To appear in International Journal of Recycling of Organic Waste in Agriculture (IJROWA)
Online ISSN: 2251-7715 Print ISSN: 2195-3228

Received: 25 Oct 2023 Revised: 28 May 2024

Accepted: 27 Jul 2024

DOI: 10.57647/ijrowa-7erk-zg29

ORIGINAL RESEARCH

Evaluation of different phosphate organomineral fertilizers in maize cultivation on soils with contrasting phosphorus contents

Paulo César Teixeira[1]*, João Augusto Dourado Loiola[2], Ricardo Castro Dias[2], Jorge Makhlouta Alonso[1], Everaldo Zonta[2], Rosângela Straliotto[1]

[1] Embrapa Soils, Rio de Janeiro – RJ, Brazil.

[2] Soil Department, Institute of Agronomy, Federal Rural University of Rio de Janeiro, Seropédica – RJ, Brazil

*Corresponding author email: paulo.c.teixeira@embrapa.br

Abstract

Purpose: Organomineral fertilizers (OMFs) are agronomic inputs combining organic material with mineral fertilizers. The study evaluates the biomass production and P accumulation in maize by applying phosphate OMFs from different organic sources.

Method: Two soils with high (Arenosol) and low (Planosol) P content were used. For each soil, an experiment with a factorial arrangement (4 x 4 + 1) was carried out, with the factors being P doses (50, 100, 200, and 300 mg kg^{-1}) and P sources [mono-ammonium phosphate (MAP), OMF from vegetable waste and horse manure compost (VHW), OMF from swine waste compost (SW), and OMF from calcined bone meal

(BM)]. P was not applied in the additional treatment. Three successive cycles of maize were carried out, and shoot dry mass (SDM) and shoot phosphorus accumulation (APS) were measured.

Results: The response of plants to P sources and doses was more evident in the Planosol. The OMFs obtained from different organic sources generally showed similar results for APS and SDM. MAP promoted superior results for the accumulated values of both variables in the accumulated crops, mainly in the Planosol and at the higher tested doses.

Conclusion: Different OMF showed similar results for shoot phosphorus accumulation and shoot dry matter. MAP provided better results than OMF in the highest rates for cumulative SDM and APS in the Planosol. Phosphorus fertilization in built-fertility soils is only necessary to maintain the P extracted by crops.

Keywords: Phosphorus fertilization, Organic matter, *Zea mays*, Agronomic efficiency, Soil fertility.

Introduction

Most Brazilian soils are weathered, acidic, and characterized by high aluminum concentrations and low phosphorus availability (Santos et al., 2018). As a result, the correction and maintenance of soil fertility for most crops in Brazil are typically carried out using highly soluble mineral sources (Herrera et al., 2016). The built fertility soils are an emerging reality in Brazilian agriculture, and their exploitation is linked with intensified and diversified crop production. This shift requires conceptual and operational changes involving more dynamic and complex nutrient transfer processes.

The dynamics of nutrients applied to soils with increased fertility can vary in terms of compartments and flows in the soil-plant relationship, differing from the routes classically considered standard behavior, which, in general, were established from studies developed in areas of recent incorporation cultivated and worked (low fertility) with conventional tillage (Resende et al., 2019). It can be expected that the components that act as “nutrient drains” at first (area opening) are already relatively saturated in soils with constructed fertility, which over the time of cultivation begin to express their characteristic “source of nutrients” in a more pronounced way. Under these conditions, most of the nutrients added via fertilization remain capable of immediate use by crops, reducing the chance of responses to increases in fertilizer doses (Resende et al., 2019). However, corn is more sensitive to fertilization than soybeans and responds economically to fertilization, even in conditions of high soil fertility (Lacerda et al., 2015).

The use of highly soluble fertilizers can lead to nutrient losses and directly impact crops nutrient supply. Phosphorus (P) fixation is a major factor limiting crop optimal growth, its fertilization efficiency is generally low, as it is observed in lower quantities in the soil solution, and a significant portion of the applied P becomes unavailable to plants due to immobilization (Novais and Smith, 1999).

Besides the limitations regarding P fixation, soil texture can affect fertilizing efficiency, as it occurs with sandy-textured soils, which exhibit low fertilizer efficiency. In this regard, organic and organomineral fertilizers (OMFs), particularly those derived from agricultural residues, serve as alternatives to soluble fertilizers (Antille et al., 2014). OMFs result from the physical mixture or combination of mineral and organic nutrient sources (Smith et al., 2020). The organic fraction of OMFs contains fulvic and humic acids that, when accumulated in the soil, can slightly increase specific surface area, cation exchange capacity (CEC), and buffering capacity (Caron et al., 2015).

Due to their characteristics, OMFs can theoretically improve nutrient absorption efficiency. Araújo et al. (2020) observed enhanced nutrient uptake efficiency in millet using OMF (obtained by combining organic compost derived from small ruminant residues with MAP) compared to MAP. Similarly, Sá et al. (2017) compared granulated OMF (obtained by combining poultry litter and MAP) and found no significant difference in residual phosphorus analysis. Notably, the OMF exhibited greater agronomic efficiency for dry matter production in this study. According to Martins et al. (2017), the OMF combining poultry litter with soluble or reactive phosphates showed technical efficiency comparable to triple superphosphate.

Although studies and products involving mixtures of different organic matrices with mineral phosphate sources have been developed and tested, there is a lack of research comparing OMFs manufactured using different organic matrices. The characteristics of organic sources can influence the agronomic effectiveness of fertilizing, which is also influenced by soil characteristics such as initial fertility level and texture.

Thus, this study aimed to evaluate dry matter production, phosphorus accumulation, and the residual effect of P in maize plants fertilized with phosphate OMF from different organic sources and grown in soils with contrasting textures and P concentrations.

Materials and methods

The experiment was conducted within a greenhouse in the municipality of Seropédica – RJ (latitude 22°45'S, longitude 43°41'W) with an average altitude of 30 m. The region's climate is classified as Aw, according to the Köppen classification, characterized by hot and humid summers and dry winters. The annual averages of temperature and precipitation of the last 20 years are 23.7 ℃, 1,275 mm, with a relative humidity of 69.3%, obtained from the meteorological station of PESAGRO, RJ (latitude 22°76'S, longitude 43°68'W), the closest to the experiment site.

