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REMINERALIZATION OF AGRICULTURAL SOIL: STUDY OF CHEMICAL CHANGES RESULTING FROM ACCELERATED WEATHERING

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ABSTRACT

Soil remineralization in Brazil has gained prominence in the world for being a source of nutrients for the soil, due to its ability to form new crystalline phases. Also known as accelerated weathering of rocks, this practice has shown potential for chemical and physical recovery of agricultural soils. It also has the appeal of decarbonization via rock weathering, which in fact tends to occur faster when compared to natural conditions of soil formation. This research aimed to analyze the effects and remineralization potential of two agricultural soils using a sustainable solution of Compact Shale with Ca and Mg contents from mining tailings in the region of Itabira/MG. The experiment was conducted in two locations. One in Nazareno, Minas Gerais, and the other in Piracicaba, São Paulo. The rock dust was ground at 0.106mm and applied at a rate of 22 tons/ha. In both locations, the material was deposited under the soil and incorporated with the aid of a plow harrow up to a depth of 30cm. The experiment installed in Piracicaba was irrigated to field capacity and the trial in Nazareno waited for the regularity of the rainfall in the region. In both locations, the experimental design was in randomized blocks with 5 treatments and 6 replications. For the experiments, the following treatments were adopted: control (T1 without application), T2 of pure compact shale, T3 dolomitic limestone in Nazareno-MG and pure calcitics in Piracicaba-SP, T4 of compact shale added of dolomitic and calcitic limestone (Nazareno-MG and Piracicaba-SP respectively), and T5 of market remineralizer (Agrifértil Mg+ in Nazareno-MG and ErgoFert Grow+ in Piracicaba-SP. The chemical/agronomic indicators of soil quality were analyzed. Compact shale modified soil pH during the experimental period. The compact shale showed superior behavior to the commercial limestone for the indicators of pH (CaCl2 and H2O), saturation by base, exchangeable aluminum (Al3+) and potential acidity (H+Al). These results were similar to those of the isolated and combined limestones for the Effective CTC (t) and Sum of bases (SB) indicators.

Keywords: Conditioners. Fertility. Rock Dust. Sustainability.

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INTRODUCTION

The remineralization of soils through the application of rock dust aims to restore fertility, increase agricultural productivity, and strengthen the soil ecosystem. This practice has gained prominence for offering a sustainable alternative to soil depletion, caused by intensive agricultural practices in tropical soils, in addition to contributing to environmental preservation and food security (Junior et al., 2022).

Rock powders used in remineralization can be derived from volcanic materials, such as basalt, or from igneous, sedimentary, and metamorphic silicate rocks. The remineralizers are extracted from silicate rocks and have high crystallinity and low solubility in water, releasing the minerals gradually. This release depends on interactions with the atmosphere, water and soil, which promote the availability of essential elements, improving the chemical and physical structure of the soil. Rock dusts, in addition to providing macro and micronutrients, can balance pH and favor the formation of secondary minerals, essential for the productivity of agricultural crops (Martins et al., 2023; Steiner et al., 2017; Smith et al., 2023).

In contemporary agricultural production, sustainable management practices, such as no-tillage and the use of remineralizers, have been adopted to protect the soil and ensure its long-term productive capacity. These materials release nutrients in a controlled manner, reducing the need for synthetic fertilizers and promoting a macro and microenvironment suitable for plant development (Ribeiro et al., 2020). The use of remineralizers helps neutralize toxic Al3+ to most agricultural commodities, makes plants more resistant to pests and diseases and increases resistance to biotic and abiotic stresses (Manning, 2018).

A relevant aspect of the use of remineralizers in tropical soils is the regionalization of the sources of production of these inputs. Iron mining waste, when processed correctly, can be turned into rock dust for agricultural remineralization, reducing environmental liabilities and encouraging the circular economy. This reuse reduces the accumulation of materials without economic application and reduces the environmental impact of iron mining, making it a sustainable non-cliché solution for soil recovery and the preservation of natural resources (Carvalho et al., 2018; Blaskowski et al., 2019).

