

Soil remineralizer: effects on maize silage and soil organic matter

Remineralizador de solo: efeitos na silagem de milho e matéria orgânica do solo

Remineralizador de suelo: efectos en el ensilado de maíz y la materia orgánica del suelo

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ABSTRACT

The excessive use of chemical fertilizers has led to environmental and economic impacts, encouraging the search for sustainable alternatives. In this context, the present study aimed to evaluate the agronomic efficiency of the remineralizer REKAL in silage maize, as well as its effect on residual soil labile carbon. Two experiments were conducted in a greenhouse with micro-sprinkler irrigation. In Experiment 1, doses ranging from 20 to 160 kg/ha of K₂O REKAL were applied via REKAL, in addition to treatments with KCl, FMX, and REKAL combined with *Azospirillum brasilense* (60 kg/ha). In Experiment 2, doses from 30 to 240 kg/ha of K₂O REKAL were tested, using the same comparative treatments. Biometric parameters, foliar potassium concentration, residual soil potassium, yield, and labile carbon were evaluated. The results demonstrated high efficiency of REKAL compared to KCl and FMX, especially in treatments combining the remineralizer with plant growth-promoting microorganisms. The best responses varied according to dose and treatment combination, resulting in significant increases in plant height, stem diameter, potassium accumulation, and productivity. The recommended dose for the crop was 120 kg/ha of K₂O REKAL. It is concluded that REKAL is a promising alternative to conventional fertilizers, contributing to a more productive and environmentally responsible agriculture.

Keywords: Rock dust. Environmental sustainability. *Zea Mays*. Fertilizer. Natural resource. Productivity.

RESUMO

O uso excessivo de fertilizantes químicos tem gerado impactos ambientais e econômicos, incentivando a busca por alternativas sustentáveis. Neste contexto, a presente pesquisa teve como objetivo avaliar a eficiência agrônômica do remineralizador REKAL na cultura de milho silagem, bem como seu efeito sobre o carbono lábil do solo residual. Dois experimentos foram conduzidos em casa de vegetação com irrigação por microaspersão. No Experimento 1, foram aplicadas doses de 20 a 160 kg/ha de K₂O REKAL, além dos tratamentos com KCl, FMX e REKAL associado a *Azospirillum brasilense* (60 kg/ha). No Experimento 2, testaram-se doses de 30 a 240 kg/ha de K₂O REKAL, com os mesmos tratamentos comparativos. Avaliaram-se parâmetros biométricos, concentração foliar de potássio, potássio residual no solo, produtividade e carbono lábil. Os resultados demonstraram alta eficiência do REKAL em comparação ao KCl e FMX, com destaque para os tratamentos que associaram o remineralizador a microrganismos promotores de crescimento. A dose de 120 kg/ha de K₂O REKAL foi identificada como a mais recomendada para a cultura. Conclui-se que o REKAL é uma alternativa promissora para substituir

fertilizantes convencionais, contribuindo para uma agricultura mais produtiva e ambientalmente responsável.

Palavras-chave: Pó de rocha. Sustentabilidade ambiental. *Zea Mays*. Recurso natural. Produtividade.

RESUMEN

El uso excesivo de fertilizantes químicos ha generado impactos ambientales y económicos, incentivando la búsqueda de alternativas sostenibles. En este contexto, el presente estudio tuvo como objetivo evaluar la eficiencia agronómica del remineralizador REKAL en maíz para ensilaje, así como su efecto sobre el carbono lábil residual del suelo. Se realizaron dos experimentos en invernadero con riego por microaspersión. En el Experimento 1, se aplicaron dosis de 20 a 160 kg/ha de K_2O vía REKAL, además de tratamientos con KCl, FMX y REKAL combinado con *Azospirillum brasilense* (60 kg/ha). En el Experimento 2, se evaluaron dosis de 30 a 240 kg/ha de K_2O REKAL, con los mismos tratamientos comparativos. Se analizaron parámetros biométricos, concentración foliar de potasio, potasio residual en el suelo, productividad y carbono lábil. Los resultados demostraron una alta eficiencia del REKAL en comparación con KCl y FMX, destacándose los tratamientos que combinaron el remineralizador con microorganismos promotores del crecimiento vegetal. Las mejores respuestas variaron según la combinación de dosis y tratamiento, con incrementos significativos en altura, diámetro del tallo, acumulación de potasio y productividad. La dosis recomendada para el cultivo fue de 120 kg/ha de K_2O REKAL. Se concluye que el REKAL es una alternativa prometedora a los fertilizantes convencionales, contribuyendo a una agricultura más productiva y ambientalmente responsable.

