RGe
ISSN: 2177-3246

RESIDUAL FERTILITY OF OXISOL FERTILIZED WITH ORGANIC RESIDUES AND ALTERNATIVE PHOSPHATE IN MANAUS, BRAZIL

FERTILIDADE RESIDUAL DE LATOSSOLO FERTILIZADO COM RESÍDUOS ORGÂNICOS E FOSFATO ALTERNATIVO EM MANAUS, AMAZONAS, BRASIL

FERTILIDAD RESIDUAL DE OXISOL FERTILIZADO CON RESIDUOS ORGÁNICOS Y FOSFATO ALTERNATIVO EN MANAUS, AMAZONAS, BRASIL

10.56238/revgeov17n5-060

Ana Carla de Souza Vieira[1], Almir Ignácio Cardoso[2], Francimara Souza da Costa[3], Luiz Carlos da Silva[4]

ABSTRACT

Organic residues restore soil fertility through the use of animal manure. Partially acidulated alternative phosphates contain small amounts of soluble phosphorus in addition to the non-acidulated portion. In this context, it is important to understand the effects of homogeneous fertilization with organic residues and the application of increasing doses of alternative phosphates on phosphorus availability and the recovery of nutrient-poor soils. Therefore, monitoring the fertility of these soils is necessary to determine the effects of this management on their medium-term recovery. Our objective was to evaluate the residual fertility of an Oxisol fertilized with organic residues and alternative phosphate one year after the cultivation of Indian spinach (Basella alba L. cv. Tatá, INPA) in Manaus, Amazonas, Brazil. In December 2018, homogeneous doses of different animal byproducts were applied to supply 505.68 kg ha^{-1} of total nitrogen. Subsequently, doses of 0, 25, 50, 100, 200, 400, and 800 kg ha^{-1} of total phosphorus, derived from partially acidulated phosphorite, were applied to the soil cultivated with Indian spinach for 60 days. In December 2019, soil samples were collected to evaluate their fertility attributes. The overall fertility pattern of the Latosol improved due to increased availability of phosphorus, sulfur, and calcium when doses of 400 and 800 kg ha^{-1} of P were applied. However, the availability of manganese and zinc remained low. High iron availability can cause phytotoxicity, and therefore, the continuous use of animal manure is recommended to control its availability and contribute to the supply of nutrients to crops.

Keywords: Waste. Phosphate. Sustainability. Environment. Agroecology.

---

[1] Undergraduate student in Animal Science. Universidade Federal do Amazonas (UFAM).
E-mail: carlasouza1401@gmail.com Orcid: https://orcid.org/0009-0000-6966-8584
[2] Agricultural Engineer. Associação Acauã de Homens e Mulheres Indígenas e Não-Indígenas.
E-mail: almir.cardoso@gmail.com Orcid: https://orcid.org/my-orcid?orcid=0009-0003-7890-1781
[3] Dr. in Socioenvironmental Sciences. (Universidade Federal do Pará (UFPA). Universidade Federal do Amazonas (UFAM). E-mail: francimara@ufam.edu.br Orcid: https://orcid.org/0000-0003-4352-0826
[4] Dr. in Environmental Physics: Biosphere-Atmosphere Interaction. Universidade Federal de Mato Grosso (UFMT). Universidade Federal do Amazonas (UFAM).E-mail: luizcs11111@gmail.com
Orcid: https://orcid.org/0000-0002-4604-9358

RESUMO

Resíduos orgânicos recuperam a fertilidade do solo por meio do uso de esterco animal. Fosfatos alternativos parcialmente acidulados contêm pequenas quantidades de fósforo solúvel, além da parte não acidulada. Nesse contexto, é importante compreender os efeitos da fertilização homogênea com resíduos orgânicos e da aplicação de doses crescentes de fosfatos alternativos na disponibilidade de fósforo e na recuperação de solos pobres em nutrientes. Portanto, o monitoramento da fertilidade desses solos é necessário para determinar os efeitos desse manejo em sua recuperação a médio prazo. Nosso objetivo foi avaliar a fertilidade residual de um Latossolo fertilizado com resíduos orgânicos e fosfato alternativo um ano após o cultivo de espinafre-da-índia (Basella alba L. cv. Tatá, INPA) em Manaus, Amazonas, Brasil. Em dezembro de 2018, doses homogêneas de diferentes subprodutos animais foram aplicadas para fornecer 505,68 kg ha^{-1} de nitrogênio total. Posteriormente, doses de 0, 25, 50, 100, 200, 400 e 800 kg ha^{-1} de fósforo total, derivado de fosforita parcialmente acidulada, foram aplicadas ao solo cultivado com espinafre-da-índia por 60 dias. Em dezembro de 2019, amostras de solo foram coletadas para avaliar seus atributos de fertilidade. O padrão geral de fertilidade do Latossolo melhorou devido ao aumento da disponibilidade de fósforo, enxofre e cálcio quando doses de 400 e 800 kg ha-1 de P foram aplicadas. No entanto, a disponibilidade de manganês e zinco permaneceu baixa. A alta disponibilidade de ferro pode causar fitotoxicidade e, portanto, recomenda-se o uso contínuo de esterco animal para controlar sua disponibilidade e contribuir para o fornecimento de nutrientes às culturas.

Palavras-chave: Resíduos. Fosfato. Sustentabilidade. Meio Ambiente. Agroecologia.

