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SOILS

Long-term successive poultry litter application improves Oxisol fertility in the Brazilian Cerrado

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ABSTRACT. Brazilian Savannah (Cerrado) soils have insufficient nutrient concentrations for attaining high crop yields. Properly applied poultry litter (PL) may improve soil fertility and forage productivity. Herein, we aimed to evaluate the vertical distribution of acidity and nutrient availability in an Oxisol (Latossolo Vermelho distroférrico) subjected to increasing PL doses over 7 years. We determined the vertical distribution and levels of total organic C, total N, Ca, Mg, K, P, and pH in seven soil layers (0–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.30, 0.30–0.50, 0.50–0.75, and 0.75–1.00 m) where four different PL treatments were applied (cumulative levels: 0, 26.32, 43.15, and 57.6 Mg ha^{-1}) over seven years. Potential acidity and low total organic C content indicated the chemical limitations of natural soil. The application of PL reduced soil acidity and increased K, Ca, and Mg levels and base saturation to 1.00-m depth. The highest PL dose (57.6 Mg ha^{-1}) increased the vertical mobility of Ca, K, and Mg while increasing their stocks by 157, 140, and 135%, respectively, in the deeper soil layers. However, even in the long term, the tested PL doses did not increase total organic C, total N, or P levels in the subsurface soil layers. The dual effects of soil acidity correction and improved nutrient content attest to PL application as an effective strategy for improving soil fertility and ensuring sustainable agricultural development in the Brazilian Cerrado.

Keywords: organic fertilizer; rotational grazing; Savannah; sustainability; *Urochloa decumbens*.

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Introduction

As continuous cultivation and unnecessary nutrient replacement lead to soil degradation, a sustainable production system is required (Silva et al., 2018; Tounkara et al., 2020). In tropical scenarios with highly weathered soils, traditional agricultural production utilizes mineral fertilizers from finite natural reserves (Sharpley et al., 2013; Pantano et al., 2016). Productivity on a linear scale leads to mineral resource wastage. Improper system management strategies increase food production costs and cause severe environmental risks, such as aquatic eutrophication and water salinization (Silva et al., 2018). These reasons justify investing in organic fertilizers (Chojnacka et al., 2020) for sustainable food production.

Animal wastes are used in soils, both in Brazil (Scherer et al., 2010; Vieira et al., 2015; Rogeri et al., 2016) and worldwide (Kobierski et al., 2017; Dróżdż et al., 2020), owing to their high nutrient content, for instance, N, P, K, and other macro and micronutrients, compared with that in other organic sources. As a plant nutrient source, poultry litter (PL) adds organic matter, improves cation exchange capacity (CEC) and C and N stocks, and stimulates soil microbial activity (Zhang et al., 2017; Liang et al., 2017). It also improves soil physical attributes, such as aggregate stability, water retention, and aeration (Al-Gaadi et al., 2019).

Adequate PL application increases soil C and N stocks in the soil, making it an efficient strategy for mitigating greenhouse gas emissions (Pinto et al., 2012; Maillard & Angers, 2014). Despite being a valuable organic nutrient source, high PL levels lead to nutrient leaching, eutrophication, soil acidification, and the emission of harmful gases such as ammonia (Joardar et al., 2020; Kiss et al., 2023). Pathogens, pesticides, and heavy metal contaminants in PL reinforce that its high doses can lead to contaminant dissemination and pose an imminent risk to human and environmental health (Kyakuwaire et al., 2019). Considering these deleterious effects, PL use in agricultural areas reinforces the adoption of firm environmental laws for rational management to ensure the protection and sustainability of the agricultural ecosystem.

Concerns regarding poultry waste and its management and destination have increased as the poultry sector developed. In 2020, Brazil produced ~14.6 thousand tons of broiler chicken (Companhia Nacional de Abastecimento [CONAB], 2020), resulting in tons of bird-dropping, feather, and poultry feed residue waste. With an area of >200 million ha, the Brazilian Cerrado is known for grain and animal production (Ferreira et al., 2019). Increased animal production generates substantial waste, which lacks a sustainable environmental destination. Therefore, reusing manure from permanent pastures is a useful way to reduce nutrient loss caused by runoff and erosion and can be a promising alternative for re–establishing the fertility of pasture Oxisols, the dominant soil class in the Brazilian Cerrado, characterized by depth and low fertility.

Using animal waste as organic soil fertilizers has been explored in Brazil and worldwide (Szogi et al., 2012; United States Department of Agriculture - National Agricultural Statistics Service [USDA-NASS], 2015; Zhang et al., 2017; Liang et al., 2017; Dróżdż et al., 2020; Chojnacka et al., 2020; Chakraborty et al., 2021). However, information regarding long-term PL application to increase pasture soil fertility is scarce. In this study, we evaluated the vertical distribution of acidity and nutrient availability in an Oxisol treated with increasing doses of PL over 7 years.

Material and methods

Study location

The study began in 2008 at *Fazenda Alvorada* in Portelândia (17°57'11" S, 52°04'45" W, altitude 872 m), Goiás State, Brazil. The predominant climate in the region is hot, semi-humid, and seasonal, with rainy summers and dry winters, classified as "Aw" based on the Köppen system, with average annual temperature and rainfall of 24.2°C and 1,700 mm, respectively. The soil with an iron content of $80 \leqslant Fe_2O_3 \leqslant 360$ g kg^{-1} is classified as *Latossolo Vermelho distroférrico* based on the Brazilian soil classification system (Santos et al., 2018) and as Oxisol based on the Soil Taxonomy classification (Soil Survey Staff, 2014). It is extremely clayey, with clay, silt, and sand contents of 739, 125, and 136 g kg^{-1}, respectively, in the 0–0.2 m layer.