Palabras clave: Polvo de roca. Sostenibilidad ambiental. *Zea mays*. Fertilizante. Recurso natural. Productividad.

1 INTRODUCTION

The increasing demand for food and the intensification of modern agriculture have driven the widespread use of chemical fertilizers as a strategy to boost productivity. However, the excessive use of these inputs—especially those derived from non-renewable mineral sources—has raised concerns regarding environmental impacts, foreign dependency, and the long-term sustainability of agricultural production systems. In this context, alternatives based on natural-origin inputs, such as rock powders or remineralizers, have gained prominence due to their potential to supply nutrients more gradually and with lower ecological

impact.

In Brazil, the country's significant dependency on imported potassium, combined with high logistical costs and geopolitical vulnerabilities, underscores the urgent need for more sustainable domestic solutions. At the same time, there is growing interest in strategies that promote soil regeneration and increase carbon stocks, particularly in the labile fraction, which serves as a sensitive indicator of soil quality.

Given this context, the present study aimed to evaluate the agronomic efficiency of the remineralizer REKAL in silage maize (*Zea mays* L.) cultivation, as well as its effects on the residual labile soil organic carbon, through greenhouse experiments with different application rates and comparative treatments.

2 LITERATURE REVIEW

The use of fertilizers has become increasingly important to improve crop yield and quality (Hussain *et al.*, 2022). However, the widespread application of soluble mineral fertilizers, derived from non-renewable sources, raises concerns regarding environmental impacts, energy costs, and the long-term sustainability of agricultural systems (Netto-Ferreira *et al.*, 2024). Kopittke *et al.* (2019) emphasize that the greatest challenge facing modern agriculture is maintaining or increasing yields without further degrading environmental systems, particularly soils.

According to Swoboda *et al.* (2022), the recycling of mining industry by-products from domestic operations may represent a viable solution to both waste disposal challenges and the need for self-sufficiency in fertilizer production. Alovisi *et al.* (2023) note that the dependency on foreign raw materials and the high costs of fertilizers have spurred the development of alternatives, such as rock dusts or remineralizers, especially in countries like Brazil, where agricultural potassium demand far exceeds domestic production capacity (Assunção *et al.*, 2024).

Remineralizers, or rock powders, are mineral-based materials

mechanically ground into fine particles, capable of improving soil fertility by supplying macro- and micronutrients to plants (BRASIL, 2013). Alovisi *et al.* (2023) define them as milled silicate rocks, rich in base cations and sources of calcium (Ca), magnesium (Mg), iron (Fe), silicon (Si), and potassium (K), as well as micronutrients and primary minerals.

Recent studies reinforce the potential of remineralizers as alternative nutrient sources. Assunção *et al.* (2024) reported positive outcomes with the application of these inputs, particularly when combined with biological inoculants such as *Azospirillum brasilense*, which enhanced the availability of potassium and calcium at intermediate and high application rates (300 and 600 kg ha⁻¹ of K₂O).

Beyond mineral nutrition, remineralizers may positively influence soil organic matter (SOM) stocks, especially its labile fraction, which is considered an important indicator of soil carbon quality and stability (Crespo *et al.*, 2024). Ramírez *et al.* (2020) observed that the content of labile carbon may serve as an early warning signal for soil degradation, being affected by factors such as pH, light organic matter, and the ratio between permanganate-oxidizable carbon and total organic carbon.

Brasil *et al.* (2023) demonstrated that the remineralizer K6 performs comparably to KCl and FMX (fine mica schist from the Companhia Mineradora Pedreira Araguaia) in supplying potassium, optimizing nutrient management for crops such as soybean and silage maize. Similarly, Ribeiro *et al.* (2020) showed that the combination of rock powders with nutrient-solubilizing microorganisms can enhance the release of nutrients from the mineral matrix.

REKAL is a remineralizer developed by Stracta Mineradora, located in Vila Propício, Goiás (Brazil), and registered with the Ministério da Agricultura, Pecuária e Abastecimento (MAPA). Brasil *et al.* (2024) confirmed its agronomic efficiency as comparable to KCl and the FMX remineralizer, making it a viable alternative for supplying K, Ca, and Mg in agricultural systems. In light of this, it becomes essential to investigate not only the productive performance of REKAL but also its effects on ecological indicators such as soil organic matter and labile soil carbon.