RESUMEN

Los residuos orgánicos recuperan la fertilidad del suelo mediante el uso de estiércol animal. Los fosfatos alternativos parcialmente acidulados contienen pequeñas cantidades de fósforo soluble, además de la fracción no acidulada. En este contexto, es importante comprender los efectos de la fertilización homogénea con residuos orgánicos y de la aplicación de dosis crecientes de fosfatos alternativos sobre la disponibilidad de fósforo y la recuperación de suelos pobres en nutrientes. Por lo tanto, el monitoreo de la fertilidad de estos suelos es necesario para determinar los efectos de este manejo en su recuperación a mediano plazo. Nuestro objetivo fue evaluar la fertilidad residual de un Oxisol fertilizado con residuos orgánicos y fosfato alternativo un año después del cultivo de espinaca de la India (Basella alba L. cv. Tatá, INPA) en Manaus, Amazonas, Brasil. En diciembre de 2018, se aplicaron dosis homogéneas de diferentes subproductos animales para suministrar 505,68 kg ha^{-1} de nitrógeno total. Posteriormente, se aplicaron al suelo dosis de 0, 25, 50, 100, 200, 400 y 800 kg ha^{-1} de fósforo total, derivado de fosforita parcialmente acidulada, en un cultivo de espinaca de la India durante 60 días. En diciembre de 2019, se recolectaron muestras de suelo para evaluar sus atributos de fertilidad. El patrón general de fertilidad del Oxisol mejoró debido al aumento de la disponibilidad de fósforo, azufre y calcio cuando se aplicaron dosis de 400 y 800 kg ha^{-1} de P. Sin embargo, la disponibilidad de manganeso y zinc permaneció baja. La alta disponibilidad de hierro puede causar fitotoxicidad y, por lo tanto, se recomienda el uso continuo de estiércol animal para controlar su disponibilidad y contribuir al suministro de nutrientes a los cultivos.

Palabras clave: Residuos. Fosfato. Sostenibilidad. Medio ambiente. Agroecología.

1 INTRODUCTION

Applying organic residues to soil has the potential to recover its fertility attributes, making it suitable for crop growth, development and production (Giácomo et al., 2019). This potential can be attributed to the regular fertilization with organic materials in cultivated soils. The aggregation of decomposition products generates beneficial effects on the soil physical properties (Agne; Klein, 2014), resulting in the reduction of erosion processes, increasing cation exchange capacity (CEC), and the retention and supply of nutrients to plants (Ronquin, 2020).

According to Primavesi (2006), the importance of incorporating organic matter into soils is evidenced by the fact that...

> … the managed and periodic production of intermediate aggregating substances from the complete decomposition of organic matter is... a means of maintaining the productivity of agricultural soil.

However, in degraded soils undergoing agroecological transition, it is initially necessary to build its fertility. Alternative phosphorus (P) sources can play a fundamental role in increasing the availability of this nutrient, which is the greatest limiting factor for plant productivity (Taiz et al., 2017). When applied together with organic materials, sources of low concentrations of soluble P can increase the soil availability of nutrients and productivity of cultivated species (Silva; Costa, 2016; Amanullah et al., 2019). These alternative phosphates additionally bring other nutrients such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sulphur ($S\text{-}SO4^{2-}$) and traces of micronutrients in its basic composition. Therefore, using these P sources, it is expected that the growth and crop yield of species cultivated on degraded, unlimed and unfertilized dry land soils will increase.

Overcultivated soils that have not received any type of management with liming or fertilizers reach a point where they are unable to supply plants with nutrients (Ronquin. 2020). Such circumstances emphasize the importance of understanding the effects of organic fertilization and the use of alternative phosphates on the availability of P and other nutrients in medium term. Furthermore, the assessment of the chemical quality of low-fertility soils under fertilization by organic and alternative phosphate is necessary to evaluate its recovery along the time in order to make them available and fertile in medium term. According to Araújo et al. (2021), the use of phosphate fertilizers alters plant yield, which reaches its maximum depending on the chosen dose, source and application time. However, the lack of information regarding the appropriate agronomic dose of P for some cultivated species remains a challenge for crop production.

In a specific context, such as the conventional-organic transition systems, Coelho et al. (2018) evaluated the fertility of Oxisol treated by phosphate sources and organic fertilization. The authors found significant and positive changes in the soil acidity variables, Ca^{2+} and Mg^{2+}, soil organic matter (SOM) and available P. These results were attributed to the addition of organic materials into the soil. Cavallet et al. (2015) observed an increase in the concentration of Ca^{2+} in addition to a non-significant effect of different organic management forms on P, potassium (K^+), SOM, pH, Mg^{2+} and CEC (pH 7.0) in an Oxisol since 2008. The results obtained by Kamiyama et al. (2011) suggest that soil under different organic fertilization systems have a higher SOM content and a lower K^+ than soils under conventional systems.

The residual effects of phosphate sources have been measured by extractable P since the 1960's (Ensminger; Pearson, 1957). These authors evidenced that raw phosphates have greater residual effects, as evidenced by the high cotton yields observed in experimental conditions. Based on this information, the aim of this study was to evaluate the residual fertility of Oxisol fertilized with organic residues and an alternative phosphate one year after the cultivation of Indian spinach (*Basella alba* L. cv. Tatá, INPA) in Manaus, Amazonas, Brazil.

