PAB Pesquisa Agropecuária Brasileira 60 years

COP30
Soil Science/ Original Article

jornada pelo CLIMA #TemQueTerCiência

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Soil carbon and nitrogen in silicate agromineral-managed pasture: a seven-year study in the Cerrado

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Received
May 11, 2025

Accepted
July 10, 2025

How to cite
SILVA, P.B. da; CARVALHO, A.M. de; JUNQUEIRA, A.M.R.; SOARES, J.P.G.; SÁ, M.A.C. de; MARCHI, G.; MARTINS, E. de S.; FIGUEIREDO, C.C. de; SANTOS, L.F. dos; SOUSA, T.R. de; OLIVEIRA, A.D. de. Soil carbon and nitrogen in silicate agromineral-managed pasture: a seven-year study in the Cerrado. **Pesquisa Agropecuária Brasileira**, v.60, e04133, 2025. DOI: https://doi.org/10.1590/S1678-3921.pab2025.v60.04133.

Abstract – The objective of this work was to investigate the long-term effect of the silicate agrominerals – basalt, biotite schist, and kamafugite –, as well as of potassium chloride fertilizer on soil carbon (C) and nitrogen (N) contents in pasture systems cultivated with *Urochloa brizantha* 'BRS Paiaguás', in the Brazilian Cerrado biome. The evaluated parameters were soil C and N stocks, organic matter fractions, and chemical and physical attributes. No significant differences were observed across treatments for C and N stocks. The total organic carbon (TOC) content of kamafugite and basalt was 15.56 g kg^{-1} and 8.21 g kg^{-1}, respectively, which were not significant. TOC correlated positively with the biological soil quality index and nutrient cycling. The particulate organic carbon fraction contributed to carbon retention near the surface, accounting for approximately 50% of C, due to biomass input and microbial activity. Micronutrient levels varied among treatments, and kamafugite showed the highest concentrations. Soil correction and fertilization applied across all treatments, before the application of silicate agrominerals, limited the isolation of agromineral effects. The study underscores the need of undertaking extended research on silicate agrominerals in chronosequences, particularly regarding nutrient dynamics and C stabilization in tropical soils.

Index terms: basalt, carbon stock, particulate organic carbon, silicate minerals, soil organic carbon.

Carbono e nitrogênio em pastagem manejada com agrominerais silicáticos: estudo de sete anos no Cerrado

Resumo – O objetivo deste trabalho foi avaliar o efeito dos agrominerais silicáticos – basalto, biotita xisto e kamafugito – e de fertilizante de cloreto de potássio sobre os teores de carbono (C) e nitrogênio (N) do solo, em pastos cultivados com *Urochloa brizantha* 'BRS Paiaguás' no bioma Cerrado brasileiro. Os parâmetros avaliados foram estoques de C e N, frações da matéria orgânica e atributos químico-físicos do solo. Não foram observadas diferenças significativas entre os tratamentos quanto aos estoques de C e N. O teor de C orgânico total (COT) do kamafugito e do basalto foi de 15,56 g kg^{-1} e 8,21 g kg^{-1}, respectivamente, não tendo sido significativos. O COT correlacionou-se positivamente ao índice biológico de qualidade do solo e ao ciclo de nutrientes. A fração de C orgânico particulado contribuiu para a retenção de C na superfície, tendo representado cerca de 50% do C, devido ao aporte de biomassa e à atividade microbiana. Os níveis de micronutrientes variaram entre os tratamentos, e o kamafugito apresentou as maiores concentrações. A correção do solo e a adubação aplicadas aos tratamentos, antes dos agrominerais silicáticos, limitaram o isolamento dos efeitos dos agrominerais. O estudo destaca a necessidade de realizar pesquisas sobre os agrominerais silicáticos em cronossequência, particularmente em relação à dinâmica de nutrientes e à estabilização de C em solos tropicais.

Termos para indexação: basalto, estoque de carbono, carbono orgânico particulado, minerais silicáticos, carbono orgânico do solo.

Introduction

Brazilian cultivated lands heavily rely on imported fertilizers which account for 85% of domestic needs of fertilizers, corresponding to 44.26 million Mg in 2024, or USD 13.5 billion (Brasil, 2025). In order to keep productivity, pastures also require fertilizers. Besides, approximately half of the Brazilian pastures are degraded (Santos et al., 2022), which means an extra demand for fertilizers. Thirty one percent of the Brazilian pastures are located in the Cerrado biome (MapBiomas, 2023).

As part of the efforts to reduce dependency on external fertilizers, as well as to lower environmental impacts, the use of silicate agrominerals has come as a long-term regional strategy (Theodoro et al., 2021).

Agrominerals can address the problem of pasture degradation and enhance soil fertility by gradually releasing essential nutrients such as potassium, calcium, and magnesium. Silicate agrominerals applied to soils concurrently capture and fix carbon to the soil, during reactions associated with enhanced weathering (Lefebvre et al., 2019; Kelland et al., 2020). In addition, these minerals are potential stabilizers of soil organic matter with the effect of fixing carbon to the earth's compartment (Buss et al., 2024). Similarly, the use of minerals of agronomic interest has the potential to favor the formation and stability of aggregates, due to the interactions established with soil organic matter and minerals present in the soil (Mao et al., 2020). Silicate minerals, soil organic matter, plants, and microorganisms act as soil weathering control agents and are also capable of modulating the community of microorganisms that forms during the process (Reis et al., 2024), impacting on organic matter fraction distribution in the soil (Buss et al., 2024; Rodrigues et al., 2024a, 2024b).