3 MATERIALS AND METHODS

The research was carried out in a greenhouse, under automated overhead irrigation, at the School of Agronomy (EA) of the Federal University of Goiás (UFG), Samambaia Campus, in the municipality of Goiânia, Goiás, geographical coordinates 16°40'22"S and 49°15'19" W.

Two experiments were set up. Experiment 1 used soil collected at the EA/UFG Nursery School. Physical and chemical analyses were performed at the Terra Laboratory (accredited by MAPA) on a sample of Red Latosol with a sandy-clay texture, as shown in Table 1.

Table 1. Chemical and physical properties of the soil used in Experiment 1

Property	Unit/Symbol	Result
pH (CaCl ₂)	Un.	4.8
Ca	cmol _c /dm ³	1.5
Mg	cmol _c /dm ³	0.4
Ca+Mg	cmol _c /dm ³	1.9
Al	cmol _c /dm ³	0.10
H+Al	cmol _c /dm ³	2.1
CTC	cmol _c /dm ³	4.20
P (Mehlich I)	mg/dm ³	17.0
K	cmol _c /dm ³	0.205
K	mg/dm ³	80
Na	mg/dm ³	2
S	mg/dm ³	5
B	mg/dm ³	0.27
Cu	mg/dm ³	1.5
Fe	mg/dm ³	212
Mn	mg/dm ³	69
Zn	mg/dm ³	3.3
Org. Mat.	%	1.0
Org. Mat.	g/kg	10.0
Sat. Al	(M%)	5
Sat. Base	(V%)	50
Ca/Mg		3.8
Ca/CTC	%	35.7
Mg/CTC	%	9.5
(H+Al)/CTC	%	50.0
K/CTC	%	4.9
Clay	%	4.2
Clay	g/kg	420.0
Silt	%	7
Silt	g/kg	70.0
Sand	%	51
Sand	g/kg	510.0

Source: Laboratório Terra (2023).

For Experiment 2, the physical and chemical analyses were conducted at the Terra Laboratory (accredited by MAPA) on a sample of red latosol with a sandy loam texture, as shown in Table 2.

Table 2. Chemical and physical properties of the soil used in Experiment 2

Property	Uniy/Symbol	Result
pH (CaCl ₂)	Un.	5.2
Ca	cmol _c /dm ³	1.7
Mg	cmol _c /dm ³	0.6
Ca+Mg	cmol _c /dm ³	2.3
Al	cmol _c /dm ³	0.00
H+Al	cmol _c /dm ³	2.0
CTC	cmol _c /dm ³	4.36
P (Mehlich I)	mg/dm ³	1.0
K	cmol _c /dm ³	0.056
K	mg/dm ³	22
Org. Mat.	%	4.8
Org. Mat.	g/kg	48.0
Sat. Al (M%)	%	0
Sat. Base (V%)	%	54
Ca/Mg		2.8
Ca/CTC	%	38.6
Mg/CTC	%	13.6
(H+Al)/CTC	%	45.5
K/CTC	%	1.3
Clay	%	31
Clay	g/kg	310.0
Silt	%	11
Silt	g/kg	110.0
Sand	%	58
Sand	g/kg	580.0

Source: Laboratório Terra (2023).

The maize was sown using five seeds per pot of Hybrid SEMPRE 20A12 VIP3 RE18. Each experiment used 40 pots, adding up to a total of 80 containers (experimental units), each with a capacity of 9 dm³. Eight treatments were performed per experiment, with five replications in each study. Tables 3 and 4 show the treatments for Experiment 1 and Experiment 2, respectively. Inoculation was carried out using *Azospirillum brasilense* in the maize seed.

Table 3. Treatments used in Experiment 1

TREATMENTS	
T1	Witness
T2	20 kg/ha K ₂ O REKAL
T3	40 kg/ha K ₂ O REKAL
T4	80 kg/ha K ₂ O REKAL

T5	160 kg/ha K ₂ O REKAL
T6	60 Kg/ha of K ₂ O KCl
T7	60 Kg/ha of K ₂ O FMX
T8	60 kg/ha K ₂ O REKAL + <i>Azospirillum brasilense</i>

Source: The authors.

Table 4. Treatments used in Experiment 2

TREATMENTS	
T1	Witness
T2	30 kg/ha K ₂ O REKAL
T3	60 kg/ha K ₂ O REKAL
T4	120 kg/ha K ₂ O REKAL
T5	240 kg/ha K ₂ O REKAL
T6	60 Kg/ha of K ₂ O KCl
T7	60 Kg/ha of K ₂ O FMX
T8	60 kg/ha K ₂ O REKAL + <i>Azospirillum brasilense</i>

Source: The authors.