The soils used in the experiment pots were collected in the 0-20 cm depth layer in the municipalities of Seropédica – RJ and Luis Eduardo Magalhães – BA. They were classified respectively as Planossolo Háplico and Neossolo Quartzarênico, according to Santos et al. (2018), and as Planosol and Arenosol, according to IUSS Working Group WRB (2015). Soil samples were air-dried, sieved through a 4 mm sieve, and chemically and physically characterized (Table 1), using methodologies described in Teixeira et al. (2017). Soil pH was measured using a combined electrode immersed in a soil/water suspension, in a ratio of 1/2.5. Mehlich 1 extractant was used to determine the levels of P, Na and K. The exchangeable cations (Al^{3+}, Ca^{2+} and Mg^{2+}) were determined using a 1 mol L^{-1} KCl extractant solution. The extraction of soil potential acidity (H+Al) was carried out with buffered calcium acetate at pH 7.0 and volumetric determination with NaOH solution in the presence of phenolphthalein as an indicator. The determination of the sand, silt and clay content was done by mechanical dispersion and stabilization of the soil sample using a shaker in a suitable dispersant solution, followed by separation of the fractions by sieving and sedimentation. The determination of sand was done by sieving and weighing and that of silt and clay by the pipette method using 1 mol L^{-1} sodium hydroxide solution. Planosol and Arenosol presented low and very high phosphorous contents, respectively (Freire et al., 2013).

Table 1. Chemical and physical characteristics of the experimental soils before the application of treatments

Soils	pH H_2O	P	Al	H+Al	Ca	Mg	Na	K	SB	CEC	V	Sand	Silt	Clay
		mg dm^{-3}	-------------- cmol$_c$ dm^{-3} ---------------						--------- % ---------			---------- g kg^{-1}---------		
Planosol	6.5	16	0	1.2	2.8	2.0	0.01	0.03	4.8	6.0	80	780	50	170
Arenosol	6.0	227	0	2.5	2.4	1.4	0.01	0.04	3.8	6.3	60	71	710	220

SB = (Ca + Mg + K + Na); CEC= SB + (H+Al); V= (SB/CEC) x 100

A different experiment was conducted for each soil in a randomized block design with a 4 x 4 + 1 factorial arrangement. The factors were four sources of phosphate fertilizers and four rates of P (50, 100, 200, and 300 mg kg^{-1} of P), totaling 17 treatments, repeated in three blocks, and resulting in 51 experimental units for each soil. The fertilizer sources were: 1) mono-ammonium phosphate mineral fertilizer (MAP); 2) OMF made with compost from vegetable waste and horse manure (VHW); 3) OMF made with swine manure compost (SW); and 4) OMF made with calcined bovine bone meal (BM). The additional treatment consisted of control without phosphorus fertilization for each soil.

The OMFs were made in Embrapa Soils Fertilizer Laboratory, Rio de Janeiro – RJ, Brazil, from the powder mixture of each of the organic sources with MAP, bentonite, boron, copper, and zinc and subjected to a granulation process in a plate pelletizer. The N content in the three organic residues was very low (<3% N) and the amounts used (proportion) of each residue and of MAP to produce the FOMs were the same, therefore, the final N content in the three products was very similar. The MAP used had 19.80% P and 9% N. The OMFs were analyzed according to methodologies described in Brasil (2017) and the results are presented in Table 2.

Table 2. Chemical characterization of organomineral fertilizers (OMF) made from vegetable waste and horse manure compost (VHW), swine manure compost (SW), and calcined bovine bone meal (BM), and MAP

OMF	P	B	Cu	Zn	CEC$^{1/}$
	----------------------------------%------------------------------------				mmol$_c$ kg^{-1}
VHW	12.23	0.55	0.47	1.18	209.91
SW	11.57	0.46	0.29	1.15	287.99
BM	13.45	0.45	0.30	1.10	211.71

^{1} Cation exchange capacity

The experimental units (UE) consisted of plastic pots with 2.8 dm^{-3} of volume and 2 dm^{-3} of soil. The indicator plant was hybrid maize AG1051, with eight seeds being sown per UE. After sowing, 0.1 L UE^{-1} of a nutrient solution was applied in doses equivalent (mg kg^{-1}) to 100 N, 80 K, 80 Mg, 4 Cu, 4 Fe, 8 Mn, 0.15 Mo, and 4 Zn. The sources of these nutrients were respectively NH_4NO_3, KCl, $MgSO_4$, $CuSO_4.5H_2O$, $FeCl_3.6H_2O$, $MnCl_2.4H_2O$, $NaMo_4.2H_2O$ and $ZnSO_4.7H_20$. The applied amount of N was adjusted with the addition of urea in all treatments to have the same amount of N applied in the MAP treatment.

The granular phosphate fertilizers were applied in furrows approximately 5 cm deep; then sowing was performed. Eight days after sowing, the plants were thinned, leaving two plants per pot. At 26 days after sowing, the aboveground biomass was collected, cutting it close to the soil. Initially scheduled for 45 days, this cut was conducted earlier in the first crop cycle due to problems in the greenhouse's electrical network, making it impossible to continue the experiment. Two more successive crop cycles of 45 days each were carried out without applying P but supplying 50% of the rate of the basic nutrient solution applied after sowing. All the other procedures were the same for all crop cycles.

Plant tissue samples collected from the shoots were placed in labeled paper bags and dried in a forced air circulation oven at 65°C until reaching a constant weight. After drying, the samples were weighed to obtain the shoot dry mass (SDM) per pot. Then, the samples were ground in a Wiley-type mill and submitted to digestion to determine the phosphorus levels. The aboveground phosphorus accumulation per pot (APS) was calculated based on the P content and the SDM.

The relative efficiency (RE) of the OMFs in relation to MAP was expressed as percentage, as follows (Equation 1):

$$RE = \frac{OMF\ yield - Control\ yield}{Standard\ yield - Control\ yield} \times 100\% \qquad (1)$$

where OMF yield represents shoot dry matter for the rate of 200 mg kg^{-1}; Control yield represents shoot dry matter without fertilizer application, and Standard yield represents the shoot dry matter for the corresponding MAP treatment.

All the statistical analysis was performed using R (R Core Team, 2023). Before the analysis of variance (ANOVA), the data was subjected to Bartlett's test to assess the homogeneity of variances and the Shapiro-Wilk test to evaluate the normality of the residue distribution. Whenever required, data were transformed and reevaluated to meet the assumptions.

A two-way ANOVA with a control group was conducted using the ExpDes.pt package (Ferreira et al., 2021). When statistically significant at a 10% probability level based on the F test, the means of the qualitative factor (P sources) were compared using Tukey's test at a 10% significance level, and the data for the quantitative factor (P rates) were subjected to regression analysis. The significance of the coefficients was assessed using the ANOVA F test at a 5% significance level. The graphical visualization of the results was elaborated using the ggplot2 package (Wickham, 2016).