Silicate agrominerals have been selected for their agricultural relevance and ability to form new mineral phases upon dissolution, exhibiting low and high crystallinity with variable and permanent charges alongside high-surface areas (Busato et al., 2022). These attributes influence the physical protection of carbon and reduce the oxidation of soil organic matter. For instance, Rodrigues et al. (2024a) observed 38% increase of total organic carbon in a greenhouse incubation trial, using up to 48 g kg^{-1} (equivalent to 96 Mg ha^{-1}) basalt, in comparison with the control group. This increase was attributed to the formation of new mineral phases enhancing soil organic carbon and labile fractions of soil organic matter. Despite these promising findings, long-term field studies are limited in examining the effects of silicate agrominerals under tropical conditions.

The objective of this work was to investigate the long-term effect of the silicate agrominerals – basalt, biotite schist, and kamafugite –, as well as of potassium chloride fertilizer on soil carbon and nitrogen contents in pasture systems cultivated with *Urochloa brizantha* 'BRS Paiaguás', in the Brazilian Cerrado biome.

Materials and Methods

The study was carried out in experimental areas at Embrapa Cerrados, located in Brasília (15°36'28"S, 47°44'54"W, at 1,171 m altitude), in the Federal District (DF), Brazil. The experimental area has a tropical savanna climate (Aw), according to the Köppen-Geiger's classification. The annual averages recorded from January 2016 to October 2023 for rainfall and air temperature were 1,134.3 mm, and 21.5°C, respectively.

The soil in the experimental area was classified as a Latossolo Vermelho-Amarelo dystrophic (LVAd) according to the Brazilian Soil Classification System (Santos et al., 2018), i.e., Oxisol, characterized by medium fertility, and a clayey texture. The soil chemical properties of the area, at 0–20 cm soil depth, are the following ones: pH H_2O, 5.63; Al^{3+}, 0.01 $cmol_c$ dm^{-3}; K^+, 0.09 $cmol_c$ dm^{-3}; Ca^{2+}, 2.06 $cmol_c$ dm^{-3}; Mg^{2+}, 0.83 $cmol_c$ dm^{-3}; H+Al, 4.01 $cmol_c$ dm^{-3}; P Mehlich-1, 0.23 mg dm^{-3}; SOM, 28.7 g kg^{-1}; effective CEC, 3.0 $cmol_c$ dm^{-3}; and base saturation, 42.13%.

The experiment evaluated the permanent charges produced by silicate agrominerals. This type of agromineral was selected due to its regional

DOI: 10.1590/S1678-3921.pab2025.v60.04133

availability, representativeness, and potential to release essential nutrients. It was also selected because its dissolution generates permanent charges that can influence various soil properties (Busato et al., 2022; Krahl et al., 2022a). The chemical and mineralogical composition of basalt, biotite schist, and kamafugite used in the present study are presented (Table 1). The mineralogical composition determination encompassed: calcite, $CaCO_3$; pyroxene, (Ca, Na)(Mg, Fe, Al, Ti)(Si, Al)$_2$O$_6$; plagioclase, (Na, Ca)(Si, Al)$_4$O$_8$; potassium feldspar, $KAlSi_3O_8$; biotite K(Mg, Fe^{2+})$_3$[$AlSi_3O_{10}$(OH, F)$_2$]; phlogopite, $KMgSi_3O_{10}$(OH, F)$_2$; muscovite, $KAl_2(Si_3Al)O_{10}$(OH, F)$_2$; chlorite (Mg, Fe^{2+})$_5$Al(Si_3Al)O_{10}(OH)$_8$; apatite, Ca_5(PO4)$_3$(OH, F, Cl); amphibole, A0-1B2C5T8O22 (OH, F)$_2$ (where: A = Na^+, K^+; B = Ca^{2+}, Na^+, Mg^{2+}, Fe^{2+}; Mn^{2+}, Li^+; C = Mg^{2+}, Fe^{2+}, Al^{3+}, Fe^{3+}; Mn^{2+}, Zn^{2+}, Cr^{3+}, Li^+, or Ti^{4+}; T=Si, Al); smectite, (Na, Ca)$_{0.3}$(Al, Mg)$_2$$Si_4O_{10}(OH)_2$•n($H_2O$); vermiculite, (Mg, Fe^{2+}, Al)$_3$(Al, Si)$_4$$O_{10}(OH)_2$•4($H_2O$); feldspathoid, (Na, K)$AlSiO_4$; quartz, SiO_2; ilmenite, $Fe^{2+}TiO_3$; magnetite, $Fe^{2+}Fe^{3+}{}_2O_4$; hematite, Fe_2O_3; epidote, (Ca, Ce, La, Y, Th, Fe^{2+}, Mn^{2+}, Mn^{3+})$_2$(Al, Fe^{3+}, Mn^{3+}, Mn^{2+}, Ti, Cr)$_3$O(SiO_4)(Si_2O_7)(OH); zeolite chabazite, (Ca, K_2, Na_2)$_2$[$Al_2Si_4O_{12}$]$_2$•12H_2O; olivine, (Mg, Fe)$_2$$SiO_4$; melilite, (Ca, Na)$_2$(Mg, Al)(Si, Al)$_2$$O_7$; and tobermorite, $Ca_5Si_6O_{16}(OH)_2$•4H_2O.

The soil fertility correction was performed in October 2015, involving the application of 500 kg ha^{-1} of dolomitic limestone and 1 Mg ha^{-1} of gypsum. The amendments were mixed into the soil, at the 0−20 cm soil depths, using a leveling harrow. In December 2015, fertilization was carried out with 120 kg ha^{-1} of P_2O_5 (magnesium thermophosphate), and 100 kg ha^{-1} of FTE-BR12 (3.9% sulfur; 1.8% boron; 2.0% manganese, and 9.0% zinc) as a source of micronutrients. The fertilizers were mixed into the soil at 0−20 cm soil depths using a leveling harrow.