Considering the importance of sustainability in agriculture, it is essential to adopt management strategies that preserve the soil and ensure long-term production efficiency. The use of remineralizers presents itself as a viable alternative, promoting soil fertility, reducing dependence on chemical inputs, and supporting more equitable and sustainable

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agricultural production. Thus, this research seeks to analyze the chemical action of remineralizers, exploring their potential for use in the soil from mining overburden.

MATERIAL AND METHODS

After receiving, identifying and weighing the samples, they were homogenized and crushed 100% <3.35 mm in a bench-scale jaw crusher. Then, the crushed sample was homogenized in a conical and elongated pile, quartering aliquots for granulometric analysis of the mill feed. The rest of the crushed sample was directed to a pilot grinding circuit, aiming at P100 0.106 mm in a Furlan ball mill. The mill was fed with 50kg/h and 30 RPM rotation. The ground material was homogenized and stored in aliquots for chemical analysis and x-ray diffractometry. determination of the total contents of the elements and of the crystalline phases by x-ray diffraction (Table 1).

Table 1. Chemical composition of Compact Shale and identification of crystal phases by X-ray diffraction (XRD).

Lithology	Chemical Parameters								
Compact shale	Fe	SiO2	Al2O3	P	Mn	Dog	MgO	TiO2	K2O
	7,01	49,40	11,04	0,046	0,128	10,211	7,249	0,829	0,199

X-ray Diffraction						
Crystalline phase	Chlorita	Calcite	Albite	Quartz	Dolomite	Amphibole.
Chemical formula	$(Mg,Fe)_3(Al,Si)_4O_{10}(OH)_2.(Mg,Fe)_3(OH)_6$	Ca(CO3)	(Na,Ca)AlSi3O8	SiO2	$(CaMg(CO3)_2)$	$(Mg,Fe)_2Al_4Si_5O_{18}$
%	38,4	19,3	17,2	11,5	9,8	3,8
PRNT (%)	23,6					
Reactivity (%)	99,1					

EXPERIMENTAL AREA AND CONDUCT OF TRIALS

Two experiments are being conducted in soils of different textural and chemical classes, located in Piracicaba-SP and Nazareno-MG. The first experiment was carried out in a Dystrophic Red Yellow Latosol in Piracicaba-SP, while the second was conducted in a Red Yellow Latosol in Nazareno-MG.

The dose of rock dust applied was adjusted to 22.7 tons per hectare, aiming to increase the contact surface of soil remineralization. To ensure the increase of base saturation (V) to 70%, the amount of correctives was calculated according to the chemical results of the soil analysis before application. Before the implementation of the experiments, laboratory analyses were carried out for chemical, physical and micronutrient

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characterization of these soils, establishing a baseline for comparison of changes over the experimental period.

The experiments were structured in a randomized block design with five different treatments and six replications, with the experimental plots dimensioned as 3 meters wide by 5 meters long. Within these plots, the useful area, intended for collection and analysis, comprised 1.5 meters wide by 3 meters long, totaling 4.5 m². The total area occupied by the experiment was 1,100 m² (Figure 1).

Figure 1. Sketch of the essay with delimitation of plots and treatments in both locations.

B1		**B2**		**B3**		**B4**		**B5**		**B6**	
T1		**T2**		**T3**		**T4**		**T5**		**T1**	5
3	2									2	
T4		**T3**		**T1**		**T3**		**T2**		**T5**	
T2		**T5**		**T4**		**T1**		**T3**		**T2**	
T5		**T4**		**T5**		**T2**		**T1**		**T3**	
T3		**T1**		**T2**		**T5**		**T4**		**T4**	

The specific treatments for each soil type were established in the same experimental design. In the first experiment, conducted in the Red-Yellow Latosol in Nazareno-MG, the treatments applied were:

1. Control (no application) – no application of remineralizers;
2. Compact Shale (Xc);
3. dolomitic limestone (Cd);
4. Compact Schist + Dolomitic Limestone (Xc + Cd);
5. Agrifértil Mg+ (AMg).

