MOBILITY AND LEACHING OF NUTRIENTS IN SOIL COLUMNS WITH THE APPLICATION OF LIQUID SWINE MANURE

Rayza Trindade Silva[1]
Mayra Sauceda[2]
Nelson Castellón[3]
Ariane Isis Barros[4]
Oscarlina Lúcia dos Santos Weber[5]

ABSTRACT

Applying organic waste to soil can replenish nutrients removed by crop production and reduce reliance on mineral fertilizers. However, improper use particularly at high application rates can negatively impact the environment. Excess nutrients may leach into water bodies, threatening water quality. Understanding how nutrients move vertically through the soil profile is therefore essential for designing safe and effective fertilization practices. This study aimed to assess the effect of increasing doses of liquid swine manure (LSM) on nutrient mobility in soil and quantify ion leaching. Soil was collected from the 0–0.20 m layer of native Cerrado vegetation. The experiment used a completely randomized design with five LSM application rates (0, 50, 150, 450, and 600 m³ ha^{-1}), each replicated three times. Manure was mixed with soil samples and incubated at 60% field capacity for 20 days. After incubation, a 5 cm layer of treated soil was placed over untreated soil in 100 mm PVC columns. These columns were moistened to field capacity and subjected to five irrigation cycles over 15 days, totaling 400 mm of water. Leachate was collected after each cycle and analyzed via ion chromatography. Nutrient concentrations (Al, Ca, K, Mg, Na, and P), pH, cation exchange capacity (CEC), and water-dispersible clay were measured at 5 cm intervals to a depth of 30 cm. Results showed that the LSM application altered most physical and chemical soil properties, except for K content and total CEC, which remained unchanged across all treatments.

Keywords: nutrient dynamics, organic residues, percolation, soil fertility

MOBILIDADE E LIXIVIAÇÃO DE NUTRIENTES EM COLUNAS DE SOLO COM A APLICAÇÃO DE DEJETO LÍQUIDO DE SUÍNOS

RESUMO

A aplicação de resíduos orgânicos ao solo pode repor os nutrientes extraídos pelas culturas, reduzindo a necessidade de fertilizantes minerais. No entanto, o manejo inadequado, especialmente com altas doses, pode causar impactos ambientais negativos, como a lixiviação de nutrientes para os recursos hídricos, comprometendo a qualidade ambiental. Assim, compreender a mobilidade vertical dos nutrientes no solo é essencial para o desenvolvimento de práticas de fertilização mais seguras e eficientes. Este estudo teve como objetivo avaliar o efeito de doses crescentes de dejeto líquido de suínos (DLS) na mobilidade de nutrientes no solo e na lixiviação de íons. As amostras de solo foram coletadas na camada de 0–0,20 m em área de vegetação nativa do Cerrado. O experimento foi conduzido em delineamento inteiramente casualizado, com cinco doses de DLS (0, 50, 150, 450 e 600 m³ ha^{-1}) e três repetições. O solo tratado foi incubado por 20 dias a 60% da capacidade de campo. Em seguida, 5 cm desse solo foram colocados sobre solo não tratado em colunas de PVC (100 mm). As colunas foram saturadas por capilaridade e irrigadas em cinco ciclos ao longo de 15 dias, totalizando 400 mm de água. O lixiviado coletado ao final de cada ciclo foi analisado por cromatografia iônica. Foram avaliados os teores de Al, Ca, K, Mg, Na, P, pH em H_2O, CTC e argila dispersa em água em intervalos de 5 cm até 30 cm de profundidade. O DLS alterou diversos atributos químicos e físicos do solo, exceto os níveis de K e a CTC total.

Palavras-chave: dinâmica de nutrientes, fertilidade do solo, percolação, resíduos orgânicos

Recebido em 20 de janeiro de 2026. Aprovado em 25 de março de 2026

[1]Federal University of Mato Grosso (UFMT), 78605-091 Cuiabá - MT, Brazil. E-mail: rayzatrindadesilva@gmail.com
[2]PhD in Tropical Agriculture. Federal University of Mato Grosso (UFMT), Cuiabá, MT, Brazil. E-mail: samayradr20@gmail.com
[3]PhD in Environmental Science Federal University of Pará (UFPA). Belém, Pará, Brazil. E-mail:castellonnr@gmail.com
[4]Professor PhD, Graduate Program in Tropical Agriculture (PPGAT), UFMT, Brazil. E-mail: ariane.isis@hotmail.com
[5]Professor PhD, Department of Soil and Rural Engineering, UFMT. Brazil. E-mail: oscarlinaweber@gmail.com

INTRODUCTION

The application of organic waste to soil helps replenish nutrients removed by crops, reduces the reliance on mineral fertilizers, and can influence nutrient availability and mobility either positively or negatively depending on how it is managed. Among organic fertilization options, liquid swine manure (LSM) stands out as a widely used and economically viable alternative, particularly in areas of intensive animal production (Silva et al., 2015a; Oliveira Filho et al., 2020). LSM is rich in essential nutrients, including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), and various micronutrients, making it a valuable contributor to soil fertility (Krajeski & Povaluk, 2014). However, careful attention must be given to the application rates. When applied excessively or too frequently, LSM can exceed the soil's capacity to retain solutes and the plants' ability to absorb nutrients, increasing the risk of nutrient leaching into nearby water bodies and potentially causing environmental harm.

The nutrient retention capacity of soils varies depending on the nature and composition of the applied residues, precipitation levels (Rosa et al., 2017), soil pH, cation exchange capacity, and organic matter content (Cardoso et al., 2013). The presence of salts in organic fertilizers can lead to clay dispersion and alter the soil's physical structure, potentially causing salinization (Cichelero et al., 2023; Rosa et al., 2017). In contrast, the organic matter present in these residues can enhance flocculation in the soil's surface layer (Silva et al., 2017).