The experimental design was a randomized block encompassing three blocks and five treatments, totaling fifteen plots measuring 9 m^2 (3 x 3 m) each. Sowing was performed in the plots with pure seed (3 kg ha^{-1}) of *Urochloa brizantha* 'BRS Paiaguás', on January 25, 2016. Two doses of 50 kg ha^{-1} ammonium sulfate (20% N) were applied at 30 and 60 days after sowing (DAS). Between 2016 and 2023, the plots remained undisturbed and ungrazed. During this period, biomass cuts were made twice a year, in the dry and rainy seasons, in order to simulate grazing. The cut material was removed from the plots. Throughout the rest of the period, the senescent material was kept within the respective plots. The treatments were: 40 Mg ha^{-1} basalt; 151 Mg ha^{-1} biotite schist; 40 Mg ha^{-1} kamafugite; 33.3 kg ha^{-1} potassium chloride fertilizer; and 5) and the control without silicate agromineral or potassium chloride fertilizer. The agrominerals and the fertilizer were incorporated, using a rotary hoe, at 0−10 cm soil depths.

Soil samples were collected in October 2023, seven years and ten months after the experiment starting. Composite samples of 5 subsamples were collected at 0−10, 10−20, 20−30, 30−40, and 40−60 cm soil depths. Soil chemical attributes and granulometry (Teixeira et al., 2017) were analyzed (Table 2). Two undisturbed samples were collected, one using 100 cm^3 rings to

Table 1. Chemical and mineralogical composition of basalt, biotite schist, and kamafugite.

Agromineral	Chemical composition(1) (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	P_2O_5	Na_2O	K_2O	MnO	LOI(2)
Basalt	49.5	11.6	15.6	9.8	5.6	3.2	0.4	2.2	1.2	0.2	1.1
Biotite schist	62.6	16.8	7.8	1.44	3.2	0.86	0.2	1.93	3.19	0.12	2.17
Kamafugite	37.6	1.8	10.6	15.1	16.9	7.8	0.93	2.5	2.65	0.17	3.6

	Mineralogical composition(3) (%)																						
	MBC	Cc	Px	Pl	FK	Bt	Fl	Mu	Ct	Ap	Am	St	Vm	Fp	Qz	Im	Mt	Hm	Ep	Ze	Ol	Me	Tb2	Total
Basalt	11.1	0	35	35	5	0	0	0	0	0.9	0	2.5	0	0	2.1	6.8	1.1	0.6	0	0	0	0	0	100.1
Biotite schist	0	0	1.7	22.1	0	11.2	0	17.9	11.3	0	0	0	0	0	35.7	0	0	0	0	0	0	0	0	99.9
Kamafugite	13.9	1.77	1.77	0	1.72	0	18.1	0	2.03	2.7	0	0	1.15	8.57	3.0	0	2.9	1.07	2.8	2.16	22.1	2.2	3.39	91.3[4]

(1) Analyses carried out by the SGS Geosol laboratory (https://www.sgsgeosol.com.br) and CRTI laboratory (https://crti.ufg.br). (2) LOI: ignition loss. (3)Mineralogical analysis carried out by CRTI (https://crti.ufg.br) and the laboratory of the Universidade Federal of Pará. The analyzed materials included: MBC, low crystallinity minerals; CC, calcite; Px, pyroxene; Pl, plagioclase; FK, potassium feldspar; Bt, biotite; Fl, phlogopite; Mu, muscovite; Ct, chlorite; Ap, apatite; Am, amphibole; St, smectite; Vm, vermiculite; Fp, feldspathoid; Qz, quartz; Im, ilmenite; Hm, hematite; Ep, epidote; Ze, zeolite chabazite; Ol, olivine; Me, melilite; and Tb, tobermorite. (4) 8.7% as trace minerals.

DOI: 10.1590/S1678-3921.pab2025.v60.04133

measure soil density, and the other using a core-type auger to analyze the distribution of aggregates resistant to wet screening. Both samples were collected at 0–10, 10–20, 20–30, 30–40, and 40–60 cm soil depths. Mean weight diameter (MWD) and geometric mean diameter (GMD) of the aggregates were calculated following the method of Teixeira et al. (2017). They were categorized into four classes: ultramacroaggregates (4–8 mm); macroaggregates (2–4 mm); mesoaggregates (0.25–2 mm); and microaggregates (< 0.25 mm).

The total carbon (TC) content of the soil was determined through dry combustion, using an elemental analyzer model Vario Macro Cube (Elementar Analysensysteme, Langenselbold, Germany). Total organic carbon (TOC) was determined in soil samples collected at 0–30 cm soil depths, using wet oxidation with potassium dichromate ($K_2Cr_2O_7$) solution in acid medium (Teixeira et al., 2017). The carbon stock (CS) was determined following the protocol of Fontana et al. (2024). Particulate organic carbon (POC) was determined, and mineral-associated organic carbon (MAOC) was performed by physical fractionation of particle sizes from the 0–10, 10–20 and 20–30 cm soil depths (Teixeira et al., 2017). The determination of POC (0.053-2.00 mm) was conducted using the elemental analyzer, and the MAOC (<0.053 mm) fraction was calculated by the difference. Carbon determination of humic substances in humic acid (HA), fulvic acid (FA), and humin (HUM) fractions were performed in 0–10, 10–20, and 20–30 cm depths (Teixeira et al., 2017).

The enzymatic activities of β-glucosidase (GLU) and arylsulfatase (ARYL) were analyzed (Tabatabai, 1994). Fine earth samples (< 2.0 mm) were air-dried and incubated in A buffered solution at 37°C for one hour. The activities of GLU and ARYL were measured by the p-nitrophenol released (expressed in µg p-nitrophenol g^{-1} soil h^{-1}). Enzyme activities were measured colorimetrically, using a UV/VIS spectrophotometer model 600S (Femto, São Paulo, SP, Brazil), with detections at 420 nm for β-glucosidase and 410 nm for arylsulfatase. The enzymatic activity, and the chemical and physical analyses of soil samples from the 0–10 cm soil depths were used to calculate the quality, cycling, storage, and nutrient supply indices through the BioAS Technology. The soil quality index (SQI) was quantified integrating chemical (FERT) and biological (BIO) indicators (Mendes et al., 2021).

