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AGRONOMIC EVALUATION OF NEPHELINE SYENITE AS A POTASSIUM SOURCE FOR SOYBEAN AND MAIZE GROWN IN A RED LATOSOL

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ABSTRACT

Objective: To evaluate the agronomic efficiency of nepheline syenite (NS) as a potassium (K) source for soybean and maize crops during the 2021/2022 and 2022/2023 growing seasons, in comparison with KCl.

Theoretical Framework: The theories underlying the findings of this study are related to sustainability in agriculture, focusing on the agronomic potential of silicate rocks for crop production.

Method: The experimental design was a randomized complete block with four replications. The K rates applied were 0; 70, and 140 kg K_2O ha^{-1}. For the 140 kg K_2O ha^{-1} rate, eight plots were established: four were evaluated in both the first and second seasons, and four were evaluated only in the second season, when they received an additional 70 kg K_2O ha^{-1}, resulting in a total of 140 + 70 kg K_2O ha^{-1}.

Results and Conclusion: Soybean yield with NS was similar to the control and lower than that obtained with KCl in the 2021/2022 season. In the following season, 140 kg K_2O ha^{-1} applied via NS increased soybean yield by up to 8%. In maize, the highest yields were obtained with 140 + 70 kg K_2O ha^{-1} applied via NS (7%) and KCl (8%). At this rate, final soil K contents increased by up to 26% with NS. A residual effect of NS was observed, as well as similar agronomic efficiency between NS and KCl at the 140 + 70 kg K_2O ha^{-1} rate.

Originality/Value: This study contributes to the development of alternatives that promote sustainability in agricultural systems and support the maintenance or restoration of soil fertility while reducing dependence on imported inputs.

Keywords: Silicate Rock, Remineralizers, Potassium Fertilization, Nutrient Availability.

AVALIAÇÃO AGRONÔMICA DO NEFELINA SIENITO COMO FONTE DE POTÁSSIO PARA SOJA E MILHO CULTIVADOS EM LATOSSOLO VERMELHO

RESUMO

Objetivo: Avaliar a eficiência agronômica do nefelina sienito (NS) como fonte de K para as culturas da soja e do milho nas safras 2021/2022 e 2022/2023, comparando com o KCl.

Referencial Teórico: As teorias que fundamentam as descobertas deste estudo são relativas à sustentabilidade na agricultura, voltadas para o potencial agronômico de rochas silicatadas no cultivo de plantas agrícolas.

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Método: O delineamento foi em blocos casualizados com quatro repetições. As doses utilizadas foram: 0; 70 e 140 kg de K_2O ha^{-1}. Para a dose de 140 kg K_2O ha^{-1}, foram estabelecidas oito parcelas: quatro foram avaliadas na primeira e na segunda safra, e quatro foram avaliadas apenas na segunda safra, quando receberam 70 kg K_2O ha^{-1}, estabelecendo 140 + 70 kg K_2O ha^{-1}.

Resultados e Conclusão: A produtividade da soja com NS foi igual ao Controle e abaixo da obtida com KCl na safra 2021/2022. Na safra seguinte, 140 kg de K_2O ha^{-1} via NS aumentou a produtividade da soja em até 8%. No milho, os maiores rendimentos foram obtidos com 140 + 70 kg de K_2O ha^{-1} via NS (7%) e KCl (8%). Para essa dose os teores de K do solo final aumentaram em até 26% com NS. Foi constatado um efeito residual do NS e uma similaridade na eficiência agronômica com 140 + 70 kg de K_2O ha^{-1} via NS e KCl.

Originalidade/Valor: Este estudo contribui para o desenvolvimento de alternativas que promovam a sustentabilidade dos sistemas agrícolas e contribuam para a manutenção ou recuperação da fertilidade do solo reduzindo a dependência de insumos importados.

Palavras-chave: Rocha Silicática, Remineralizadores, Adubação Potássica, Disponibilidade de Nutrientes.

EVALUACIÓN AGRONÓMICA DEL SIENITO NEFELÍNICO COMO FUENTE DE POTASIO PARA SOJA Y MAÍZ CULTIVADOS EN UN LATOSOL ROJO

RESUMEN

Objetivo: Evaluar la eficiencia agronómica del sienito nefelínico (NS) como fuente de potasio (K) para los cultivos de soja y maíz durante las campañas 2021/2022 y 2022/2023, en comparación con KCl.

Marco Teórico: Las teorías que fundamentan los hallazgos de este estudio están relacionadas con la sostenibilidad en la agricultura, enfocándose en el potencial agronómico de las rocas silicatadas para el cultivo de plantas agrícolas.

