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Chemical properties of soils submitted to the application of a bioactivator and basalt and serpentinite powders[1]

Atributos químicos de solos submetidos à aplicação de bioativo e dos pós de basalto e serpentinito

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HIGHLIGHTS:
Basalt and serpentinite powders are complementary alternatives to correctives and mineral fertilizers.
Basalt and serpentinite remineralizers must be added at least three months before cultivation for soil acidity correction.
The Penergetic bioactivator accelerates the reaction of remineralizers in the soil.

ABSTRACT: Dependence on external raw materials, the high cost of fertilizers, and the search for more sustainable alternatives have encouraged research with remineralizers. This study aimed to evaluate the effect of adding remineralizers associated or not with a bioactivator on pH, H+Al, Al, P, and K in two soils after four incubation times. A completely randomized experimental design was used in a 5 x 2 x 2 x 2 factorial scheme, as follows: doses of remineralizers (0, 2, 4, 8, and 16 Mg ha^{-1}), bioactivator (with and without application), type of remineralizer (basalt and serpentinite), and soil class (Oxisol and Entisol), with four replications. The soils were incubated for 30, 90, 120, and 240 days after the treatment applications. The samples were submitted to pH, Al, H+Al, P, and K analyses at the end of each incubation period. The use of increasing doses of remineralizers favored an increase in pH, P, and K and a reduction in Al and H+Al in the studied soils. Serpentinite powder was more efficient in neutralizing soil acidity, while basalt powder was more efficient in providing P and K to soils. The bioactivator reduced the reaction time of the remineralizers and favored the increase in K availability.

Key words: rock dust, bioactivator, soil incubation time, soil chemical characteristics

RESUMO: A dependência de matérias-primas externas, o alto custo dos fertilizantes e a busca por alternativas mais sustentáveis têm incentivado a pesquisa com remineralizadores. O objetivo deste estudo foi avaliar o efeito da adição de remineralizadores, associados ou não ao bioativador, sobre o pH, H+Al, Al, P e K em dois solos, após quatro períodos de incubação. Utilizou-se delineamento experimental inteiramente casualizado, em esquema fatorial 5 × 2 × 2 × 2, sendo: doses de remineralizadores (0, 2, 4, 8 e 16 Mg ha^{-1}), bioativador (com e sem aplicação), tipo de remineralizador (basalto e serpentinito) e classe de solo (Latossolo Vermelho e Neossolo), com quatro repetições. Após a aplicação dos tratamentos, os solos foram incubados por 30, 90, 120 e 240 dias. Ao final de cada período de incubação, as amostras foram submetidas as análises de pH, Al, H+Al, P e K. A utilização de doses crescentes dos remineralizadores favoreceu o aumento do pH, P e K e redução do Al e H+Al nos solos estudados. O pó de serpentinito apresentou maior eficiência para a neutralização da acidez dos solos, enquanto o pó de basalto apresentou maior eficiência para fornecer P e K para os solos. O bioativo reduziu o tempo de reação dos remineralizadores e favoreceu o aumento da disponibilidade de K.

Palavras-chave: pós de rocha, bioativador, tempo de incubação do solo, características químicas dos solos

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Introduction

Brazil has an agricultural cultivation area of 60 million hectares (CONAB, 2019), with a predominance of acid soils and low natural fertility, thus requiring correction and fertilization for these soils to become productive. However, mineral fertilizers used in Brazilian agriculture are mostly imported and costly. Thus, the search for more sustainable alternatives has encouraged research with remineralizers.

Remineralizers (REM) are derived from comminuted, abundant silicate rocks rich in bases and a source mainly of Ca, Mg, Fe, Si, and K, in addition to micronutrients and primary minerals. According to Krahl et al. (2022), pure and ground biotite schist and biotite syenite rock samples are sources of macro-and micronutrients for corn plants. Due to these characteristics, materials derived from these rocks have a high potential to meet, at least partially, the demand for fertilizers in agriculture (Theodoro et al., 2021).