Results and discussion

Different results were observed for most variables and in both soils between the control and the treatments with phosphorus fertilization (Table 3). The results did not differ only for APS in the third crop for Planosol, while in Arenosol, there was no difference for SDM in the first crop and APS in the second crop. In all cases, the treatments that received fertilizers showed higher values for SDM and APS than the control, except for SDM in the third cultivation for the Planosol.

Table 3. Mean squares for shoot dry matter (SDM) and shoot phosphorus accumulation (APS) of maize in the first, second, and third crop, as well as the cumulative value across the three crop cycles (Total) in both soils

Sources of variation	DF	SDM				APS			
		1st crop	2nd crop	3rd crop	Total	1st crop	2nd crop	3rd crop	Total
PLANOSOL									
Block	2	7.45^{***}	71.9^{***}	0.269^{ns}	28.3^{***}	1.69^{***}	1392.8^{***}	31.3^{*}	242.3^{ns}
Fertilizer (F)	3	2.27^{**}	59.2^{***}	0.095^{ns}	37.9^{***}	0.03^{ns}	1462.8^{***}	21.0^{ns}	1078.8^{***}
Rates (R)	3	2.80^{**}	223.9^{***}	0.058^{ns}	243.6^{***}	1.81^{***}	13299^{***}	62.8^{***}	21370^{***}
F x R	9	0.44^{ns}	15.1^{**}	0.229^{ns}	14.3^{***}	0.39^{ns}	401.35^{ns}	19.2^{ns}	405.7^{*}
Control x treatments	1	24.1^{***}	121.6^{***}	1.05^{**}	222.5^{***}	82.9^{***}	8943.2^{***}	2.12^{ns}	14678^{***}
Residue		0.71	6.55	0.174	4.49	0.812	225.4	12.4	203.0
CV (%)		14.6	18.8	15.8	9.6	8.3	17.7	16.9	11.4
ARENOSOL									
Block	2	14.4^{***}	232.3^{***}	0.24^{ns}	85.0^{***}	452.7^{***}	3640^{*}	11.6^{ns}	1799^{ns}
Fertilizer (F)	3	0.25^{ns}	10.2^{ns}	0.27^{ns}	9.80^{ns}	4.24^{ns}	1819^{ns}	39.5^{ns}	1535^{ns}
Rates (R)	3	1.87^{ns}	189.3^{***}	1.41^{*}	130.1^{***}	67.5^{ns}	9377^{***}	259.0^{***}	14304^{***}
F x R	9	0.80^{ns}	15.6^{ns}	1.01^{*}	13.6^{ns}	37.6^{ns}	1224^{ns}	30.2^{ns}	1191^{ns}
Control x treatments	1	0.02^{ns}	53.2^{*}	1.71^{*}	72.1^{**}	428.8^{***}	3109^{ns}	165.9^{*}	7983^{**}
Residue		0.84	16.4	0.53	9.15	43.6	1392	42.4	1218
CV (%)		15.5	11.5	25.3	6.9	23.8	19.6	25.4	14.3

The control group comprises an experimental unit without P fertilizer. Based on the F test, the symbols *, **, and *** represent statistical significance at the 10%, 5%, and 1% levels. The symbol "ns" indicates non-significance based on the F test at the 10% level.

For the Planosol, the soil with the lowest P content (most responsive), a significant interaction was observed between the fertilizer types and rates for SDM in the second crop and for SDM and APS accumulated over the three crops (Table 4). When there was no interaction between the factors, both P sources and rates showed significance for SDM in the first and second crops and the cumulative total of crops in Planosol. For the less responsive soil (Arenosol), an interaction between the factors was observed only for SDM in the third crop. For the main effects, there was a significant response for the rates for both variables, except for the first and third crops. This soil was less affected by the P source; no significance was observed between the fertilizers for both variables.

Table 4. Effects of P fertilizer sources inside each fertilizer and P rate for the variables that presented interaction between these factors for maize plants in the first, second, and third crop, as well as the cumulative value across the three crop cycles (Total) in both soils

		P rates (mg kg^{-1})			
Variables	Fertilizers	50	100	200	300
		PLANOSOL			
SDM in the 2nd crop	VHW	6.36 (1.93) b	11.27 (0.87)	11.92 (0.87) b	18.96 (5.16) b
	SW	12.71 (5.90) a	12.31 (3.94)	14.23 (2.75) b	16.96 (3.77) b
	BM	8.52 (0.34) ab	12.69 (1.86)	10.65 (3.95) b	19.40 (0.72) b
	MAP	11.81 (4.76) a	12.72 (4.01)	19.46 (2.24) a	24.58 (1.43) a
Total SDM	VHW	15.14 (1.34) b	20.34 (1.24)	20.97 (0.82) b	27.81 (4.53) b
	SW	20.25 (4.49) a	20.40 (3.45)	23.42 (0.93) b	25.53 (2.53) b
	BM	17.50 (1.38) ab	21.13 (1.50)	19.96 (3.40) b	28.65 (0.42) ab
	MAP	18.85 (3.27) ab	21.07 (2.19)	28.47 (1.67) a	32.17 (0.49) a
Total APS	VHW	70.79 (10.70) b	100.69 (5.41)	132.81 (10.17) b	175.91 (26.16)
	SW	105.03 (25.60) a	104.06 (21.32)	145.09 (7.71) ab	175.10 (15.29)
	BM	76.95 (5.45) b	115.02 (8.34)	128.07 (27.57) b	174.49 (1.10)
	MAP	82.33 (7.27) ab	115.02 (11.94)	171.19 (6.04) a	196.48 (7.76)
		ARENOSOL			
SDM in the 3rd crop	VHW	3.03 (1.27)	2.74 (0.31)	3.04 (0.78)	2.95 (0.49) b
	SW	2.23 (0.58)	2.57 (0.65)	3.36 (0.89)	2.97 (0.30) b
	BM	2.83 (0.28)	2.83 (0.60)	3.23 (0.31)	2.35 (0.32) b
	MAP	2.18 (0.13)	2.51 (0.43)	3.21 (1.49)	4.55 (1.01) a

Which: SDM – shoot dry matter, in g pot^{-1}; APS – shoot phosphorus accumulation, in mg pot^{-1}; MAP – mono ammonium phosphate mineral fertilizer; VHW – organomineral fertilizer (OMF) produced with compost from vegetable waste and horse manure; SW – OMF produced with swine manure compost; BM – OMF produced with calcined bovine bone meal. Means followed by the same letter on the same column do not differ by the Tukey test with 10% of the significance level. Values in parentheses represent the mean standard deviation.