The assumptions of normality and homoscedasticity of the residuals were evaluated using the Shapiro-

Table 2. Mean (standard deviation) and coefficient of variation of chemical attributes of soil at 0–10 cm soil depths, under cultivation of *U. brizantha* 'BRS Paiaguás', after seven years of the incorporation of silicate agrominerals in a Latossolo Vermelho-Amarelo dystrophic (Oxisol), in the Cerrado biome, Brazil(1).

Soil property(2)	Treatment										CV(3) (%)
	Control		KCl		Basalt		Biotite schist		Kamafugite		
pH in $CaCl_2$	5.6 (±0.5)	ns	5.2 (±0.3)	ns	5.1 (±0.2)	ns	5.4 (±0.3)	ns	5.7 (±0.1)	ns	5.3
K^+ ($cmol_c\ dm^{-3}$)	0.1 (±0.0)	ns	0.1 (±0.0)	ns	0.1 (±0.0)	ns	0.1 (±0.0)	ns	0.3 (±0.2)	ns	52.8
Ca^{2+} ($cmol_c\ dm^{-3}$)	2.2 (±0.5)	ns	1.9 (±0.2)	ns	1.7 (±0.3)	ns	2.1 (±0.2)	ns	2.5 (±0.2)	ns	15.5
Mg^{2+} ($cmol_c\ dm^{-3}$)	1.3 (±0.4)	ns	1.3 (±0.4)	ns	1.0 (±0.4)	ns	1.4 (±0.2)	ns	1.8 (±0.3)	ns	20.8
Al^{3+} ($cmol_c\ dm^{-3}$)	0.0 (±0.0)	ns	0.0 (±0.0)	ns	0.00 (±0.0)	ns	0.0 (±0.0)	ns	0.0 (±0.0)	ns	38.7
H+Al ($cmol_c\ dm^{-3}$)	3.8 (±1.3)	ns	4.8 (±0.7)	ns	4.9 (±0.4)	ns	4.4 (±0.9)	ns	3.5 (±0.5)	ns	18.5
$P_{Meh\ 1}$ ($mg\ dm^{-3}$)	6.2 (±0.7)	ns	5.9 (±0.0)	ns	5.8 (±0.1)	ns	5.9 (±0.2)	ns	8.4 (±3.5)	ns	25.4
SB ($cmol_c\ dm^{-3}$)	3.6 (±1.0)	ns	3.4 (±0.5)	ns	2.8 (±0.7)	ns	3.6 (±0.4)	ns	4.5 (±0.2)	ns	15.6
CEC ($cmol_c\ dm^{-3}$)	7.4 (±0.5)	ns	8.1 (±0.7)	ns	7.7 (±0.3)	ns	8.0 (±0.8)	ns	8.0 (±0.5)	ns	7
V ($cmol_c\ dm^{-3}$)	48.9 (±14.6)	ns	41.2 (±6.0)	ns	36.8 (±7.6)	ns	45.5 (±6.9)	ns	56.8 (±4.2)	ns	17.5
Zn ($mg\ dm^{-3}$)	11.1 (±3.9)	ab	10.1 (±4.8)	b	7.1 (±3.0)	b	9.5 (±2.6)	b	18.6 (±0.8)	a	26.1
Fe ($mg\ dm^{-3}$)	48.0 (±12.2)	a	52.6 (±3.8)	a	48.8 (±3.0)	a	49.3 (±8.0)	a	72.9 (±36.2)	a	30.1
Mn ($mg\ dm^{-3}$)	13.3 (±2.7)	ab	11.7 (±1.0)	b	10.5 (±3.0)	b	13.1 (±2.9)	b	19.6 (±1.1)	a	16.9
Cu ($mg\ dm^{-3}$)	6.0 (±0.2)	a	5.9 (±0.6)	a	5.7 (±0.1)	a	5.9 (±0.2)	a	6.4 (±0.1)	a	4.4

(1)Means followed by equal letters, in the columns, did not differ, by the Tukey's test, at 5% probability. nsNonsignificant. (2)K^+, potassium; Ca^{2+}, calcium; Mg^{2+}, magnesium; Al^{3+}, exchangeable aluminum; H+Al, potential acidity; P_{Meh-1}, phosphorus extracted by Mehlich-1; SB, sum of bases; CEC, cation exchange capacity; V, base saturation; Zn, zinc; Fe, iron; Mn, manganese; Cu, copper. (3)CV = coefficient of variation.

Wilk's test and O'Neill-Mathews' test (both at α=0.05), respectively. The independence of errors was verified through the inspection of the distribution boxplot graph and the scatter plot of the residuals against the predicted values. All assumptions were met. Means were analyzed through an one-way analysis of variance, and the Tukey's test was applied, at 5% probability, to compare the means between treatments for the parameters showing significance. Statistical analyses were carried out using the R software (R Core Team, 2024).

Results and Discussion

The application of fertilizers affected some variables associated with the selected silicate agrominerals, including changes of pH and nutrient levels. The natural variation of the soil and the application of agrominerals resulted in high coefficient of variation (Table 2). The mechanical methods used in the treatments to achieve full homogenization of the agrominerals in the soil did not work as expected, since clusters of silicate agrominerals were found during the soil sampling. This homogenization is important because the dissolution of silicate agrominerals forms new mineral phases, which may be responsible for increasing the soil charges and surface area (Krahl et al., 2022a). These new mineral phases affect the physical, chemical, and organic matter properties in the treated soil (Busato et al., 2022). Thus, if clusters are observed during the sample collection, the sample should be discarded and a new one should be collected.