However, applying high doses of LSM can negatively impact soil health by accumulating cations such as Ca, K, Mg, and Na. This accumulation increases electrical conductivity, promoting soil salinization and clay dispersion, thereby reducing particle aggregation. Consequently, these changes can cause pore blockage, reduced hydraulic conductivity, and surface crusting—conditions that increase the risk of water erosion (Agne, 2014).

In this context, understanding the vertical mobility of individual nutrients within the soil profile is essential for evaluating their behavior and for establishing safe, efficient, and sustainable fertilization practices. Based on this premise, the present study aimed to assess the effect of increasing doses of pig manure on nutrient mobility in soil columns and quantify ion leaching throughout the soil profile.

MATERIAL AND METHODS

A soil sample was obtained from the 0–0.20 m layer of a clay-rich Latossolo (SEPLAN-MT, 2001), located in the municipality of Campo Verde, Mato Grosso (15º22'43.13"S, 55º09'31.33"W). Soil physical and chemical attributes were characterized according to the standardized procedures outlined by Teixeira et al. (2017), as presented in Table 1.

Table 1. Physical and chemical characteristics of Cerrado Latosol after liming

Sand	Silt	Clay	CDW(1)	Apparent Density
g kg^{-1}				g cm^{-3}
198	147	655	479.49	1.05

pH		ΔpH	MO	K^+	Na^+	Ca^{2+}+Mg^{2+}	Al^{3+}	H^++Al^{3+}(2)	SB(3)	T(4)	V(5)
H_2O	KCl		g kg^{-1}	cmol$_c$ dm^{-3}							%
6.41	5.96	0.45	40	0.41	0.06	7.85	0	1.65	8.32	9.97	83.45

(1)Clay dispersed in water, (2)Potential acidity; (3)Sum of bases; (4)Cation exchange capacity at pH 7; (5)Base saturation.

The LSM treated in a biodigester was collected from the Bordignon farm, which operates an entirely confined pig finishing unit in the municipality of Campo Verde, Mato Grosso. The chemical composition of the LSM sample (Table 2) was determined following the methodology established by the Ministry of Agriculture, Livestock, and Supply (MAPA, 2014).

Table 2. Composition of liquid swine manure

pH	N	Ca	Mg	BOD [1]	COD [2]	DM [3]	EC [4]	SAR [5]
H_2O	$g.L^{-1}$	$mg.L^{-1}$				$g.L^{-1}$	$mS\ cm^{-1}$	$mmol_c.L^{-1}$
7.61	34.44	117.5	20.4	1.491	6.350	52.18	10.04	1.29
P- total	K	Na	S	Mn	Fe	Cu	Zn	SS[6]
$mg.L^{-1}$								$g.L^{-1}$
85.21	39.58	57.9	161.33	26.04	191.85	81.81	149.19	12.49

[1]Biochemical oxygen demand; [2]Chemical oxygen demand; [3]Dry mass; [4]Electrical conductivity; [5]Sodium adsorption ratio; [6]Sedimentable solids

Soil column assembly

The soil was incubated with six LSM dosages (0, 50, 150, 450, and 600 $m^3\ ha^{-1}$) for 20 days to allow adequate contact time between the residue and the soil. After incubation, the soil was dried in a forced-air circulation oven at 60 °C, manually disaggregated, and placed into PVC tubes measuring 100 mm in diameter and 35 cm in height. The inner walls of the tubes were previously sanded in the direction opposite to water flow to minimize preferential flow paths. The bottom of each tube was covered with organza fabric and secured with adhesive tape to support the weight of the soil column (Figure 1A). A completely randomized design with three replicates was used.

Each soil column was constructed by packing 25 cm of air-dried fine soil (ADFS) (Figure 1B), followed by a 5 cm layer of dry soil previously incubated with the respective LSM dosages. The soil was compacted to achieve a target bulk density of 1.05 $g\ cm^{-3}$, confirmed by weighing the filled columns. Following assembly, the columns were saturated via capillary rise until the field capacity was reached.

Water was applied using a hospital feeding bottle connected to a flow meter and an Equipo-type hose (Figure 1C), with the hose tip fitted into the tube cap. To prevent surface disruption caused by dripping and to ensure uniform water distribution, a sheet of quantitative filter paper was placed over the top of the soil column, covering the entire surface.

(A) (B) (C)

Figure 1. Steps in setting up the leaching experiment: (A) Tubes with organza-lined bottoms; (B) Packing the soil mixture to a height of 25 cm; (C) Installing the tubes on the support rack for the test.

The volume of water applied was calculated using a methodology adapted from Bamberg et al. (2012), totaling 400 mm of water distributed over five cycles, each lasting three days. Water was applied in installments: 300 mL on two consecutive days, followed by a oneday pause to allow for percolation before the next cycle began. At the end of each cycle, the percolated water was collected, its volume recorded, and samples were stored in a freezer until ion analysis.

After the completion of the water application cycles, the soil columns were sectioned into layers at depths of 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.30 m. The collected samples were dried in a forced-air oven at 60 °C, gently crushed, and then analyzed for water-dispersible clay, as well as for standard chemical and physical Properties.

Determination of physical and chemical attributes of the soil column

For the extraction of Ca^{+}, Mg^{2+}, and Al, a 1 mol L^{-1} KCl solution was used as the extractant. P, Na, and K^{+} were extracted using a dilute solution of HCl and H_2SO_4 (0.01 mol L^{-1}), following the Mehlich 1 method. Total acidity ($H^{+} + Al^{3+}$) was extracted using calcium acetate, according to the methodology described by Teixeira (2017).