Método: El diseño experimental fue en bloques completos al azar con cuatro repeticiones. Las dosis de K aplicadas fueron 0; 70 y 140 kg de K_2O ha^{-1}. Para la dosis de 140 kg de K_2O ha^{-1} se establecieron ocho parcelas: cuatro fueron evaluadas en la primera y en la segunda campaña, y cuatro fueron evaluadas únicamente en la segunda campaña, cuando recibieron 70 kg de K_2O ha^{-1} adicionales, totalizando 140 + 70 kg de K_2O ha^{-1}.

Resultados y Discusión: El rendimiento de la soja con NS fue similar al control e inferior al obtenido con KCl en la campaña 2021/2022. En la campaña siguiente, 140 kg de K_2O ha^{-1} aplicados vía NS aumentaron el rendimiento de la soja hasta en un 8%. En maíz, los mayores rendimientos se obtuvieron con 140 + 70 kg de K_2O ha^{-1} aplicados vía NS (7%) y KCl (8%). Para esta dosis, los contenidos finales de K en el suelo aumentaron hasta un 26% con NS. Se constató un efecto residual del NS y una similitud en la eficiencia agronómica entre NS y KCl a la dosis de 140 + 70 kg de K_2O ha^{-1}.

Originalidad/Valor: Este estudio contribuye al desarrollo de alternativas que promuevan la sostenibilidad de los sistemas agrícolas y favorezcan el mantenimiento o la recuperación de la fertilidad del suelo, reduciendo la dependencia de insumos importados.

Palabras clave: Roca Silicatada, Remineralizadores, Fertilización Potásica, Disponibilidad de Nutrientes.

1 INTRODUCTION

Brazil is one of the world's largest grain producers, reaching an average production of 298.6 million tons in the 2023/24 season on 79.5 million hectares planted (CONAB, 2024). Excessive use of synthetic fertilizers has created environmental crises in many regions worldwide, directly affecting terrestrial, marine and freshwater ecosystems through soil acidification, eutrophication, nutrient runoff and reductions in biodiversity (Mosier *et al*., 2013; Sharpley, 2016; Kumar and Prakash, 2019). Therefore, pursuing more sustainable agricultural practices remains a major challenge for Brazilian agriculture.

Currently, Brazil imports 85% of the fertilizers consumed domestically and is the fourth largest global consumer after China, India and the United States (ANDA, 2024). Although Brazil has abundant small phosphorus (P) deposits (Pantano *et al*., 2016), the same is not true for potassium (K) deposits; Brazil imports more than 96% of the consumed K fertilizer (COMEXSTAT, 2024), resulting in high import dependence and rising production costs. In 2022, the Brazilian government introduced the National Fertilizer Plan (PNF 2022–2050) to enhance food security and mitigate the nation's exposure to external geopolitical risks associated with fertilizer imports. One objective of the plan is to increase national fertilizer production, including the discovery and development of alternative nutrient sources (Martins *et al*., 2024).

Finding alternatives that maintain soil fertility and support crop development without harming the environment is increasingly necessary. Silicate agrominerals have emerged as a promising solution, capable of improving fertility and supplying nutrients for plant growth (Van Straaten, 2022; Martins *et al*., 2014; Ramos *et al*., 2022; Luchese *et al*., 2023). Their use can sustainably raise agricultural productivity (Castro *et al*., 2021; Writzl *et al*., 2019), taking advantage of local geology and the mining potential of countries with active mineral extraction. Appropriate selection of locally available materials, combined with organic inputs, has shown significant benefits to agriculture (Van Straaten, 2006). Additionally, this practice provides an environmentally appropriate destination for mining residues (Medeiros *et al*., 2021). Brazil is rich in several silicate rocks (Brazil, 2018) with potential use as crushed K sources. When applied to soils with high organic matter, high biological activity and abundant edaphic fauna, such materials can weather and release nutrients such as K (Swoboda *et al*., 2022). In recent years, rock powders have been studied for their agronomic potential, especially for supplying K, with reports of yield gains (Nogueira *et al*., 2021; Crusciol *et al*., 2022; Barbosa *et al*., 2025; Oliveira *et al*., 2025). Soybean and maize are Brazil's main crops and together account for more than half the country’s fertilizer consumption (Globalfert, 2020). Research using agrominerals as K sources for soybean has shown promising results (Medeiros *et al*., 2021, Luchese *et al*., 2023).