In 1995, native Cerrado vegetation in the region was replaced with pastures, with no acidity correction or fertilization during the 10 years preceding the experiment, which began in 2008 and covered 16 plots (0.5 ha each). The area was managed 2 days after the end of the grazing period, with a 30-day fallow period following animal removal. *Urochloa decumbens* was used in a rotational grazing system. In the rainy season (October–May), 20–25 cows (Girolando breed) weighing 550–600 kg were maintained within each enclosure, and in the dry season (June–September), they were fed corn silage during the day and left to graze at night in the area.

PL waste was used as the organic fertilizer, and its composition (average of 7 years of application), was determined after sample wet digestion with sulfuric acid and hydrogen peroxide (Tedesco et al., 1995). K (20.8 g kg^{-1}) and P (15.3 g kg^{-1}) contents were determined by emission spectroscopy and colorimetry, respectively (Murphy & Riley, 1962). Ca (40 g kg^{-1}) and Mg (9 g kg^{-1}) contents were determined by atomic absorption spectrophotometry, and pH (7.7) was determined in a solvent: sample ratio of 20:1 using water as a solvent. Total organic C (TOC, 308 g kg^{-1}) and total N (TN, 32 g kg^{-1}) were determined using a 2400 CHN elemental analyzer (Perkin-Elmer), and a C/N ratio of 10/1 was estimated. Table 1 lists the annual and accumulated doses of turkey litter residue based on its wet weight with 73.3% dry matter content.

Table 1. Annual and accumulated doses of poultry litter (PL) applied during 7 years of experiment (2008–2014) in an Oxisol in Portelândia, Goiás State, Midwest Brazil.

	PL application rate (wet wt., Mg ha^{-1})			
Year	PL0	PL1	PL2	PL3
2008	-	8.70	7.81	14.45
2009	-	-	-	7.81
2010	-	-	8.69	8.69
2011	-	7.32	7.89	7.89
2012	-	5.30	7.34	7.34
2013	-	-	5.71	5.71
2014	-	5.00	5.71	5.71
Cumulative total	0	26.32	43.15	57.6

Experimental design

A randomized complete block design with four replicates, each represented by a plot, was used. The treatments included cumulative PL dosages of 0 Mg ha^{-1} (PL0), 26.32 Mg ha^{-1} (PL1), 43.15 Mg ha^{-1} (PL2), and 57.6 Mg ha^{-1} (PL3) maintained throughout the 7 years (Table 1). Litter was applied annually, invariably at the beginning of the rainy season, using a spreader attached to a tractor following the recommendations of the farm management. Subsequently, the pasture was left for 45 days before the animals entered for grazing.

Soil sampling

Soil samples were collected in November 2015 from the 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.30 m layers using trenching and spatulas and from the 0.30–0.50, 0.50–0.75, and 0.75–1.00 m layers using a Dutch auger. The samples were packed in plastic bags, duly identified, air-dried, and sieved through a 2-mm mesh for particle size standardization. These size-standardized air-dried samples were subsequently used for chemical analyses.

Chemical analyses and soil nutrient stocks

Soil pH was measured in distilled water using a glass electrode (soil: water ratio 1:2.5). Ca^{2+} and Mg^{2+} levels were determined by extraction with KCl 1.0 mol L^{-1} (soil: extractor ratio 1:20). Available P and K^+ concentrations were determined using Mehlich-1 extraction (soil: extractor ratio 1:10), and P content was determined using the molybdenum blue method (Murphy & Riley, 1962). Potential acidity (H+Al) was determined by extraction with 0.5 mol L^{-1} calcium acetate, pH 7.0, and quantified by titration with 0.025 mol L^{-1} NaOH (Teixeira et al., 2017). Based on these results, three parameters were calculated: sum of bases (SB) = Ca + Mg + K, CEC = SB + H^+ + Al^{3+}, and base saturation (V%) = SB / CEC × 100).

TOC content was determined by moist digestion with sulfuric acid and dichromate, as described earlier (Walkley & Black, 1934), with modifications (Tedesco et al., 1995). TN content was determined by distillation using the Kjeldahl semi–micro method (Tedesco et al., 1995). TOC and TN stocks, available P and K, and exchangeable Ca and Mg were estimated using the equivalent soil mass method, considering the mass of the treated soils in terms of the mass of the soil with the lowest mass (Ellert & Bettany, 1995). Stock calculation was based on bulk density measured in a volumetric ring (Teixeira et al., 2017), which was 0.84 and 0.90 g cm^{-3} in the 0.0–0.05 m layer and the other layers, respectively, and considered low for the studied soil (Pinto et al., 2012; Vasconcelos et al., 2014). The total stock of each element was the sum of its stocks in all layers.

Statistical analyses

Data were evaluated using multivariate principal component analysis (PCA) to identify variables with discriminatory power and determine the effects of PL on the soil profile. Original values were normalized to zero mean and unit variance ($\mu = 0$, $\sigma = 1$), and the number of principal components (PCs) was chosen based on variables with eigenvalues > 1.00, with a cumulative variance > 70% (Jeffers, 1978; Hair et al., 2009). The effects of factors (soil layer × PL shot) were evaluated by the mixed analysis of variance (ANOVA) (two factors) based on the correlation matrix of PC score data, and a heat map was generated based on the significance of these scores (Pinheiro et al., 2021). All analyses were performed using Statistics 7 (Statsoft, 2004).

The original data were subjected to ANOVA and normality tests for residuals (Shapiro–Wilk), and the means were compared by regression analysis, testing linear and quadratic models. For the normally distributed data, the means between treatments were compared using Tukey's test at $p < 0.05$. Statistical relationships between individual continuous variables were evaluated using Pearson's correlation analysis at 5% significance in SISVAR (v. 5.6).

