ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.30, n.9, e301320, 2026
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: https://doi.org/10.1590/1807-1929/agriambi.v30n9e301320 ORIGINAL ARTICLE

Residual effects of acidity amendments and phosphorus sources on sunflower growth and soil chemical attributes[1]

Efeito residual de corretivos de acidez e fontes de fósforo no crescimento de girassol e atributos químicos do solo

Thaynara G. da Silva[2*], Antonio Nolla[2], Alessandra M. T. Alovisi[3], Tiago R. B. da Silva[2] & Adriely V. Bordin[4]

[1] Research developed at Experimental Farm of the Universidade Estadual de Maringá, Umuarama, Paraná, Brazil
[2] Universidade Estadual de Maringá/Departamento de Ciências Agronômicas, Umuarama, Paraná, Brazil
[3] Universidade Federal da Grande Dourados/Faculdade de Ciências Agrárias, Dourados, Minas Gerais, Brazil
[4] Programa Paraná Mais Orgânico, Umuarama, Paraná, Brazil

HIGHLIGHTS:

Organic and mineral phosphorus fertilizers exhibit satisfactory residual effects on sunflower cultivation.
Liming is more effective than calcium–magnesium silicate in promoting sunflower growth.
Calcium–magnesium silicate and lime show similar effects on soil pH and exchangeable Al^{3+} after cultivation.

ABSTRACT: Sunflower cultivation has expanded in recent years; however, phosphorus deficiency and soil acidity constrain crop productivity. This study evaluated sunflower development and soil chemical properties of an Ultisol in northwest Paraná State, Brazil, under the residual effects of phosphorus sources and acidity amendments. The experiment followed a randomized block design in a factorial arrangement, combining nine phosphorus sources: control without phosphorus (T1), hen manure (T2), carbonized rice chaff (T3), soil remineralizer (T4), thermophosphate with micronutrients (T5), magnesium thermophosphate (T6), single superphosphate (T7), triple superphosphate (T8), and potassium thermophosphate with micronutrients (T9), with two acidity amendments (lime and calcium–magnesium silicate), with six replicates. Plant growth, yield components, and root development were assessed, and soil samples were analyzed for pH, available phosphorus, and exchangeable aluminum. Among phosphorus sources, carbonized rice chaff promoted the greatest increases in growth and yield. Liming increased crop yield, whereas acidity amendments did not differ in their isolated effects on soil pH and aluminum; however, significant interactions with phosphorus sources were observed for phosphorus availability. The combined use of lime and organic phosphorus sources, particularly carbonized rice chaff, represents a viable strategy to improve sunflower yield and root development in acid soils of northwest Paraná.

Key words: *Helianthus annuus,* phosphate fertilization, liming, silicate

RESUMO: O cultivo de girassol tem se expandido nos últimos anos, mas a deficiência de fósforo e a acidez do solo limitam a produtividade da cultura. Este estudo teve como objetivo avaliar o desenvolvimento do girassol e atributos químicos de um Argissolo no Noroeste do Paraná, Brasil, submetido ao efeito residual de fontes de fósforo e de corretivos de acidez do solo. O experimento foi conduzido em delineamento em blocos casualizados, em arranjo fatorial, combinando nove fontes de fósforo: controle sem fósforo (T1), esterco de aves (T2), casca de arroz carbonizada (T3), remineralizador de solo (T4), termofosfato com micronutrientes (T5), termofosfato magnesiano (T6), superfosfato simples (T7), superfosfato triplo (T8) e termofosfato potássico com micronutrientes (T9) com dois corretivos da acidez (calcário e silicato de cálcio e magnésio), com seis repetições. Avaliaram-se o crescimento do girassol, os componentes de rendimento e o desenvolvimento radicular, além de análises de pH, fósforo e alumínio do solo. Entre as fontes de fósforo, a casca de arroz carbonizada proporcionou os maiores incrementos no crescimento e rendimento do girassol. O calcário aumentou a produtividade das plantas, enquanto os corretivos de acidez não diferiram quanto aos seus efeitos isolados sobre o pH do solo e o alumínio, embora interações significativas com as fontes de fósforo tenham sido observadas na disponibilidade de fósforo no solo. O uso de calcário combinado com fontes de fósforo orgânicas (casca de arroz carbonizada) é uma estratégia viável para melhorar a produtividade e o desenvolvimento radicular do girassol em solos ácidos do noroeste do Paraná.

Palavras-chave: *Helianthus annuus,* adubação fosfatada, calagem, silicatagem

Ref. 301320 – Received 26/09/2025
* Corresponding author - E-mail: thaynaragarceztg@gmail.com
• Accepted 11/05/2026 • Published 27/08/2026
Editors: Ítalo Herbet Lucena Cavalcante & Walter Esfrain Pereira

Publisher's Note: The statements, opinions, and data contained in this article are the sole responsibility of the author(s). The Agriambi Journal and/or Editor(s) disclaim any liability for damages to persons or property resulting from any ideas, methods, instructions, or products mentioned in the article.

This is an open-access article distributed under the Creative Commons Attribution 4.0 International License.

Introduction

Sunflower (*Helianthus annuus* L.) cultivation has expanded in Brazil and worldwide due to high chemical quality of its oil, which is suitable for human and animal consumption and attractive to health-conscious consumers (Adeleke & Babalola, 2020). According to CONAB (2026), the cultivated area in Brazil increased from 61,900 ha (2024/25) to 63,800 ha (2025/26), highlighting economic importance, particularly in the Central-West region and southern states. However, sunflower is sensitive to acidic soils (pH < 5.2) and low fertility conditions (base saturation < 50%), mainly due to high phosphorus (P) demand, estimated at 140 kg ha^{-1} of P_2O_5 (Sutradhar et al., 2014; Alzamel et al., 2022).