Ca^{2+} and Mg^{2+} contents were determined by complexometric titration with EDTA, while aluminum and total acidity ($H^{+} + Al^{3+}$) were quantified by neutralization with 0.025 mol L^{-1} NaOH. Na and K^{+} were measured by flame photometry, and P was determined by spectrophotometry at a wavelength of 660 nm.

The sum of bases (SB) was calculated by summing the concentrations of Ca^{2+}, Mg^{2+}, and K^{+}, and the Effective (t) and total (T) cation exchange capacities, base saturation (V%), and pH in both H_2O and KCl were determined according to Teixeira (2017). Organic matter (OM) content was estimated from organic carbon using the Walkley-Black method (Mendonça, 2005).

Chemical analysis of leached nutrients

To determine the concentrations of Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}, NH_4^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, and NO_2^{-} in the leachates, water samples were first filtered under vacuum using quantitative filter paper membranes (specify brand/model if needed). The filtered samples were then transferred to vials for analysis using an ion chromatograph (940 Professional IC Vario, Metrohm).

Statistical Analysis

The data obtained were subjected to multiple regression analysis as a function of LSM doses and soil depth layers. Variables showing significant interactions with soil layer were analyzed using the Scott–Knott test at the 5% significance level, performed with SISVAR 5.3 (Ferreira, 2001). For attributes with significant effects from both dose and layer, the Model Identity test was also applied using NCSS 7.0 (2005).

Data from the leachate analyses were subjected to regression analysis as a function of LSM dosages, at a 5% significance level. The regression was based on the mean nutrient concentrations, calculated by summing the average values across the five water application cycles for each treatment.

RESULTS AND DISCUSSION

Chemical and physical attributes of the soil column

Multiple regression analysis revealed a significant interaction between LSM dosages and soil depth for P, pH, and potential acidity ($H^{+} + Al^{3+}$), indicating that both application rate and soil depth influence these attributes. In contrast, K^{+} and CEC at pH 7 (T) were significantly affected by dose and depth independently, while available Al^{3+}, Ca^{2+}, Mg^{2+}, Na^{+}, and effective CEC (t) were significantly influenced only by the LSM dosage (Table 3).

Table 3. Soil chemical attributes with significant interaction (p>0.05) after application of increasing dosages of LSM

Depth (m)	Dosage m³ ha⁻¹												Equation	R²
	0		**50**		**150**		**300**		**450**		**600**			
							pH							
0.0-0.05	6.71	a	6.23	c	6.15	c	6.77	b	6.94	b	6.89	a	$y = 0.001x + 6.3689$	0.4544*
0.05-0.10	6.83	a	6.56	b	6.64	b	6.95	a	7.10	a	7.05	a	$y = 0.0007x + 6.6671$	0.6535*
0.10-0.20	6.88	a	6.98	a	7.01	a	7.06	a	7.14	a	6.76	a	$y = -3E\text{-}06x^2 + 0.0017x + 6.8746$	0.7581*
0.20-0.30	6.76	a	7.19	a	7.23	a	7.04	a	6.88	b	6.84	a	$y = -3E\text{-}06x^2 + 0.0013x + 6.9589$	0.4183 *
							P (mg.dm⁻³)							
0.0-0.05	5.15	a	6.19	a	7.86	a	7.90	a	10.19	a	14.06	a	$y = 0.013x + 5.192$	0.9233*
0.05-0.10	5.17	a	5.23	a	5.67	b	5.17	b	5.31	b	7.01	b	$y = 0.0021x + 5.0475$	0.4835*
0.10-0.20	5.11	a	5.68	a	5.09	b	4.76	b	5.21	b	5.19	c	na(1)	---
0.20-0.30	4.62	a	5.41	a	5.47	b	4.90	b	4.78	b	4.42	c	na	---
							H+Al ($cmol_c.dm^{-3}$)							
0.0-0.05	3.57	a	4.45	a	4.78	a	2.51	a	2.57	a	2.81	a	$y = -0.0029x + 4.2094$	0.4870*
0.05-0.10	2.75	a	3.85	a	3.63	b	2.39	a	2.27	a	2.51	a	$y = -0.0018x + 3.3797$	0.4164*
0.10-0.20	3.19	a	2.75	b	2.90	b	2.39	a	2.51	a	2.81	a	na	---
0.20-0.30	3.85	a	2.91	b	2.75	b	2.15	a	3.23	a	2.99	a	$y = 8E\text{-}06x^2 – 0.0055x + 3.4968$	0.5018*

(1) Not adjusted by regression equation. Averages followed by the same letter in the column do not differ from each other according to Scott Knott's test (p>0.05). * Significant (p>0.05). H+Al: potential acidity

A decrease in pH and an increase in potential acidity ($H^+ + Al^{3+}$) were observed in the 0–0.05 m layer at LSM dosages of 50, 150, 300, and 450 m³ ha⁻¹, and in the 0.05–0.10 m layer at 50 and 150 m³ ha⁻¹. These results suggest that the decomposition of organic matter from LSM releases organic acids, contributing to acidification, particularly in the upper layers.

Similar trends were reported by Da Ros et al. (2017), who observed a significant decrease in pH with depth after repeated LSM applications in grain crops, with values ranging from 6.1 in the 0–2.5 cm layer to 5.4 in the 15–20 cm layer. These effects are likely due to the interplay between the alkalinizing components of the LSM and soil acidification, modulated by the soil's buffering capacity.

Barros et al. (2019) also noted that excessive application of organic residues such as manure can lead to soil acidification and a reduction in organic matter over time, potentially causing nutrient imbalances, increased crop dependence on organic inputs, and greater susceptibility to pests and diseases due to plant stress.