2 MATERIAL AND METHODS

2.1 EXPERIMENTAL SITE

A field experiment was carried out at the Experimental Farm of the Federal University of Amazonas/FAEXP/UFAM, at km 38 of BR-174, Manaus - AM (2º38'57.6" S - 60º3'11" W), in which bertalha (*Basella alba* L) was grown in full sun under the effect of increasing doses of phosphorus (P) from an alternative source. The soil is classified as a Typic Haplustox (Yellow Latosol), acidic, very clayey (Santos et al., 2018) and flat relief. Before the experiment in December 2018, the chemical soil fertility was characterized according to Silva (2009): pH (H_2O) = 3.8; Al^{3+} = 1.35 cmol$_c$ dm^{-3}; H + Al = 9.8 cmol$_c$ dm^{-3}; Ca^{2+} = 0.50 cmol$_c$ dm^{-3}; Mg^{2+} = 0.10 cmol$_c$ dm^{-3}; K^+ = 20 mg dm^{-3}; SO_4^{2-} = 2.5 mg dm^{-3}; p (Mehlich - 1) = 3.0 mg dm^{-3}; CTC pH 7.0 = 10.45 cmol$_c$ dm^{-3}; V% = 6.23; m% = 67.46; MO = 26.05 g kg^{-1}; Cu^{2+} = 0.01 mg dm^{-3}; Fe^{2+} = 225 mg dm^{-3}; Mn^{2+} = 1.25 mg dm^{-3}; Zn^{2+} = 0.50 mg dm^{-3}. Sulfur (S - SO_4^{2-}) = 4.15 mg dm^{-3} and B (hot water) = 0.35 mg dm^{-3} were determined according to Raij et al. (2001). The soil was classified as clayey as it contains 12.6 g kg^{-1} of sand, 8.8 g kg^{-1} of clay and 78.6 g kg^{-1} of clay (EMBRAPA, 2017).

The experimental blocks and plots were located in an area 12.0 m wide by 26.0 m long, oriented north-south. The plots were oriented in an east-west direction and measured

1.50 m x 2.80 m. A spacing of 0.50 m was established as the boundary between the blocks and experimental plots.

2.2 CHEMICAL CHARACTERIZATION OF MATERIALS AND ESTABLISHMENT OF SOIL MANAGEMENT

The experiment consisted of a conventional cropping system which different organic material were added, with increasing rates of total P from an alternative mineral source. Different organic materials were applied to provide a total N rate of over 500.0 kg ha^{-1} in each experimental plot. The total N content was supplied from: horse manure, and liquid pig manure resulted in a rate of 505.68 kg ha^{-1}. According to the CFSMG (1999) recommendations for various crop species, this rate is considered high. Based on dry mass, the proportions of solid horse manure and liquid swine manure were 85.01% (429.88 kg ha^{-1} of N), 14.99% (75.8 kg ha^{-1} of N), and 7.25% (36.68 kg ha^{-1} of N), respectively. A dose of forest soil, based on dry mass, proportional to 21.8 Mg ha^{-1} was also applied to the plots, corresponding to approximately 1/3 of the dose used in agriculture in the Manaus region. Table 1 presents the total nutrient contents contained in the organic materials, as well as their respective doses.

Table 1

Quantity of organic materials applied and nutrients incorporated into the soil according to their chemical characteristics

Organic material	TQdm[2]	Total nutrient content										
		N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	Mgha^{-1}	-------------------g kg^{-1}--------------------						------------------mg kg^{-1}-----------------				
Horse manure	5,0	15,17	6,6	8,42	17,52	2,81	2,41	12,83	20,2	757,6	161,5	87,0
Organic compost	20,5	20,97	3,32	1,87	13,65	1,64	2,26	20,35	22,47	5674,8	139,7	95,05
Pig manure	1,31[3]	28,0	18,0	24,1	35,0	13,0	6,0	16,0	937,0	3700,0	484,0	673,0

Source: Prepared by the authors (2026). [1]Analyses carried out at the Soil and Plant Laboratory of EMBRAPA-CPAA according to Silva (2009). [2]Total quantity of residues based on dry mass (TQdm), incorporated into the soil to supply the N dose. [3]Incorporated into the soil in liquid form (diluted in water). Note: Total nutrients incorporated into the soil by this manure, in kg ha^{-1}, based on the total dry mass content of organic matter.

The proportional rates of organic materials (Table 1) were incorporated into the soil of the experimental plots soil at a depth of 0.20 m using a pickaxe and a hoe.

On November 17th, 2018, a dose equivalent to 2.0 t ha^{-1} of quicklime (PRNT = 93%) was recommended, which is equivalent to 0.20 kg m^{-2} of quicklime and corresponding to 50% of the economical dose for soil amendment reported by Natale et al. (2011). This was manually applied on the soil surface of all plots and incorporated using a hoe and rake. On November 11st, 2018, the doses of organic compost, and solid horse manure (Table 1) were calculated proportionally for the plot area (4.2 m^2).

The amounts of a partially acidulated alternative rock phosphate (PPR) provided were 0, 25, 50, 100, 200, 400, and 800 kg ha^{-1} based on its total P content (Table 2). These were then applied superficially and incorporated homogeneously to a depth of 0.15 m using a hoe and rake. These PPR doses incorporated the increasing doses of soluble forms of P found in Table 3.

Table 3 shows the amounts of PPR required for the treatments, as well as the amounts of other nutrients incorporated into the soil based on the application of the P. Thus, the experiment design consisted of seven P rates with four randomized blocks, totalling 28 experimental units.

Table 2

Chemical characteristics and granulometry of partially acidulated rock phosphate (PPR)[1].

Phosphorus content				Granulometric fraction retention on the sieve (mm)[6]						
TP[2]	TP_2O_5[3]	P_2O_5 (CNA+H_2O)[4]	P_2O_5 (H_2O)[5]							
---------------------- g kg^{-1} ------------------				0.075	0.10	0.25	0.50	1.0	2.0	4.0
				---------------------------- g kg^{-1} ---------------------------						
118.0	270.0	76.30	28.30	64.0	150.7	236.8	300.3	40.6	0.0	0.0
Other macronutrient				Micronutrient						
Ca		Mg	SO_4	B	Cu	Fe		Mn	Zn	Mo
---------------- g kg^{-1} ----------------				------------------------- mg kg^{-1} --------------------------						
141.60		8.60	41.35	0.04	0.09	62.90		5.90	0.2	<0.01

Source: Prepared by the authors (2026). [1]Alvorada partially acidulated rock phosphate (SOCAL, Registro, SP) which contains a large amount of natural phosphorite (4% P_2O_5 soluble in citric acid). [2]TP: total phosphorus content; [3]TP_2O_5: total P_2O_5 content. [4]P_2O_5 (CNA + H_2O): total P_2O_5 content in neutral ammonium citrate + water. [5]P_2O_5 H_2O: water-soluble P_2O_5 (2:1). Note: 207.2 g kg^{-1} of PPR that passed through the 0.075 mm sieve.