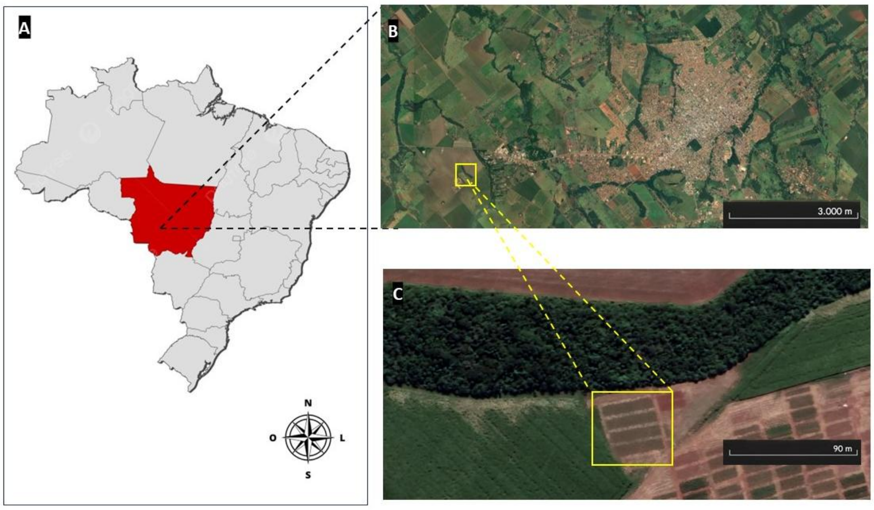
Silicate rocks have been identified as promising sources of potassium for agricultural use, with the dissolution rate being an essential factor; it is further recommended to prioritize rocks containing feldspathoids, such as nepheline (Manning, 2010). Nepheline syenite (NS) is an intrusive igneous rock with considerable K_2O content, notable for its composition of potassium feldspar and nepheline (Jena *et al*., 2014). El Messbahi *et al*., (2025) reported that NS can supply K to plants when subjected to alkaline hydrothermal treatment and found temperature to be a significant factor for K release. Soratto *et al*., (2021), seeking alternative K sources in a soybean–wheat–maize succession, found that phonolite, a feldspathoid-rich igneous rock like NS, had a more pronounced residual effect than KCl, especially in crops grown more than one year after application and at K doses above recommended levels. However, few studies have evaluated NS as a K source in rotational cropping systems over multiple seasons, an important question for production systems in Brazil’s Central-West region. Given the occurrence of NS deposits in Brazil, this study sought to assess the agronomic efficiency and residual effects of NS relative to KCl as potassium sources for soybean and maize cultivation on a Red Latosol in Mato Grosso.

2 METHOD

The experiment took place on a rainfed plot at the ASSOBASE Experimental Station near Tangará da Serra, in southwest Mato Grosso, Brazil, central South America, spanning from October 2021 to October 2023 (Figure 1). The central part of the plot is at 427 m altitude (14°38'10.66" S, 57°34'03.16" W). The regional climate is Aw (Köppen), with dry winters and rainy summers. Mean annual temperature is 24.9 °C and annual precipitation averages 1,499 mm, concentrated between October and April. During the drier months (May–September), relative humidity can fall to 47% in August. The soil of the experiment was classified as a dystrophic Red Latosol (LVd) (Embrapa, 2013). On October 5, 2021, soil samples from the 0–10 cm layer were collected, air-dried, and sieved at 2 mm for initial chemical analysis (Embrapa, 2009) (Table 1).

Figure 1

Map of Brazil with identification of the state of Mato Grosso (A); Satellite image of the city of Tangará da Serra (Google Earth) (B); Satellite image highlighting the experimental area (Google Earth®) (C).



Source: Image collected by the author, 2022.

Table 1

Chemical properties of the soil at the experimental area (0–10 cm).

Layer	pH	P	K^+	Ca^{2+}	Mg^{2+}	T	H + Al	Al^{3+}	V	O.M
cm	$CaCl_2$	mg dm^{-3}		cmol$_c$ dm^{-3}					%	g kg^{-1}
0 - 10	4.64	2.63	20	0.70	0.33	4.20	3.12	0.11	28	15.25