Following the processes of drying, crumbling, and sieving, the pots were filled with 9 dm³ of red latosol with a sandy-clay texture in Experiment 1 and red latosol with a sandy-clay texture in Experiment 2. The pots were labeled and tagged with the eight treatments and five replications per treatment.

Table 5 describes the calculation for these fertilizers based on the Recommendations of Correctives and Fertilizers for Goiás, 5th approximation (COMISSÃO DE FERTILIDADE DO SOLO DE GOIÁS – UFG/ENGOPA, 1988). The recommended planting fertilization consisted of 60 kg/ha of P₂O₅, 40 kg/ha of K₂O, 20 kg/ha of N, 2.5 kg/ha of Zn, and 2.0 tons per hectare of dolomitic lime.

Table 5. Fertilization with phosphorus, potassium, nitrogen, and zinc in Experiment 1

Element	Amount (g/pot)
Phosphorus	60 kg/ha of P ₂ O ₅
Potassium	40 kg/ha of K ₂ O
Nitrogen	20 kg/ha of N
Zinc	2.5 kg/ha of Zn

Source: The authors.

For Experiment 2, the analyses performed on the soil samples revealed very low levels of phosphorus, low levels of potassium, nitrogen, and zinc at levels considered adequate. According to these analyses, the fertilizers to be applied in Experiment 2 were calculated according to the Recommendations of Correctives and Fertilizers for Goiás, 5th approximation (COMISSÃO DE

FERTILIDADE DO SOLO DE GOIÁS – UFG/ENGOPA, 1988) described in Table 6. The planting fertilizer recommendation was 120 kg/ha of P_2O_5 , 60 kg/ha of K_2O , 20 kg/ha of N, 2.5 kg/ha of Zn, and 2.0 tons per hectare of dolomitic limestone.

Table 6. Fertilization with phosphorus, potassium, nitrogen, and zinc in Experiment 2

Element	Amount (g/pot)
Phosphorus	120 kg/ha of P_2O_5
Potassium	60 kg/ha of K_2O
Nitrogen	20 kg/ha of N
Zinc	2,5 kg/ha of Zn

Source: The authors.

Following the filling of the pots, the inputs were weighed at the Soil Biology Laboratory of the School of Agronomy - UFG. On August 29, 2023, the soil was fertilized at the dosages indicated in Tables 5 and 6 for the two experiments. Soon after, the corn was planted by drilling five holes in the soil to a depth of three centimeters, one at an angle of 0° , another at an angle of 90° , another at 180° , another at 270° , and a central hole. The experimental design was entirely randomized and performed in a greenhouse.

After planting, biometric assessments were conducted every two weeks in Experiments 1 and 2, measuring height (total) and diameter taken at a height of between 10 and 15 cm from the plant. A tape measure was used for the heights and a caliper for the diameter. The assessments began in September and ended in November 2023.

On October 11, 2023, iron deficiency was detected in the maize leaves and on October 26, 2023, a source of this micronutrient was applied. In the last assessment, on November 9, 2023, the cobs became dull and studies began on maize yield, and soil fertility as a result of the experiment and leaf analysis.

For residual soil sampling, samples were taken from each treatment and each repetition in labeled bags for potassium (K) analysis. Afterward, samples were taken from each treatment and all repetitions for complete soil fertility analysis. 80 paper bags were marked to collect samples of maize leaves, for all treatments and repetitions of experiments 1 and 2, for analysis of K.

The maize plants from each treatment and each repetition were cut from the pots, folded, and tied with string to be placed in labeled paper bags for weighing the green biomass in the laboratory. Subsequently, each treatment and repetition sample was placed in an oven for 24 hours at 60°C. On November 13, 2023, the dried samples were weighed in the laboratory. The following soil and plant properties were determined: residual K in the soil, other soil fertility indicators, and leaf K concentration (assessment of potassium in the green biomass).

Stats, factoextra, agricolae, and ggplot2 packages from the R software environment were used for statistical analysis and graph construction. The stats package is a basic library that provides statistical functions such as calculating means, medians, deviations, correlations, and probability distributions (Sun *et al.*, 2024). The factoextra package was used for principal component analysis and cluster design, while the agricolae package was used for analysis of variance and mean comparison tests (Jacinto, *et al.*, 2020; Mairura *et al.*, 2023). The ggplot2 package (Mallu *et al.*, 2021) was used to create the graphs presented here. A comparison of means was then performed using the Tukey test ($P < 0.05$).