The use of rocks that have nutrients in their composition currently represents an alternative practice for complementing or partially replacing conventional fertilizers in agriculture. However, rock dust generally has low solubility (Alovisi et al., 2021). Therefore, alternatives that increase solubilization and add value to products derived from rocks have been sought. In this context, modern agriculture has invested in technologies such as the use of microbiota bioactivation products, which would allow better use of available and immobilized nutrients in the soil.

However, there is a lack of information to compare the use of remineralizers and bioactivators and the interference of these associations in the solubility of remineralizers and the release of nutrients to soils over time.

Thus, this study aimed to evaluate the effect of adding remineralizers associated or not with a bioactivator on pH, H+Al, Al, P, and K in two soils after four incubation times.

Material and Methods

The study was conducted in a greenhouse at the School of Agricultural Sciences of the Federal University of Grande Dourados, Dourados-MS, Brazil, in 2020. The greenhouse was 20 m long, 6 m wide, and 4 m high (north-south direction) and was covered with a transparent low-density polyethylene film, a transparent light diffuser (LDPE – low-density polyethylene) with a thickness of 150 μm and treated against ultraviolet rays. The sides of the greenhouse were covered with a low-density polyethylene film and fixed throughout the experimental period.

The soils were classified as Oxisol (United States, 2014), which corresponds to a clayey-textured (59% clay) dystroferric Red Latosol (Santos et al., 2018) (22° 14’ 88” S; 54° 59’ 13” W), and Entisol (United States, 2014), which corresponds to a sandy-textured (6% clay) Neosol (Santos et al., 2018) (16° 56’ 25” S; 53° 31’ 14” W). Both soils were collected at a depth of 0–20 cm. The soil chemical characteristics, according to the methodology described by Claessen (1997), are: pH in $CaCl_2$ 5.0 of and 3.9; organic matter of 27 and 11 g dm^{-3}; P of 49 and 1 mg dm^{-3}; K of 2.7 and 0.3 $mmol_c$ dm^{-3}; Ca of 36 and 2 $mmol_c$ dm^{-3}; Mg 19 and 1 $mmol_c$ dm^{-3}; Al of 0 and 8 $mmol_c$ dm^{-3}; H+Al of 61 and 39 $mmol_c$ dm^{-3}; the sum of bases (SB) of 58 and 3 $mmol_c$ dm^{-3}; CEC at pH 7.0 of 119 and 42 $mmol_c$ dm^{-3}; and base saturation (BS) of 48 and 8%, respectively for the Oxisol and Entisol.

A completely randomized experimental design was used in a 5 x 2 x 2 x 2 factorial scheme, with five doses of remineralizers (0, 2, 4, 8, and 16 Mg ha^{-1}) to cover situations from moderate to intensive application rates, bioactivator (with and without application), type of remineralizers (basalt and serpentinite), and soil class (Oxisol and Entisol), with four replications.

The remineralizer basalt powder was obtained from a mining company located in the municipality of Itaporã (MS, Brazil) (22° 07’ 44” S; 54° 58’ 05” W) and had the following mineralogical characteristics: SiO_2 (49.35%), Al_2O_3 (12.17%), FeO_2 (15.45%), CaO (7.74%), MgO (3.67%), K_2O (1.60%), N_2O (2.62%), TiO_2 (3.67%), MnO (0.23%), and P_2O_5 (0.61%). Serpentinite was supplied by a stone industry located in the municipality of Nova Lima (MG, Brazil) and presented the following composition: SiO_2 (38.40%), Al_2O_3 (1.31%), FeO_2 (12.66%), CaO (0.66%), MgO (35.07%), K_2O (0.01%), N_2O (<0.01%), TiO_2 (0.03%), MnO (0.09%), and P_2O5 (0.02%). These remineralizers had a particle size ≤0.5 mm.

The remineralizer analyses followed the sample reference method by the Environmental Protection Agency – EPA 3051 A:2007 – Microwave assisted acid digestion. This method uses extraction by heating in an acid medium for the partial decomposition of the elements. The method EPA 6010C:2007, referring to the determination of metals by ICP OES, was used for sample determinations.