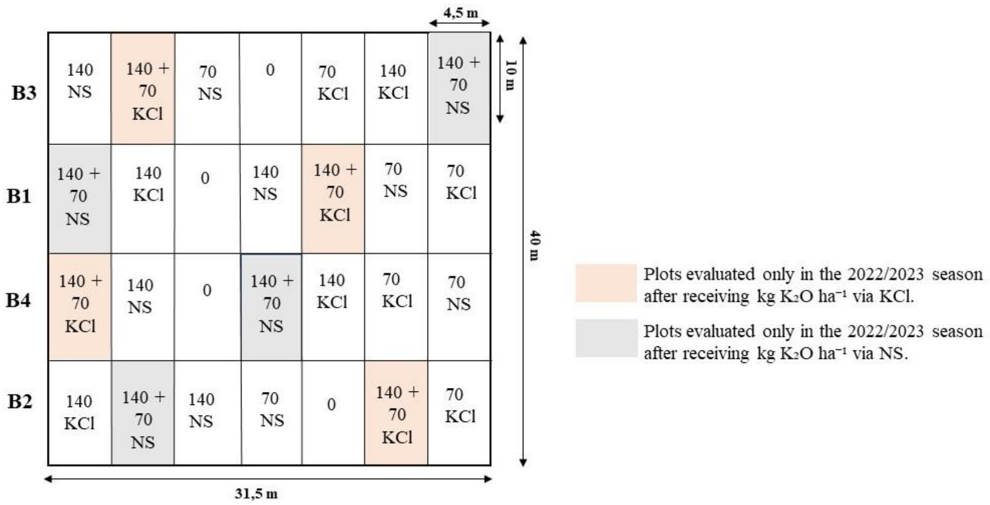
Cation exchange capacity at pH 7.0 (T) = [K^+ + Ca^{2+} + Mg^{2+} + (H + Al)]; H + Al = Potential acidity; V = base saturation; O.M = organic matter. Source: Data collected by the author, 2021.

The NS used was obtained from the western extremity of the Goiás Alkaline Province (PAGO), formed in the Upper Cretaceous. PAGO contains several agriculturally interesting rocks such as kamafugite, dunite, peridotite, pyroxenite, gabbro, phonolite and NS (Junqueira *et al.*, 2002). X-ray diffraction (XRD) analyses by the CRTI laboratory (https://crti.ufg.br/) indicated that the NS used here has a saprolitic NS mineralogy dominated by orthoclase (51.59%), microcline (24.01%), muscovite (10.50%), kaolinite (5.16%), magnetite (3.35%), albite (1.31%), chlorite (0.88%), biotite (0.83%), dolomite (0.67%) and hematite (0.55%). Major-oxide composition was: SiO_2 58.02%, Al_2O_3 22.43%, K_2O 11.70% and Fe_2O_3 2.36%. MgO, Na_2O and TiO_2 were 0.39%, 0.67% and 0.46%, respectively. CaO, P_2O_5 and MnO were below quantification limits. Loss on ignition (structural volatiles) was 3.50%. Particle size analysis of NS performed by Mineragro (https://mineragro.agr.br/) was: 100% passing a 2.0 mm sieve, at least 75% passing 0.84 mm, and at least 50% passing 0.3 mm.

The experiment was a completely randomized block design with four replications and two K sources: NS (11.70% K_2O) and KCl (60% K_2O). Potassium was broadcast and applied only once before the first cultivation at the beginning of the 2021/2022 growing season. The K rates for both sources were 0; 70, and 140 kg K_2O ha^{-1}. For the 140 kg K_2O ha^{-1} treatment, eight plots were established: four were evaluated in both the first and second growing seasons, and four were evaluated only in the second season (2022/2023), when they received an additional 70 kg K_2O ha^{-1} at planting, totaling 140 + 70 kg K_2O ha^{-1} for each source. The experiment comprised 28 plots, each measuring 45 m² (4.5 × 10 m) (Figure 2).

Figure 2

Illustration of the blocks and plots subjected to potassium rates.



Source: by the author, 2021.

Soybean (*Glycine max L.*, cv. CZ 48B32 IPRO) and maize (*Zea mays L.*, cv. AG 8480 VTPRO 4) were grown during the 2021/2022 and 2022/2023 seasons. Soybean was the main crop, sown in October, and maize was grown after soybean harvest until the end of the local cropping calendar.

Stand density was assessed by counting plants per linear meter in two parallel rows, each 4.5 m long, in the central region of each plot. Plant height was measured on four randomly selected plants per plot: for soybean from base to insertion of the last pod, and for maize from base to the last expanded leaf. Maize stem diameter was measured with a digital caliper.

Harvest was performed manually over 16 linear meters. For yield assessment, two parallel rows of 8 meters in the center of each plot were defined as the useful area. After harvest, grain samples were bagged and weighed with a hanging scale; grain moisture was recorded at harvest. Yields were adjusted to 13% moisture and converted to bags (60 kg) per hectare (bags ha^{-1}). A grain sample was also collected to determine the K export by the grains. Thousand-seed weight (TSW) was determined from four repetitions of 1000 grains, weighed on a precision scale and moisture-corrected to 13% moisture.