The availability of P was higher in the 0–0.05 m layer at LSM dosages of 150, 300, 450, and 600 m³ ha⁻¹, with the highest dose (600 m³ ha⁻¹) also increasing P content in the 0.05–0.10 m layer (Table 3). This downward movement of P may be attributed to the high initial P concentration in the incubated soil (Table 1), which contained 51.3 kg ha⁻¹ of total P (inorganic and organic forms), with 14.06 mg dm⁻³ available in the top 0–0.05 m layer. According to Sousa and Lobato (2004), values above 9 mg P dm⁻³ are considered high for clayey soils.

Da Ros et al. (2017) found a similar stratification, reporting that doses of 75 and 100 m³ ha⁻¹ of pig wastewater led to a vertical P gradient, with surface-layer values up to 5.5 times higher than at 2.6–5.0 cm depth. Such variation is influenced by application rate, frequency, and soil properties (Da Ros et al., 2017; Silva et al., 2015b). In longer-term studies, Lourenzi et al. (2013) observed the downward movement of available P to depths up to 60 cm after 19 successive LSM applications, which they attributed to P accumulation and migration over time. According to Pereira et al. (2016), P movement in the soil profile can also result from saturation of P adsorption sites on iron and aluminum oxides, increasing the risk of P leaching and surface water contamination.

Exchangeable K increased linearly with LSM dosages (Table 4), with higher concentrations in the 0.20–0.30 m layer. This distribution is consistent with K's high mobility under leaching conditions, especially in coarse or structured soils. The model identity test indicated an 87% probability that the rate of increase was similar across dosages, although K content varied with depth. The deeper the layer, the higher the K content observed for the same dosage (Figure 2), reinforcing the nutrient's susceptibility to vertical movement in the soil profile.

These findings demonstrate that LSM application alters key soil chemical properties in a depth dependent manner. While LSM can enrich the soil with essential nutrients such as P, K, Ca, and Mg, it may also contribute to acidification, particularly in surface layers, and promote the leaching of nutrients like K and P under certain conditions. Therefore, careful management of LSM dosage is essential to maximize its agronomic benefits while mitigating risks such as acidification and nutrient loss.

Table 4. Average potassium (K) content in soil layers following increasing LSM dosage

Layer (m)	K ($cmol_c.dm^{-3}$)	Regression equation	R^2
0.0-0.05	0.201 c	$y = 0.00020x + 0.1488$	0.8968*
0.05-0.10	0.219 c	$y = 0.00018x + 0.1721$	0.9608*
0.10-0.20	0.283 b	$y = 0.00013x + 0.2499$	0.8581*
0.20-0.30	0.340 a	$y = 0.00014x + 0.3047$	0.9520*

Average followed by the same letter in the column do not differ from each other according to Scott Knott's test ($p>0.05$). *Significant ($p>0.05$).

A similar effect was reported by Da Ros et al. (2017), likely due to the downward movement of nutrients facilitated by the high initial K content in the 0–0.10 m soil layer. Maggi et al. (2013) also observed that higher dosages of LSM increase soil concentrations of K, P, and N, and result in elevated content of K and P in the leachate. In a study on LSM application in pasture systems, Homem et al. (2014) found a reduction in K availability in the 0.20–0.40 m layer, which they attributed to the nutrient's mobility toward deeper soil layers, likely influenced by a decrease in CEC with depth.

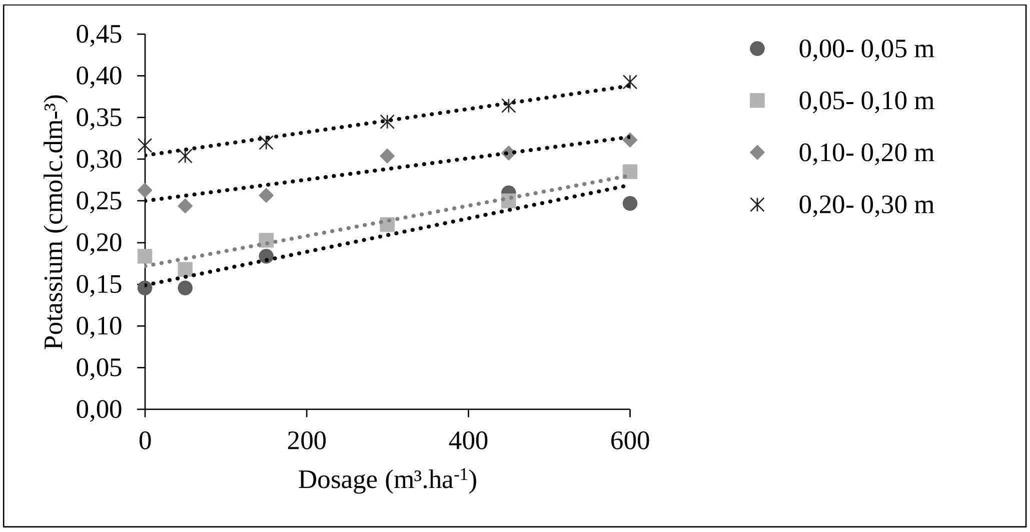

Figure 2. Potassium content as a function of LSM dosages for each layer studied

For CEC_7, the response to the LSM application varied with soil depth. According to the model identity test (Table 5), except for the 0.05–0.10 m layer, both the slope (x^2) and the Y-intercept (x) of the regression equations showed probabilities above 80% of being equal across layers. In contrast, the curves' concavity had only a 30% chance of being equal, indicating differences in shape. These results suggest that, while the general trend of increasing CEC_7 with increasing LSM dosage is consistent, the magnitude and rate of change differ across soil layers. Notably, deeper layers exhibited a more pronounced increase in CEC_7, implying a stronger response to LSM application at depth (Figure 3).

