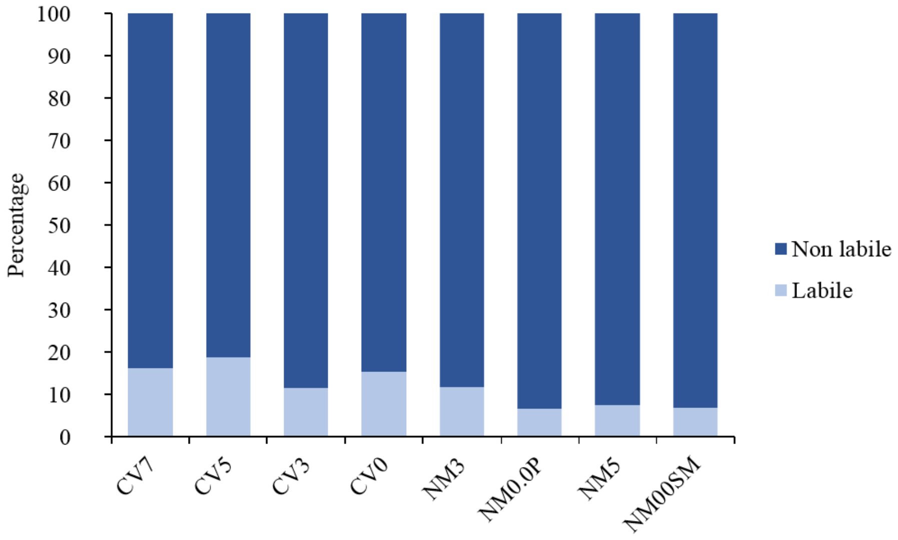
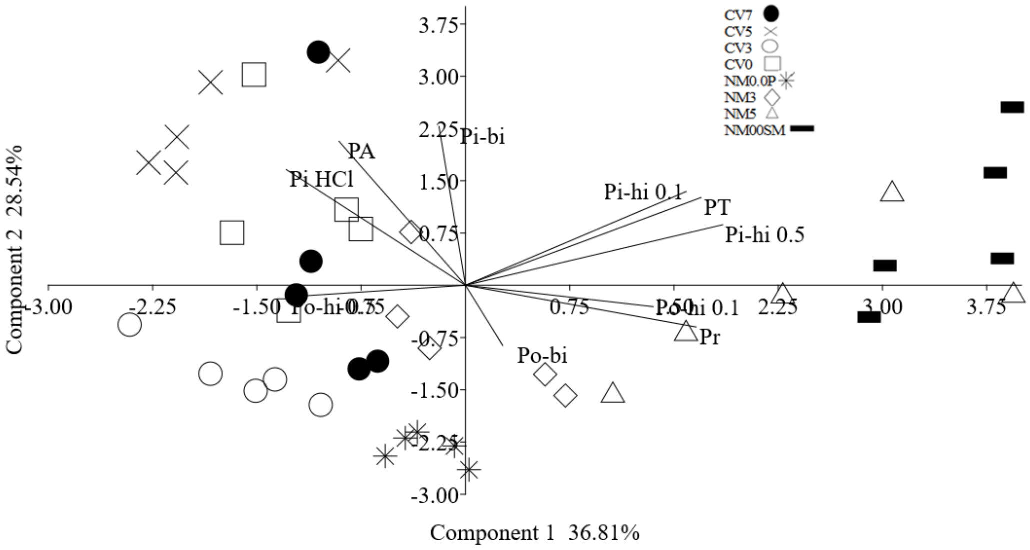


Figure 2. Phosphorus percentages in the labile and non-labile forms in the 0-0.20 m layer of Oxisols in Campo Verde and Nova Mutum, MT, Brazil



PA - Available phosphorus; Pi-bi - Inorganic phosphorus extracted with NaHCO$_3$; Po-bi - Organic phosphorus extracted with NaHCO$_3$; Pi-hi 0.1 - Inorganic phosphorus extracted with NaOH 0.1 mol L^{-1}; Po-hi 0.1 - Organic phosphorus extracted with NaOH 0.1 mol L^{-1}; Pi-hi 0.5 - Inorganic phosphorus extracted with NaOH 0.5 mol L^{-1}; Po-hi 0.5 - Organic phosphorus extracted with NaOH 0.5 mol L^{-1}; P-HCl - Phosphorus extracted with HCl; Pr - Residual phosphorus; Pt - Total phosphorus

Figure 3. Relation between P fractions in the 0-0.20 m layer in Oxisols of Campo Verde (CV) and Nova Mutum (NM), MT, Brazil, based on the scores of the principal components 1 and 2

CONCLUSIONS

1. There was no predominance of more available P forms concerning the unavailable forms when comparing the areas with and without swine wastewater.

2. The main forms of P accumulated in the 0-0.20 m soil layer, despite the soil texture and usage or not of swine wastewater, were residual P and moderately labile P.

3. P is in low loss compartments, remaining for longer periods stored in the studied soils.

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