Results

Contribution of PL to soil nutrients

The factor analysis (Table S1, disponble in the link https://l1nk.dev/jkOHF) and PCA (Figure 1A–G) results revealed that PL doses (PL0, PL1, PL2, and PL3) affected nutrient vertical distribution to a depth of 1.00 m. The first two factors explained 90.0, 87.2, 85.2, 80.3, 72.5, 75.7, and 73.0% of the total cumulative variance of the data for the 0–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.30, 0.30–0.50, 0.50–0.75, and 0.75–1.00 m soil layers, respectively, with eigenvalues > 1 for PC1 and PC2 and factor loadings (correlation values) > 0.50 for all layers. Negative loadings for PC1 (explaining > 50% of total variation) for pH, Ca, Mg, P, K, H+Al, V%, $CEC_{pH7.0}$, BS, TOC, and TN indicate soil chemical limitations without PL application (PL0).

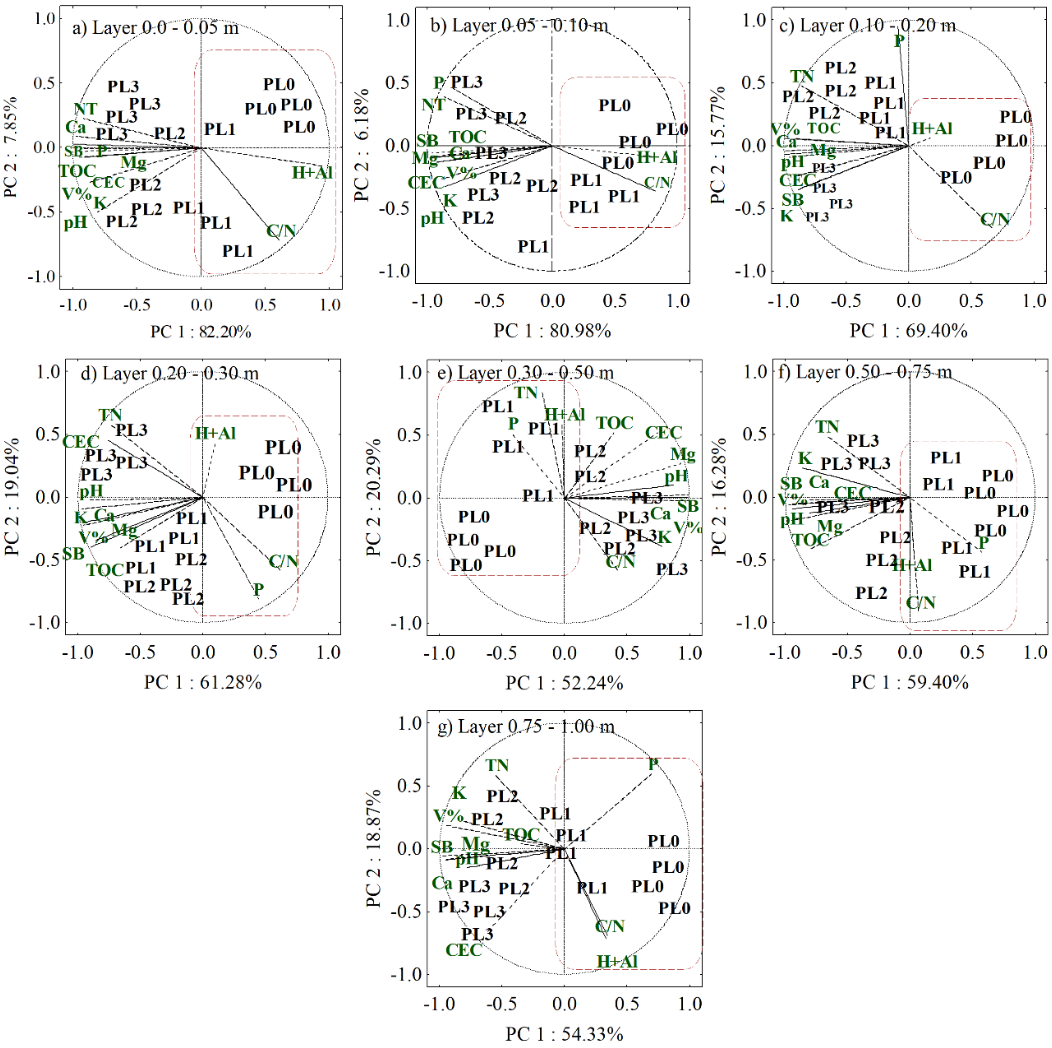
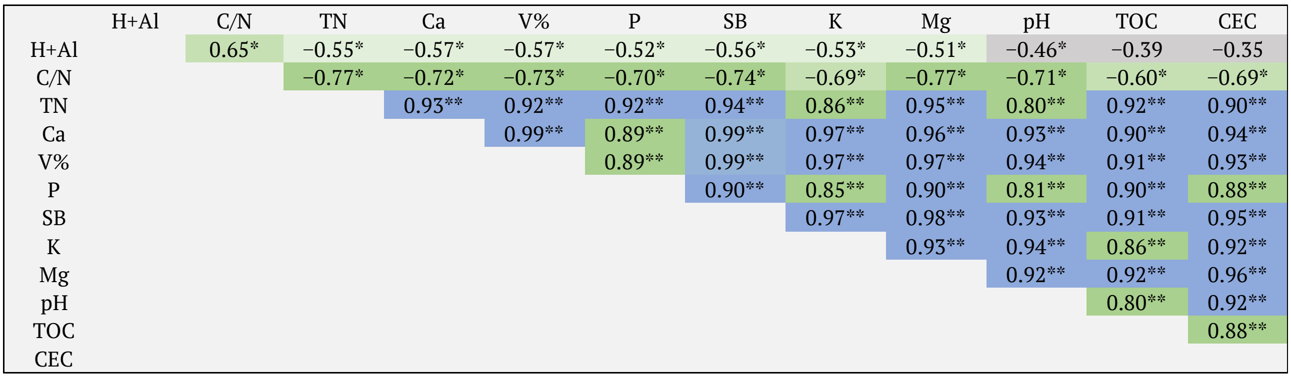


Figure 1. Principal component analysis (PCA) for the chemical conditioning effects of poultry litter (PL) at increasing doses (PL0, PL1, PL2, and PL3) on (A–E) superficial (A) 0.0–0.05 m, (B) 0.05–0.10 m, (C) 0.10–0.20 m, (D) 0.20–0.30 m, and (E–G) subsurface layers (E) 0.30–0.50 m, (F) 0.50–0.75 m, and (G) 0.75–1.00 m in an Oxisol in Portelândia, Goiás State, Midwest Brazil. H+Al, potential acidity; TN, total N; TOC, total organic C; CEC, cation exchange capacity at pH 7.0; SB, sum of base; V%, base saturation.