Proper soil fertility management, including liming and fertilization, is therefore essential to ensure adequate crop performance (Oliveira et al., 2022). Most Brazilian soils exhibit low fertility, characterized by limited phosphorus availability (< 12 mg kg^{-1}), low pH (< 5.0), and exchangeable aluminum (Al^{3+}) concentrations that often exceed phytotoxic levels for sensitive crops. In sunflower, root development is severely restricted when exchangeable Al^{3+} exceeds 0.3 cmolc kg^{-1} (Sutradhar et al., 2014). This condition must be distinguished from aluminum saturation (m%), as absolute Al^{3+} concentration directly governs ion activity in soil solution (Pauletti & Motta, 2019). In this context, soil amendments are required, with liming being the most widely adopted practice (Almeida et al., 2023). In addition to neutralizing toxic elements such as Al^{3+}, H^+, and Mn^{2+}, lime shows limited mobility, with effects largely confined to the topsoil (Nolla et al., 2020; Alves et al., 2021b). As an alternative, calcium–magnesium silicate, an industrial byproduct, may present higher solubility and promote root growth at greater depths; however, its effectiveness for sunflower remains poorly documented (Blamey et al., 2018; Almeida et al., 2023).

Phosphorus deficiency represents another major constraint in Brazilian soils due to strong adsorption of phosphate by Fe and Al oxides, combined with low organic matter content and soil acidity (Johan et al., 2021). Conventional mineral fertilizers provide rapid nutrient availability but are associated with excessive cost, limited residual effect, and strong fixation in soil (Cabral et al., 2020; Sherkuziev, 2021). In contrast, thermophosphates constitute an alternative source with gradual nutrient release and potential enrichment with other nutrients (Fernandes et al., 2010; Sanagiotto et al., 2022).

Organic fertilizers, such as hen manure and carbonized rice chaff, supply phosphorus and a wide range of macro- and micronutrients while increasing soil organic matter. Their gradual mineralization promotes a residual effect that benefits both current and subsequent crops. Under controlled conditions, such as pot experiments, these materials also function as soil conditioners, enhancing cation exchange capacity (CEC) and nutrient availability over time (Sá et al., 2020; Alves et al., 2021a). This improvement in substrate chemical properties is essential to sustain plant nutrition throughout the crop cycle, particularly in low-fertility soils.

Sunflower, a member of the Asteraceae family, requires fertile soils and develops a deep root system. However, limited action depth of acidity amendments and short residual effect of soluble phosphorus sources may constrain crop expansion in Brazil, where it is commonly grown as a second crop (Ferreira et al., 2020; Alves et al., 2021b). In this context, the use of industrial and agricultural byproducts, such as silicates and carbonized rice chaff, represents a promising strategy to reduce dependence on mineral fertilizers and mitigate environmental impacts, contributing to more sustainable soil management in tropical regions (Silva et al., 2025).

The objective of this study was to evaluate sunflower growth and soil chemical attributes of an Ultisol in northwest Paraná State, Brazil, under residual effects of phosphorus sources and acidity amendments.

Material and Methods

The experiment was conducted from April to August 2022 in the experimental area of the State University of Maringá, Umuarama campus, Paraná, Brazil (23° 47′ 26.7″ S; 53° 15′ 24.5″ W; 401 m altitude). According to the Köppen classification, regional climate is Cfa, characterized by elevated temperatures and well-distributed rainfall throughout the year (Aparecido et al., 2016).

Soil was collected from the university campus, classified as a dystrophic Red Ultisol with medium texture, and used to fill polyethylene pots (30 × 40 cm), which constituted experimental units. Pots were laterally perforated to allow drainage, and soil moisture was maintained near field capacity through rainfall and supplemental irrigation when necessary.

Soil samples were collected from the 0–20 cm layer and presented the following initial chemical characteristics, determined according to Tedesco et al. (1995): pH ($CaCl_2$) = 4.0; exchangeable Al^{3+} = 0.9 cmolc kg^{-1}; Ca^{2+} = 0.75 cmolc kg^{-1}; Mg^{2+} = 0.25 cmolc kg^{-1}; potential acidity ($H^+ + Al^{3+}$) = 4.28 cmolc kg^{-1}; cation exchange capacity at pH 7.0 = 5.41 cmolc kg^{-1}; available P = 4.7 mg kg^{-1}; K = 0.13 cmolc kg^{-1}; base saturation (V) = 20.86%; and organic matter = 3.02 g kg^{-1}. Particle-size distribution was 190 g kg^{-1} clay, 2.5 g kg^{-1} silt, and 807.5 g kg^{-1} sand. Phosphorus and K were extracted using Mehlich-1, whereas Ca, Mg, and Al were extracted with KCl.

Treatments consisted of nine phosphorus sources: control without phosphorus (T1), hen manure (T2), carbonized rice chaff (T3), soil remineralizer (T4), thermophosphate with micronutrients (T5), magnesium thermophosphate (T6), single superphosphate (T7), triple superphosphate (T8), and potassium thermophosphate with micronutrients (T9). These sources were combined with two acidity amendments: lime and calcium–magnesium silicate. Their respective chemical characteristics were as follows: reactivity (RE) = 70.0 and 76.0%; neutralizing value (NV) = 100.0 and 86.0%; relative neutralizing value (RNV) = 70.0 and 65.0%; SiO_2 = 0.0 and 43.2%; MgO = 17.0 and 6.9%; and CaO = 25.0 and 19.2%.

Treatments were arranged in a factorial scheme (2 × 9), corresponding to two acidity amendments and nine

phosphorus sources, in a randomized block design with six replicates (pots). Chemical composition of phosphorus sources is presented in Table 1.