After each season, soil sampling (0–10 cm) for chemical analysis and fertility attributes was conducted. Six samples from each plot were pooled into one composite sample. Soil pH was measured potentiometrically in fine earth air-dry (FEAD) suspensions in 0.01 M $CaCl_2$. P and K^+ were extracted with Mehlich-1; P was measured by colorimetry and K by flame photometry. Ca^{2+} and Mg^+ were extracted with 1.0 M KCl and quantified by atomic absorption spectroscopy (AAS). From these data, sum of bases (K^+ + Ca^{2+} + Mg^2), cation exchange capacity at pH 7.0 (CTC) and base saturation (V%) were calculated. Potential acidity (H+Al) was measured using 0.5 mol L^{-1} calcium acetate extractant at pH 7.0; the released acidity was titrated with a standardized NaOH solution (Embrapa, 2011). Data were subjected to analysis of variance and, when the F-test was significant, means were compared by Tukey's test at $p < 0.05$. Statistical analyses were performed with Minitab (Minitab, 2006).

3 RESULTS AND DISCUSSIONS

This section presents the results in the following order: first, the data from the 2021/2022 growing season are presented, followed by the data from the 2022/2023 growing season. For each season, the results of the agronomic evaluations and soil fertility analyses are presented.

3.1 SEASON 2021/2022

In the first season, the slow K release from NS treatments directly impacted results. Compared with the unfertilized control, NS treatments did not differ significantly ($p < 0.05$) for any measured attribute. Plant height and yield obtained with KCl were superior to the other treatments (Table 2). The initially lower response with NS can be attributed to the low water solubility of K-bearing silicate minerals, whose nutrient release is slow (Teixeira *et al.*, 2012). Minerals such as microcline and muscovite, present in NS, are highly resistant to weathering and are not good medium-term nutrient sources or precursors of new minerals (Manning and Theodoro, 2020). Availability also depends on soil biological activity, which may delay agronomic effects to subsequent cycles, indicating a possible residual effect for a subsequent crop. Grain K export was highest in plants that received 140 kg K_2O ha^{-1} as KCl (Table 2).

Potassium rates via KCl also produced slight increases in plant height and yield, possibly related to the high solubility of KCl (Table 2). In this season, soybean yield with KCl was significantly higher than other treatments: at the lower tested rate (70 kg K_2O ha^{-1}), yield was 7% (4 bags ha^{-1}) higher than the control and 8% (4.7 bags ha^{-1}) higher than the NS treatment. With 140 kg K_2O ha^{-1}, soybean yield with KCl was 7% (3.9 bags ha^{-1}) higher than the control and 8% (4.6 bags ha^{-1}) higher than the NS treatment (Table 2).

Table 2

Soybean plant height, stand, thousand-seed weight, K export and yield (2021/2022).

Rate (kg K_2O ha^{-1})	Height (cm)	Stand (plants ha^{-1})	TSW (g)	Exported K (g kg^{-1})	Yield (bags ha^{-1})
0	70.25 b	219,000	138.91	15.79 cd	56.02 b
70 (NS)	69.80 b	220,000	139.82	15.04 d	55.39 b
140 (NS)	70.68 b	219,750	140.04	16.51 bc	55.33 b
70 (KCl)	72.26 a	220,000	139.70	17.66 ab	60.09 a
140 (KCl)	72.70 a	220,250	139.95	18.15 a	59.90 a

Means followed by different letters in the same column differ by Tukey's test ($p < 0.05$). Absence of letters in a column does not indicate difference. TSW = thousand-seed weight. Source: data collected by the author.

During maize cultivation, precipitation was well below the crop's seasonal water requirement (≈590 mm) (Andrade *et al*., 2006). In May 2022 rainfall was 0 mm (Table 3). This drought negatively affected plant development, grain filling and thus the evaluations.

Table 3

Monthly temperature, relative humidity (RH) and precipitation (months spanning Sep 2021–May 2022).

Month	Mean Temperature (°C)	RH (%)	Precipitation (mm)
Sep/21	30.23	39.78	57
Oct/21	27.81	56.26	83
Nov/21	25.95	74.75	126
Dec/21	26.43	75.08	276
Jan/22	26.03	71.69	232
Feb/22	25.62	77.75	388
Mar/22	25.27	78.60	167
Apr/22	25.09	86.89	29
May/22	26.75	81.34	0
Mean	26.58	71.35	150.88

Source: ASSOBASE

Low K availability in NS-treated soils likely limited soybean yields in the first season, as slow nutrient release and low solubility of K-bearing silicates, combined with a short experimental duration, may not have allowed sufficient nutrient release to increase K levels (Table 4). Compared with the unfertilized soil, there was no difference in soil K with NS at either 70 or 140 kg K_2O ha^{-1}. Both NS treatments also underperformed relative to 70 and 140 kg K_2O ha^{-1} applied as KCl. In a leaching study, only 1.6% of the K present in NS was leached, indicating that K remains bound in mineral structures and requires acid or alkaline treatment to be released (Jena *et al*., 2014). K availability from NS depends on mineralogy and mineral reactivity. Jena *et al*. (2014) also observed, using different K extraction methods, that K in NS is intrinsically associated with multiple mineral phases in the host rock. Conversely, due to its high solubility, KCl use resulted in higher soil K contents: increases of 15% for 70 kg K_2O ha^{-1} and 22% for 140 kg K_2O ha^{-1} compared with the control (Table 4).