Table 3

Partially acidulated rock phosphate (PPR)[1] doses and amounts of other macronutrients incorporated with PPR

Tn[2]	Dose of P	Soluble P	Quantity of PPR		Other nutrients applied via PPR		
			PPR[3]	PPR[4]	Ca	Mg	S
	kg ha^{-1}	kg ha^{-1}	kg parc^{-1}	kg ha^{-1}	…………kg ha^{-1}…………		
1	0	0.0	0.0	0.0	0.0	0.0	0.0
2	25	0.7	0.089	212	3	0.18	2.93
3	50	1.4	0.178	424	6	0.36	5.86
4	100	2.8	0.356	848	12	0.72	11.72
5	200	5.6	0.712	1696	24	1.44	23.44
6	400	11.2	1.424	3392	48	2.88	46.88
7	800	22.4	2.848	6784	96	5.76	93.76

Source: Prepared by the authors (2026). [1]Partially acidulated rock phosphate Alvorada (PPR) (SOCAL, Registro, SP). [2]Tn: Treatments 1 to 7. [3]Amount of PPR (kg plot^{-1}). [4]Amount of PPR (kg ha^{-1}).

On 16 February 2020, representative soil samples were taken from 9 subsamples per plot for analysis of chemical fertility. The samples were analysed according to Silva (2009) for the following attributes: i) acidity attributes (pH in water), potential acidity (H+Al), exchangeable aluminum (Al^{3+}) and aluminum saturation (m%)); ii) base saturation (V%), cation exchange capacity (CEC pH 7.0) and soil organic carbon (OC), which was converted to soil organic matter (OM) using the factor of 1.724; iii) P (Mehlich-1), K^{+}, Ca^{2+}, Mg^{2+}, Cu^{2+}, Fe^{2+}, Mn^{2+} and Zn^{2+}. Boron (hot water B) and available sulfur (SO_4^{2-} calcium sulphate) analyses were performed according to Raij et al. (2001).

The normality and homoscedasticity of the soil chemical fertility data was verified by the Cochran test ($p \geq 0.05$) in Excel spreadsheet. Normal and homoscedastic data were subjected to simple linear regression analysis. The homoscedastic data were analysed using an F test ($p \leq 0.05$) in the MStatC statistical software from Michigan State University (MSU, USA). The Tukey test ($p \leq 0.05$) was used for the means comparison.

3 RESULTS

No significant regression coefficients were found for any of the pairs of soil fertility attributes. Analysis of variance indicated that the treatments altered values of m% and CEC (pH 7.0) (Table 4). However, the doses of P show inconclusive results, with no consistent trend observed for these soil attributes using the Tukey's Test ($p \leq 0,05$).

Table 4

Analysis of variances of aluminum saturation, saturation of basis and cation exchange capacity of oxisol one year after cultivation of Indian spinach

Dose of P	m%	V	$CEC_{pH\ 7.0}$
	$cmol_c\ dm^{-3}$	%	$cmol_c\ dm^{-3}$
0.0	5.01 ab	47.29 a	6.70 b
25.0	4.34 ab	46.07 a	7.06 ab
50.0	3.55 b	52.84 a	6.54 b
100.0	6.10 a	42.49 a	6.65 b
200.0	3.56 b	53.59 a	7.06 ab
400.0	4.11 ab	51.02 a	7.37 b
800.0	3.02 b	51.40 a	7.85 a
DMS	2.21	11.34	0.94
$SM_{Residue}$	0.901^{**}	23.603^{*}	0.162^{*}
CV (%)	22.38	9.87	5.73
C	0.391	0.410	0.420
W	0.882	0.969	0.976

Source: Prepared by the authors (2026). Values followed by the same letters in the same column do not differ between each other at $p \leq 0.05$ by Tukey's test. *: Significant at $p \leq 0.05$. **: Significant at $p \leq 0.01$, NS: not significant. CV (%): coefficient of variation, in %. C: Cochran statistic ($p \geq 0.05$). Least significant difference (LSD) of Tukey's test. W: Shapiro-Wilke statistic.

The P availability increased by 92.03% and 93.59%, respectively, when 400 kg ha^{-1} of total P (11.32 kg ha^{-1} of soluble P) and 800 kg ha^{-1} of total P (22.64 kg ha^{-1} of soluble P) were applied to the soil from PPR (Table 5). Similar results were observed for P for Ca^{2+} and the anion SO_4^{2-}. P availability was 25.16%, 21.20% and 28.06% for Ca^{2+} and 59.14%, 66.07% and 54.24% for SO_4^2, respectively, for doses of 200, 400 and 800 kg ha^{-1} of P (Table 6). For Fe^{2+} (Table 5), the same occurrence of base saturation (V%) occurs, with the F test being significant ($p \leq 0.05$), but with no differences between means by the Tukey test ($p \leq 0.05$).

The P rates also affected the soil concentrations of P, Ca^{2+} and SO_4^{2-} (Table 5). The P availability was increased, respectively, in 92.03% and 93.59% when 400 kg ha^{-1} of total P (11.32 kg ha^{-1} de P soluble) and 800 kg ha^{-1} of total P (22.64 kg ha^{-1} de P soluble) were applied to the soil from PPR. Similar results were observed for Ca^{2+} and SO_4^{2-}, with respective availabilities of 25.16%, 21.20% and 28.06% for Ca^{2+} and 59.14%, 66.07% and 54.24% for SO_4^{2-}, respectively, for the doses of 200, 400 and 800 kg ha^{-1} of P from MP (Table 5).