Pearson's correlation (Figure 2) showed that the chemical variables correlated positively with PL, evidenced by the relationships between TOC and the other variables, that is, TN ($r = 0.92$; $p < 0.01$), Ca exchangeable ($r = 0.90$; $p < 0.01$), Mg exchangeable ($r = 0.92$; $p < 0.01$), V% ($r = 0.91$; $p < 0.01$), P ($r = 0.90$; $p < 0.01$), SB ($r = 0.91$; $p < 0.01$), K available ($r = 0.86$; $p < 0.01$), pH ($r = 0.80$; $p < 0.01$), and CEC ($r = 0.88$; $p < 0.01$). A negative correlation existed between TOC and H+Al ($r = -0.39$; $p > 0.05$) and C/N ($r = -0.60$; $p < 0.05$).



	H+Al	C/N	TN	Ca	V%	P	SB	K	Mg	pH	TOC	CEC
H+Al		0.65*	−0.55*	−0.57*	−0.57*	−0.52*	−0.56*	−0.53*	−0.51*	−0.46*	−0.39	−0.35
C/N			−0.77*	−0.72*	−0.73*	−0.70*	−0.74*	−0.69*	−0.77*	−0.71*	−0.60*	−0.69*
TN				0.93**	0.92**	0.92**	0.94**	0.86**	0.95**	0.80**	0.92**	0.90**
Ca					0.99**	0.89**	0.99**	0.97**	0.96**	0.93**	0.90**	0.94**
V%						0.89**	0.99**	0.97**	0.97**	0.94**	0.91**	0.93**
P							0.90**	0.85**	0.90**	0.81**	0.90**	0.88**
SB								0.97**	0.98**	0.93**	0.91**	0.95**
K									0.93**	0.94**	0.86**	0.92**
Mg										0.92**	0.92**	0.96**
pH											0.80**	0.92**
TOC												0.88**
CEC												

Figure 2. Correlations between chemical variables in an Oxisol in Portelândia, Goiás, Brazil, subjected to different poultry litter doses to build fertility. Potential acidity (H+Al), total N (TN), total organic C (TOC), available P and K, exchangeable Ca and Mg, cation exchange capacity at pH 7.0 (CEC), sum of base (SB), and base saturation (V%). *$p < 0.05$, **$p < 0.01$.

The effects of soil layer × PL dose interactions on soil chemical quality were inferred using mixed ANOVA results and PC scores (Table 2). PL doses correlated positively with pH (r = 0.68), Ca (r = 0.97), Mg (r = 0.97), P (r = 0.82), K (r = 0.92), SB (r = 0.98), $CEC_{pH7.0}$ (r = 0.95), V% (r = 0.94), TOC (r = 0.95), and TN (r = 0.93) contents, indicating a significant effect ($p < 0.01$) of PL doses on soil chemical properties. The same was observed for the soil layer factor, except for the C/N ratio (p = 0.220). Moreover, a dose × layer interaction indicates the synergistic effects of these factors on soil chemical variables, except for H+Al (p = 0.056).

Table 2. Mixed analysis of variance with factorial loadings of variables after poultry litter (PL) application and its effects on the chemical quality of an Oxisol profile in Portelândia, Goiás State, Brazil.

Variables	F1 (70.4%)	F2 (13.1%)	PL	Depth (D)	PL × D
DF			3	6	18
pH	0.68		0.000**	0.000**	0.009**
Ca	0.97		0.000**	0.000**	0.000**
Mg	0.97		0.000**	0.000**	0.000**
P	0.82		0.000**	0.000**	0.000**
K	0.92		0.000**	0.000**	0.000**
H+Al		−0.83	0.000**	0.000**	0.056^{ns}
SB	0.98		0.000**	0.000**	0.000**
$CEC_{pH\ 7.0}$	0.95		0.000**	0.000**	0.000**
V%	0.94		0.000**	0.000**	0.000**
TOC	0.95		0.000**	0.000**	0.000**
TN	0.93		0.000**	0.000**	0.000**
C/N		−0.72	0.000**	0.220^{ns}	0.000**

ns = not significant. *$p < 0.05$, **$p < 0.01$. Factor 1 (F1), factor 2 (F2), potential acidity (H+Al), total N (TN), total organic C (TOC), cation exchange capacity at pH 7.0 (CEC), sum of base (SB), and base saturation (V%).

F1 (70.4%) and F2 (13.1%) summarized the results of Tukey's tests for the factorial scores extracted from the PCA for the chemical variables, PL doses, and stratified layers, explaining 83.5% of the total variation. Although a positive correlation was observed for the soil layer × PL dose interaction down to 0.20 m, it was statistically significant only for the 0–0.05 m layer at all tested doses (Figure 3A and B), indicating that this layer is most impacted by PL use.