Table 4

Chemical characteristics of the Red Latosol at the end of the 2021/2022 season (0–10 cm).

Rate kg de K_2O ha^{-1}	**pH** $CaCl_2$	**P** mg dm^{-3}	**K^+**	**Ca^{2+}** $cmol_c$ dm^{-3}	**Mg^{2+}**
0	4.80	2.53	21.30 bc	0.67	0.35
70 (NS)	4.81	2.49	20.26 c	0.72	0.37
140 (NS)	4.82	2.78	22.53 b	0.70	0.30
70 (KCl)	4.80	2.51	24.46 a	0.72	0.27
140 (KCl)	4.81	2.89	26.18 a	0.67	0.30
Rate kg de K_2O ha^{-1}	**H +Al** $cmol_c$ dm^{-3}	**Al^{3+}**	**T**	**V** %	**O.M** g kg^{-1}
0	3.05	0.14	4.12	26.13	15.23
70 (NS)	3.00	0.13	4.15	27.72	14.57
140 (NS)	2.92	0.13	3.98	26.53	14.92
70 (KCl)	2.90	0.14	3.96	26.79	14.53
140 (KCl)	3.00	0.13	4.06	25.57	14.30

Means followed by different letters in the same line differ by Tukey's test ($p < 0.05$). Absence of letters in the same column does not indicate difference by Tukey's test. H + Al = Potential acidity; T = cation exchange capacity at pH 7.0 [K^+ + Ca^{2+} + Mg^{2+} + (H + Al)]; H + Al = Potential acidity; V = base saturation; O.M = organic matter. Source: data collected by the authors.

3.2 SEASON 2022/2023

Except for the lower NS rate (70 kg K_2O ha^{-1}) and compared with the control treatment, all other treatments had significant effects on plant height and TSW ($p < 0.05$; Table 5). The NS rates of 140 and 140 + 70 kg K_2O ha^{-1} increased soybean plant height by up to 10% and 11%, respectively. For height, there was no difference between the 140 + 70 kg K_2O ha^{-1} NS treatment and KCl treatments. However, the largest difference relative to the control was observed with the 140 + 70 kg K_2O ha^{-1} applied as KCl, with increases up to 13%. When compared with the control treatment potassium fertilization also increased TSW: NS rates raised TSW by up to 4% (7.2 g) and 3% (5.0 g) for 140 and 140 + 70 kg K_2O ha^{-1}, respectively.

Nevertheless, TSW was higher in plants that received the 140 and 140 + 70 kg K_2O ha^{-1} rates as KCl (Table 5).

Although no significant difference in K export was observed between NS treatments and the control, an agronomically relevant result was seen with 140 kg K_2O ha^{-1} via NS: productivity increased by up to 8% (5.2 bags ha^{-1}) over the control, reaching 66.43 bags ha^{-1} (Table 5), a value above the national average for that year (CONAB, 2023). For the same rate as KCl, yields increased by up to 6% (3.9 bags ha^{-1}) compared with the control (Table 5). There was no significant difference by Tukey's test in soybean grain yield between NS and KCl at 140 kg K_2O ha^{-1}. Similar research using fine microgabbro rock powders on an Argissol has reported soybean yields above the national average (Almeida Junior *et al*., 2020), including studies using dacite rock powder (Medeiros *et al*., 2021).

The yield increase with 140 kg K_2O ha^{-1} via NS may be associated with bioweathering, the primary mechanism of mineral transformation on agronomic time scales (Krahl *et al*., 2022). Minerals such as biotite and potassium feldspar rely on this process for compositional change, and organic matter from previous crop residues may have contributed to improving nutrient availability and soil chemical and microbiological quality (Rodrigues *et al*., 2014). Considering the yield results and the experiment duration, there was a similarity in agronomic efficiency between the two sources tested and a likely residual effect of the 140 kg K_2O ha^{-1} NS treatment approximately one year after application.

Table 5

Soybean height, stand, thousand-seed weight, K export and yield (2022/2023).