Table 5

Analysis of variances of soil nutrient availability one year after cultivation of Indian spinach

Dose of P	Macronutrient			
	P	Ca^{2+}	SO_4^{2-}	Fe^{2+}
	mg dm^{-3}	cmol_c dm^{-3}	.........mg dm^{-3}.........	
0.0	6.25 c	2.23 cd	38.0 c	259.68 a
25.0	8.50 c	2.33 bcd	45.0 bc	264.14 a
50.0	15.25 c	2.65 bcd	51.75 bc	260.74 a
100.0	20.00 c	2.05 d	54.25 bc	270.94 a
200.0	69.00 b	2.98 b	93.00 a	275.61 a
400.0	78.50 ab	2.83 abc	112.0 a	282.84 a
800.0	97.50 a	3.10 a	83.05 ab	279.65 a
DMS	23.96	0.73	33.11	24,26
SM$_{Residue}$	105.33**	0.097**	201.13**	107.99*
CV (%)	24.35	11.98	22.81	3.84
C	0.428	0.321	0.447	0.350
W	0.829	0.962	0.884	0.932

Source: Prepared by the authors (2026). Values followed by the same letters in the same column do not vary among themselves at $p \leq 0.05$ by Tukey's test. *: Significant at $p \leq 0.05$ by the F test. **: Significant at $p \leq 0.01$ by the F test. ^{NS}: not significance by the F test by the F test. CV (%): coefficient of variation, in %. C: Cochran statistic ($p \geq 0.05$). DMS: Least significant difference of the Tukey test. W: Shapiro-Wilke statistic.

The global means of non-significant soil attributes (Table 6) or those means presenting a significant F - test followed by a non-significant Tukey's test, indicate a soil low soil pH and an elevated potential acidity (H+Al) value. These results indicate that the treatments caused a low value of Zn^{2+} availability one year after its application.

Table 6

Global means (FNS)1 of acidity attributes, organic matter, saturation of bases, cation exchange capacity and nutrient availability in oxisol one year after cultivation of Indian spinach

Attribute	Global mean	CV (%)	Class of fertility
pH H_2O	4.58	5.10	Low[3]
Al^{3+} (cmol_c dm^{-3})	0.15	19.01	Low[3]
H+Al (cmol_c dm^{-3})	3.64	12.60	Very high[2]
m (%)	4,24	24,55	Low[2]
SOM (%)	2.03%	19.56	Medium[2]
$\text{CTC}_{\text{pH 7.0}}$ (cmol_c dm^{-3})	7,03	6,58	Medium[2]
V (%)	49,24	8,25	Medium[2]
Attribute	Global mean	CV (%)	Class of fertility
K^+ (mg dm^{-3})	46.18	20,59	Medium[3]
Mg^{2+} (cmol_c dm^{-3})	0,68	22.82	Medium[3]
B (mg dm^{-3})	1,06	35.92	High[3]
Cu^{2+} (mg dm^{-3})	0,63	5.71	Low[3]
Fe^{2+} (mg dm^{-3})	270,5	3,38	High[2]
Mn^{2+} (mg dm^{-3})	1,84	6.03	Low[3]
Zn^{2+} (mg dm^{-3})	0,58	5.11	Low[3]

Source: Prepared by the authors (2026). 1Statistically not significative by the F test ($p \leq 0.05$). 2Segundo Alvarez et al. (1999). 3Segundo Brasil et al. (2020).

4 DISCUSSION

Regarding the increase on soil P availability (Table 5), it could indeed be expected that higher doses of fertiliser would be superior (Machado et al., 2011), given that the nutrient applications were made through increasing doses from the PPR (Table 2). Doses of 56.3 kg ha^{-1} of P (Carvalho et al., 2023) and 54.15 kg ha^{-1} of soluble P (Souza; Lira Jr; Ferreira, 2012) were considered more efficient in soils cultivated for sorghum (*Sorghum bicolor*) and Indian spinach (*B. alba*), respectively. However, P phytotoxicity was reported when higher doses were applied to Indian spinach, despite the species being highly demanding of the nutrient (Souza; Lira Jr; Ferreira, 2012).

In the present study, small quantities of soluble P encountered at the PPR (Table 1) were released during the trial period and during the period when the soil was isolated and uncultivated. Consequently, this P fraction was added to the P released through dissociation reactions of the insoluble P from the PPR under highly acidic soil with a low level of Ca^{2+} found in the field conditions (Novais et al., 2007; Rajan, 1986). The P released by dissociation most likely remained available over the course of a year due to the organic acids released during the gradual decomposition of the applied residues, which bound to P adsorption sites on the surface of the colloidal soil particles (Maluf et al., 2018).

This P fraction was also released from the animal waste, whose release mechanisms are still kept partially unknown (Adesemoye; Kloepper, 2009). However, it could contribute to the resilience of P availability limitation in high wheatered soils in the tropical region, as related by Cleveland et al. (2011). Sun; Chen (2024) reported evidence of interaction between the carbon and P cycles. According to several authors, higher amounts of total organic carbon were found to decrease the soil P adsorption capacity under different management strategies (Ahmed et al., 2019; Hopkins; Hansen, 2019; Schneider et al., 2019; Szara; Sosulski; Szymańska, 2019; Tomasi et al., 2012). As a consequence of this interaction, a residual P reserve is created in the soil (Conijn et al., 2018), which affects crop production. According to Ros et al. (2020), soils with approximately 5% organic matter led to P responses that were 41 to 80% higher than those in soils with less than 2% organic matter, where the response decreased to 11%. Similar to P, Ca^{2+} is part of the natural chemical composition of the phosphorite used in PPR production (Table 1). Consequently, partial acidification of the remaining phosphorite with sulfuric acid resulted in dissociation reactions that released not only P but also Ca^{2+} from this material. This is due to the highly acidic nature of the soil and the low availability of Ca^{2+} before PPR application (Novais et al., 2007; Rajan, 1986).