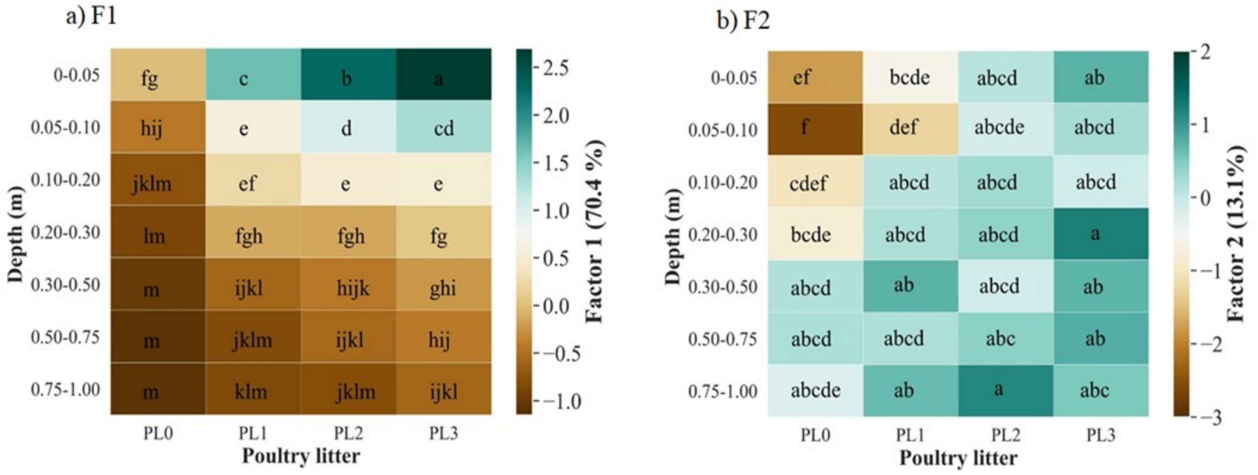


Figure 3. Heat maps of the factorial analysis for the interaction between poultry litter (PL) and soil depth in an Oxisol subjected to different PL doses for fertility improvement in Portelândia, Goiás State, Brazil.

Vertical availability of soil nutrients

The vertical distributions and availabilities of TOC, TN, P, K, Ca, and Mg in the soil were affected by different PL doses and the electrochemical nature of nutrients (Figure 4A–F). All variables were impacted by at least one PL dose and soil layer, except for potential acidity (H+Al), showing no difference ($p > 0.05$) in the 0.10–1.00 m layer. Soil pH (4.9–6.5) differed between PL0 and the other doses but was not significantly different between PL1, PL2, and PL3. The PL3 dose caused a 15 and 13% increase in soil pH in the surface (0–0.10 m) and subsurface (0.2–1.00 m) layers (Figure 4I), increasing CEC by 45 and 36% in the 0–0.20 and 0.20–1.00 m layers, respectively (Figure 4H).

PL doses increased nutrient accumulation in the 0–0.20 m layer (Figure 4A–I). PL3 treatment showed the highest TOC (9.7 g kg^{-1}), TN (1.0 g kg^{-1}), Ca (3.8 $cmol_c$ dm^{-3}), Mg (1.5 $cmol_c$ dm^{-3}), K (81 mg dm^{-3}), and P (24.3 mg dm^{-3}) levels. Increments in TOC, TN, K, Ca, and Mg contents in the 0.20–1.00 m layer were 0.4 g kg^{-1}, 1.6 g kg^{-1}, 54.3 mg dm^{-3}, 1.2 $cmol_c$ dm^{-3}, and 0.4 $cmol_c$ dm^{-3}, respectively, compared with those at PL0. PL1, PL2, and PL3 increased exchangeable Ca, Mg, and K along the soil profile but reduced TOC and TN by 41% below the 0–0.20 m layer (Figure 4A and B). PL application raised available P in the 0–0.5 m layer but drastically reduced its vertical mobility by 90% (Figure 4C) to 1.00 m depth, at all doses.