Rate (kg K_2O ha^{-1})	**Height (cm)**	**Stand (plants ha^{-1})**	**TSW (g)**	**K export (g kg^{-1})**	**Yield (bags ha^{-1})**
0	62.55 d	221,000	162.36 c	13.77 b	61.18 cd
70 (NS)	67.95 cd	221,500	162.64 c	14.16 b	61.76 cd
140 (NS)	68.87 bc	221,500	169.62 b	14.71 ab	66.43 a
140 + 70 (NS)	69.62 ab	221,500	167.43 b	14.61 ab	63.57 bc
70 (KCl)	69.85 ab	222,000	168.15 b	14.27 ab	60.74 d
140 (KCl)	69.65 ab	221,000	172.32 a	14.78 ab	65.11 ab
140 + 70 (KCl)	70.87 a	222,000	173.61 a	15.43 a	67.22 a

Means followed by different letters in the same column differ by Tukey's test ($p < 0.05$). Absence of letters in the same column does not indicate difference. TSW = thousand-seed weight. Source: data collected by the authors.

In maize, the replacement rate (140 + 70 kg K_2O ha^{-1}) with NS produced significant increases in plant height, stem diameter, K export by grains and yield (Table 6). Regardless of source, plants receiving 140 + 70 kg K_2O ha^{-1} had greater apical growth than other treatments, with increases of up to 5 cm for plants grown with NS and KCl compared to the control (Table

6). The replacement rate with NS also increased maize stem diameter by up to 7% (Table 6), a beneficial effect because greater stem diameter is associated with increased lateral root growth, facilitating nutrient uptake. The highest K export by grain was obtained with 140 + 70 kg K_2O ha^{-1} via NS, with increases up to 34% compared to control. There was no significant difference between NS and KCl for the same treatment (Table 6). The increased K export in this study aligns with Santos *et al*., (2021), who found increased K uptake by maize using biotite syenite as an alternative nutrient source in a Latosol.

Because NS is a low-solubility, slow-release source, rhizosphere activity may have promoted nutrient release via root exudation of organic acids, increasing solubility of K-bearing minerals (Bray *et al*., 2015; Burghelea *et al*., 2015). Plant-induced weathering of silicate minerals and nutrient release has been studied for decades (Hinsinger *et al*., 2001; Landeweert *et al*., 2001). Nogueira *et al*. (2021) also showed that when ground to a fine fraction, NS is a natural K source. Grinding can convert structural K into more available forms and increase the proportion of fine fractions (Madaras *et al*., 2013).

Possible release of Fe from NS minerals did not hinder K export increases (Table 6). Murakami *et al*. (2004) reported that greater structural Fe concentration accelerates modification and K release from biotite, favoring formation of secondary minerals like hydrobiotite and vermiculite. However, differences in charge and membrane saturation effects among cations can influence absorption; some cations in high soil availability can antagonize others. Grasses (monocots) have evolved efficient Fe mobilization compared with dicots, which may influence interactions (Broadley *et al*., 2012). Crusciol *et al*. (2022) also demonstrated that broadcast application of K-rich silicate agrominerals (mainly potassium feldspar) can have high agronomic efficiency relative to KCl.

Maize yield at the NS replacement rate (140 + 70 kg K_2O ha^{-1}) was lower than yield at the same rate with KCl. Nevertheless, yields increased by up to 7% (5.4 bags ha^{-1}) with NS and 8% (6.5 bags ha^{-1}) with KCl relative to the control (Table 6), indicating that the NS effect combined with the supplementary dose in the second season produced significant improvements in maize development.

Table 6

Maize height, stand, thousand-seed weight, stem diameter, K export and yield (2022/2023).

Rate (kg K_2O ha^{-1})	Height (cm)	Stand (plants ha^{-1})	TSW (g)
0	162.98 c	71,250	298.86
70 (NS)	163.01 c	71,750	298.60
140 (NS)	165.10 b	71,500	298.25
140 + 70 (NS)	168.61 a	71,750	299.22
70 (KCl)	164.05 bc	71,250	298.38
140 (KCl)	164.92 b	71,500	298.26
140 + 70 (KCl)	168.27 a	72,250	299.94
Rate (kg K_2O ha^{-1})	**Stem diameter (mm)**	**K export (g kg^{-1})**	**Yield (bags ha^{-1})**
0	16.57 b	3.20 b	78.44 d
70 (NS)	17.18 ab	3.52 b	79.36 cd
140 (NS)	17.14 ab	3.64 b	79.55 cd
140 + 70 (NS)	17.72 a	4.29 a	83.83 ab
70 (KCl)	16.70 b	3.49 b	80.03 cd
140 (KCl)	17.03 ab	3.54 b	81.32 bc
140 + 70 (KCl)	17.16 ab	4.32 a	85.00 a

Different letters in the same column differ by Tukey's test ($p < 0.05$). TSW = thousand-seed weight. Source: data collected by the authors.