Regarding SO_4^{2-}, this anion was introduced into the PPR by the industry through the partial acidulation process. These results stem from the increased doses of this nutrient applied along with the PPR to meet the applied treatments (Table 2). Applying sulfur (S) along with phosphorus (P) sources tends to increase the availability of these nutrients in the soil as doses increase, improving the efficiency of phosphate fertilization due to a synergistic effect between the nutrients (Nicchio et al., 2021; Suma; Kalpana, 2019).

The overall averages for the other soil fertility attributes (Table 6) indicate a low pH and high values of potential acidity (H+Al), according to Alvarez et al. (1999). Zn^{2+} availability was also classified as low (Brasil; Cravo; Viegas, 2020). The results verified for the statistically significant soil attributes according to the F-test, but not significant by Tukey's test (V% and Fe^{2+}), occurred due to the conservative nature of this test. Results like these are rare because these tests generally show consistent behaviour with each other for probabilistic data (Souza; Lira Jr; Ferreira, 2012).

These results also indicate that, under these acidic soil conditions, larger quantities of limestone are required for correction, as reported by Silva et al. (2023) and Brignoli et al. (2020). This occurs because, as the pH increases due to an alkaline reaction, acidity is released from the soil surface particles in the form of H^+ and Al^{3+}, which consume more limestone to decrease soil acidity and precipitate Al^{3+} (Novais et al., 2007). The other soil acidity attributes showed average values, more indicative of an agricultural soil in the process of building fertility than of a chemically degraded soil, as this Oxisol showed before the application of the treatments and the cultivation of Indian spinach one year before this evaluation.

The global average of available Fe^{2+} (270.5 mg dm-3) (Table 6) was classified as high (Alvarez et al., 1999) and requires caution when cultivating soils under this level of availability of this nutrient. Under these conditions, excessive absorption of the micronutrient by plants may occur, potentially causing iron phytotoxicity (Zaid et al., 2020) and reduced productivity.

Therefore, it is reasonable to indicate that there are three reasons for the continuous and adequate incorporation of organic residues into the soil in the case of future crops: 1) to supply the soil with the micronutrients Mn^{2+} and Zn^{2+}; 2) to maintain the availability of nutrients, mainly N, and improve the physical conditions of the soil for plant growth. According to Brasil Neto et al. (2018), organic materials improve the physical conditions of the soil and water retention. This allows plants to extend their roots deeper into the soil profile and access nutrients and water available in greater volume, which ultimately contributes to increased biomass production; 3) to control the high availability of Fe^{2+} and its potential phytotoxicity, which is increased by the decomposition products of residues interacting with soil micronutrients (Molnár et al., 2023; Zaid et al., 2020). Amanullah et al. (2019) reported that the use of organic materials in production systems maintains greater availability and retention of nutrients in the soil.

These results also show that the overall availability of nutrients does not limit the growth and production of future crops at the beginning of their life cycle. The two micronutrients most likely to cause deficiencies are Mn^{2+} (Fernandes; Souza; Santos, 2018) and Zn^{2+} (Tsuioshi et al., 2021), which require supplementation via fertilization due to their low availability in the soil. Deficiency of either of these micronutrients can result in slow plant growth and decreased productivity (Fernandes; Souza; Santos, 2018). However, the initial nutritional plant requirements in relation to these micronutrients must definitely be supplied through the input of organic matter, mineralization, and release of micronutrients into the soil.

5 CONCLUSION

Under these experimental conditions, soil fertility improved with the application of 400 and 800 kg ha^{-1} of phosphorus, which provided, respectively, an increase in phosphorus availability of 92.03% and 93.59%, in exchangeable calcium content of 21.20% and 28.06%, and in available sulfur content of 66.07% and 54.24%.

Active acidity and potential acidity imply the need to apply larger amounts of agricultural limestone to prepare the soil for future crops. The availability of manganese and zinc remained low, as also determined at the end of the main experiment, one year earlier. This implies the need to incorporate organic fertilizers to adapt the soil to the growth of future crops, in order to supply the nutrients found below the critical level and control the excessive availability of iron.

These results also allow us to conclude that the fertility management strategies proposed in this study can restore the main fertility attributes in degraded Oxisol. Future cultivation is possible, provided that animal manure and organic compost are applied along with low-solubility phosphates containing additional nutrients, such as calcium and sulfur, in their composition.

ACKNOWLEDGEMENTS

To the Vice-Rectorate for Research and Graduate Studies of the Federal University of Amazonas/PROPESP/UFAM, and to the Amazonas State Research Support Foundation/FAPEAM, for granting undergraduate research scholarships to undergraduate research students.

REFERENCES

Adesemoye, A. O., & Kloepper, J. W. (2009). Plant-microbe interactions in enhanced fertilizer-use efficiency. Applied Microbiology and Biotechnology, 85, 1–12. https://pubmed.ncbi.nlm.nih.gov/19707753/

Agne, S. A. A., & Klein, V. A. (2014). Matéria orgânica e atributos físicos de um Latossolo Vermelho após aplicações de dejeto de suínos. Revista Brasileira de Engenharia Agrícola e Ambiental, 18(7), 720–726. https://www.scielo.br/j/rbeaa/a/7xZK36kKHLrR7nnkpbkCvdk/?format=pdf&lang=pt

Alvarez, V. V. H., Novais, R. F., Barros, N. F., Cantarutti, R. B., & Lopes, A. S. (1999). Interpretação dos resultados das análises de solos. In A. C. Ribeiro, P. T. G. Guimarães, & V. V. H. Alvarez (Eds.), Recomendações para uso de corretivos e fertilizantes em Minas Gerais: 5ª aproximação (pp. 25–32). CFSEMG.