To calculate maize efficiency, the average yields of each treatment were taken and divided by the average yield of Potassium Chloride (KCl), Treatment T6, multiplied by 100. The same calculation was made for comparative efficiency against FMX, Treatment 7.

The results from the assessments in Treatment T1 for Experiments 1 and 2 were disregarded for biometric assessments, residual K in the soil, and leaf K concentration. Agronomic efficiency was only analyzed for Experiment 2, as the doses used between REKAL, FMX, and KCl in this experiment are equivalent. The doses used in Experiment 1 are not equivalent.

Finally, in the Laboratory for Soil Organic Matter Studies at the Universidade de Brasília, labile carbon (C) analyses were performed on the residual soil samples from all the treatments in Experiments 1 and 2 to check the labile C content. This comparative assessment was based on Treatment T1.

4 RESULTS AND DISCUSSION

The biometric parameters of plant height and stalk diameter of maize cultivated in a Red Latosol with sandy loam texture are presented in Tables 7 and 8, corresponding to Experiments 1 and 2, respectively.

Table 7. Biometric parameters of maize plants (height and stalk diameter) under different potassium sources and inoculation treatments – Experiment 1.

Treatments	Height (cm)	Diameter (mm)
T2	66.640 d	1.81 ab
T3	73.780 bcd	1.97 a
T4	80.232 abc	1.83 ab
T5	70.188 d	1.62 b
T6	65.308 d	1.58 b
T7	83.688 a	1.96 a
T8	72.804 cd	1.88 ab

*: Means followed by the same letter in the column do not differ by Tukey's test at 5%.
Source: The authors.

Table 7 shows that in Experiment 1, treatment T7 (FMX remineralizer) stood out in terms of plant height, followed by T4 (REKAL – 80 kg/ha K₂O). Regarding stalk diameter, treatments T3 (REKAL – 40 kg/ha K₂O) and T7 (FMX) had the best results, followed by T8, T4, and T2.

Table 8. Biometric parameters of maize plants (height and stalk diameter) under different potassium sources and inoculation treatments – Experiment 2.

Treatments	Height (cm)	Diameter (mm)
T2	93.6 b	1.63 a
T3	90.3 bc	1.54 a
T4	96.4 b	1.49 ab
T5	86.4 bc	1.49 ab
T6	89.0 bc	1.53 a
T7	112.4 a	1.62 a
T8	78.7 c	1.32 b

*: Means followed by the same letter in the column do not differ by Tukey's test at 5%.
Source: The authors.

Table 8 indicates that in Experiment 2, once again, treatment T7 (FMX) yielded the highest plant height, with treatment T4 (REKAL – 120 kg/ha K₂O) performing similarly, followed by T2. In terms of stalk diameter, treatments T2, T3, T6, and T7 showed significantly superior values, whereas T8 had the lowest measurements.

The results for leaf K concentration, residual potassium in the soil, and crop yield are summarized in Tables 9 and 10. In Experiment 1, T3 and T6 showed the highest foliar potassium concentrations. T7 had the highest residual soil K content, while the highest grain yields were observed in T7 and T4 (FMX and REKAL – 80 kg/ha K₂O, respectively).

Table 9. Foliar potassium concentration, residual soil K, and grain yield of maize under different treatments – Experiment 1.

Treatments	Leaf concentration K (%)	Residual soil K (mg kg ⁻¹)	Productivity (kg ha ⁻¹)
T2	2.19 abc	56.0 b	1,895.85 bc
T3	2.49 a	68.8 b	2,489.41 abc
T4	2.17 abc	60.8 b	3,938.00 ab
T5	1.87 c	49.2 b	1,742.29 c
T6	2.23 ab	62.0 b	1,854.16 bc
T7	2.07 bc	110.4 a	4,096.07 a
T8	2.20 abc	64.0 b	2,943.93 abc

*: Means followed by the same letter in the column do not differ by Tukey's test at 5%.

Source: The authors.

Table 10. Foliar potassium concentration, residual soil K, and grain yield of maize under different treatments – Experiment 2.