Despite the expectation for changes, the soil fertility attributes of pH in $CaCl_2$, K^+, Ca^{2+}, Mg^{2+}, Al^{3+}, potential acidity (H+Al), P by Mehlich-1, Fe, sum of exchangeable bases (SB), effective CEC, total CEC at pH 7, and base saturation (V%) were not significantly influenced by the application of silicate agrominerals or KCl (p>0.05) to 10 cm depth (Table 2).

Silicate agrominerals, primarily biotite schist, release K into the soil gradually as they weather (Krahl et al., 2022b; Reis et al., 2024). However, the exchangeable K contents at 0–10 cm soil depths showed no significant differences (Table 2). Part of K was removed with the harvested grass. The content K in the soil was 0.09 $cmol_c$ dm^{-3} before the experiment. According to the data obtained for the dose of 40 Mg ha^{-1} kamafugite, 0.3 $cmol_c$ dm^{-3} K content (Table 2) was verified. Current levels exceed the recommended critical level of 0.14 $cmol_c$ dm^{-3} for *U. brizantha* grown in the Cerrado (Martha Júnior et al., 2007).

Regarding Ca and Mg, the contents of these nutrients were not affected by silicate minerals or KCl, ($p > 0.05$). Basalt, biotite schist, and kamafugite are rich in Ca and Mg, in the silicate and/or carbonate forms (Table 1), which makes these nutrients available through weathering (Krahl et al., 2022b; Reis et al., 2024, Rodrigues et al., 2024a). At 0–10 cm soil depths, the contents were from 1.7 to 2.5 $cmol_c$ dm^{-3} for Ca, and from 1.0 to 1.8 $cmol_c$ dm^{-3} for Mg (Table 2). Although there was an upward trend, in comparison with the initial values (Table 3), all plots received dolomitic limestone and magnesium thermophosphate, both sources of Ca and Mg. Therefore, it is not possible to isolate the exclusive effect of silicate minerals.

At 0–10 cm soil depths, pH in $CaCl_2$ varied from 5.1 (basalt) to 5.7 (biotite schist), with no significant differences between treatments (p>0.05) (Table 3). The extractable micronutrients Zn, Mn, and Cu exhibited statistically significant differences between

Table 3. Mean composition of sand, silt, and clay, soil flocculation at three soil depths, and aggregate attributes of mean weight diameter (MWD) and geometric mean diameter (GMD) of the soil, in each treatment, in a Latossolo Vermelho-Amarelo dystrophic (Oxisol), in the Cerrado biome, Brazil.

Treatment	Sand	Silt	Clay	Floculation (%)			MWD	GMD
	($g\ kg^{-1}$)			0–10 cm	10–20 cm	20–30 cm	(mm)	
Control	393.56a	160.56a	445.88a	65.10b	67.70a	58.06ab	2.23	1.26
KCl	375.80ab	161.92a	462.28a	73.34ab	63.98ab	55.65b	2.34	1.37
Basalt	382.83a	139.06a	478.11a	76.01a	66.23a	64.52a	2.13	1.26
Biotite schist	380.44ab	148.96a	470.60a	73.74a	62.78ab	61.45ab	2.65	1.60
Kamafugite	348.42b	154.52a	497.06a	77.15a	58.61b	60.54ab	2.23	1.33

(1)Means followed by equal letters, in the same column, did not differ, by Tukey's test, at 5% probability.

the treatments ($p<0.05$) at 0–10 cm soil depths (Table 3). The averages obtained for Zn, Mn, and Cu are considered high, in comparison with the recommended levels for *U. brizantha* in the Cerrado (Martha Júnior et al., 2007). Although silicate agrominerals provide micronutrients (Rodrigues et al., 2024a, 2024b), the increased levels observed in comparison with the control and the KCl treatment cannot be solely attributed to the treatments, since FTE 12 and magnesium thermophosphate, both sources of micronutrients, were also incorporated.

The soil density values within the 0-60 cm soil depths were 1.13 and 1.21 g cm^{-3} for the KCl treatment and the control, respectively, which were not affected by the agrominerals added ($p>0.05$). The coefficient of variation for soil density was 11.51%. The application of silicate agrominerals did not affect silt and clay contents (Table 3). Sand content was significantly influenced by the application of basalt, biotite schist, and kamafugite ($p<0.05$). The soil with kamafugite application had the lowest sand content, 366.8 g kg^{-1}. Kamafugite is an ultramafic rock characterized by the composition of 22.1% olivine (Table 1). Olivine is a mineral that rapidly undergoes biological weathering, which may have played a role in the formation of particles smaller than 2 μm. In basalt, pyroxenes and plagioclase are predominant, each one representing 35% of the composition (Table 1). These minerals may dissolve and subsequently form clays within the soil.

There was no significant difference ($p>0.05$) in the distribution of stable aggregate classes in water between the treatments at 0−60 cm depth. Ultramacroaggregates ranged from 19.7% in basalt to 29.0% in biotite-schist, while macroaggregates ranged from 12.6% in basalt to 15.6% in kamafugite. Mesoaggregates varied from 43.0% in biotite-schist to 49.9% in kamafugite. Microaggregates ranged from 14.4% in biotite-schist to 19.1% in basalt. The coefficients of variation for the water-stable aggregate classes were: 28.59% for ultramacroaggregates, 10.37% for macroaggregates, 12.05% for mesoaggregates, and 28.06% for microaggregates.