Ahmed, W., Jing, H., Kaillou, L., Qaswar, M., Khan, M. N., Jin, C., Geng, S., et al. (2019). Changes in phosphorus fractions associated with soil chemical properties under long-term organic and inorganic fertilization in paddy soils of southern China. PLOS ONE. https://doi.org/10.1371/journal.pone.0216881

Amanullah, A. I., Khan, A., Khalid, S., Shah, B. P. A., & Muhammad, A. (2019). Integrated management of phosphorus, organic sources, and beneficial microbes improve dry matter partitioning of maize. Communications in Soil Science and Plant Analysis, 50(20). https://doi.org/10.1080/00103624.2019.1667378

Araújo, M. S., Oliveira, C. S., Calixto Júnior, J. E. D., Barretto, V. C. M., & Rodrigues, F. F. (2021). Fósforo no crescimento inicial de mogno-africano. Advances in Forestry Science, 8(1), 1301–1309. http://dx.doi.org/10.34062/afs.v8i1.9728

Brasil, E. C., Cravo, M. S., & Viegas, I. J. M. (2020). Recomendações de calagem e adubação para o estado do Pará (2ª ed. rev. e atual.). Embrapa. https://www.infoteca.cnptia.embrapa.br/handle/doc/1125022

Brasil Neto, A. B., Santos, C. R. C., Noronha, N. C., Gama, M. A. P., Carvalho, E. J. M., et al. (2018). Matéria orgânica e atributos físico-hídricos de um latossolo sob diferentes sistemas de manejo. Agroecossistemas, 10(2), 147–164. http://dx.doi.org/10.18542/ragros.v10i2.5134

Brignoli, F. M., Souza Júnior, A. A., Grando, D. L., Mumbach, G. L., & Pajara, F. F. D. (2020). Atributos biométricos da soja influenciados pelo nível de pH do solo. Revista Científica Rural, 22(2). https://doi.org/10.30945/rcr-v22i2.3211

Carvalho, F. H., Alves, J. M., Veloso, T. G., Alcântara, R. S., Ventura, M. V. A., & Ventura, H. R. F. B. (2023). Different phosphorus doses in grain sorghum under Cerrado conditions, Goiás, Brazil. Revista de Agricultura Neotropical, 10(2), e7039. https://doi.org/10.32404/rean.v10i2.4842

Cavallet, L. E., Di Foggia, M., & Rusin, C. (2015). Características químicas de solo com viticultura orgânica e biodinâmica. Scientia Agraria, 16(4), 31–48. http://dx.doi.org/10.5380/rsa.v16i4.47841

Cleveland, C. C., Townsend, A. R., Taylor, P., Alvarez-Clare, S., Bustamante, M. M., et al. (2011). Relationships among net primary productivity, nutrients and climate in tropical rain forest: A pantropical analysis. Ecology Letters, 14, 939–947. http://dx.doi.org/10.1111/j.1461-0248.2011.01658

CFSMG – Comissão de Fertilidade do Solo do Estado de Minas Gerais. (1999). Recomendações para o uso de corretivos e fertilizantes em Minas Gerais: 5ª aproximação. CFSMG.

Coelho, J. V., Costa, R. G. A., Iwata, B. F., Cunha, L. M., Santos, J. G. P., & Clementino, G. E. S. (2018). Atributos de qualidade em Latossolo Vermelho-Amarelo sob efeito de diferentes doses de biossólido comparado à adubação mineral e esterco bovino. Multi-Science Journal, 1(13), 384–389. https://periodicos.ifgoiano.edu.br/multiscience/article/view/911

Conijn, J. G., Bindraban, P. S., Schröder, J. J., & Jongschaap, R. E. E. (2018). Can our global food system meet food demand within planetary boundaries? Agriculture, Ecosystems & Environment, 244–256. https://doi.org/10.1016/j.agee.2017.06.001

EMBRAPA. (2017). Manual de métodos de análise de solo (3ª ed. rev. e ampl.; P. C. Teixeira et al., Eds.). Embrapa. https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1085209/1/ManualdeMetodosdeAnalisedeSolo2017.pdf

Ensminger, L. E., & Pearson, R. W. (1957). Residual effects of various phosphates as measured by yields, P32 uptake, and extractable phosphorus. Soil Science Society of America Journal, 21(1). https://doi.org/10.2136/sssaj1957.03615995002100010016x

Fernandes, M. S., Souza, S. R., & Santos, L. A. (2018). Nutrição mineral de plantas (2ª ed.). Sociedade Brasileira de Ciência do Solo.

Giácomo, R. G., Alves, M. C., Arruda, O. G., Souto, S. N., Pereira, M. G., & Moraes, M. L. T. (2019). Atributos químicos de um solo degradado após aplicação de composto orgânico e crescimento de Mabea fistulifera Mart. Ciência Florestal, 29(2), 754–768. https://doi.org/10.5902/198050987638

Hopkins, B. G., & Hansen, N. C. (2019). Phosphorus management in high-yield systems. Journal of Environmental Quality, 48, 1265–1280. https://doi.org/10.2134/jeq2019.03.0130

Kamiyama, A., De Maria, I. C., Souza, D. C. C., & Silveira, A. P. D. (2011). Percepção ambiental dos produtores e qualidade do solo em propriedades orgânicas e convencionais. Bragantia, 70(1), 176–184.