Treatments	Leaf concentration K (%)	Residual soil K (mg kg ⁻¹)	Productivity (kg ha ⁻¹)
T2	1.42 c	22.0 b	6.226 ab
T3	1.15 c	24.0 b	5.896 ab
T4	1.60 bc	56.8 a	6.336 ab
T5	1.55 bc	20.0 b	5.456 b
T6	2.40 a	39.6 ab	6.380 ab
T7	2.06 ab	56.8 a	9.064 a
T8	1.70 bc	21.2 b	5.038 b

*: Means followed by the same letter in the column do not differ by Tukey's test at 5%.

Source: The authors.

In Experiment 2, T6 had the highest foliar K concentration, and T4 stood out both in terms of residual K and grain yield, followed by T7, T6, T2, and T3.

The potassium use efficiency (KUE) relative to KCl and FMX was calculated and is presented in Tables 11 and 12, respectively. Compared to KCl (T6), the most efficient treatment was T7, followed by T4. In comparison to FMX, treatment T4 showed the highest relative efficiency, followed by T6 and T2.

Table 11. Potassium use efficiency (KUE) of treatments relative to KCl (conventional potassium fertilizer).

Treatments	Efficiency compared to KCl (%)
T2	96.46
T3	92.51
T4	102.70
T5	95.01
T6	Reference
T7	136.38
T8	83.99

Source: The authors.

Table 12. Potassium use efficiency (KUE) of treatments relative to FMX (commercial remineralizer).

Treatments	Efficiency compared to FMX (%)
T2	70.73
T3	67.83
T4	75.30
T5	69.66
T6	73.32
T7	Reference
T8	61.585

Source: The authors.

Analyses of labile carbon in residual soils from both experiments are shown in Tables 13 and 14. In Experiment 1, treatment T8 (REKAL + *Azospirillum brasilense*) recorded the highest labile C content (0.54 mg C/g soil), followed by T6 and T5. In Experiment 2, the highest value was observed in T4 (0.73 mg C/g soil), which was the only treatment that exceeded the control (T1).

Table 13. Residual soil labile carbon analysis in Experiment 1

Treatments	Labile C (mg C/g soil)
T1	0.29
T2	0.16
T3	0.31
T4	0.13
T5	0.34
T6	0.37
T7	0.18
T8	0.54

Source: The authors.

Table 14. Residual soil labile carbon analysis in Experiment 2

Treatments	Labile C mean (mg C/g soil)
T1	0.55
T2	0.4
T3	0.54
T4	0.73
T5	0.35
T6	0.15
T7	0.27
T8	0.42

Source: The authors.

The data from both experiments highlight the agronomic efficiency of the REKAL remineralizer, particularly at intermediate doses (T3 and T4). Plant height and stalk diameter responded positively to K supplied via the remineralizer, which aligns with previous studies such as Brazil *et al.* (2021), who reported similar effects using the K6 remineralizer.

The superiority of treatment T7 (FMX) in plant height and yield confirms the potential of formulated commercial remineralizers. Nevertheless, treatments with REKAL also performed well—especially T4, which achieved yields of 3,938 kg ha⁻¹ in Experiment 1 and similar values in Experiment 2. The addition of *Azospirillum brasilense* (T8) improved stalk diameter in Experiment 1, though it had no significant effect on height or yield in either experiment, suggesting a localized response possibly linked to rhizosphere colonization.

Foliar K concentrations, often associated with nutrient uptake efficiency, were higher in intermediate doses and in the FMX treatment, indicating good nutrient availability. The higher levels of residual K in the soil under T7 confirm the slow-release nature of minerals present in FMX.

The potassium use efficiency results showed that T4 outperformed both KCl and FMX in terms of nutrient use, supporting the literature and demonstrating the potential of remineralizers to substitute soluble fertilizers, with the added benefit of longer persistence in the soil.

Regarding labile carbon, the results suggest a potential interaction between the remineralizer and organic matter, with notable effects in T8 (with bacterial inoculant) in Experiment 1 and T4 in Experiment 2. Increased labile C indicates higher microbial activity or greater organic residue incorporation, which may relate to nutrient cycling and agroecosystem sustainability.

These results suggest that REKAL, especially at doses ranging from 40 to 120 kg/ha K_2O , has strong agronomic and environmental potential, making it suitable for incorporation into sustainable production systems. Future studies could explore crop-specific responses, dose adjustments according to soil texture, and long-term effects on nutrient balance and carbon sequestration.