Fertilization and acidity amendment rates were calculated according to Pauletti & Motta (2019) and CQFS–RS/SC (2016). Soil acidity was corrected in December 2021 to increase base saturation to 70%. Phosphorus treatments (140 kg ha^{-1} of P_2O_5), along with nitrogen (90 kg ha^{-1} as urea) and potassium (60 kg ha^{-1} of K_2O as KCl), were applied in January 2022 at sowing of common bean (*Phaseolus vulgaris*), cultivated for 90 days. All pots received equal amounts of N, P, and K, differing only in phosphorus source.

After bean cultivation, sunflower cv. Multissol was sown under residual effects of applied fertilizers in April 2022, approximately 90 days after fertilization. Thinning was performed 15 days after emergence, maintaining two plants per pot.

At approximately 120 days after emergence, plants were harvested. The following variables were measured: plant height, stem diameter, fresh and dry shoot mass, capitulum diameter, fresh and dry capitulum mass, and grain mass, used to estimate yield (Leite et al., 2005). Root system was evaluated for fresh and dry mass and total root length, following Tennant (1975).

After harvest, soil samples were collected from the 0–10 cm layer of each pot. This layer was selected because it represents the primary zone of chemical interaction between phosphorus sources and acidity amendments. Given low mobility and diffusion of phosphorus in soil, this surface layer is most suitable for assessing P availability and residual treatment effects. Samples were air-dried, sieved (2 mm), and analyzed for pH ($CaCl_2$), exchangeable Al^{3+}, and available P according to Tedesco et al. (1995).

Data were subjected to analysis of variance (ANOVA), and phosphorus sources were compared using the Scott–Knott test at $p \leq 0.05$. All analyses were performed using SISVAR software, version 5.6 (Ferreira, 2019).

Table 1. Chemical composition of phosphorus sources used in the experiment (%)

Phosphorus source	Ca	Mg	N	P_2O_5	K_2O
T2	-	-	3.2	3.5	2.5
T3	0.41	0.9	0.66	0.15	0.29
T4	-	-	1	16	-
T5	16	2	-	17	-
T6	18	7	-	16	-
T7	16	-	-	18	-
T8	10	-	-	41	-
T9	9	1	2	16	7

T2 - Hen manure; T3 - Carbonized rice chaff; T4 - Soil remineralizer; T5 - Thermophosphate with micronutrients; T6 - Magnesium thermophosphate; T7 - Single superphosphate; T8 - Triple superphosphate; T9 - Potassium thermophosphate with micronutrients

Results and Discussion

Phosphorus sources and acidity amendments significantly affected shoot fresh and dry mass, capitulum mass, grain yield, root fresh and dry mass, and root length. Phosphorus sources also influenced 100-grain mass. Significant interactions between phosphorus sources and acidity amendments were observed for shoot fresh and dry mass, capitulum mass, grain yield, and root fresh mass (Table 2).

Single superphosphate and carbonized rice chaff increased 100-grain mass (1.45 and 1.32 g) and root dry mass (0.88 and 0.89 g), respectively (Figures 1A and B). Hen manure also increased root dry mass (0.72 g) (Figure 1B). All phosphorus sources increased root length compared with the control (Figure 1C), without differing from each other.

These responses may be attributed to the supply of additional nutrients from both mineral and organic phosphorus sources. Carbonized rice chaff contains calcium (0.41%), magnesium (0.9%), nitrogen (0.66%), and potassium (0.29%), which, combined with phosphorus, promote plant growth (Table 1). Although single superphosphate is a soluble fertilizer, it also supplies calcium and sulfur (Sherkuziev, 2021). This nutrient combination favors development of a deeper root system, enhancing nutrient uptake from subsurface layers. Comparable results were reported by Rodrigues et al. (2022), who observed improved sunflower development under both organic and mineral fertilization compared with control.

In addition to direct nutrient supply, carbonized rice chaff provides indirect benefits, including formation of a surface organic residue layer that acts as a physical barrier, reducing light incidence on soil and limiting weed emergence. This effect decreases competition with sunflower for water, light, and nutrients (Martins Filho et al., 2020).

Table 2. Analysis of variance for plant height, stem diameter, shoot fresh and dry mass, capitulum diameter and mass, 100-grain mass, grain yield, root fresh and dry mass, and root length of sunflower under phosphorus sources and acidity amendments