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The incorporation of the materials was carried out in the 0-30 cm layer, using a 36-inch harrow, followed by a leveling harrow for soil homogenization and better distribution of treatments.

In the second experiment, carried out in the Red-Yellow-Dystrophic Latosol (LvA-d) in Piracicaba-SP, the treatments used were:

1. Control (No application) – no application of remineralizers;
2. Compact Shale (Xc);
3. commercial calcitic limestone (Cd);
4. Compact Shale + Commercial Calcitic Limestone (Xc + Cc);
5. ErgoFert Grow (Ef).

EVALUATIONS AND SAMPLE COLLECTION

To evaluate the effects of the treatments over time, chemical and physical analyses of the soil were carried out at different periods and depths. Soil collections occurred in the 0-20 cm and 20-40 cm (Piracicaba-SP) and 0-15 cm and 15-30 cm (Nazareno-MG) layers, allowing a detailed evaluation of nutrient mobility and the influence of remineralizers at different depths of the soil profile. Samplings were carried out before the installation of the experiments and in the periods of 30, 60, 90 and 120 days after the application of the treatments.

The sample collection followed an Embrapa protocol (2017) to obtain the soil, which was duly homogenized to form representative composite samples of each experimental plot. These samples were sent for laboratory analysis, in which soil fertility parameters were determined, including pH, organic matter, macronutrient contents (N, P, K, Ca, Mg, S) and essential micronutrients (Fe, Mn, Zn, Cu, B). Particle size analyses were performed to determine the soil texture, using the pipette method to quantify the contents of clay, silt and sand.

RESULTS AND DISCUSSION

In order to evaluate the before and after of the chemical characteristics of the soils where the experiments were implemented, soil analyses were carried out before the application of Compact Shale (Tables 2 and 3). The results of the analyses indicate the chemical state of the soil that proves the need for mineral input, common in tropical soils.

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Indicators such as pH and Sum of Bases direct the contents and volumes to be supplied from the remineralizer.

Table 2. Chemical and micronutrient analysis of a Red Yellow Latosol from the experimental area with sampling carried out in Piracicaba-SP.

Prof.	ph	P-M1	K	S	Ca	Mg	t	V	WE	B	Ass	Fe	Mn	Zn
Cm	*H2O*	*mg/dm3*			*CMOLC/DM3*			*%*		*mg/dm3*				
0-20	4,6	2	3,7	13	29	15	8,9	50	19	0,39	8,8	20	27,2	2,6
20-40														

Table 3. Chemical and micronutrient analysis of a Red Yellow Latosol from the experimental area with sampling carried out in Nazareno-MG.

Prof.	ph	P-M1	K	S	Ca	Mg	t	V	WE	B	Ass	Fe	Mn	Zn
Cm	*H2O*	*mg/dm3*			*CMOLC/DM3*			*%*		*mg/dm3*				
0-20	5,4	8	78,2	47	1,5	0,4	8,2	26	3,7	0,51	1,7	34	15,7	1,7
20-40	5,5	3	66,5	78	1,1	0,2	6,7	22	2,8	0,41	1,5	38	9,5	0,8

*P-M1 = P extracted by Mehlich1. **Cu, Fe, Mn and Zn mined by Mehlich1.

According to Raij et al. (2001) soil acidity is an important factor that limits production in tropical regions. The authors point out that liming alters the chemical attributes of the soil linked to acidity, raising the pH, raising the levels of calcium, magnesium, sum of bases and saturation by bases, in addition to reducing the levels of toxic aluminum, up to depths of 60 cm. These practices are categorically demanded to improve the immediate fertility of tropical soils and increase or maintain agricultural productivity.