The low representation of macroaggregates and microaggregates in relation to other classes may have contributed to the limited stabilization of the particulate fraction by physical protection and the MAOC sorption. Furthermore, there was a significant difference ($p<0.05$) among treatments concerning flocculation (Table 3), which is essential for maintaining the structural and functional stability of the soil. The flocculation capacity is attributed to clay minerals − including kaolinite, as well as metal oxides and hydroxides (such as iron and aluminum) − that is facilitated by electrostatic interactions (Six et al.,

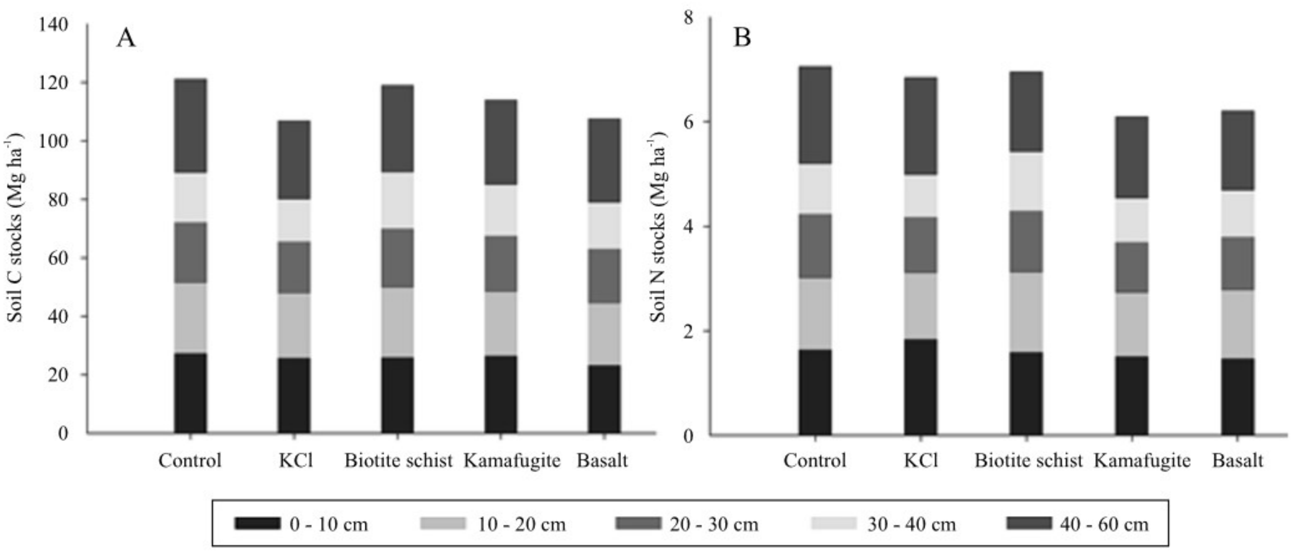

Figure 1. Soil carbon stock (A) and soil nitrogen stock (B) in the 0–60 cm soil profile of the experimental areas cultivated with *Urochloa brizantha* 'Paiaguás', for seven years, subjected to different treatments with KCl, biotite schist, kamafugite, basalt, and a control.

2002a). The tendency of soil clays to flocculate likely generates denser formation nuclei, which may reduce the formation of macroaggregates. This can result in less aeration, infiltration, and biological activity.

No significant differences ($p>0.05$) were found between the treatments for the MWD and GMD (Table 3). The concentration of aggregates within the mesoaggregate class may have influenced the results of the DMP and DMG's indexes. The higher values may be due to the high proportion of macroaggregates in the Latosol (~90%) (Silva et al., 2022).

There were no significant differences ($p>0.05$) observed for carbon stock (Figure 1A) and nitrogen stock (Figure 1B) across the treatments, despite notable variations at the 0−60 cm soil depths, from 106.83 to 121.07 Mg ha^{-1} for carbon. Although there was no significant difference between treatments, the accumulated contents in the profile are comparable to the average carbon stocks for native vegetation (117 Mg ha^{-1}) and for areas subjected to soybean-corn rotation (110.4 Mg ha^{-1}), over three decades, on Oxisol (Ferreira et al., 2016). The means observed in the present study corroborate those for carbon stock in Oxisols (98.2 Mg ha^{-1}) (Gomes et al., 2019), and for the native vegetation of Cerrado (121.23 Mg ha^{-1}) (Gonçalves et al., 2024). Soil nitrogen stocks ranged from 6.08 to 7.06 Mg ha^{-1} (Figure 1 B), and the lowest values were observed at 30−40 cm soil depths. In comparison, a study conducted in a well-managed pasture area, for 11 years, reported soil carbon stocks of 75.5 Mg ha^{-1} at 0–30 cm soil depths, and 143.6 Mg ha^{-1} down to 100 cm soil depths (Tenelli et al., 2025), which are values higher than those observed in the area of the present study. Studies assessing the impact of silicate agrominerals on soil carbon did not quantify the stock parameter (Buss et al., 2024; Reis et al., 2024; Rodrigues et al., 2024a, 2024b). Additionally, the present study did not identify any studies on the evaluation of nitrogen levels and stocks for such treatment sources.