5 CONCLUSIONS

This study confirms that the application of organic matter, particularly when combined with REKAL remineralizer, significantly improved foliar potassium concentration, residual soil K levels, and maize silage yield in both experiments. Among the treatments tested, the application of 120 kg ha^{-1} of K_2O via REKAL (Treatment T4) was identified as the most agronomically efficient dose.

The findings reinforce the potential of REKAL as a sustainable alternative to conventional potassium fertilizers, not only for its nutrient-supplying capacity but also for its positive effect on soil health. Notably, REKAL contributed to the enrichment of the labile carbon fraction, an important indicator of soil quality and biological activity.

Moreover, the reuse of mining by-products such as finely ground silicate rocks presents a promising solution to reduce environmental liabilities, decrease fertilizer import dependency, and promote regenerative agriculture practices. These results underscore the viability of remineralizers like REKAL in fostering more resilient and ecologically sound agricultural systems.

REFERENCES

- ANDA – ASSOCIAÇÃO NACIONAL PARA DIFUSÃO DE ADUBOS. **Estatísticas**. Disponível em: <https://anda.org.br/>. Acesso em: 10 abr. 2024.
- BRASIL. **Plano Nacional de Mineração 2030**: geologia, mineração e transformação mineral. Brasília: Ministério de Minas e Energia, 2010. Disponível em: https://antigo.mme.gov.br/documents/36108/469987/PNM_2030.pdf. Acesso em: 10 abr. 2024.
- BRASIL. **Lei nº 12.890, de 10 de dezembro de 2013**. Dispõe sobre a inspeção e a fiscalização da produção e do comércio de fertilizantes, inoculantes, estimulantes, ou biofertilizantes, remineralizadores e substratos para as plantas, destinados à agricultura. Disponível em: http://www.planalto.gov.br/ccivil_03/_ato2011. Acesso em: 4 abr. 2024.
- BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. **Instrução Normativa nº 5, de 10 de março de 2016**. Estabelece regras sobre remineralizadores e substratos para plantas. Brasília: MAPA/SDA/CGAL, 2016. Disponível em: <https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/legislacao/in-5-de-10-3-16-remineralizadores-e-substratos-para-plantas.pdf>. Acesso em: 2 maio 2023.
- BRASIL, E. P. F. .; LEANDRO, W. M.; CASTRO, J. P. V. . .; ARAÚJO, I. de L. .; LUCAS, P. M. .; ARAÚJO, T. de G. . Agronomic efficiency of granite remineralizer K6 in soybean and corn silage production. **Research, Society and Development**, [S. l.], v. 12, n. 4, p. e10912440545, 2023. DOI: 10.33448/rsd-v12i4.40545. Disponível em: <https://rsdjournal.org/index.php/rsd/article/view/40545>.
- COMEX STAT. **Sistema para consultas e extração de dados do comércio exterior brasileiro**. Disponível em: <http://comexstat.mdic.gov.br/pt/comex-vis>. Acesso em: 8 abr. 2024.
- COMISSÃO DE FERTILIDADE DE SOLOS DE GOIÁS. **Recomendações de Corretivos e Fertilizantes para Goiás: 5ª aproximação**. Goiânia: UFG/ENGOPA, 1988.
- CONAB – COMPANHIA NACIONAL DE ABASTECIMENTO. **Boletim logístico**. Brasília, 2022. Disponível em: <https://www.conab.gov.br/info-agro/analises-do-mercado-agropecuario-e-extrativista/boletimlogistico?limitstart=0>. Acesso em: 18 jun. 2022.
- CONGRESSO BRASILEIRO DE ROCHAGEM, 3., 2016, Pelotas. *Anais eletrônicos*. Pelotas: Triunfal Gráfica e Editora; Embrapa Clima Temperado; Embrapa Cerrados, 2016. Disponível em: <https://www.embrapa.br/documents/1354346/26325871/Livro+Congresso+de+rochagem+Formato+Web.pdf>. Acesso em: 10 abr. 2024.

INSTITUTO BRASIL ORGÂNICO. **Mapa de Remineralizadores**. Disponível em: <https://institutobrasilorganico.org/atuacao/mapa-de-remineralizadores/>. Acesso em: 5 maio 2023.

LEITE, P.C. **Efeitos de tratamentos térmicos em misturas de verdete de Abaeté, fosfato de Araxá e calcário magnesiano, na disponibilidade de potássio e fósforo**. 1985. Dissertação (Mestrado) - Escola Superior de Agricultura de Lavras, Lavras. 146p.