In general, the parameters analyzed refer to acidity and cation availability in the soil. The experiment installed in Nazareno-MG resulted in an increase of 1.1% in pH (CaCl2) indicating strong aptitude for soil correction. In this same experiment, comparing the treatments with pure compact shale or combined with dolomitic limestone with the control treatment and pure dolomitic limestone, significantly increased the pH in $CaCl_2$ and H_2O, decreased the exchangeable aluminum content (Al^{3+}) and the potential acidity (H+Al), in addition to increasing the sum of bases (SB) and the saturation by bases (V%). As expected, in the control treatment, there was no variation in the values of Al^{3+} and H+Al and presented the lowest pH, SB and V%, indicating the high acidity of the uncorrected soil. Evaluated as a positive control treatment, the commercial product Ergofert, an alternative conditioner, also provided an increase in soil fertility, but in a smaller proportion than the treatments based on shale or limestone (Table 4).

In the field experiment installed in Piracicaba-SP, the treatment composed of isolated Compact Shale performed with an increase in pH in $CaCl_2$ and H_2O. The V% and SB indicators obtained the highest significant averages, following the same pattern of Al^{3+}

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neutralization and reduction of potential acidity observed in the field experiment installed in Nazareno-MG. The combination of Compact Shale with Calcitic Limestone and Dolomitic Limestone itself also provided chemical improvements to the soil, but performed with slightly lower averages than the isolated shale treatment. The AMg^+ corrective decreased soil acidity in a smaller proportion when compared to the other treatments and was superior only to the control treatment, which remained with a higher concentration of Al^{3+} and H+Al.

The results indicate the effectiveness of Compact Shale in correcting soil acidity, with equal or superior performance in certain indicators compared to traditional limestones. It should not be lost sight of the fact that both dolomitic and calcitic limestone are well-established products in the market and widely used, as they improve the pH and supply the demand for Ca and Mg, depending on the need of the soil. Other conditioners, such as Ergofert and AMg^+, can contribute to the improvement of chemical characteristics, but with results of acidity neutralization and pH increase not as efficient as those observed in treatments with shale and/or limestone.

According to authors (Ribeiro et al.1999, Sousa & Lobato, 2004), the pH range between 5.5 and 6.5 is suitable for many agricultural crops because it reduces aluminum toxicity and favors nutrient availability (Malavolta, 2006). Therefore, raising pH and reducing Al^{3+} are non-negotiable to ensure the creation of a root environment and increase plant growth potential (Raij, 2001). According to Embrapa (2018), base saturation (V%) above 50% is generally desirable in tropical soils, having been achieved by shale and limestone-based treatments. It is important to emphasize that the choice of corrective or remineralizing material should consider aspects such as the availability of Mg in the soil, the cost-benefit, the reaction speed and the final goal of saturation by bases or pH to be achieved.

Table 4. Summary of the analysis of variance and comparison of the means of the chemical fertility indicators of Red Yellow Latosol in Nazareno-MG(A) and Red Yellow Dystrophic Latosol in Piracicaba SP (B)

A	pH (CaCL2)	pH (H20)	V%	t	SB	Al3+	H+Al	m
Source of Variation								
Compact Shale (Xc)	5.8a	6.51a	65.60a	6.68a	6.66a	0.027 c	3.44c	1.77c
Schist + dolomitic limestone	5.7a	6.48a	64.77a	6.64a	6.61a	0.030 c	3.5c	2.39c
Dolomitic limestone (Cd)	5.7a	6.53a	65.59a	6.88a	6.87a	0.015 c	3.38b	2.72c

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Ergofert	5.0b	6.14b	53.78b	5.43b	5.33b	0.099 b	4.5b	5.18b
Control	4.7c	5.99c	48.46c	4.94c	4.75c	0.19a	5.03a	10.66 a
CV (%)	6,46	2.86	9,42	13,81	14,43	89,93	12,73	83.09
B								
Source of Variation								
Compact Shale	5.12a	5.72a	46.93a	7.17a	34.28 a	0.59c	37.41c	0.29c
Compact Schist + Calcitic Limestone	4.95b	5.55b	43.52a b	6.93a b	30.76 a	0.62c	38.56b c	0.33c
Calcitic limestone	4.93b	5.53b	41.89b	7.19a b	30.13 a	0.75a b	41.81b	0.16c
Agrifértil Mg+	4.66c	5.2c	31.54c	7.05a b	22.35 b	0.98b	48.18b	1.04b
Control	4.47d	5.07d	23.97d	7.033 b	16.78 c	1.67a	53.5a	1.95a
CV (%)	5,03	4,48	23,21	6,9	28,03	62,58	13,79	92.72

The means followed by the same letter do not show significant difference by the Tukey Test at 5% probability.