The responses to treatments, particularly concerning the fertilizer type, were more pronounced in Planosol, which exhibited lower levels of available phosphorus. Regarding dry matter production, soils with lower levels of available phosphorus tend to display greater responsiveness to phosphorus fertilization (Ros et al., 2020). This result highlights the importance of carefully selecting soils that exhibit responsiveness to the specific fertilizer or input tested in experimental studies. In the present study, the results obtained from the Planosol demonstrated that selecting an appropriate soil could ensure experimental findings that better represented the prevailing conditions where phosphate fertilizers are required, which is crucial to optimize their application.

The lack of responses in the first crop cycle in the Arenosol is another result that supports the discussion above. The phosphorus available to plants in the Arenosol was very good/very high (Ribeiro et al., 1999; Freire et al., 2013). There was no need for P application, so the control treatment showed high SDM production, and the possible effects of the treatments were nullified. Plant response in subsequent crops can be attributed to the residual effect of P applied in the experiment treatments (Gatiboni et al., 2021). During the first crop, some of the P was extracted by plants, while some of it became unavailable in the soil. In subsequent crops, some treatments were more efficient in keeping the applied P available to the plants.

Interaction between fertilizer sources and rates was significant in the Arenosol, only for SDM in the third crop cycle. Differences among fertilizers were only observed for the 300 mg kg^{-1} of P rate, in which the MAP obtained the highest average (Table 4). In the Planosol, the interaction was significant for more variables (Table 4). Focusing on the cumulative results after three crops, it is observed that for APS at the lowest rate, SW presented higher values than VHW and BM, while MAP was similar to all fertilizers. For the dose of 200 mg kg^{-1}, also for APS, MAP showed values higher than VHW and BM, while SW was similar to the other treatments. No differences were observed among P sources for 100 and 300 mg kg^{-1} doses. For the accumulated SDM, at the lowest rate, the SW was superior to VHW, while MAP and BM did not differ from the other fertilizers. With the increase in rates, there was a tendency for MAP to present the best results since at 200 mg kg^{-1}, it was superior to other treatments, and at a dose of 300 mg kg^{-1}, it was superior to VHW and SW and similar to BM. For the 100 mg kg^{-1} rate, no difference was observed in SDM among the P sources.

Although there were variations in the results among different rates and crop cycles for the P sources, no clear pattern was identified in either of the two soils. Overall, the results were generally similar for the different sources, with a tendency for MAP to exhibit the best results for total SDM and APS at the higher rates of 200 and 300 mg kg^{-1}. Such results corroborate those obtained by Grohskopf et al. (2019), while studying an OMF compared to a mineral source of phosphorus (rates of 20, 40, 60, and 80 kg ha^{-1} of P), found no significant difference between the sources regarding the accumulation of phosphorus in the plants of maize after three successive crop cycles. Similar results were also verified by Cabral et al. (2020), who obtained equivalent production for maize among different P sources. Considering that MAP is a consolidated and efficient source of phosphorus for tropical agriculture, it is possible to state that the studied OMFs presented great agronomic potential, considering that their results in some situations were equal to those of MAP.

When no interaction between factors was observed, the isolated effect of fertilizer sources was significant only in Planosol for SDM in the first crop and APS in the second (Table 5). For SDM in the first cycle, BM was superior to MAP, while the other two treatments did not show significant differences from either. MAP was superior to VHW and BM for APS in the second cycle, while SW was similar to all treatments.

Table 5. Effects of P fertilizer sources for the variables that presented no interaction between factors for maize plants in the first and second crop cycles for the Planosol.

Variables/sources	VHW	SW	BM	MAP
SDM in the 1st crop	6.25 (0.74) ab	5.69 (1.20) ab	6.41 (0.99) a	5.51 (1.22) b
APS in the 2nd crop	77.18 (42.77) b	89.94 (34.92) ab	82.63 (38.50) b	102.70 (47.58) a

Which: SDM – shoot dry matter, in g pot^{-1}; APS – shoot phosphorus accumulation, in mg pot^{-1}; MAP – mono ammonium phosphate mineral fertilizer; VHW – organomineral fertilizer (OMF) produced with compost from vegetable waste and horse manure; SW – OMF produced with swine manure compost; BM – OMF produced with calcined bovine bone meal. Means followed by the same letter on the same column do not differ by the Tukey test with 10% of the significance level. Values in parentheses represent the mean standard deviation.

The results show little difference between the sources of phosphorus for the variables SDM and APS, mainly among the three OMFs tested. Thus, considering the results of the present experiment, the different organic matrices used to produce the OMFs could be considered equivalent. In contrast, Bouhia et al. (2022) discussed in their literature review that the organic matrix used to manufacture OMF could interfere with the physical-chemical relationships of the fertilizer with the soil, which was not observed in this study. Due to the scarcity of work on this topic and the diversity of organic residues that can be studied, it is recommended to conduct new studies testing OMFs with different organic matrices for cultures and soils different from those evaluated in the present work and under field conditions.

Only for SDM in the third crop, there was no difference among the rates of P in the Planosol. When the interaction between the factors of fertilizer sources and rates was found, the response for the rates within the sources of phosphorus (for the variables SDM in the second crop cycle and SDM and APS in total) was generally linear. Hence, the higher the rate, the greater the mass or accumulation of phosphorus in the plants (Figs. 1 and 2).