This depth-dependent variation in CEC_7 may be attributed to several factors, including the vertical redistribution of organic compounds and cations derived from LSM, as well as inherent differences in soil mineralogy and organic matter content along the profile. Organic residues, such as LSM, are known to increase CEC by adding organic matter and functional groups that contribute to surface charge (Silva & Mendonça, 2007). Moreover, cations like Ca^{2+}, Mg^{2+}, and K^+ released during residue decomposition can migrate through the soil profile, altering exchange properties at depth (Lourenzi et al., 2013). The increase in CEC_7 in deeper layers highlights the potential of LSM not only to supply nutrients but also to improve the soil's ability to retain and exchange essential cations, especially in subsurface horizons where natural CEC levels tend to be lower due to reduced organic matter and clay reactivity (Brady & Weil, 2016).

Table 5. Variation of cation exchange capacity (CEC) and potassium (K) in soil layers following increasing LSM dosage

Layer (m)	CEC(1)			
	K ($cmol_c.dm^{-3}$)		Regression equation	R^2
0.0-0.05	13.34	a	$y = 1E\text{-}05x^2 – 0.0057x + 13.458$	0.5167*
0.05-0.10	12.82	b	na(2)	---
0.10-0.20	12.60	b	$y = 2E\text{-}05x^2 – 0.0079x + 12.818$	0.8483*
0.20-0.30	12.97	b	$y = 1E\text{-}05x^2 – 0.0067x + 13.088$	0.6631*

(1) CEC at pH 7

The manure treatments also demonstrated greater nutrient retention capacity, as indicated by the higher CEC values. This effect may be attributed to the increased base saturation observed in these treatments (Balota et al., 2014). Additionally, the application of manure can raise soil pH, which, in turn, increases the number of negative charges on the surface of organic colloids, thereby increasing CEC. Conversely, a reduction in soil pH increases the proportion of positive charges relative to negative ones, ultimately decreasing the soil's ability to retain cations.

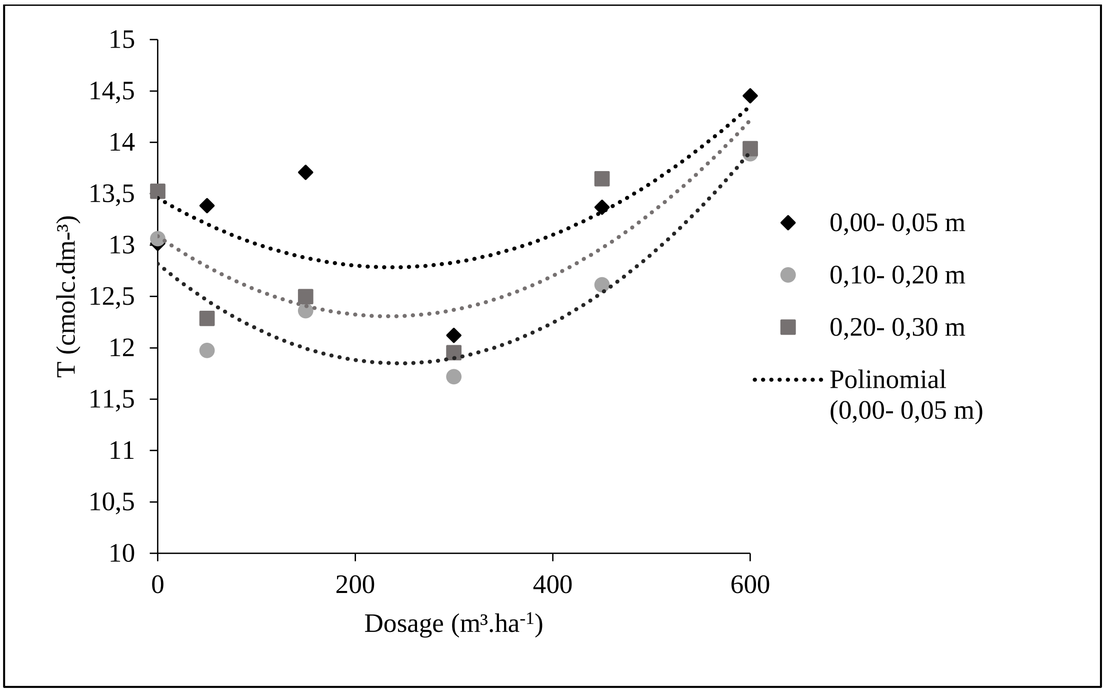

Figure 3. Cation exchange capacity at pH 7 (T) as a function of LSM dosages for each layer studied

Magnesium (Mg) content varied significantly with different LSM dosages, with the highest concentrations observed in the control treatment. This decrease in soil Mg with increasing LSM application is likely due to LSM's lower Mg content compared to Ca. As more Ca is added to the soil through LSM, it can displace Mg from the soil's cation exchange sites, thereby reducing Mg availability. This displacement occurs because, according to the lyotropic series, Ca is preferentially retained over Mg (Ribeiro et al., 2009).

Clay dispersed in water (CDW) also varied with LSM dosages (Table 6). In weathered soils, pH fluctuations and the ionic strength of the soil solution are the primary factors influencing CDW. Both increases and decreases in pH can lead to enhanced repulsion among similarly charged particles—negatively or positively charged according to Inda et al. (2012).

The effective CEC (denoted as *t*) exhibited a linear trend across treatments, whereas the potential CEC at pH 7 (denoted as *T*) showed higher values in the 0–0.05 m soil layer. As reported by Vieira et al. (2022), CEC is influenced by various chemical properties, including Ca, Mg, and K concentrations, as well as pH. Moreover, increases in soil CEC are often associated with organic matter inputs and reduced mineralization losses (Oliveira et al., 2014).