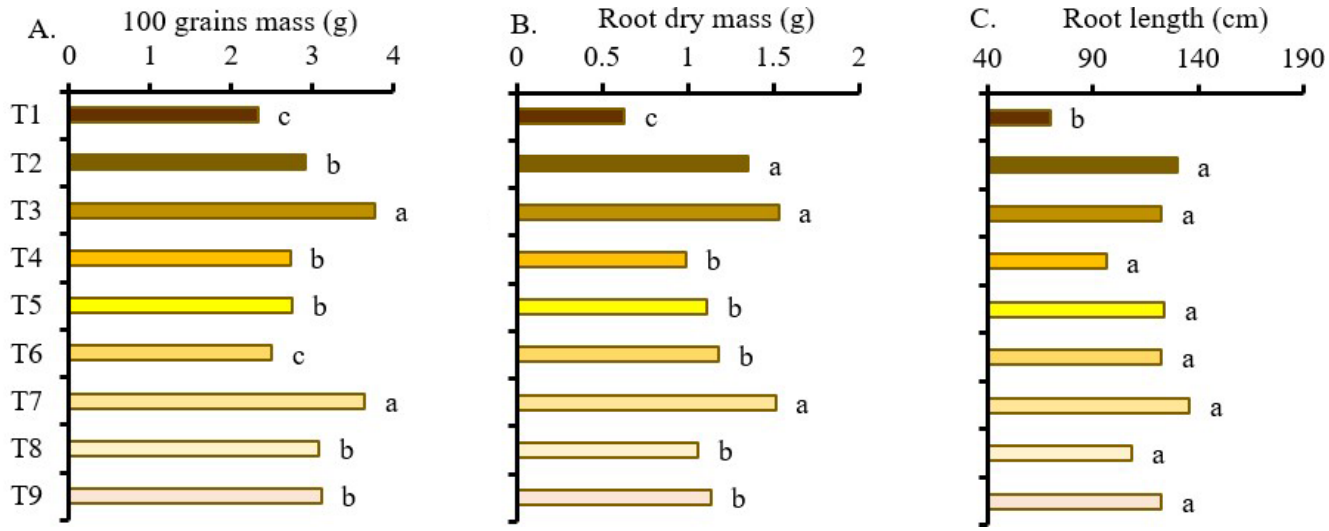
SV	Plant height	Stem diameter	Shoot fresh mass	Shoot dry mass	Capitulum diameter	Capitulum mass	100-grain mass	Grain yield	Root fresh mass	Root dry mass	Root length
Block	0.8156	0.2828	0.1425	0.3918	0.1272	0.1148	0.6899	0.1148	0.1753	0.6407	0.0067
P	0.6904^{ns}	0.6356^{ns}	0.0001**	0.0001**	0.3620^{ns}	0.0002**	0.0001**	0.0002**	0.0001**	0.0001**	0.0001**
A	0.8809^{ns}	0.1073^{ns}	0.0001**	0.0002**	0.3333^{ns}	0.0001**	0.0701^{ns}	0.0001**	0.0001*	0.0001**	0.0108**
P×A	0.9685^{ns}	0.3006^{ns}	0.0001**	0.0035**	0.4384^{ns}	0.0014**	0.6180^{ns}	0.0014**	0.0195**	0.1834^{ns}	0.7128^{ns}
CV (%)	16.59	22.18	16.36	17.80	24.67	17.81	21.03	17.81	24.76	25.38	29.36

P - Phosphorus sources; A - Acidity amendments; P × A - Interaction between phosphorus sources and acidity amendments; "**" and "^{ns}" - Significant at $p \leq 0.01$ and not significant by F test, respectively; CV - Coefficient of variation; SV - Sources of variation

Liming increased root dry mass (0.23 g) and root length (17 cm) compared with calcium–magnesium silicate (Figures 2A and B). These results agree with Mar et al. (2022) and Amoakwah et al. (2023), confirming greater efficiency of lime in correcting soil acidity and promoting sunflower growth. The amendments differed in composition, with lime containing 5.8% more CaO and 10.1% more MgO than silicate, as well as higher relative neutralizing value (RNV). These differences may explain superior performance of lime, as calcium plays structural and signaling roles in enzyme activation, whereas magnesium is essential for respiration, photosynthesis, and nucleic acid synthesis (Taiz et al., 2017).

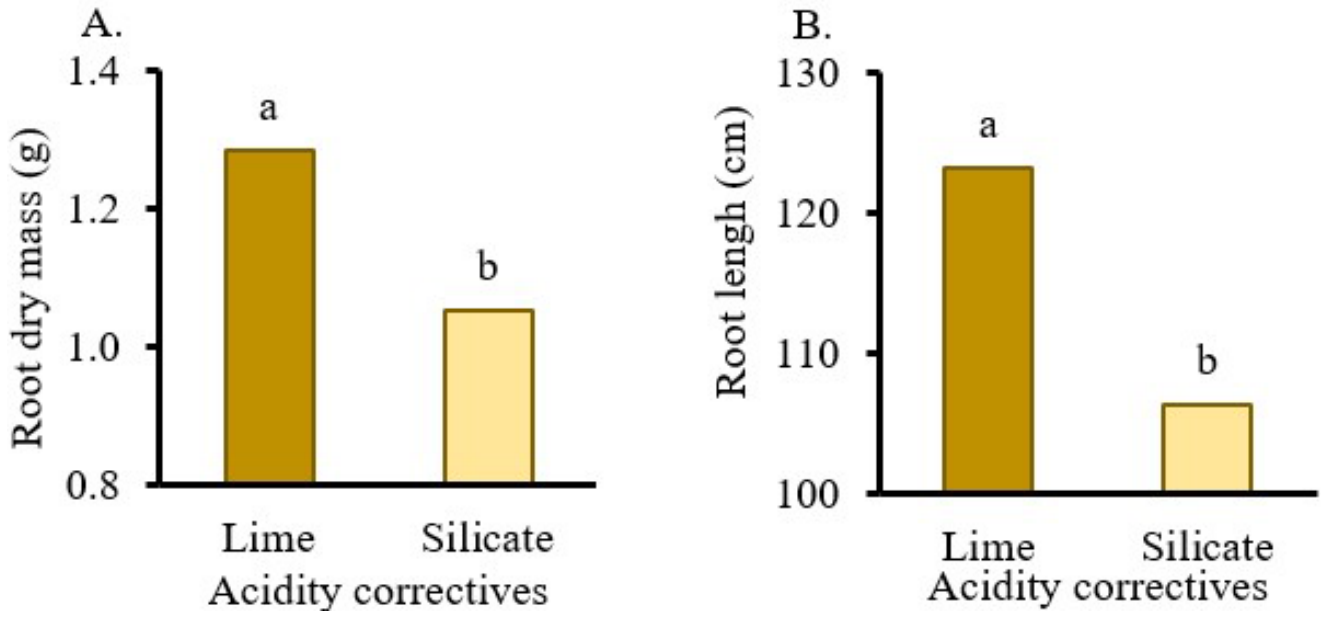
According to Zobiole et al. (2010), sunflower accumulates approximately 89 mg kg^{-1} of calcium and 30.2 mg kg^{-1} of magnesium in biomass until physiological maturity. In addition, by increasing soil pH, lime neutralizes Al^{3+}, reducing chemical constraints on root growth. Consequently, root development is enhanced, which is reflected in shoot growth and crop yield (Campos et al., 2022; Singh et al., 2022).