Table 5. Analysis of variance and comparison of the means of the chemical indicators of fertility of the Red Yellow Latosol Piracicaba - SP.

	Source of Variation	GL	Medium Square							
			pH (CaCl2)	pH (H20)	V%	t	SB	Al3+	H+Al	m
LvA-d Piracicaba-SP	Treatments	4	11,128*	3,020*	3213,26*	36,383*	42,52*	0,258*	27,34*	27,28*
	Date	3	1,539*	0,124*	1418,01*	21,071*	22,29*	0,034*	15,14*	4,42*
	Depth	1	1,773*	0,111**	550,03*	18,59*	20,92*	0,070*	0,88**	9,20*
	Block	5	0,307*	0,079*	140,89*	2,88*	3,33*	0,016*	0,761*	2,088*
	Residue	199	0,124	0,032	31,76	0,71	0,761	0,004	0,258	0,49
	Cv (%)		6,46	2,86	9,42	13,81	14,43	89,93	12,73	92,72
	*Significant at 5% probability by the Tukey Test. ** Not significant.									
	Date	pH (CaCl2)	pH (H20)	V%	t	SB	Al3+	H+Al	m	
	30	5.31b	9.49c	53,95c	5.24b	5.14b	0.097a	4.34a	1.07a	
	60	5.35b	10.68a	57.81b	6.26a	6.19a	0.070ab	4.49a	0.67bc	
	90	5.47b	10.08b	62.90a	6.44a	6.40a	0.040b	3.68b	0.43c	
	120	5.66a	9.89b	64.60a	6.52a	6.44a	0.080b	3.45b	0.85ab	
	Depth	pH (CaCl2)	pH (H20)	V%	t	SB	Al3+	H+Al	m	
	0-20cm	5.53a	10.27a	61.33a	6.39a	6.34a	0.05a	3.93a	6.34a	
	20-40cm	5.36b	9.80b	58.30b	5.84b	5.75b	0.08b	4.05a	5.75b	

The means followed by the same letter did not differ statistically by the Tukey Test at 5% probability. V%: Saturation by base. t: Effective CTC. SB: Sum of Bases. Al3+: Swappable aluminium. H+Al: Potential acidity. m: Aluminum Saturation.

The results obtained in the analysis of variance (Table 5) and in the comparison of the means of the fertility indicators (pH in $CaCl_2$, pH in H_2O, base saturation – V%, effective CEC – t, sum of bases – SB, exchangeable aluminum – Al^{3+}, potential acidity – H+Al and aluminum saturation – m) in a Red-Yellow Latosol (LVA-d) of Piracicaba (SP)

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indicate the behavior of soil mineral availability as a function of the treatments, the dates of sample collection for soil analysis and the depth of the soil profile.

In general, the analysis of variance confirms that the treatments tested and the time factor had a significant impact on fertility attributes, reinforcing the importance of making soil corrections and monitoring changes throughout the agricultural cycles (Embrapa, 2018). In addition, the stratification of the results by depth indicates the need for adequate management so that chemical improvements can reach deeper layers, improving the root environment and the sustainability of the production system (Sousa & Lobato, 2004).