The soil bioactivator consisted of the Penergetic K™ (energized bentonite clay), composed of SiO_2 (56%), Al_2O_3 (16%), Fe_2O_3 (4.0%), CaO (4.0%), MgO (4.0%), K_2O (2.0%), Na_2O (0.4%), and trace elements (3.5%) (basic composition of general contents). Penergetic is a natural bioactivation technology that allows the copying and transfer of specific information from original substances to a carrier substance through the process of energizing electromagnetic waves in the reduced spectrum (Penergetic, 2017).

The remineralizers were incorporated into the soil of each pot with a capacity of 500 cm^3, filled with 200 cm^3 of soil. The pots with bioactivator received a dose of 0.1 g pot^{-1}. The Penergetic dose was defined according to the manufacturer’s technical recommendations. The products were added to the soil and homogenized.

After homogenization, distilled water was added in equal amounts to each container, enough to occupy 60% of the total pore volume (Freire et al., 1980). Water replacement was controlled with distilled water every two days by weighing each container containing the soil.

The experimental units were incubated for 30, 90, 120, and 240 days after applying the treatments to the soil samples. Four subsamples of soil were collected in each pot at the end of each incubation period, using a screw auger specific for this purpose. The auger was inserted into the bottom of the pot at each sampling and the soil samples were mixed thoroughly to provide a composite sample, which was air-dried and then sieved (2 mm mesh) and subjected to analysis for the following soil chemical attributes: pH in $CaCl_2$, exchangeable aluminum, potential acidity, phosphorus, and potassium, according to the methodology described by Claessen (1997).

The Time (T) factor was studied by making measurements on the experimental units over time. Factors D (doses), B (bioactivator), R (remineralizer), S (soil), and T (time) were considered as a fixed effect and the plot as a random effect. Wald's chi-square test was performed at the 5% level to assess the significance of fixed effects. Two-by-two interactions of the factors were analyzed, as the other interactions were not significant. The analyses were performed in the R software (R Core Team, 2017), using lme4 (Bates et al., 2015).

Results and Discussion

Table 1 shows the results of the analysis of variance for the variables aluminum, pH in 0.01M $CaCl_2$, potential acidity, phosphorus, and potassium. A double interaction ($p < 0.05$) was observed for all studied sources of variation.

Table 2 shows the details of interactions involving soil, remineralizer, and bioactivator factors. The values for the Oxisol were significantly ($p < 0.05$) higher for pH, H+Al, P, and K compared to the Entisol, regardless of the used remineralizer. It is an expected result, as the Oxisol already presented higher values of these attributes before the addition of treatments when compared to the Entisol.

Table 1. Results of the Wald test (χ^2) of the analysis of variance for the variables aluminum (Al), pH in 0.01M $CaCl_2$, potential acidity (H+Al), phosphorus (P), and potassium (K) in the soil

Source of variation	Al	pH ($CaCl_2$)	H + Al	P	K
Dose (D)	**	**	**	**	ns
Bioactivator (B)	**	ns	**	ns	**
Remineralizer (R)	**	**	**	**	ns
Time (T)	**	**	**	**	**
Soil (S)	**	**	**	**	**
D:B	ns	ns	ns	ns	**
D:R	ns	**	ns	**	ns
D:S	**	**	**	**	**
D:T	ns	**	ns	**	**
B:R	ns	ns	ns	ns	**
B:S	ns	ns	**	ns	ns
B:T	ns	**	ns	ns	ns
R:S	**	**	**	**	**
R:T	**	**	**	**	**
T:S	**	**	**	**	**

**, significant at $p < 0.05$ by the Wald test; ns, non-significant by the Wald test

The use of the bioactive altered the values of potential acidity and K concentration in the soil (Table 2). A significant difference was found for H+Al only in the Entisol, with the highest value observed in the treatment that received no bioactivator. A significant difference was found for K only with the use of serpentinite powder, with a higher concentration in the soil in the presence of the bioactivator. According to Arif et al. (2019), the use of the bioactivator induces microbial activity, resulting in increased mineralization of nutrients, mainly P and K.