Machado, V. J., Souza, C. H. E., Andrade, B. B., Lana, R. M. Q., & Korndörfer, G. H. (2011). Curvas de disponibilidade de fósforo em solos com diferentes texturas após aplicação de doses crescentes de fosfato monoamônico. Bioscience Journal, 27, 70–76. https://seer.ufu.br/index.php/biosciencejournal/article/view/7389/6843

Maluf, H. J. G. M., Silva, C. A., Curi, N., Norton, L. D., & Rosa, S. D. (2018). Adsorption and availability of phosphorus in response to humic acid rates in soils limed with CaCO3 or MgCO3. Ciência e Agrotecnologia, 42(1), 7–20. http://dx.doi.org/10.1590/1413-70542018421014518

Molnár, M., Solomon, W., Mutum, L., & Janda, T. (2023). Understanding the mechanisms of Fe deficiency in the rhizosphere to promote plant resilience. Plants, 12, 1945. https://doi.org/10.3390/plants12101945

Natale, W., Rozane, D. E., Prado, R. M., Romualdo, L. M., Souza, H. A., & Hernandes, A. (2011). Economical dose of liming in yield of star fruit. Revista Brasileira de Fruticultura, 33(4), 1294–1299. http://dx.doi.org/10.1590/S0100-29452011000400030

Novais, R. F., Alvarez, V. H., Barros, N. F., et al. (2007). Fertilidade do solo (1ª ed.). Sociedade Brasileira de Ciência do Solo.

Primavesi, A. (2006). Manejo ecológico do solo: A agricultura em regiões tropicais (18ª ed.). Nobel.

Ronquim, C. C. (2020). Conceitos de fertilidade do solo e manejo adequado para as regiões tropicais (2ª ed.). Embrapa Territorial. https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1128267/1/5840.pdf

Santos, H. G., Jacomine, P. K. T., Dos Anjos, L. H. C., Oliveira, V. A., et al. (2018). Sistema Brasileiro de Classificação de Solo (5ª ed. rev. e ampl.). Embrapa. https://www.infoteca.cnptia.embrapa.br/handle/doc/1094003

Raij, B. V. (2001). Análise química para avaliação da fertilidade de solos tropicais (1ª ed.). IAC.

Rajan, S. S. S. (1986). Partial acidulation of an ‘unground’ phosphate rock: II. Plant availability of phosphate. Fertilizer Research, 8(3), 219–229. https://link.springer.com/article/10.1007/BF01048623

Ros, M. B. H., Koopmans, G. F., van Groenigen, K. J., Abalos, D., Oenema, O., Vos, H. M. J., & van Groenigen, J. W. (2020). Towards optimal use of phosphorus fertiliser. Scientific Reports, 10, 17804. https://doi.org/10.1038/s41598-020-74736-z

Schneider, K. D., Joane, R., Thiessen, M., Francis, Z., Reid, D. K., Fraser, T. D., Lynch, D. H., O'Halloran, I. P., & Wilson, H. F. (2019). Options for improved phosphorus cycling and use in agriculture at the field and regional scales. Journal of Environmental Quality, 48, 1247–1264. https://doi.org/10.2134/jeq2019.02.0070

Sousa, C. A., Lira Junior, M. A., & Ferreira, R. L. C. (2012). Avaliação de testes estatísticos de comparações múltiplas de médias. Revista Ceres, 59(3), 350–354. https://doi.org/10.1590/S0034-737X2012000300008

Silva, L. C., & Costa, F. S. (2016). Eficiência da mistura de fosforita com composto orgânico para alface (Lactuca sativa L.) no sudoeste da Amazônia. Agricultura Familiar: Pesquisa, Formação e Desenvolvimento, 16(1–2), 162–179. https://periodicos.ufpa.br/index.php/agriculturafamiliar/article/view/17928

Silva, F. C. (2009). Manual de análises químicas de solos, plantas e fertilizantes (2ª ed.). Embrapa Informação Tecnológica; Embrapa Solos. https://www.infoteca.cnptia.embrapa.br/handle/doc/3304968

Silva, T., Silva, J. N., Parente, O. M., Silva, C. M., Silva, W. A., Silva, A., & Fernandes, E. N. (2023). Calibração do método SMP para os solos intemperizados da região sudoeste do Maranhão. Contribuciones a las Ciencias Sociales, 16(12), 30235–30247. https://doi.org/10.55905/revconv.16n.12-071

Suma, R., & Kalpana, P. R. (2019). Interaction effect of phosphorus and sulphur application on their availability and tomato productivity in calcareous soil. Research Journal of Chemistry and Environmental Sciences, 7(4), 34–43.

Sun, Y., & Chen, X. (2024). Phosphorus fertilization enhances terrestrial carbon cycling in phosphorus-deficient ecosystems. Journal of Environmental Management, 351, 119941. https://doi.org/10.1016/j.jenvman.2023.119941

Szara, E., Sosulski, T., & Szymańska, M. (2019). Soil phosphorus sorption properties in different fertilization systems. Plant, Soil and Environment, 65(2), 78–82. https://doi.org/10.17221/696/2018-PSE

Taiz, L., Zeiger, E., Moller, I. M., & Murphy, A. (2017). Plant physiology and development (6th ed.). Artmed.

Tomasi, C. A., Inda, A. V., Dick, D. P., et al. (2012). Atributos químicos e área superficial específica em Latossolo subtropical de altitude sob usos e manejos distintos. Ciência Rural, 42(12), 2172–2179. https://doi.org/10.1590/S0103-84782012005000095

Tsuyoshi, K. W., Campos, L. M., Ribeiro, R., & Caione, G. (2021). Desordens nutricionais provocadas por deficiência e excesso de zinco em plantas de milho. Científica, 49(4), 165–173. https://doi.org/10.15361/1984-5529.2021v49n4p165-173

Zaid, A., Ahmad, B., Jaleel, H., Wani, S. H., & Hasanuzzaman, M. A. (2020). Critical review on iron toxicity and tolerance in plants: Role of exogenous phytoprotectants. In T. Aftab & K. R. Hakeem (Eds.), Plant micronutrients (pp. 83–99). Springer Verlag.

https://dokumen.pub/plant-micronutrients-deficiency-and-toxicity-management-1st-ed-9783030498559-9783030498566.html