Table 6. Summary of the analysis of variance of the chemical indicators of the LVA soil in Nazareno – MG

	Source of Variation	GL	Medium Square							
			pH (CaCl2)	pH (H20)	V%	t	SB	Al3+	H+Al	m
LvA-Nazareno-MG	Treatments	4	3,24*	3,24*	4355,12*	56,76*	2433,95*	9,52*	22,25*	641,99*
	Date	3	0,61*	0,61*	728,49*	4023,99*	623,52*	21,16*	24,8*	184,63*
	Depth	1	1,40*	1,40*	3047,21*	2604,38*	3237,38*	0,43*	30,25*	158,28*
	Block	5	0,43*	0,43*	504,01*	497,08*	381,13*	2,09*	46,01*	113,36*
	Residue	199	0,05	0,05	76,90	23,84	5578	0,33	34,30	14,29
	Cv (%)		4,95	4,40	23,34	6,90	27,80	62,75	13,34	8309
	Date	pH (CaCl2)	pH (H20)	V%	t	SB	Al3+	H+Al	m	
	30	4.94a	5.54a	36.43bc	82.16a	30.12a	0.43b	51.96a	3.05b	
	60	4.84a	5.44a	39.45ab	62.63c	25.21b	0.39b	37.46c	3.43b	
	90	4.70b	5.30b	33.25c	69.28b	23.18a	1.51a	45.95b	6.93a	
	120	4.83a	5.43a	41.16a	69.06b	28.93a	1.36a	40.20c	4.78a	
	Depth	pH (CaCl2)	pH (H20)	V%	t	SB	Al3+	H+Al	m	
	0-20cm	4.90a	5.50A	41.16a	74.10a	30.56a	0.96a	44.24a	3.73b	
	20-40cm	4.75b	5.35b	34.04b	67.52b	23.22b	0.88a	43.53a	5.35a	

The means followed by the same letter did not differ statistically by the Tukey Test at 5% probability.
*Significant at 5% probability by the Tukey Test. ** Not significant. V%: Saturation by base. t: Effective CTC. SB: Sum of Bases. Al3+: Swappable aluminium. H+Al: Potential acidity. m: Aluminum Saturation.

The analysis of variance (ANOVA) applied to the data indicated statistically significant differences ($p<0.05$) for most of the soil chemical indicators as a function of the variation factors, treatments, evaluation dates and depth (Table 6). The tables of means compared by Tukey's test at 5% probability confirmed that the means with different letters are statistically distinguished, so that the acidity correction strategies adopted and the evaluation period (30, 60, 90 and 120 days after incorporation) modify the chemical properties of the Red-Yellow Latosol (LvA) in Nazareno (MG).

The variation in pH ($CaCl_2$ and H_2O) over the time (dates) of evaluation was affected by the application of isolated shale and shale combined with limestone. The intention was

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to perceive the mineralization speed of the elements every 30 days. Thus, 30 days after the incorporation of the compact shale, the pH ($CaCl_2$) allowed the pH to rise, differing from later periods. In general, the initial response of the correctives raised the pH significantly, however, at 90 days, a decrease in this indicator was observed, showing a possible chemical adjustment in soil solution in the neutralization process (Zhang et al., 2020; Kumar et al., 2022). At 120 days, the pH rose again, not differing statistically from 30 and 60 days, which suggests a possible stabilization of the corrective effect at the end of this time evaluation interval (Wang et al., 2024).

Similarly, the base saturation (V%) also varied over time: the initial reading (30 days) increased and reached 41.16% at 120 days, confirming the trend of gradual increase in the availability of basic cations (Ca^{2+}, Mg^{2+}, and K^+) in the exchange complex (Smith et al., 2023). However, at 90 days, there was a relative minimum value of V%, indicating a fluctuation that may be related to the solubilization of the correctives and the soil moisture and temperature conditions during the period (Lopez et al., 2022). The observed cyclical behavior reinforces the importance of periodic evaluations to verify whether liming is effectively achieving the objectives of neutralization of Al^{3+} and raising the bases (Roy et al., 2025).

The effective CEC parameter (t) in 30 days reached 82.16 cmolc dm^{-3}, significantly surpassing the other dates, such as 60 days, 90 and 120 days. This statistical difference indicates that, at first, the presence of ions released by the correctives and the dynamics of cation exchange increased the amount of loads occupied in the soil, possibly resulting in greater immediate availability of nutrients (Ding et al., 2023).

Over time, the reduction in effective CEC values suggests secondary adsorption and/or precipitation reactions, as well as possible variations in the shape of aluminum (Kumar et al., 2021).