Carbonized rice chaff increased shoot fresh mass under both lime and calcium–magnesium silicate, whereas magnesium thermophosphate increased shoot fresh mass only under liming. For shoot dry mass, hen manure, carbonized rice chaff, soil remineralizer, and thermophosphate with micronutrients outperformed control under liming. Under silicate application, hen manure, carbonized rice chaff, and single superphosphate also increased shoot dry mass. Carbonized rice chaff produced the highest values of capitulum mass, grain yield, and root fresh mass under both amendments (Table 3).



T1 - Control; T2 - Hen manure; T3 - Carbonized rice chaff; T4 - Soil remineralizer; T5 - Thermophosphate with micronutrients; T6 - Magnesium thermophosphate; T7 - Single superphosphate; T8 - Triple superphosphate; T9 - Potassium thermophosphate with micronutrients. Bars followed by the same letter do not differ among phosphorus sources by the Scott–Knott test at $p \leq 0.05$

Figure 1. 100-grain mass (A), root dry mass (B), and root length (C) of sunflower under phosphorus sources



Bars followed by the same letter do not differ by F test at $p \leq 0.05$

Figure 2. Root dry mass (A) and root length (B) of sunflower under lime and calcium–magnesium silicate application

In general, acidity amendments enhanced efficiency of phosphorus sources. By increasing pH and neutralizing Al^{3+}, these materials reduce phosphorus fixation in soil, thereby improving effectiveness of phosphorus fertilization (Johan et al., 2021). Carbonized rice chaff was the most consistent source for promoting vegetative growth and final yield, even under residual conditions. This effect is attributed to gradual release of multiple nutrients, which reduces P fixation by Fe and Al oxides and sustains nutrient availability throughout the crop cycle (Vasallo & Nagal, 2025).

When comparing acidity amendments, liming increased shoot fresh mass with soil remineralizer, thermophosphate with micronutrients, magnesium thermophosphate, triple superphosphate, and potassium thermophosphate with micronutrients. Liming also increased shoot dry mass with soil remineralizer, thermophosphate with micronutrients, magnesium thermophosphate, and potassium thermophosphate with micronutrients. In addition, liming resulted in higher capitulum mass and grain yield with magnesium thermophosphate and potassium thermophosphate with micronutrients, and greater root fresh mass with soil remineralizer, single superphosphate, triple superphosphate, and potassium thermophosphate with micronutrients (Table 3).

These results indicate a synergistic effect of lime with several phosphorus sources, enhancing sunflower growth and yield. By increasing soil pH and reducing Al^{3+} phytotoxicity, lime improves nutrient availability and uptake, particularly from less soluble sources such as thermophosphates and remineralizers. This interaction promotes development of heavier reproductive structures and higher grain yield, especially when associated with sources supplying magnesium and potassium (Silva et al., 2025). Similar advantages of lime over silicate for sunflower growth were reported by Oliveira et al. (2023) and Menezes et al. (2025).

Phosphorus sources significantly affected soil Al^{3+} and P contents, with a highly significant interaction ($p < 0.01$) between phosphorus sources and acidity amendments for phosphorus availability (Table 4). Soil pH was not affected by phosphorus sources, acidity amendments, or their interaction ($p > 0.05$). The effect of acidity amendments on soil P availability depended on the phosphorus source applied, as indicated by the significant interaction.

All phosphorus sources increased soil Al^{3+} content compared with control, with no differences among sources (Figure 3). This effect may be attributed to reactions between fertilizers and Fe and Al oxides in soil, which enhance dissolution of aluminum hydroxide [$Al(OH)_3$] and release Al^{3+} into soil solution. In organic sources such as hen manure and carbonized rice chaff, this effect may be partially mitigated by the buffering capacity of organic matter, which complexes Al^{3+} and reduces its activity in solution.

Despite the slight increase in Al^{3+}, concentrations remained below the phytotoxic threshold of 0.3 cmolc kg^{-1} for sunflower, according to Pauletti & Motta (2019) and Omenda et al. (2021). These results indicate that phosphorus sources used in this study did not raise soil Al^{3+} to levels harmful to plant growth.

Soil remineralizer increased soil P by 51.11 mg kg^{-1} with lime and 53.57 mg kg^{-1} with calcium–magnesium silicate compared with control (Table 5). This response may be associated with the Mehlich-1 extractor, which solubilizes less labile P forms, potentially overestimating plant-available phosphorus (Ferreira Júnior et al., 2022). Although higher extractable P values were observed with remineralizer application, this did not translate proportionally into plant growth, as agronomic performance remained lower than that observed in the control treatment (Tables 3 and 5). This result indicates that the remineralizer increased soil P availability; however, Mehlich-1 may overestimate plant-available P under these conditions, and alternative methods such as resin extraction are recommended (Oliveira et al., 2015).