Table 6. Regression equations for soil chemical attributes, significant for dosage (p>0.05), after application of increasing dosages of LSM

Variables	Dosage						Regression Equations	R^2
	0	50	150	300	450	600		
Ca	5.63	5.86	6.02	6.09	6.96	7.80	$y = 6E\text{-}06x^2 – 0.0001x +$	0.9789*
Mg	3.58	2.93	3.08	3.08	3.08	2.95	$y = -0.0005x + 3.2501$	0.2763*
Na	0.21	0.12	0.09	0.11	0.13	0.12	$y = 6E\text{-}07x^2 – 0.0004x +$	0.4500*
t(1)	9.65	9.13	9.43	9.55	10.46	11.19	$y = 0.003x + 9.1411$	0.7947*
CDW(2)	312.01	305.05	271.06	333.37	322.74	330.49	$y = 0.0548x + 298.31$	0.3153*

(1)Effective cation exchange capacity; (2) Clay dispersed in water. * Significant (p>0.05).

Nutrients in percolated water

Chloride and sulfate concentrations remained within the limits established for potable water. However, nitrate content observed in this study pose a significant risk of surface water contamination, particularly following LSM application, with concentrations ranging from 12.97 to 70.36 mg L^{-1}. Given the high nitrate content in LSM (Table 7), this potential environmental risk warrants further evaluation under field conditions.

Table 7. Average nutrient content in percolated water after 400 mm of water volume and application of increasing dosages of LSM

Dosage	Na	NH_4^+	K	Ca	Mg	Cl^-	NO_2^-	NO_3^-	SO_4^{2-}
(m^3 ha^{-1})					mg.L^{-1}				
0	0.62	42.98	18.38	10.58	11.77	16.24	7.98	8.25	8.11
50	1.69	30.22	22.24	13.63	14.40	16.02	11.20	59.92	10.32
150	2.68	23.21	19.84	13.34	14.46	16.99	4.98	70.36	8.89
300	1.68	27.70	20.02	12.74	13.29	18.84	7.22	31.30	10.76
450	2.39	35.00	20.50	10.29	13.45	21.50	4.68	12.97	8.27
600	1.65	35.10	22.75	14.25	12.94	24.70	11.78	31.84	12.89

Ammonium (NH_4^+) is the least toxic form of nitrogen in water. However, it is an unstable molecule, especially under less acidic (more alkaline) conditions, where it is readily converted to ammonia (NH_3), and subsequently, through the nitrification process, to nitrite (NO_2^-) and nitrate (NO_3^-) (Gotardo et al., 2017). This process explains the observed increase in nitrate concentrations following LSM application, likely due to enhanced ammonium nitrification by soil microorganisms stimulated by the addition of readily decomposable organic matter (Feder & Findeling, 2007). Rapid nitrification contributed to elevated nitrate content, particularly at LSM dosages of 50 and 150 m^3 ha^{-1}. However, with the application of 450 m^3 ha^{-1} of LSM, nitrate leaching decreased, indicating a non-linear response to increasing dosages.

The leaching of nitrate (NO_3^-) occurs partly due to the rapid transformation of NH_4^+ into NO_3^- and partly because nitrate, being a negatively charged anion, is weakly retained by the soil's positively charged colloidal sites. This phenomenon is most pronounced in the surface soil layers, where organic matter enhances the electronegative character of the solid phase, thereby repelling nitrate. Additionally, phosphates applied through fertilization tend to occupy the remaining positive charges, leaving nitrate in the soil solution and increasing its leaching potential. Over time, this leads to elevated nitrate concentrations in deeper soil layers and groundwater (Menezes et al., 2023).

Chloride (Cl^-) leaching increased linearly with the LSM dosages (Table 8). Both Cl^- and NO_3^- act as mobile accompanying anions, which can facilitate the movement of soil base cations, while sulfate (SO_4^{2-}) tends to form ionic pairs. The application of organic waste materials, which contribute cations such as Ca^{2+}, Mg^{2+}, K^+, and Na^+, increases soil pH and CEC, thereby promoting the leaching of anions (Gebrim, 2006).

In contrast, Hadlich and Scheibe (2007) reported that sulfate concentrations correlate with chemical oxygen demand (COD), which varies depending on pH, temperature, moisture, and organic matter content. These variables help explain the nonlinear behavior of SO_4^{2-} observed in this study, as shown by the quadratic regression model (Table 8). According to Brady and Weil (2013), sulfur when mineralized into its soluble SO_4^{2-} form is also susceptible to leaching and groundwater contamination. Despite this risk, sulfur remains essential for plant and animal development. Its deficiency can result in stunted growth, thinner plant structures, and chlorosis, particularly in younger leaves.

Table 8. Regression equations for nutrients as a function of the LSM dosages applied

Variable	Equation	R^2
Ammonium	$y = 0.0001x^2 – 0.0741x + 37.298$	0.4880*
Chloride	$y = 0.0143x + 15.347$	0.9202*
Nitrate	$y = -0.0273x + 42.829$	0.0635*
Sulfate	$y = 0.0044x + 8.7249$	0.3273*

* Significant (p>0.05)

CONCLUSIONS

The application of LSM alters several physical and chemical soil properties across the evaluated layers, except for K content and CEC, which remain unaffected.

Potassium shows mobility throughout the soil profile regardless of the LSM dosage applied, indicating that sludge application does not affect its movement.

However, the use of high LSM dosages poses an environmental risk by increasing nitrate (NO_3^-) leaching, leading to concentrations exceeding acceptable water-quality limits. Therefore, the application of LSM should be carefully managed to minimize the risk of subsurface water contamination.