Soil fertility results at the end of season two showed significant differences relative to the control in soil K contents with the 140 and 140 + 70 kg K_2O ha^{-1} rates via NS. Although K levels remained below the adequacy threshold (50 mg dm^{-3}) indicated by Sousa and Lobato., (2004), there was up to a 26% increase in soil K with the NS replacement rate (140 + 70 kg K_2O ha^{-1}) (Table 7). Importantly, there was no significant difference ($p < 0.05$) between NS and KCl at the 140 + 70 kg K_2O ha^{-1} rate. Oliveira *et al.* (2025) observed a linear increase in soil K after a 60-days incubation of Latosol subjected to increasing siltstone mining waste powder doses.

The increased K availability likely contributed to yield increases, possibly favored by bioweathering, the principal mineral transformation mechanism on agronomic time scales. Certain minerals, such as biotite present in NS, depend on bioweathering for transformation. Although mostly incongruent, dissolution rates of biotite-type minerals found in rocks like schists and syenites can be relatively rapid, indicating that such rocks can be suitable K sources (Burghelea *et al.*, 2015; Li *et al.*, 2015; Manning *et al.*, 2017).

These results are consistent with other studies suggesting use of rock powders in agriculture as slow-release alternative K supplements (Da Silva *et al.*, 2012, Teixeira *et al.*, 2012). Theodoro *et al.* (2013) demonstrated interactions between agrominerals from five rock types and the soil–plant system, showing nutrient availability in tropical soils for diverse crops. This strategy enables farmers with limited resources to access alternative effective K sources, reducing dependence on conventional fertilizers and contributing to a more sustainable agriculture in which food security is central to development (Manning and Theodoro, 2020). Soil fertility results showed no significant change in pH in either season (Table 7). Application of small doses and the low CaO and MgO concentrations in NS likely explain the unchanged soil acidity.

Table 7

Chemical characteristics of the Red Latosol at the end of the 2022/2023 season (0–10 cm).

Rate **kg K_2O ha^{-1}**	**pH** **$CaCl_2$**	**P** **mg dm^{-3}**	**K^+**	**Ca^{2+}** **cmol$_c$ dm^{-3}**	**Mg^{2+}**
0	4.75	1.72	15.21 c	0.35	0.22
70 (NS)	4.73	1.78	16.02 bc	0.45	0.25
140 (NS)	4.81	1.71	16.93 b	0.44	0.25
140 + 70 (NS)	4.75	1.69	19.14 a	0.47	0.25
70 (KCl)	4.73	1.71	16.57 bc	0.37	0.20
140 (KCl)	4.74	1.78	16.49 bc	0.47	0.20
140 + 70 (KCl)	4.82	1.80	18.98 a	0.37	0.22
Rate **kg K_2O ha^{-1}**	**H +Al** **cmol$_c$ dm^{-3}**	**Al^{3+}**	**T**	**V** **%**	**O.M** **g kg^{-1}**
0	3.06	0.12	3.67	16.66	15.94
70 (NS)	3.02	0.11	3.76	19.65	16.45
140 (NS)	3.04	0.10	3.79	19.51	16.58
140 + 70 (NS)	3.00	0.10	3.77	20.38	16.48
70 (KCl)	3.07	0.10	3.69	16.70	16.37
140 (KCl)	3.04	0.12	3.76	19.03	16.24
140 + 70 (KCl)	2.98	0.10	3.62	17.26	15.89

Means followed by different letters in the same line differ by Tukey's test ($p < 0.05$). Absence of letters in the same column does not indicate difference by Tukey's test. H + Al = Potential acidity; T = cation exchange capacity at pH 7.0 [$K^+ + Ca^{2+} + Mg^{2+} + (H + Al)$]; H + Al = Potential acidity; V = base saturation; OM = organic matter. Source: data collected by the authors.

4 CONCLUSION

In the 2021/2022 season, soybean yields with NS were inferior to those obtained with the same K_2O rates applied as KCl. In the 2022/2023 season, NS rates of 140 and 140 + 70 kg K_2O ha^{-1} increased soybean plant height by up to 10% and 11%, respectively, and TSW by up to 4% and 3%, respectively. Soybean yield increased by up to 8% with 140 kg K_2O ha^{-1} via NS. For that rate, there was no significant difference in yield between NS and KCl. For maize in 2022/2023, plants receiving 140 + 70 kg K_2O ha^{-1} via NS showed increases in height (3.5%), stem diameter (7%), K export (34%) and productivity (7%). For the same rate, soil K contents increased by up to 26% with NS. Agronomic efficiency was similar between NS and KCl at the 140 + 70 kg K_2O ha^{-1} rate. A residual effect of NS was observed in the 2022/2023 season: the 140 kg K_2O ha^{-1} NS rate produced residual yield benefits for soybean, and the 140 + 70 kg K_2O

ha^{-1} NS rate produced residual yield benefits for maize. These residual effects were also reflected in soil K contents.

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