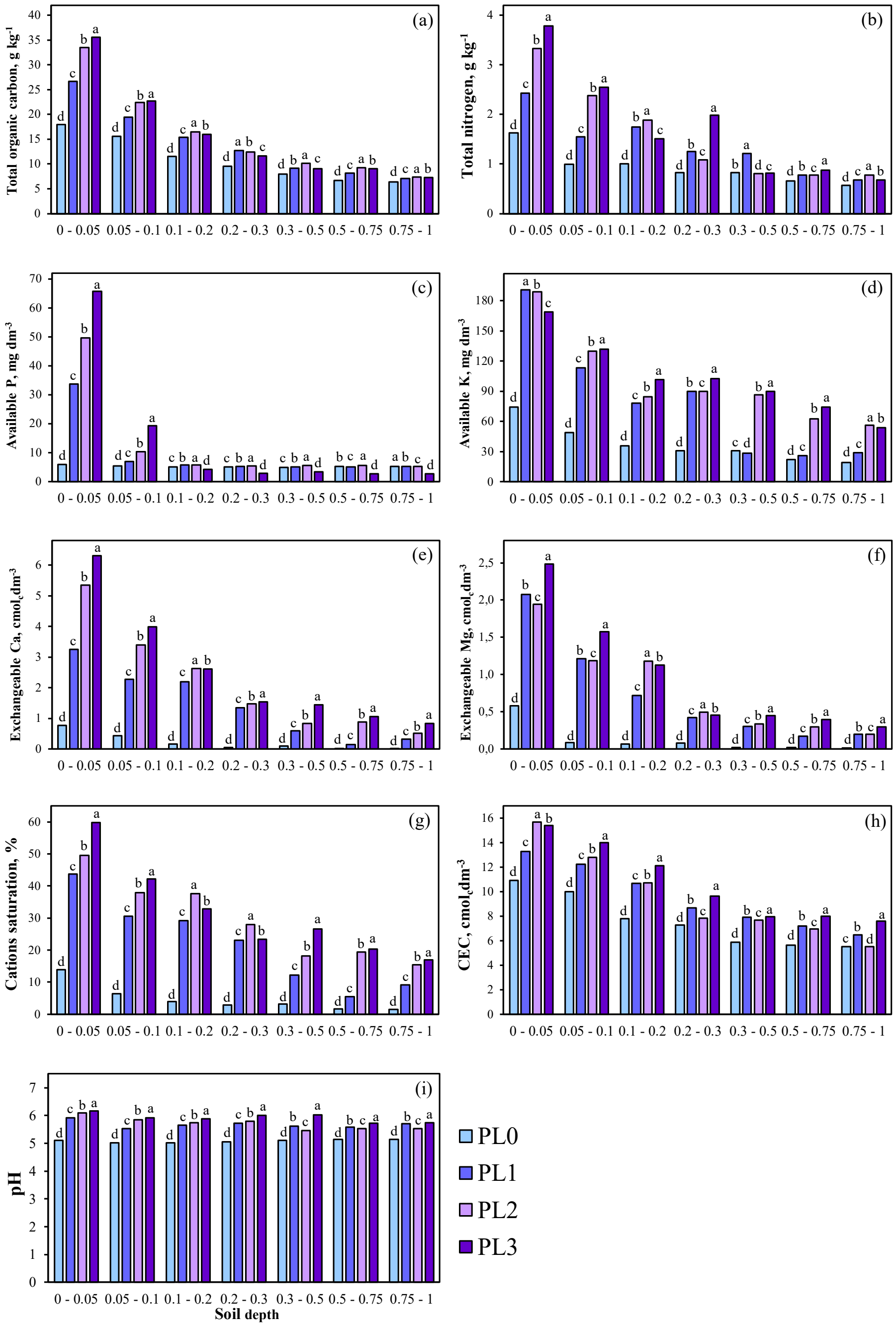


Figure 4. Total organic C (A), total N (B), available P (based on Mehlich-1 extraction) (C), available K (based on Mehlich-1 extraction) (D), exchangeable Ca (E), exchangeable Mg (F), base saturation (G), cation exchange capacity (CEC) (H), and pH (I) in an Oxisol in Portelândia, Goiás State, Brazil, subjected to poultry litter (PL) treatments PL0, PL1, PL2, and PL3 at 0, 26.32, 43.15, and 57.6 Mg ha^{-1}, respectively. *Averages followed by the same letter do not differ significantly based on Tukey's test at $p < 0.05$.

Soil nutrient stocks

The highest PL dose achieved the highest nutrient concentrations in the 0.0–0.20 m layer, in the following order (Table 3): P (50.5 kg ha^{-1}) > TN (12.4 Mg ha^{-1}) > TOC (114.2 Mg ha^{-1}) > Mg (741.2 kg ha^{-1}) > K (880.4 kg ha^{-1}) > Ca

(3,403.4 kg ha^{-1}) (Figure 5A–F). The PL3 treatment increased TOC and TN by 21 and 4 Mg ha^{-1}, respectively, and K, P, Ca, and Mg contents by 597, 32, 3,194, and 664 kg ha^{-1}, respectively, compared with those in the PL0 treatment.

Table 3. Total accumulated contents (kg ha^{-1}) of the analyzed soil chemical constituents during the 7 years of experiment (2008–2014) in an Oxisol in Portelândia, Goiás State, Midwest Brazil.

Treatment	TOC[e]	TN[f]	P	K	Ca	Mg
	––––––––––––––––––––––– kg ha^{-1} –––––––––––––––––––––––					
PL0[a]	0	0	0	0	0	0
PL1[b]	8,107	842	403	548	1,053	237
PL2[c]	13,290	1,381	660	898	1,726	388
PL3[d]	17,741	1,843	881	1,198	2,304	518

[a] no poultry litter (PL); [b, c, d] 26.32, 43.15, and 57.6 Mg ha^{-1}, respectively; [e] total organic C; [f] total N.