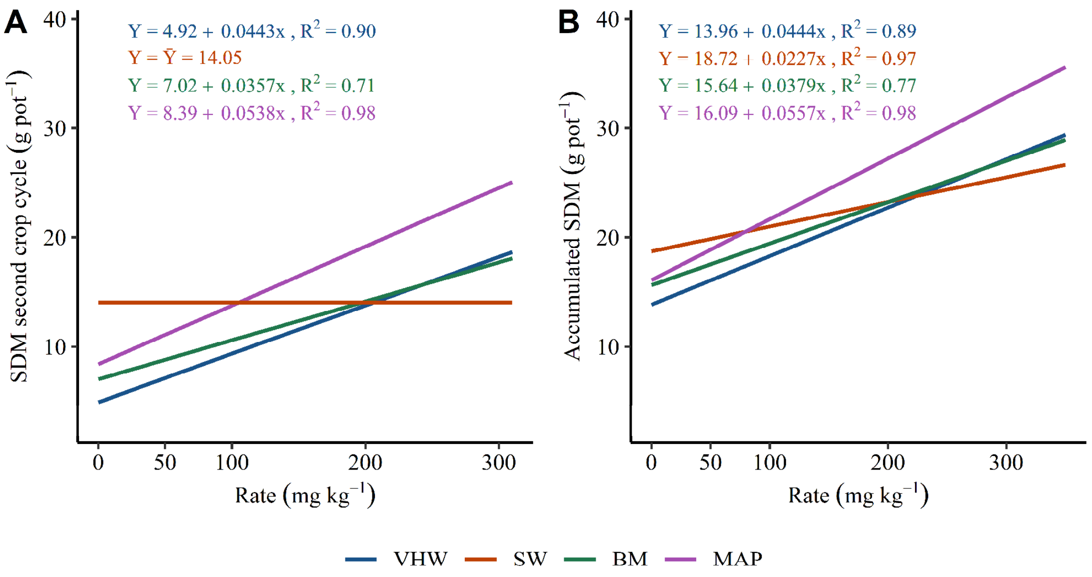

Figure 1. Shoot dry matter (SDM) of maize plants in the second crop cycle (A) and the cumulative SDM in the three crop cycles (B) due to the application of growing rates of MAP and phosphate organomineral fertilizers produced with compost from vegetable waste and horse manure (VHW), swine manure compost (SW), and calcined bovine bone meal (BM) in the Planosol.

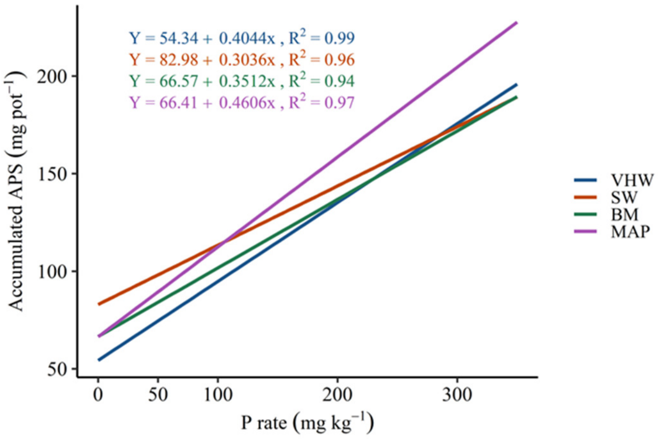

Figure 2. Shoot phosphorus accumulation (APS) of maize plants in the cumulative value across the three crop cycles due to the application of growing rates of MAP and phosphate organomineral fertilizers produced with compost from vegetable waste and horse manure (VHW), swine manure compost (SW), and calcined bovine bone meal (BM) in Planosol samples.

The adjusted models for the fertilizer rates, in general, could explain a significant portion of the data variation, with coefficients of determination (R^2) greater than 0.90, except for the models adjusted for BM for SDM in the second crop and for the accumulated values ($R^2 > 0.70$). By examining the regression coefficient value (β), represented by the slope of the lines, it becomes apparent that the response to increasing rates was more pronounced for the MAP fertilizer in both variables (SDM and APS).

For the variables without interaction between fertilizer sources and rates, the response of maize plants in the Planosol was quadratic for SDM and APS in the first crop cycle (Fig. 3 and 4A). In the first cycle, the SDM response curve reached a maximum close to the rate of 200 mg kg^{-1} (Fig. 3). For APS, the curve reached its maximum between doses of 200 and 300 mg kg^{-1} (Fig. 4A). The quadratic response to rates in the first crop reveals that fertilizers were applied beyond necessary, resulting in decreased production at the highest rate. This situation leads to double damage, involving unnecessary expenditure on fertilizers and a decline in plant production (Raij, 2011).

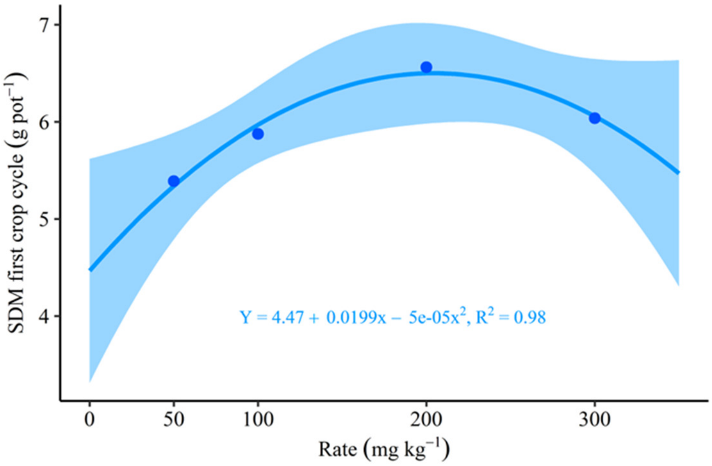

Figure 3. Shoot dry matter (SDM) of maize plants in response to growing rates of phosphate fertilizers during the first crop cycle in the Planosol. The points represent the mean of the samples in each treatment, and the shaded area around the line represents the 95% confidence interval for the model prediction.

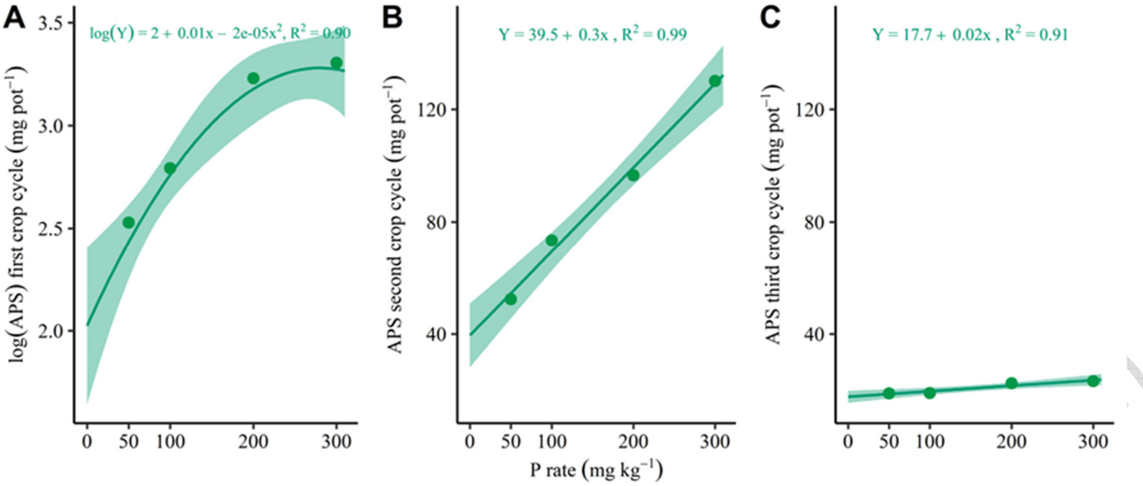

Figure 4. Shoot phosphorus accumulation (APS) of maize plants in response to growing rates of phosphate fertilizers during the first, second, and third crop cycles in the Planosol. The points represent the mean of the samples in each treatment, and the shaded area around the line represents the 95% confidence interval for the model prediction.