In contrast, carbonized rice chaff showed superior performance for most growth variables, despite lower extractable P concentrations in soil (Table 5). This discrepancy indicates that phosphorus released from organic and carbonized sources may be more gradually released and synchronized with plant demand. Rice chaff carbonization produces a porous structure

Table 3. Interaction effects of phosphorus sources and acidity amendments on shoot fresh and dry mass, capitulum mass, grain yield, and root fresh mass of sunflower

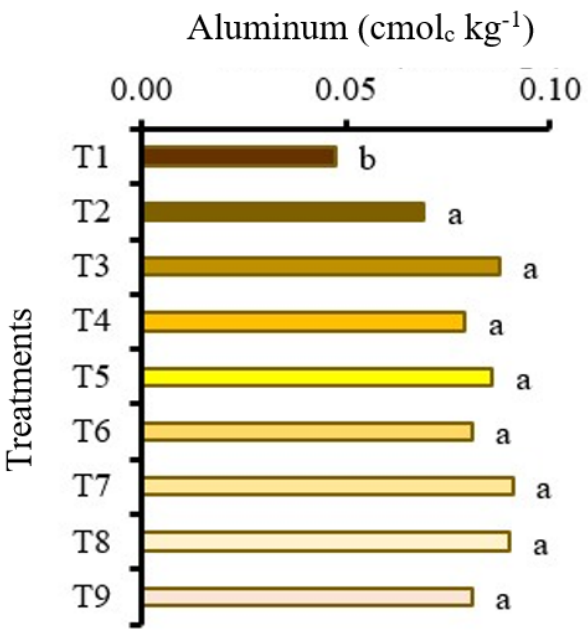
	Shoot fresh mass (g)				Shoot dry mass (g)				Capitulum mass (g)				Grain yield (kg ha^{-1})				Root fresh mass (g)			
	Lime		Silicate		Lime		Silicate		Lime		Silicate		Lime		Silicate		Lime		Silicate	
T1	14.68	aC	16.51	aC	7.91	aB	7.63	aB	6.62	aD	7.78	aC	330.83	aD	389.17	aC	1.28	aC	1.23	aC
T2	17.86	aC	18.56	aC	10.68	aA	11.49	aA	10.52	aC	11.59	aB	525.83	aC	579.58	aB	2.92	aB	2.38	aB
T3	30.54	aA	33.54	aA	12.79	aA	12.94	aA	15.68	aA	13.88	aA	783.75	aA	693.75	aA	3.97	aA	4.08	aA
T4	25.15	aB	19.20	bC	11.85	aA	9.04	bB	12.09	aB	10.09	aC	604.58	aB	504.58	aC	3.06	aB	1.61	aC
T5	24.11	aB	15.13	bC	12.55	aA	7.65	bB	9.39	aC	7.88	aC	469.58	aC	393.75	aC	2.46	aB	2.05	aB
T6	28.40	aA	18.36	bC	11.31	aA	9.12	bB	12.48	aB	8.34	aC	624.17	aB	417.08	bC	3.03	aB	2.39	aB
T7	22.98	aB	23.56	aB	12.09	aA	10.98	aA	12.02	aB	11.64	aB	600.83	aB	582.08	aB	3.23	aB	2.15	bB
T8	21.73	aB	15.95	bC	9.03	aB	7.65	aB	10.03	aC	8.17	aC	501.67	aC	408.33	aC	3.26	aB	1.78	bC
T9	24.88	aB	15.65	bC	10.77	aA	7.15	bB	12.21	aB	7.52	bC	610.42	aB	375.83	bC	2.76	aB	1.85	bC

T1 - Control; T2 - Hen manure; T3 - Carbonized rice chaff; T4 - Soil remineralizer; T5 - Thermophosphate with micronutrients; T6 - Magnesium thermophosphate; T7 - Single superphosphate; T8 - Triple superphosphate; T9 - Potassium thermophosphate with micronutrients. Means followed by the same uppercase letter in columns and the same lowercase letter in rows do not differ among phosphorus sources by the Scott–Knott test at $p \leq 0.05$

Table 4. Analysis of variance for pH ($CaCl_2$), exchangeable Al^{3+}, and available P in an Ultisol after sunflower cultivation under phosphorus sources and acidity amendments

SV	pH $CaCl_2$	Aluminum	Phosphorus
Block	0.6208	0.2908	0.7609
P	0.3750^{ns}	0.0044**	0.0001**
A	0.1018^{ns}	0.2266^{ns}	0.1346^{ns}
A × P	0.9099^{ns}	0.6274^{ns}	0.0003**
CV (%)	7.24	33.97	11.48

P - Phosphorus sources; A - Acidity amendments; P×A - Interaction between phosphorus sources and acidity amendments; "**" and "ns" - Significant at $p \leq 0.01$ and not significant by F test, respectively; CV - Coefficient of variation ; SV - Sources of variation



T1 - Control; T2 - Hen manure; T3 - Carbonized rice chaff; T4 - Soil remineralizer; T5 - Thermophosphate with micronutrients; T6 - Magnesium thermophosphate; T7 - Single superphosphate; T8 - Triple superphosphate; T9 - Potassium thermophosphate with micronutrients. Bars followed by the same letter do not differ among phosphorus sources by the Scott–Knott test at $p \leq 0.05$

Figure 3. Exchangeable Al^{3+} in an Ultisol after sunflower cultivation under phosphorus sources

that, together with organic matter, enhances cation exchange capacity (CEC) and nutrient retention, reducing P fixation by soil oxides (Sá et al., 2020; Alves et al., 2021a). In addition, organic matter acts as a natural chelator, potentially complexing Al^{3+} and Mn^{2+}, which favors root development and phosphorus uptake.

Under both acidity amendments, soil remineralizer resulted in the highest soil P values (Table 5). However, these values likely reflect methodological overestimation by the Mehlich-1 extractor, which solubilizes non-labile mineral forms, rather than greater plant-available P, as this treatment did not produce superior plant performance. In contrast, sources such as hen manure and carbonized rice chaff provided a more effective and sustained phosphorus supply. Much of the P in these sources occurs in forms that, although requiring microbial mineralization (Alves et al., 2021a), are less prone to fixation in soil. Similarly, thermophosphates, which are not water-soluble, showed a residual effect due to gradual solubilization (Sanagiotto et al., 2022), resulting in more balanced nutrient release than that indicated by the overestimated P from the remineralizer.