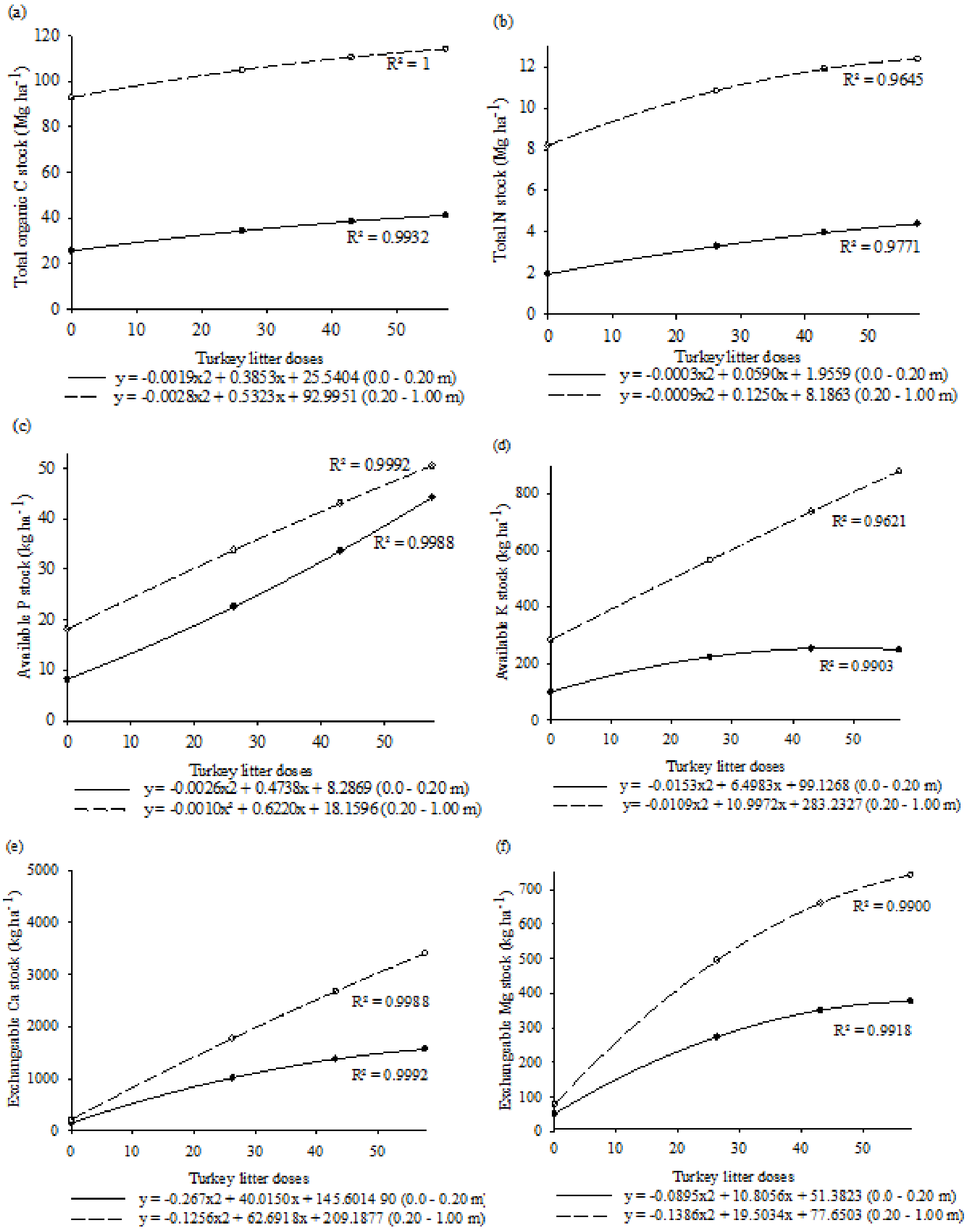


Figure 5. Total organic C (A), total N (B), available P (C), available K (D), exchangeable Ca (E), and exchangeable Mg (F) stocks in an Oxisol in Portelândia, Goiás State, Midwest Brazil.

In the soil profile, nutrient stocks differed depending on the soil layer. The 0.20–1.00 m layer had the highest Ca, Mg, K, and P stocks at 1,839, 364, 632, and 6.2 kg ha^{-1}, respectively (Figure 5A–F). However, TOC and TN stocks increased by 6 and 29%, respectively, only in the 0–0.20 m layer in the PL3 treatment compared with that in the PL0 treatment (Figure 5A and B).

Discussion

In multivariate analyses, the ability of the first two PCs to explain 70% of data variability is considered sufficient and reliable for elucidating complex soil processes (Laroca et al., 2018; Silva et al., 2018; Silva et al., 2022). The negative factorial scores associated with C/N and H+Al, but not with pH, indicate the potential of PL in complexing Al^{3+} by increasing humic substances and forming Al–humus complexes (Maikol et al., 2021). Thus, all PL doses could alleviate soil Al toxicity, a quality defended in other agronomic situations (Tang et al., 2007; Masud et al., 2020).

The naturally low soil fertility was represented by high potential acidity (H+Al) caused by intense debasification, acidification, and increased Al^{3+} content in the soil solution (Adámoli et al., 1987; Alleoni et al., 2005). Potential acidity was reduced on the surface (0–0.5 m) with PL2 and PL3 doses, confirming the role of PL organic compounds in Al complexation (Maikol et al., 2021). In the subsurface layer (0.30–1.00 m), the doses did not affect potential acidity, remaining similar to that in the PL0 treatment, considering the intense chemical transformations of Oxisol. Therefore, mixed ANOVA for F1 better expressed the improved soil chemical quality resulting from PL addition; however, for F2, it highlighted the acidic character and low natural fertility of Cerrado soils (Laroca et al., 2018; Silva et al., 2022; Davi et al., 2022).

Successive PL applications created a new chemical environment in the 0–1.00 m layer, mainly in the 0–0.20 m layer, where the accumulation of this material resulted in high TOC and TN levels. According to Costa et al. (2008), PL has a low C/N ratio. For example, the C/N ratio of the PL used in this study was 9.6, facilitating its rapid degradation and labile C incorporation into the soil. The lack of soil tillage post-planting delayed organic compound mineralization, as organic material deposited on the surface was not incorporated into the soil layers. PL was less exposed to microbial action and accumulated in the 0–0.20 m soil layer, forming an organic crust on the surface. Pinto et al. (2012) highlighted that in clayey soils, the stable aggregates formed on the soil surface protect PL from microbial composting activity, accumulating C and N on the soil surface.

The high pH values observed with PL application, particularly PL3, and their significant positive correlation with TOC and TN ($r = 0.80$; $p < 0.01$) indicate that soil pH considerably impacts C and N cycles. pH and TOC are inversely related, as high organic acid content in PL residues decreases soil pH, particularly in the surface layer (Zhou et al., 2019). However, in this study, the positive correlation between pH and TOC with increasing dose was due to the alkalinity of PL ($pH \approx 8$) (Pinto et al., 2012), owing to high calcium carbonate levels in quicklime added to manure to kill pathogenic bacteria such as *Salmonella* and *Clostridium* spp.

PL accumulation on the soil surface intensifies microbial action (Pinto et al., 2012), which, along with increased pH, may have contributed to increased mineralization and nitrification in the 0–0.20 m layer, as these processes produce high NH^{4+} levels in this layer with the accumulation of organic C, and consequently, TN. However, improved N content does not indicate improved N mobility through the soil profile. TOC stagnation and high pH in the 0–0.20 m layer result in excess negative charge (Gmach et al., 2020), responsible for adsorbing $N\text{–}NH_4^+$ at the soil surface, preventing the vertical movement of N (Mees et al., 2011; Zhang et al., 2020; Rawal et al., 2024; Ferraz-Almeida, 2024).

Considering the clayey texture of the soil (clay > 70%), available P presented medium plant availability levels (4.1–6.0 mg dm^{-1}; Sousa & Lobato, 2004) in the soil profile before PL application (0–1.00 m). Despite low soil P mobility, the classification changed from medium to high in the 0–0.10 m layer, where levels and availability improved, notably under the PL2 and PL3 doses that caused P to shift, maintaining high levels to 0.30 m. This result explains the significant positive correlation between P content and TOC ($r = 0.90$; $p < 0.01$), as organic radicals derived from organic matter block the reactive sites of P-fixing clays, increasing available soil P concentrations (Silva et al., 2018).