The treatments showed no significant differences ($p>0.05$) for POC and MAOC (Figure 2 A). Considering the 0-30 cm soil depths, there was a greater participation of POC in the TC. The ratio POC:TC showed the following results: for kamafugite, 56.90%; for biotite schist, 54.37%; for basalt, 53.72%; for the control, 53.18%; and for KCl, it was 52.33%. These percentages are comparable to those reported by Figueiredo et al. (2013), who observed 46% ratio of POC:TC in pasture. This result indicates that the particulate fraction in the experiment has an important role in the accumulation of carbon within the labile fraction. Considering the individual soil depths, the highest POC contents are found near the surface, due to the influence of carbon

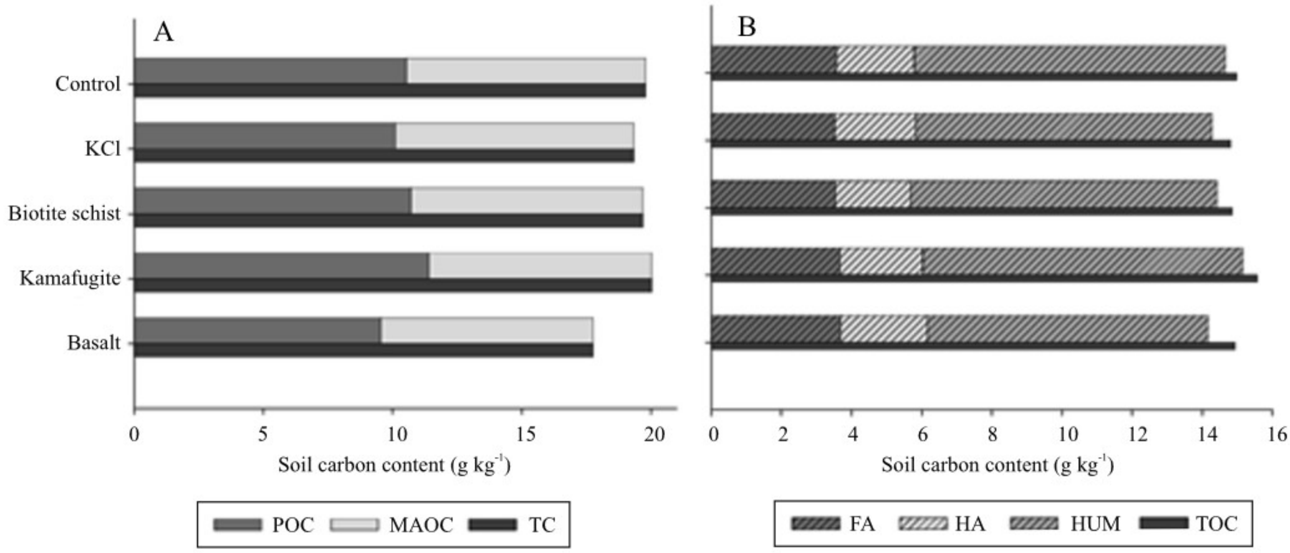

Figure 2. Soil carbon contents at 0–30 cm soil profile of the experimental areas cultivated with *Urochloa brizantha* 'Paiaguás', for seven years, subjected to different treatments: A) total soil carbon content (TC) divided into particulate organic fractions (POC) and in the mineral-associated organic carbon (MAOC); and B) total organic carbon (TOC) divided into the fulvic acid (FA), humic acid (HA), and humin (HUM).

input from the biomass of the aerial part of plants, higher root system concentration, and microbiological activity. This fraction is sensitive and quickly responds to soil management and cultivation practices (Santos et al., 2024; Sousa et al., 2024). The carbon constituent of particulate organic matter is associated with the sand fraction (> 53 μm). As a result, it lacks the chemical protection typically provided by mineral interactions (Santos et al., 2024). This finding aligns with the sensitivity of the fraction in the dynamics of organic matter in the management system (Figueiredo et al., 2018).

The observed POC means were generally higher than those recorded in *U. brizantha* pastures, which were cultivated on Oxisols in the Cerrado (Dias et al., 2019; Silva et al., 2022). In a five-year-old pasture, annually managed with conventional fertilization and without grazing, the soil showed 14.5 g kg^{-1} and 10.4 g kg^{-1} of POC at 0–10 cm and 10–20 cm soil depths, respectively (Figueiredo et al., 2013). The mean POC for the biotite schist source were similar to those results, accounting for 14.95 g kg^{-1} at 0-10 cm soil depths, and 10.78 g kg^{-1} at 10–20 cm soil depths. For the kamafugite source, the corresponding values were higher than those obtained by the authors, reaching 16.32 g kg^{-1} and 10.76 g kg^{-1}, respectively.

Although only arylsulfatase (BioAS) and Fertbio SQI were statistically significant (Table 4), some soil attributes were better correlated with the soil quality index (SQI). Total soil carbon was positively correlated with the Fertbio index (r=0.641; p<0.05), chemical properties (r=0.707; p<0.05), and nutrient storage (r=0.696; p<0.05). The POC also correlated with the Fertbio index (r=0.664, p<0.05). These correlations highlight the importance of carbon dynamics for fertility and nutrient storage capacity in weathered soils like Oxisols.

The MAOC, a stable fraction that is chemically protected by soil minerals, exhibited different properties, in comparison with POC, which is a more reactive and labile fraction. The concentration of MAOC varied between 8.21 g kg^{-1} for the basalt treatment, and 9.27 g kg^{-1} for the control treatment, with no significant difference (p>0.05). Furthermore, the MAOC exhibited uncommon concentrations in the first 10 cm, although these values were not statistically significant. The variations observed were from 7.30 to 8.91 g kg^{-1} (0–10 cm), 8.33 to 9.22 g kg^{-1} (10–20 cm), and from 8.83 to 10.50 g kg^{-1} soil (20–30 cm). Generally, the MAOC results were below the averages recorded for pastures in Oxisols, within the Cerrado biome (Figure 1 C). Specifically, the measurements were 10.4 and 20.97 g kg^{-1} for the 0–10 cm soil depths, and 10.3 and 21.09 g kg^{-1} for the 10–20 cm soil depths (Dias et al., 2019).