The linear response to increasing fertilizer rates for SDM and APS in subsequent crop cycles, as observed for APS in the second and third cultivations (Fig. 4B and 4C), suggests that the plants may have exhibited a greater response at higher doses of applied fertilizers. However, this result does not indicate that higher doses would be recommended in those cases. Instead, it indicates that fertilizing should be applied with each new crop since the residual amount of phosphorus was insufficient to reach maximum production.

No response was observed for the fertilizer rates for SDM and APS in the first crop cycle in the Arenosol. Also, in this soil, the interaction between the fertilizer rates and sources occurred only for SDM in the third cultivation, with a response observed only for the MAP rates (Fig. 5).

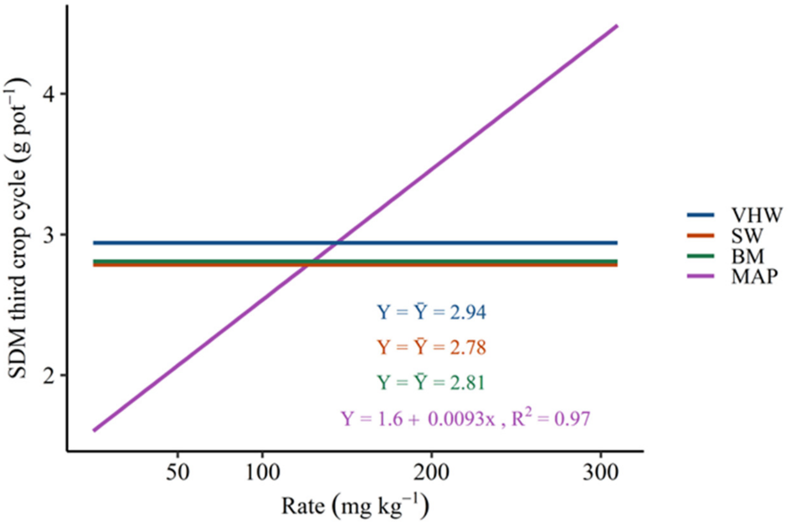

Figure 5. Shoot dry matter (SDM) of maize plants in the third crop cycle due to the application of growing rates of MAP and phosphate organomineral fertilizers produced with compost from vegetable waste and horse manure (VHW), swine manure compost (SW), and calcined bovine bone meal (BM) in the Arenosol.

The maize plants responded to fertilizer rates in the Arenosols with linear models for all variables in which no interaction was observed between rates and sources (Fig. 6 and 7). As discussed for the Planosol results, these results do not necessarily indicate that higher fertilizer rates should have been applied, but rather that the fertilizer should be applied after each crop cycle.

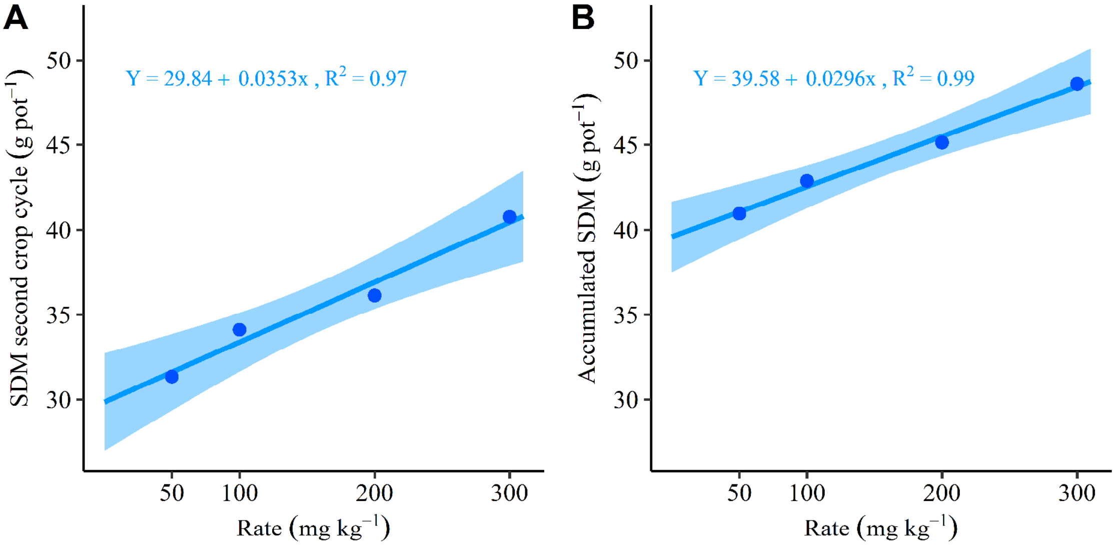

Figure 6. Shoot dry matter (SDM) of maize plants in response to growing rates of phosphate fertilizers during the second crop cycle (A) and the cumulative value across the three crop cycles (B) in the Arenosol. The points represent the mean of the samples in each treatment, and the shaded area around the line represents the 95% confidence interval for the model prediction.