In the subsurface layer, with no increase in TOC, the surfaces of P-fixing clays, such as goethite, hematite, and gibbsite, remained exposed. P fixation is a characteristic of soils with a clayey texture and "ferric" character (Tiecher et al., 2017; Poggere et al., 2020), as was the case in this study. Under these conditions, P is intensely immobilized in the 0–0.20 m layer, restricting its distribution through the soil profile. Complexes formed between the internal sphere surface of phosphate anions and Fe- and Al-oxides, organo-mineral complexes, and covalent bonds limit P distribution through the soil profile (Fink et al., 2016; Azevedo et al., 2018).

The PL dose-independent high K content in the 0–0.30 m layer indicates that 26.32 Mg ha^{-1} of PL is sufficient for the highest increments on the soil surface. If the study was limited to soil K dynamics, it could be suggested that the PL3 dose could be dispensed, as PL2 also added high K content down to 1.00-m depth, not differing significantly from the PL3 dose. The rapid percolation and surface runoff of K are concerns in decision-making regarding the appropriate dose of manure to avoid environmental problems (Ceretta et al., 2010; Hentz et al., 2016).

Owing to the monovalent character of K^+, only a small percentage is adsorbed onto soil colloids compared with those of divalent Ca^{2+} and Mg^{2+} (Ernani et al., 2007). They are adsorbed onto soil particles through an external sphere complex and low-energy electrostatic connections (Prietzel et al., 2020). Thus, depth-dependent reduction in TOC, acidic pH, and the positive charges of Oxisol clays facilitated Ca, Mg, and K vertical distribution to the subsurface through electrostatic repulsion.

The dystrophic (V% < 50%; Santos et al., 2018) character of the soil, indicative of low fertility, was attenuated by K, Ca, and Mg supply during organic fertilizer decomposition, an argument supported by the increase in base saturation (V%) from 15% in PL0 to 60% at PL3 in superficial layers possibly because PL increases soil pH, owing to high Ca and Mg contents in limestone (Lima et al., 2024). Increased K^+, Ca^{2+}, and Mg^{2+} availability from PL can displace H^+ and Al^{3+} adsorbed on negatively charged soil colloids (Sigua et al., 2016). Thus, H^+ and Al^{3+} proportions at the cation exchange site decreased, and base saturation increased (Sigua et al., 2014), explaining the close relationship between pH, CEC, and Al^{3+}, K^+, Ca^{2+}, and Mg^{2+} contents found in this investigation.

Despite increasing the V%, only PL3 could convert the dystrophic character into eutrophic (V ⩾ 50%; Santos et al., 2018) by concentrating TOC in the 0–0.5 m layer. Increased pH led to the formation of complex cations, such as Al^{3+} or Al precipitates, because of their low potential acidity. Thus, the adsorption sites, previously occupied by Al, were filled by Ca, Mg, and K (Sadeghian-Khalajabadi & Marín, 2020), increasing base saturation (Vanda-Sebastião et al., 2019).

In the seven evaluated soil layers, PL3 caused the highest TN and TOC accumulation in the 0–0.2 m layer. These results are consistent with those of Sainju et al. (2008), who reported an increase of 42.6 and 4.19 Mg ha^{-1} in TOC and TN stocks, respectively, in the surface soil (0–0.20 m) after 10 years of PL application compared with that in mineral-fertilized plots in the southeast of the United States. According to them, the contribution of PL to nutrient stocks at the soil surface may surpass that of mineral fertilizers, depending on the PL application rate.

A 256% drop was recorded in P stock in the 0.20–1.00 m layer compared with that in the 0–0.20 m layer owing to low P mobility in the 0.20–1.00 m layer and high PL concentration in the topmost layer. This pattern confirmed the interdependence between the vertical distribution of P and organic matter, with the highest TOC stocks detected in the 0–0.20 m layer. Similar results are reported for US soils (Szogi et al., 2012; Chakraborty et al., 2021).

The concentrations of Ca, Mg, and K, the macronutrients with the highest vertical mobility, increased in the deepest soil layer by 157, 135, and 140%, respectively, at the highest PL dose. A comparison of the levels achieved by PL1, PL2, and PL3 application with those in the original soil, PL0, lacking inorganic chemical correction for 7 years, validates that the stocks of these nutrients in the subsurface layers were promoted by PL mineralization, even without deep TOC enrichment. This deep enrichment is characteristic of K, considering that it does not form a part of the structure or composition of organic compounds and is weakly bound (Marschner, 2012). Thus, with cellular membrane rupture in organic tissues, K is released into the soil solution, facilitating its vertical distribution and increased accumulation in the 0.2–1.00 m layer.

The linear model optimally described Ca ($R^2 = 0.99$), K ($R^2 = 0.96$), and P ($R^2 = 0.99$) accumulation patterns in the 0.20–1.00 m layer, with their highest doses generating the highest increases in their stocks. According to the Taxonomy of Brazilian Soils (Santos et al., 2018), Oxisols exhibit chemical and physical homogeneity throughout the profile. These characteristics consolidate the depth-dependent increase in Ca, Mg, and K stocks post-PL application, which would otherwise be uniform throughout the soil profile. These results indicate that PL is an effective organic fertilizer and offers a viable strategy for improving soil fertility, leading to sustainable production.

Conclusion

Long-term PL application improved in-depth soil fertility and led to significant variations in the chemical attributes of soil layers. High PL amounts reduced soil acidity, added K, Ca, and Mg, and increased base saturation to 1.00-m depth. The potential acidity and C/N ratios of Cerrado Oxisols indicate their chemical limitations. The highest PL dose increased K, Ca, and Mg stocks in the deepest soil layers and maintained TOC, TN, and P stocks in superficial layers, demonstrating that PL is a viable alternative for improving soil fertility to 1.00-m depth.

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Data availability

The data generated and analyzed during this study (supplementary material) are available at the disponible in the link https://l1nk.dev/jkOHF

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