The lower MAOC contents at 0–10 and 10–20 cm soil depths may be related to priming effect. An incubation trial conducted with *Triticum aestivum* 'Condo', in a soil containing basalt, reported 22% increase of MAOC content, in comparison with the control (Buss et al., 2024). In the current experimental conditions, basalt showed a distinct behavior, exhibiting 11.43% reduction of carbon associated with minerals in relation to the control. Basalt exhibited the lowest average value of MAOC for treatments across the 0–10 cm and 20–30 cm soil depths, with 7.30 g kg^{-1} and 8.33 g kg^{-1}, respectively.

Nitrogen content, an essential element in the development of soil biota, can also affect the rates of stabilization and decomposition of the soil organic matter (Kuśmierz et al., 2023). Under conditions of

Table 4. Results of biological analysis of soil (BioAS) of the soils in each treatment, in a Latossolo Vermelho-Amarelo dystrophic (Oxisol) in the Cerrado biome, Brazil.

Treatment	β-Glucosidase	Arylsulfatase	Soil Quality Index (SQI)			Nutrient		
	(μg of p-nitrophenol g^{-1} soil h^{-1})		FERTBIO	Biological	Chemical	Cycling	Storage	Supply
Control	80.3	74.7 ab	0.66 ab	0.69	0.65	0.69	0.78	0.52
KCl	61.3	67.0 b	0.60 b	0.60	0.59	0.60	0.70	0.48
Basalt	66.7	67.0 b	0.60 b	0.61	0.57	0.61	0.63	0.52
Biotite schist	67.7	83.0 ab	0.62 ab	0.67	0.60	0.67	0.70	0.50
Kamafugite	80.0	104.7 a	0.68 a	0.75	0.66	0.75	0.76	0.55
CV (%)	20.91	15.05	4.61	10.71	5.37	10.71	12.24	9.97

(1)Means followed by equal letter, in the same column, did not differ by Tukey's test (α=0.05). (2)CV, coefficient of variation.

limited nitrogen and fresh exogenous carbon input, the microbiota enhances the decomposition of soil organic matter to acquire carbon, nitrogen, and other nutrients necessary for its growth (Favaro et al., 2025). While *U. brizantha* is responsive to nitrogen, fertilizing only at the start of the experiment and removing biomass twice a year might limit the nitrogen for microorganisms, leading to a positive priming effect.

The carbon content of humic substances (HS), within the fractions of fulvic acid (FA), humic acid (HA), and humin (HUM), were not significantly altered by the application of various silicate agrominerals or KCl ($p>0.05$), at depths up to 30 cm (Figure 2 B). Due to their advanced stage of humification, the humic substances exhibit reduced sensitivity to alterations resulting from short-term management practices. However, these fractions play an important role in stabilizing the soil organic matter. In the humic substance fractions, the humin fraction contains the highest concentration of carbon, accounting for approximately 60% of the carbon content among the treatments. Other studies have reported a high concentration of carbon in the humin fraction in pastures, annual crops, and integrated systems on Oxisols in the Cerrado biome (Figueiredo et al., 2018; Dias et al., 2019; Sousa et al., 2024). Among the humic substances, the fractions FA ($r=0.501$, $p<0.05$) and HA ($r=0.451$, $p<0.05$) exhibited a positive correlation with β-glucosidase. These fractions are considered the most labile ones and have the greatest propensity for microbiological activity among the chemical fractions. The fractions FA ($r=0.691$, $p<0.05$) and HA ($r=0.635$, $p<0.05$) were also found to have a significant correlation with the nutrient supply indicator, highlighting their potential to facilitate nutrient availability to plants.

Future research, especially in tropical environments, should investigate the long-term effects of silicate agrominerals on the nutrient dynamics and stabilization of organic matter, through specifically designed experiments. These studies should consider the unique characteristics of each silicate agromineral, including their ability to supply potassium, or correct soil acidity with the provision of calcium or magnesium. They should account for the pH elevation that each source provides, as this is a major factor affecting carbon capture and retention in the soil. Additionally, the added nutrient content should be considered based on their available share within the minerals prone to dissolution, during the experiment's time frame, rather than their total nutrient content.

Sources of K silicates should also be included in future studies, in order to determine their contribution, considering their slower dissolution than that of soluble K sources. To adjust the soil pH and provide calcium and magnesium, sources like limestone should be considered as supplementation. It would be also important to evaluate other carbon fractions, such as labile carbon, dissolved organic carbon, and microbial biomass carbon, as they are more sensitive indicators of short-term management changes and contribute to nutrient cycling in the soil.

Conclusions

1. Silicate agrominerals are statistically ineffective in increasing the amount of organic matter retained in the soil.
2. The correction of soil acidity and initial fertilization, combined with seven years of grass extraction from the area, decreases the efficacy of treatments as for carbon retention in new mineral particles.
3. The study provides critical insights that will inform future research on carbon accumulation in soils treated with silicate agrominerals.

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Author contributions

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Chief editor: Edemar Corazza
Edited by: Daniel Kinpara

Data availability statement

Data available upon request: research data are only available upon reasonable request to the corresponding author.

Declaration of use of AI technologies

During the preparation of this work, Giuliano Marchi used Microsoft Copilot in order to improve the translation of the manuscript to English and to edit Table 4. After this use, the authors reviewed and edited the content as needed and take full responsibility for it.

Conflict of interest statement

The authors declare no conflicts of interest.

Acknowledgments

To Fundação Arthur Bernardes (FUNARBE, cost center no. 15281 – project 7139, Vale S.A. 4600075352, Embrapa Cerrados), for the scholarships to Priscila da Silva. To Financiadora de Estudos e Projeto (FINEP), fundo setorial mineral (ref. 1541/22) and to Fundação de Apoio à Pesquisa do Distrito Federal (FAPDF, edital 09/2022), for the research grant to “Rede de PD&I sobre Remineralizadores e Agrominerais”. To Embrapa Cerrados, for their assistance during this study and to Laboratory for the Study of Soil Organic Matter (LabMOS), for providing training in laboratory analysis.