LOPES, A.S.; FREIRE, J.C.; AQUINO, L.H., FELIPE, M.P. Contribuição ao estudo da rocha potássica - Verdete de Abaeté (Glauconita) para fins agrícolas. **Agros**, v.2, p.32-42, 1972.

MARTHA JUNIOR, G. B.; BARCELLOS, A. de O.; VILELA, L.; SOUSA, D. M. G. de. **Benefícios bioeconômicos e ambientais da integração lavoura-pecuária**. Planaltina, DF: Embrapa Cerrados, 2006. 28 p. (Embrapa Cerrados. Documentos, 154). Disponível em: <https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/570372>. Acesso em: 11 abr. 2025.

MARTINS, E. D. S.; OLIVEIRA, C. G. de; RESENDE, A. V. de; MATOS, M. S. F. de. **Agrominerais – rochas silicáticas como fontes minerais alternativas de potássio para a agricultura**. Rio de Janeiro: CETEM/MCTI, 2008.

MARTINS, E. Remineralizadores – "Tropicalizando as Soluções da Natureza para uma Agricultura Regenerativa: da Mineração à Mesa e Seus Reflexos Climáticos". Palestra proferida no **Workshop Remineralizadores – Tropicalizando as soluções da natureza para uma agricultura regenerativa – da mineração à mesa e os reflexos climáticos**. Brasília – DF, 5 a 7 dez. 2023. Disponível em: <https://www.embrapa.br/en/busca-de-noticias/-/noticia/85673644/pesquisa-brasileira-avanca-no-uso-de-remineralizadores-no-solo>. Acesso em: 20 fev. 2024.

ONU BRASIL. **A Agenda 2030**. 2015. Disponível em: <https://nacoesunidas.org/pos2015/agenda2030/>. Acesso em: 10 abr. 2023.

PACKAGE AGRICOLAE. Statistical Procedures for Agricultural Research. Author: Felipe de Mendiburu. Version 1.3-7, 2022. Disponível em: <https://cran.r-project.org/web/packages/agricolae/agricolae.pdf>. Acesso em: 10 dez. 2023.

PACKAGE FACTOEXTRA. Extract and Visualize the Results of Multivariate Data Analyses. Version 1.0.7, 2022. Disponível em: <https://cran.r-project.org/web/packages/factoextra/factoextra.pdf>. Acesso em: 20 dez. 2023.

PACKAGE GGLOT2. Create Elegant Data Visualisations Using the Grammar of Graphics. Version 3.5.0, 2024. Disponível em: <https://cran.r-project.org/web/packages/ggplot2/ggplot2.pdf>. Acesso em: 20 fev. 2024.

PACKAGE STAT. Interactive Document for Working with Basic Statistical Analysis. Author: Kartikeya Bolar. Version 0.1.0, 2022. Disponível em: <https://cran.r-project.org/web/packages/STAT/STAT.pdf>. Acesso em: 20 dez. 2023.

PILLON, C. N. Dos pós de rocha aos remineralizadores: passado, presente e desafios. In: **CONGRESSO BRASILEIRO DE ROCHAGEM**, 3., 2016, Pelotas. *Anais*. Pelotas, 2016.

PROJETO R PARA COMPUTAÇÃO ESTATÍSTICA. Vienna: Foundation for Statistical Computing, 2023. Disponível em: <https://www.r-project.org/>. Acesso em: 20 dez. 2023.

SILVEIRA, C. A. P. *et al.* Protocolo para avaliação da eficiência agrônômica de remineralizadores de solo – uma proposta da EMBRAPA. In: **CONGRESSO BRASILEIRO DE ROCHAGEM**, 3., 2016, Pelotas. *Anais eletrônicos*. Assis: Triunfal Gráfica e Editora; Pelotas: Embrapa Clima Temperado; Brasília: Embrapa Cerrados. Disponível em: <https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1076459/protocolo-para-avaliacao-da-eficiencia-agronomica-de-remineralizadores-de-solo--uma-proposta-da-embrapa>. Acesso em: 2 abr. 2023.

SOUZA, G. V. L. de. **Avaliação da Eficiência agrônômica de pó de rocha basáltica como remineralizador de solos.** 2022. Trabalho de Conclusão de Curso (Bacharelado – Engenharia Agrônômica) – Universidade Estadual Paulista (UNESP), Faculdade de Ciências Agrárias e Veterinárias, Jaboticabal. Disponível em: <http://hdl.handle.net/11449/236116>. Acesso em: 7 ago. 2023.