A critical aspect for statistical interpretation is related to exchangeable aluminum (Al^{3+}), whose peak was observed at 90 days, differing significantly from the 30- and 60-day averages, which were lower. Such temporary elevation of Al^{3+} can be explained by the release of inorganic forms of aluminum from the solid phase of the soil after the application of correctives, associated with cationic competition in the exchange complex (Martínez-Ballesta et al., 2024). Subsequently, at 120 days, the Al^{3+} remained at a high level, without statistically differing at 90 days, but still higher than the initial values. From a technical point of view, the statistical result indicates the need to monitor not only the pH, but also the

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dynamics of aluminum at different stages of correction, as it can momentarily return to the system depending on the ongoing chemical and biological reactions (Kumar et al., 2022).

Statistical comparison by depth demonstrates stratification in the response of chemical attributes. The pH in $CaCl_2$, V% and SB showed statistically significantly higher results in the superficial layer (0-20 cm depth). This difference reflects the greater effectiveness of liming in the layer where the concealer was applied and incorporated, confirming recent findings that the mobility of basic ions is not always sufficient to correct subsurface layers to the same degree (Smith et al., 2023; Roy et al., 2025). The Al^{3+} value, although not showing statistically high differences, still suggests an environment of lower toxicity on the surface, positively correlating with the increase in pH in this layer (Zhang et al., 2020).

From a statistical point of view, the higher coefficients of variation for parameters such as Al^{3+} and H+Al indicate heterogeneity in the soil and the complexity of aluminum neutralization reactions, pointing to the importance of adequate replications and careful sampling (Kumar et al., 2021; Wang et al., 2024). They also indicate that the use of silicate sources for the construction of a more chemically stabilized soil profile should be considered in a longer time interval when using more soluble sources of bases such as calcitic or dolomitic limestone.

It can be inferred that the success of acidity correction in tropical and weathered soils depends not only on the product and the dose applied, but also on the reaction time, environmental conditions (rainfall, temperature), and the form of application (surface vs. incorporated), aspects widely discussed in the most recent international literature (Zhang et al., 2020; Ding et al., 2023).

CONCLUSIONS

The study demonstrated that the application of compact shale as a soil remineralizer, derived from iron mining tailings in the region of Itabira-MG, presents itself as an effective and sustainable alternative for the remineralization of tropical agricultural soils. In both experiments conducted in Nazareno-MG and Piracicaba-SP, compact shale promoted significant improvements in the chemical attributes of the soil, causing an increase in pH (in $CaCl_2$ and H_2O), a reduction in exchangeable aluminum (Al^{3+}), an increase in base saturation (V%) and in the sum of bases (SB). These effects were comparable to or superior to those observed with the use of traditional dolomitic and/or

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calcitic limestones, reinforcing its potential as an acidity corrective and a source that gradually makes nutrients available.

The fine granulometry (0.106 mm) and the dosage of 22 ton/ha facilitated the accelerated weathering of the material, ensuring progressive release of CaO and MgO cations, essential for soil fertility. However, the results showed greater efficacy in the superficial layers (0-20 cm depth), indicating the need for complementary management strategies, such as mechanical incorporation or adjustments in the frequency of application, to reach subsurface layers. The observed temporal dynamics, with peaks of Al^{3+} neutralization and pH oscillations over 120 days, highlights the importance of continuous monitoring to make the correction of acidity and nutrient availability more efficient.

In addition to the agronomic benefits, the use of compact shale as a remineralizer is in line with the principles of the circular economy, by transforming mineral waste into agricultural inputs, reducing environmental liabilities and promoting sustainable practices. The combination of shale with traditional limestones proved to be particularly advantageous, suggesting synergies that can increase the efficiency of soil correction and reduce costs and dependence on synthetic fertilizers.

The validation of low environmental impact technologies in agriculture, highlighting compact shale as a viable solution for the recovery of degraded soils in tropical regions. Future research should explore the integration of this material with conservation management practices, such as no-tillage and agroforestry, in addition to investigating its long-term effects on different crops, aiming to consolidate its adoption in sustainable production systems.

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