REFERENCES

AGNE, S. A.; KLEIN, V. A. Matéria orgânica e atributos físicos de um Latossolo Vermelho após aplicações de dejeto de suínos. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 18, p. 720–726, 2014. https://doi.org/10.1590/S1415-43662014000700008

BALOTA, E. L.; MACHINESKI, O.; HAMID, K. I. A.; YADA, I. F. U.; BARBOSA, G. M. C.; NAKATANI, A. S.; COYNE, M. S. Soil microbial properties after long-term swine slurry application to conventional and no-tillage systems in Brazil. **Science of the Total Environment**, v. 490, p. 397–404, 2014. https://doi.org/10.1016/j.scitotenv.2014.05.019

BAMBERG, A. L.; GRECCO, M. F.; SILVEIRA, C. A. P.; MARTINAZZO, R.; POTES, M. L.; LOUZADA, R. Insumos para agricultura sustentável. In: **WORKSHOP INSUMOS PARA AGRICULTURA SUSTENTÁVEL**, 2012, Pelotas. **Anais** […]. Pelotas: Embrapa Clima Temperado, 2012.

BARROS, E. C.; NICOLOSO, R.; OLIVEIRA, P. A. V.; CORRÊA, J. C. **Potencial agronômico dos dejetos suínos**. 1. ed. Concórdia: Embrapa Suínos e Aves, 2019.

BRADY, N. C.; WEIL, R. R. **Elementos da natureza e propriedades dos solos**. 3. ed. Porto Alegre: Bookman, 2013. 685p.

BRADY, N. C.; WEIL, R. R. **The nature and properties of soils**. 15th ed. Boston: Pearson, 2016. 912p.

CARDOSO, E. J. B. N.; VASCONCELLOS, R. L. F.; BINI, D.; MIYAUCHI, M. Y. H.; SANTOS, C. A.; ALVES, P. R. L.; PAULA, A. M.; NAKATANI, A. S.; PEREIRA, J. M.;

NOGUEIRA, M. A. Soil health: Looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? **Scientia Agricola**, v. 70, n. 4, p. 274–289, 2013. https://doi.org/10.1590/S0103-90162013000400009
CICHELERO, L. H.; DA SILVA, D. M.; GEHLEN BOHRER, R. E.; AMARO DA SILVA, D. A.; REDIN, M.; LORENSI DE SOUZA, E.; GUERRA, D.; VASCONCELOS, M. C.; LANZANOVA, M. E. Doses de dejetos líquidos de suínos e seu efeito na germinação de sementes de soja, trigo e milho. **Investigación Agraria**, v. 25, n. 1, p. 11–18, 2023.

DA ROS, C. O.; DA SILVA, V. R.; SILVESTRIN, T. B.; DA SILVA, R. F.; PESSOTTO, P. P. Disponibilidade de nutrientes e acidez do solo após aplicações sucessivas de água residuária de suinocultura. **Revista Brasileira de Tecnologia Agropecuária**, v. 1, n. 1, p. 35–44, 2017.

FEDER, F.; FINDELING, A. Retention and leaching of nitrate and chloride in an andic soil after pig manure amendment. **European Journal of Soil Science**, v. 58, n. 2, p. 393–404, 2007. https://doi.org/10.1111/j.1365-2389.2006.00885.

FERREIRA, D. F. Sisvar: A computer statistical analysis system. **Ciência e Agrotecnologia**, v. 25, p. 1039–1042, 2001. https://doi.org/10.1590/S1413-70542011000600001

GEBRIM, F. D. O., SILVA, I. R., NOVAIS, R. F., VERGÜTZ, L., PROCÓPIO, L. C., NUNES, T. N., JESUS, G. L. D. Lixiviação de cátions favorecida pela presença de ânions inorgânicos e ácidos orgânicos de baixa massa molecular em solos adubados com camas de aviário. **Revista Brasileira de Ciência do solo**, v. 32, p. 2255-2267, 2008. https://doi.org/10.1590/S0100-06832008000600005

GOTARDO, R.; PINHEIRO, A.; AGUIDA, L. M.; KAUFMANN, V. Evolução e magnitude das concentrações de cátions, ânions e carbono no dejeto líquido de suínos em fase de terminação. **Revista em Agronegócio e Meio Ambiente**, v. 10, n. 3, p. 849–871, 2017. https://doi.org/10.17765/2176-9168.2017v10n3p849-871

HADLICH, G. M.; SCHEIBE, L. F. Dinâmica físico-química de águas superficiais em região de intensa criação de suínos: exemplo da bacia hidrográfica do rio Coruja-Bonito, município de Braço do Norte, SC. **Geochimica Brasiliensis**, v. 21, p. 245–260, 2007.

HOMEM, B. G. C.; ALMEIDA NETO, O. B.; CONDÉ, M. S.; SILVA, M. D.; FERREIRA, I. M. Efeito do uso prolongado de água residuária da suinocultura sobre as propriedades químicas e físicas de um Latossolo Vermelho-Amarelo. **Científica**, v. 42, n. 3, p. 299–309, 2014. https://doi.org/10.15361/1984-5529.2014v42n3p299-309

INDA, J. R. A. V.; KLAMT, E.; NASCIMENTO, P. C. Composição da fase sólida do solo. In: MEURER, E. J. (org.). **Fundamentos de química do solo**. 5. ed. Porto Alegre: Gênesis, 2012. p. 29–57.