Table 5. Interaction effects of phosphorus sources and acidity amendments on soil P content in an Ultisol after sunflower cultivation

Phosphorus content (mg kg^{-1})				
Phosphorus source	Lime		Silicate	
T1	12.22	aE	12.93	aD
T2	36.24	aB	28.20	bB
T3	28.21	bC	32.48	aB
T4	63.33	aA	66.50	aA
T5	25.26	aD	22.70	aC
T6	24.88	aD	30.37	bB
T7	28.54	aC	29.54	aB
T8	21.66	aD	23.29	aC
T9	27.92	aC	31.37	aB

T1 - Control; T2 - Hen manure; T3 - Carbonized rice chaff; T4 - Soil remineralizer; T5 - Thermophosphate with micronutrients; T6 - Magnesium thermophosphate; T7 - Single superphosphate; T8 - Triple superphosphate; T9 - Potassium thermophosphate with micronutrients. Means followed by the same uppercase letter in columns and the same lowercase letter in rows do not differ by the Scott–Knott test at $p \leq 0.05$

Conclusions

1. Phosphorus sources increase soil P and Al^{3+} concentrations while maintaining Al^{3+} below the phytotoxic threshold of 0.3 cmolc kg^{-1} for sunflower. Carbonized rice chaff is the most effective source for improving growth and yield components.

2. Lime and calcium–magnesium silicate do not differ in their effects on soil pH and exchangeable Al^{3+} after sunflower cultivation. However, lime is more effective than calcium–magnesium silicate in promoting vegetative growth and grain yield, regardless of the phosphorus source applied.

3. The combination of carbonized rice chaff and lime optimizes sunflower productivity and root system development in acidic, low-fertility soils under pot conditions. Field validation is required to confirm these results under natural soil variability.

Contribution of authors: T. G. da Silva: Data collection, analysis, and interpretation; Writing the original draft and editing. A. Nolla: Conceptualization and experimental design; Methodology; Supervision. A. M. T. Alovisi: Writing the original draft and editing; Funding acquisition. T. R. B. da Silva: Literature review; Data interpretation. A. V. Bordin: Data collection; Writing the original draft and editing.

Data Availability Statement: The authors declare that there are no data underlying the text.

Conflict of Interest: The authors declare no conflict of interest.

Financing statement: This study received no external funding.

Acknowledgments: The authors thank the Coordination for the Improvement of Higher Education Personnel (CAPES) for providing a scholarship to the first author and the State University of Maringá (UEM) for institutional support and infrastructure.

Literature Cited

Adeleke, B. S.; Babalola, O. O. Oilseed crop sunflower (*Helianthus annuus*) as a source of food: Nutritional and health benefits. Food Science & Nutrition, v.8, p.4666-4684, 2020. https://doi.org/10.1002/fsn3.1783

Almeida, E. M. et al. Uso de escória de siderurgia como corretivo da acidez do solo. Revista Científica Rural, v.25, p.43-60, 2023. https://doi.org/10.29327/246831.25.1-3

Alves, D. F. et al. Efeitos de diferentes fontes de material orgânico na fertilidade e umidade do solo. Revista Brasileira de Engenharia de Biossistemas, v.15, p.644-659, 2021a. http://dx.doi.org/10.18011/bioeng2021v15n4p644-659

Alves, L. A. et al. Soil chemical properties and crop response to gypsum and limestone on a coarse-textured Ultisol under no-till in the Brazilian Pampa biome. Geoderma Regional, v.25, e00372, 2021b. https://doi.org/10.1016/j.geodrs.2021.e00372

Alzamel, N. M. et al. Effect of organic and inorganic fertilizers on soil properties, growth yield, and physiochemical properties of sunflower seeds and oils. Sustainability, v.14, 12928, 2022. https://doi.org/10.3390/su141912928

Amoakwah, E. et al. Impact of silicate and lime application on soil fertility and temporal changes in soil properties and carbon stocks in a temperate ecosystem. Geoderma, v.433, 116431, 2023. https://doi.org/10.1016/j.geoderma.2023.116431

Aparecido, L. E. O. et al. Köppen, Thornthwaite and Camargo climate classifications for climatic zoning in the State of Paraná, Brazil. Ciência e Agrotecnologia, v.40, p.405-417, 2016. https://doi.org/10.1590/1413-70542016404003916

Blamey, F. P. C. et al. Manganese distribution and speciation help to explain the effects of silicate and phosphate on manganese toxicity in four crop species. New Phytologist, v.217, p.1146-1160, 2018. https://doi.org/10.1111/nph.14878

Cabral, F. L. et al. Níveis de fertilização de fósforo mineral e organomineral na cultura do milho. Brazilian Journal of Development, v.6, p.36414-36426, 2020. https://doi.org/10.34117/bjdv6n6-255

Campos, M. et al. Effectiveness of deep lime placement and tillage systems on aluminum fractions and soil chemical attributes in sugarcane cultivation. Geoderma, v.407, 115545, 2022. https://doi.org/10.1016/j.geoderma.2021.115545

CONAB - Companhia Nacional de Abastecimento. Produção de grãos e área plantada da safra 2025/26 mantém perspectiva de novos recordes. Brasília, DF: CONAB, 2026. Available on: https://www.gov.br/conab/pt-br/assuntos/noticias/producao-de-graos-e-area-plantada-da-safra-2025-26-mantem-perspectiva-de-novos-recordes. Accessed on: Mar. 2026.

CQFS–RS/SC - Comissão de Química e Fertilidade Do Solo. Manual de calagem e adubação para os Estados de Rio Grande do Sul e de Santa Catarina. 11ª ed. Viçosa: Sociedade Brasileira de Ciência do Solo, 2016. 376p.