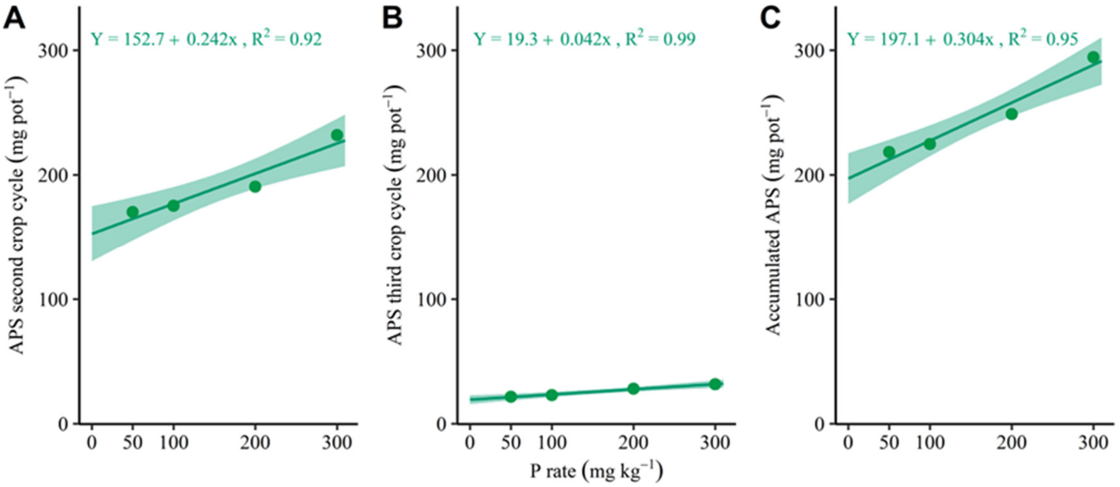

Figure 7. Shoot phosphorus accumulation (APS) of maize plants in response to growing rates of phosphate fertilizers during the first (A), the second crop cycle (B), and the cumulative value across the three crop cycles (C) in the Arenosol. The points represent the mean of the samples in each treatment, and the shaded area around the line represents the 95% confidence interval for the model prediction.

The maintenance of phosphorus fertilization is necessary to increase productivity in successive systems, even in soils with adequate initial P availability (Martins et al., 2017). These authors also verified that, under soil conditions with sufficient fertility, the technical performance of the OMF was comparable to that of their standard P source, the triple superphosphate. Built-fertility soils have high fertility attributes, including phosphorus contents and exchangeable cations (Grohskopf et al., 2019). In this way, fertilizing management in built-fertility soils ensures its maintenance, replacing the significant amounts of nutrients crops extract in each cycle (Resende et al., 2016).

Regarding the relative agronomic efficiency of the OMFs, it was observed that these fertilizers were less efficient than the MAP (Fig. 8). Both for SDM and APS, efficiency was higher in SW and lower in BM. The greater efficiency in SW can possibly be explained by its higher CEC. On the other hand, BM had lower levels of B, Cu, and Zn than the other organic matrices used to produce the OMFs. Among other studies, Sá et al. (2017) reported that an OMF derived from poultry litter showed higher agronomic efficiency than MAP for SDM production in greenhouse maize cultivation. In a field experiment studying grain cultivation, Mumbach et al. (2019) observed that organic (poultry litter), mineral (MAP), and organomineral (poultry litter and MAP) fertilizers exhibited comparable agronomic efficiency in terms of plant growth and grain production. According to Benites et al. (2022), it was found that after five crops of soybeans, the yield was higher when using OMF compared to MAP. This suggests that the benefits of these fertilizers may become evident in the long term. The authors also stated that OMF can be an efficient farm input and is successfully used as an alternative for residue management and nutrient recycling. The diverging results between studies with OMFs suggest that further research should be done on applying these fertilizers to various crops, soil types, climates, and other relevant factors.

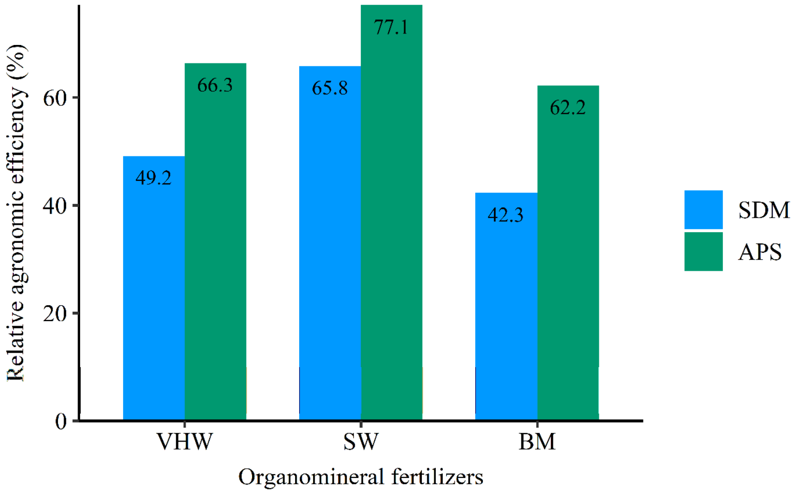

Figure 8. Relative agronomic efficiency for shoot dry matter (SDM) and shoot phosphorus accumulation (APS) of organomineral fertilizers produced with compost from vegetable waste and horse manure (VHW), swine manure compost (SW), and calcined bovine bone meal (BM) compared to MAP in the 200 mg kg^{-1} rate for the cumulative values across the three crop cycles in the Planosol.

Conclusion

The different organic matrices used to produce organomineral fertilizers showed similar results in general for shoot phosphorus accumulation and shoot dry matter. Using mono-ammonium phosphate provided better results than organomineral fertilizers in the highest rates for SDM and APS in the cumulative values over the three crop cycles in the Planosol. On the other hand, organomineral fertilizers provide an alternative to reusing residues, enriching the soil with organic matter, and can result in long-term benefits. Phosphorus fertilization in built-fertility soils is only necessary to maintain the phosphorus extracted by crops in each harvest.

Acknowledgment: The authors thank FNDCT/FINEP (Cooperation Agreement # 01.22.0080.00, Ref. 1219/21) and PIBIC/CNPq (Programa Institucional de Bolsas de Iniciação Científica / Conselho Nacional de Desenvolvimento Científico e Tecnológico), for financial support and the research grant provided for the second author, respectively.

Author contribution: Paulo César Teixeira: Conceptualization, Methodology, Validation, Investigation, Resources, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition. João Augusto Dourado Loiola: Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Funding acquisition. Ricardo Castro Dias: Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing. Jorge Maklouta Alonso: Formal analysis, Data Curation, Visualization, Writing - Original Draft, Writing - Review & Editing. Everaldo Zonta: Methodology, Validation, Investigation, Resources, Writing - Review & Editing. Rosângela Straliotto: Methodology, Validation, Investigation, Resources, Writing - Review & Editing.