KRAJESKI, A.; POVALUK, M. Alterações no solo ocasionadas pela fertirrigação dos dejetos suínos. **Saúde e Meio Ambiente: Revista Interdisciplinar**, v. 3, n. 1, p. 3–18, 2014. https://doi.org/10.24302/sma.v3i1.415

LOURENZI, C. R.; CERETTA, C. A.; SILVA, L. S.; GIROTTO, E.; LORENSINI, F.; TIECHER, T. L. Nutrients in soil layers under no-tillage after successive pig slurry applications. **Revista Brasileira de Ciência do Solo**, v. 37, n. 1, p. 157–167, 2013. https://doi.org/10.1590/S0100-06832013000100016

MAGGI, C. F.; DE FREITAS, P. S.; SAMPAIO, S. C.; DIETER, J. Impacts of the application of swine wastewater in percolate and in soil cultivated with soybean. **Engenharia Agrícola**, v. 33, n. 2, p. 279–290, 2013. https://doi.org/10.1590/S0100-69162013000200007

MINISTÉRIO DA AGRICULTURA, PECUÁRIA E ABASTECIMENTO (MAPA). **Manual de métodos analíticos oficiais para fertilizantes minerais, orgânicos, organominerais e corretivos**. Brasília, DF: MAPA/SDA/CGAL, 2014.

MENEZES, J. F. S.; MACHADO, A. T. A.; SILVA, R. G.; HEMIELEVSKI, L. S.; BERTI, M. P. S.; CANTÃO, V. C. G.; LEÃO, A. K. M. **Lixiviação de nutrientes em Latossolo com aplicação de dejeto líquido de suínos**. Relatório técnico. 2023. 50 p.

MENDONÇA, E. S. **Matéria orgânica do solo: métodos de análises**. Viçosa, MG: Universidade Federal de Viçosa, 2005. 107 p.

NCSS. **NCSS 7.0: Statistical system for Windows – user's guide I, II, III**. Kaysville, 2005.

OLIVEIRA, L. B.; ACCIOLY, A.; SANTOS, C. L.; FLORES, R. A.; BARBOSA, F. S. Características químicas do solo e produção de biomassa de alface adubada com compostos orgânicos. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 18, n. 2, p. 157–164, 2014. https://doi.org/10.1590/S1415-43662014000200005

OLIVEIRA FILHO, J. S.; FERRARI, A. C.; PEREIRA, M. G.; PINTO, L. A. S. R.; ZONTA, E.; MATOS, T. S. Phosphorus accumulation in soil after successive applications of swine manure: A long-term study in Brazil. **Environmental Earth Sciences**, v. 79, p. 62, 2020. https://doi.org/10.1007/s12665-019-8805-z

PEREIRA, P. A.; SAMPAIO, S. C.; REIS, R. R. D.; ROSA, D. M.; CORREA, M. M. Swine farm wastewater and mineral fertilization in corn cultivation. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 20, n. 1, p. 49–54, 2016. https://doi.org/10.1590/1807-1929/agriambi.v20n1p49-54

RIBEIRO, M. R.; BARROS, M. F. C.; FREIRE, M. B. G. S. Química dos solos salinos e sódicos. In: MELO, V. F.; ALLEONI, L. R. F. (org.). **Química e mineralogia do solo: Parte II – Aplicações**. Viçosa, MG: Sociedade Brasileira de Ciência do Solo, 2009. p. 449–484.

ROSA, D. M.; SAMPAIO, S. C.; PEREIRA, P. A.; MAULI, M. M.; REIS, R. R. D. Swine wastewater: Impacts on soil, plant, and leachate. **Engenharia Agrícola**, v. 37, n. 5, p. 928–939, 2017. https://doi.org/10.1590/1809-4430-Eng.Agric.v37n5p928-939/2017

SECRETARIA DE ESTADO DE PLANEJAMENTO E COORDENAÇÃO GERAL (SEPLAN). **Mapa de solos do Estado de Mato Grosso**. Cuiabá, 2001.

SILVA, I. R; MENDONÇA, E.S. Matéria orgânica do solo. In: NOVAIS, R.F.; ALVAREZ V., V.H.; BARROS, N.F.; FONTES, R.L.F.; CANTARUTTI, R.B. & NEVES, J.C.L. **Fertilidade do solo**. Viçosa, MG, Sociedade Brasileira de Ciência do Solo, 2007. p.275-374.

SILVA, D. M.; ANTONIOLLI, Z. I.; JACQUES, R. J. S.; SILVEIRA, A. O.; SILVA, D. A. A.; RACHE, M. M.; PASSOS, V. H. G.; SILVA, B. R. Indicadores microbiológicos de solo em pastagem com aplicação sucessiva de dejetos de suínos. **Revista Brasileira de Ciência do Solo**, v. 39, p. 1585–1594, 2015a. https://doi.org/10.1590/01000683rbcs20150138

SILVA, A. D. A.; LANA, Â. M.; LANA, R. M.; COSTA, A. M. Fertilização com dejetos suínos: Influência nas características bromatológicas da *Brachiaria decumbens* e alterações no solo. **Engenharia Agrícola**, v. 35, n. 2, p. 254–265, 2015b. https://doi.org/10.1590/1809-4430-Eng.Agric.v35n2p254-265/2015

SILVA, B. E. C.; MEDINA, E. F.; JOLOMBA, M. R. Propriedades físicas do solo em função de diferentes manejos de pastagem. **Revista Brasileira de Agropecuária Sustentável**, v. 7, n. 3, p. 66–75, 2017.

SOUSA, D. M. G.; LOBATO, E. **Cerrado: correção do solo e adubação**. 2. ed. Brasília, DF: Embrapa Informação Tecnológica, 2004. p. 147–168.

TEIXEIRA, P. C.; DONAGEMMA, G. K.; FONTANA, A.; TEIXEIRA, W. G. **Manual de métodos de análise de solo**. 3. ed. rev. e ampl. Brasília, DF: Embrapa, 2017. 573 p.

VIEIRA, C. R.; BOTELHO, R. A.; COSTA, P. P. Influências dos estercos nas características químicas de um Latossolo Vermelho. **Revista do Instituto Florestal**, v. 34, n. 2, p. 109–119, 2022. https://doi.org/10.24278/2178-5031.202234201