Fernandes, F. R. C. et al. Agrominerais para o Brasil. 1.ed. Rio de Janeiro: CETEM/MCT, 2010. 380p.

Ferreira, D. F. Sisvar: a computer analysis system to fixed effects split plot type designs. Brazilian Journal of Biometrics, v.37, p.529-535, 2019. https://doi.org/10.28951/rbb.v37i4.450

Ferreira Júnior, O. J. et al. Agronomic response of rice crop under effect of rock phosphate doses. Agri-Environmental Sciences, v.8, e022011, 2022. https://doi.org/10.36725/agries.v8i2.7927

Ferreira, V. et al. Economic analysis of sorghum and sunflower crops second season. Revista Agrotecnologia, v.11, p.14-24, 2020.

Johan, P. D. et al. Phosphorus transformation in soils following co-application of charcoal and wood ash. Agronomy, v.11, 2010, 2021. https://doi.org/10.3390/agronomy11102010

Leite, R. M. V. B. C. et al. Girassol no Brasil. Londrina: Embrapa Soja, 2005. 641p.

Mar, G. D. do. et al. Limestone and silicate applications by different methods to correct soil acidity. Journal of Agricultural Science, v.14, p.114-125, 2022. https://doi.org/10.5539/jas.v14n4p114

Martins Filho, M. C. F. et al. Application effect of rice husk ash on soil attributes under grassland. Agroecossistemas, v.11, p.146-163, 2020. http://dx.doi.org/10.18542/ragros.v11i2.7483

Menezes, J. F. S. et al. Surface application of calcium and magnesium silicate in soybean production. Journal of Plant Nutrition, v.48, p.3260-3272, 2025. https://doi.org/10.1080/01904167.2025.2509157

Nolla, A. et al. Correção da acidez e disponibilização de fósforo e potássio em Latossolo Vermelho Distrófico típico submetido à calagem incorporada e superficial. Brazilian Journal of Animal and Environmental Research, v.3, p.2478-2487, 2020. https://doi.org/10.34188/bjaerv3n3-156

Oliveira, A. B. et al. A cultura do girassol. 1.ed. Viçosa: UFV, 2022. 391p.

Oliveira, C. M. B. et al. Capacidade de predição da disponibilidade de fósforo em solo com aplicação de fosfato solúvel e natural. Científica, v.43, p.413–419, 2015.

Oliveira, D. D. et al. Evaluation of the normalized difference vegetation index and the concentration of carotenoids in limestone and silicate experiments in lettuce. Revista de Gestão e Secretariado, v.14, p.18832–18845, 2023. https://doi.org/10.7769/gesec.v14i10.2846

Omenda, J. A. et al. Phosphorus availability and exchangeable aluminum response to phosphate rock and organic inputs in the Central Highlands of Kenya. Heliyon, v.7, e06371, 2021. https://doi.org/10.1016/j.heliyon.2021.e06371

Pauletti, V.; Motta, A. C. V. Manual de calagem e adubação para o estado do Paraná. 2.ed. Curitiba: Núcleo Estadual Paraná da Sociedade Brasileira de Ciência do Solo, 2019. 289p.

Rodrigues, V. S. et al. Gas exchange and growth of sunflower subjected to saline stress and mineral and organic fertilization. Revista Brasileira de Engenharia Agrícola e Ambiental, v.26, p.840-847, 2022. http://dx.doi.org/10.1590/1807-1929/agriambi.v26n11p840-847

Sá, L. N. et al. A importância da cobertura vegetal no processo de erosão e degradação do solo no ensino da geografia. International Journal Education And Teaching, v.3, p.173-188, 2020. https://doi.org/10.31692/2595-2498.v3i3.151

Sanagiotto, R. et al. Efeito do termofosfato em cobertura nos componentes de produção e produtividade de cultivares de arroz. Nativa, v.10, p.163-169, 2022. https://doi.org/10.31413/nativa.v10i2.12690

Sherkuziev, D. Simple superphosphate by two-stage acid treatment of phosphate raw materials. IOP Conference Series: Earth and Environmental Science, v.939, 012057, 2021. https://doi.org/10.1088/1755-1315/939/1/012057

Silva, T. G. et al. Agronomic efficiency of phosphorus sources associated to acidity correctives for bean cultivation. Brazilian Journal of Biology, v.85, e296036, 2025. https://doi.org/10.1590/1519-6984.296036

Singh, V. K. et al. Genetic variability for aluminium tolerance in sunflower (*Helianthus annuus* L.). Czech Journal of Genetics and Plant Breeding, v.58, p.201-209, 2022. https://doi.org/10.17221/110/2021-CJGPB

Sutradhar, A. et al. Determining critical soil pH for sunflower production. International Journal of Agronomy, v.2014, 894196, 2014. http://dx.doi.org/10.1155/2014/894196

Taiz, L. et al. Fisiologia e desenvolvimento vegetal. 6.ed. Porto Alegre: ArtMed, 2017. 888p.

Tedesco, M. J. et al. Análise de solos, plantas e outros materiais. 2. ed. Porto Alegre: Universidade Federal do Rio Grande do Sul, 1995. 174p.

Tennant, D. A test of a modified line intersect method of estimating root length. The Journal of Ecology, v.63, p.995-1001, 1975. https://doi.org/10.2307/2258617

Vasallo, K. J. C.; Nagal, C. J. C. Sowing sustainability: A comprehensive review of upland kangkong cultivation and the role of carbonized rice husk in soil fertility and yield enhancement. International Journal of Multidisciplinary Research and Publications, v.7, p.83-90, 2025.

Zobiole, L. H. S. et al. Marcha de absorção de macronutrientes na cultura do girassol. Revista Brasileira de Ciência do Solo, v.34, p.425-434, 2010. https://doi.org/10.1590/S0100-06832010000200016