References

Antille DL, Sakrabani R, Godwin RJ (2014) Effects of biosolids-derived organomineral fertilizers, urea, and biosolids granules on crop and soil established with ryegrass (*Lolium perene* L.). Commun Soil Sci Plant Anal 45(12):1605-1612. https://doi.org/10.1080/00103624.2013.875205

Araújo MD, Souza HAD., Benites VM, Pompeu RC, Natale W, Leite LF (2020) Adubação fosfatada organomineral em milheto em solo arenoso. Rev Bras Eng Agric Ambient 24(10):694–699. https://doi.org/10.1590/1807-1929/agriambi.v24n10p694-699

Benites VM, Dal Molin SJ, Menezes JFS, Guimarães GS, Machado PLOA (2022). Organomineral fertilizer is an agronomic efficient alternative for poultry litter phosphorus recycling in an acidic ferralsol. Front. Agron. 4: 785753. https://doi.org/10.3389/fagro.2022.785753

Bouhia Y, Hafidi M, Ouhdouch Y, Boukhari M, Mphatso C, Zeroual Y, Lyamlouli K (2022) Conversion of waste into organo-mineral fertilizers: current technological trends and prospects. Rev Environ Sci Biotechnol 21:425-446. https://doi.org/10.1007/s11157-022-09619-y

Brasil (2017) Manual de métodos analíticos oficiais para fertilizantes e corretivos. Ministério da Agricultura, Pecuária e Abastecimento, Secretaria de Defesa Agropecuária, Brasília.

Cabral FL, Bastos AVS, Teixeira MB, Silva EC, Soares FAL, Santos LNS (2020) Níveis de fertilização de fósforo mineral e organomineral na cultura do milho. Braz J Dev 6(6):36414-36426. https://doi.org/10.34117/bjdv6n6-255

Caron VC, Graças JP, Castro PRC (2015) Condicionadores do solo: ácidos húmicos e fúlvicos. Série Produtor Rural nº 58, Divisão de Biblioteca, ESALQ/USP, Piracicaba.

IUSS Working Group WRB (2015) World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Ferreira EB, Cavalcanti PP, Nogueira DA (2021) ExpDes.pt: Pacote Experimental Designs (Português). R package version 1.2.2.

Freire LR, Balieiro FC, Zonta E, Anjos LHC, Pereira MG, Lima E, Guerra JGM, Ferreira MBC, Leal MAA, Campos DVB, Polidoro JC (2013) Manual de calagem e adubação do Estado do Rio de Janeiro. Embrapa, Brasília; Editora Universidade Federal Rural do Rio de Janeiro, Seropédica.

Gatiboni LC, Schmitt DE, Tiecher T, Veloso MG, Santos DR, Kaminski J, Brunetto G. (2021) Plant uptake of legacy phosphorus from soils without P fertilization. Nutr Cycl Agroecosyst 119, 139–151. https://doi.org/10.1007/s10705-020-10109-2

Grohskopf MA, Corrêa JC, Fernandes DM, Benites VM, Teixeira PC, Cruz CV (2019) Phosphate fertilization with organomineral fertilizer on corn crops on a Rhodic Khandiudox with a high phosphorus content. Pesq Agropec Bras 54:e00434. https://doi.org/10.1590/S1678-3921.pab2019.v54.00434

Herrera WFB, Rodrigues M, Teles APB, Barth G, Pavinato PS (2016) Crop yields and soil phosphorus lability under soluble and humic-complexed phosphate fertilizers. Agron J 108(4):1692-1702. https://doi.org/10.2134/agronj2015.0561

Lacerda, JJJ, Resende AV, Furtini Neto AE, Hickmann C, Conceição OP (2015) Fertilization, grain yield and profitability of the rotation between soybean and corn in soil with improved fertility. Pesq Agropec Bras 50(9):769-778. https://doi.org/10.1590/S0100-204X2015000900005

Martins DC, Resende AV, Galvão JCC, Simão EP, Ferreira JPC, Almeida GO (2017) Organomineral phosphorus fertilization in the production of corn, soybean and bean cultivated in succession. Am J Plant Sci 8:2407-2421. https://doi.org/10.4236/ajps.2017.810163

Mumbach GL, Gatiboni LC, Bona FD, Schmitt DE, Côrrea JC, Gabriel CA, Dall'Orsoletta DJ, Iochims DA (2020) Agronomic efficiency of organomineral fertilizer in sequential grain crops in southern Brazil. Agron J 112: 3037– 3049. https://doi.org/10.1002/agj2.20238

Novais RF, Smith TJ (1999) Fósforo em solo e planta em condições tropicais. Editora da Universidade Federal de Viçosa (UFV), Viçosa.

Raij BV (2011) Fertilidade do solo e manejo de nutrientes. International Plant Nutrition Institute (IPNI), Piracicaba.

Resende AV, Borghi E, Gontijo Neto MM, Fontoura SMV, Borin ALDC, Oliveira Junior A, Carvalho MCS., Kappes C (2019) Balanço de nutrientes e manejo da adubação em solos de fertilidade construída. In: Severiano EC, Morais MF, Paula AM. Tópicos em ciência do solo. Vol. 10. Sociedade Brasileira de Ciência do Solo, Viçosa, MG, pp.342-398.

Resende AV, Fontoura SMV, Borghi E, Santos FC, Kappes C, Moreira SG, Oliveira Junior A, Borin ALDC (2016) Solos de fertilidade construída: características, funcionamento e manejo. Inform Agron (156):1-19.

Resende AV, Furtini Neto AE (2007) Aspectos relacionados ao manejo da adubação fosfatada em solos do Cerrado. Série Documentos, Embrapa Cerrados, Planaltina.

R CORE TEAM (2023) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ribeiro AC, Guimarães PTG, Alvarez V VH (1999) Recomendações para o uso de corretivos e fertilizantes em Minas Gerais. Comissão de Fertilidade do Solo do Estado de Minas Gerais (CFSEMG), Viçosa.

Ros MBH, Koopmans GF, van Groenigen KJ, Abalos D, Oenema O, Vos HMJ, van Groenigen JW (2020) Towards optimal use of phosphorus fertilizer. Sci Rep 10:17804. https://doi.org/10.1038/s41598-020-74736-z

Sá JM, Jantalia CP, Teixeira PC, Polidoro JC, Benites VM, Araújo AP (2017) Agronomic and P recovery efficiency of organomineral phosphate fertilizer from poultry litter in Sandy and clayey soils. Pesq Agropec Bras 52:786-793. https://doi.org/10.1590/S0100-204X2017000900011

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Cunha TJF (2018) Brazilian soil classification system. 5th ed. rev. and exp. Embrapa, Brasília.

Smith WB, Wilson M, Pagliari P (2020) Organomineral fertilizers and their application to field crops. In Waldrip HM, Pagliari PH, He Z (eds.) Animal Manure: Production, Characteristics, Environmental Concerns, and Management. American Society of Agronomy, Madison WI. p. 229-243. https://doi.org/10.2134/asaspecpub67.c18

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG (2017) Manual de métodos de análise de solo. 3ª ed. rev. e ampl. Embrapa, Brasília.

Wickham H (2016) ggplot2: Elegant graphics for data analysis. Springer, New York, NY. https://doi.org/10.1007/978-3-319-24277-4