For the two remineralizers (Figures 1A and 1B), soil classes (Figures 2A and 2D), and soil incubation time (Figures 3A and 3B), the addition of increasing remineralizer doses significantly increased the pH values and phosphorus contents and were described by linear regression models ($p < 0.05$).

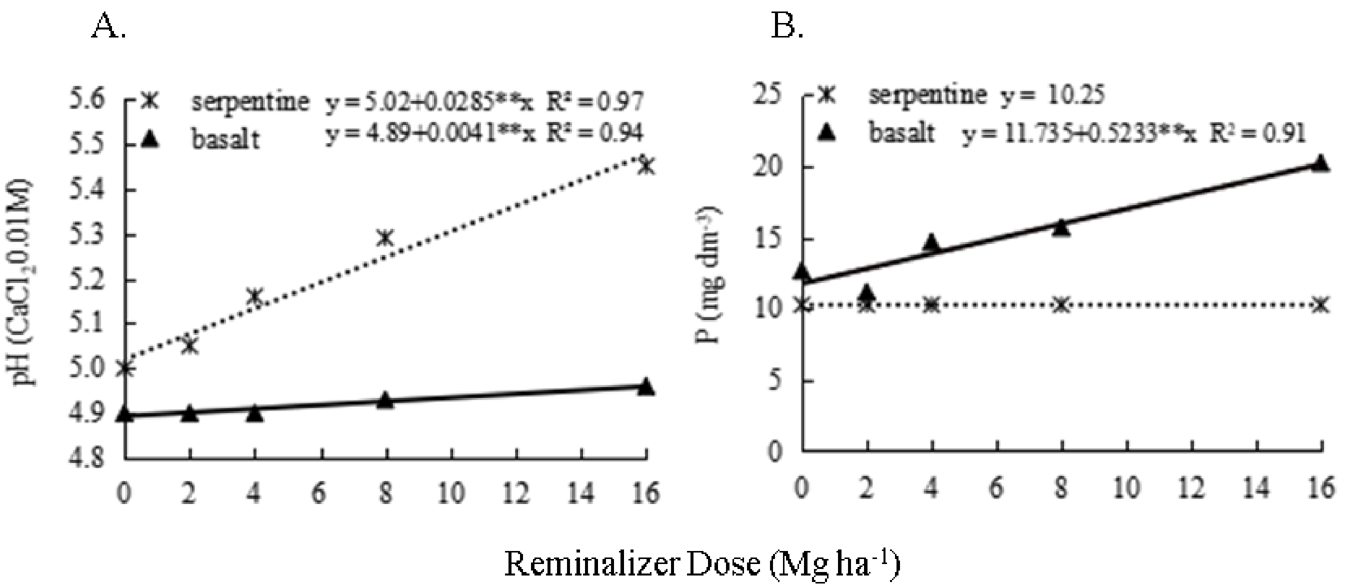
Regarding soil class, the Entisol showed a higher change in pH and P values than the Oxisol (Figure 1A). The pH value increased by 0.01 for the Oxisol and 0.02 for the Entisol for each 1 Mg ha^{-1} of remineralizers (Figure 2A). Moreover, the addition of 1 Mg ha^{-1} of remineralizers increased P concentration by 0.10 and 0.43 mg dm^{-3}, respectively for the Oxisol and Entisol (Figure 2D). The initial values of pH in $CaCl_2$ (5.0 and 3.9) and P concentration (49.0 and 1.0 mg dm^{-3}) showed an increase of 8.8% in pH and 19.5% in P content in the Oxisol and 16.5% in pH and 151% in P content in the Entisol, both at a dose of 16 Mg ha^{-1}. P concentration in the Oxisol was already high and remained in this range after the addition of remineralizers, but the range for the Entisol changed from very low to medium P content in the soil, based on the criteria by Sousa & Lobato (2004).

This result can be attributed to the low buffering capacity of the Entisol compared to that of the Oxisol (Fontana et al., 2021). This finding results in less resistance of the Entisol to pH changes and, on the other hand, higher P availability, as there is

Table 2. Results of the Tukey test ($p < 0.05$) for the slicing of significant interactions involving Soil, Rock, and Bioactivator factors

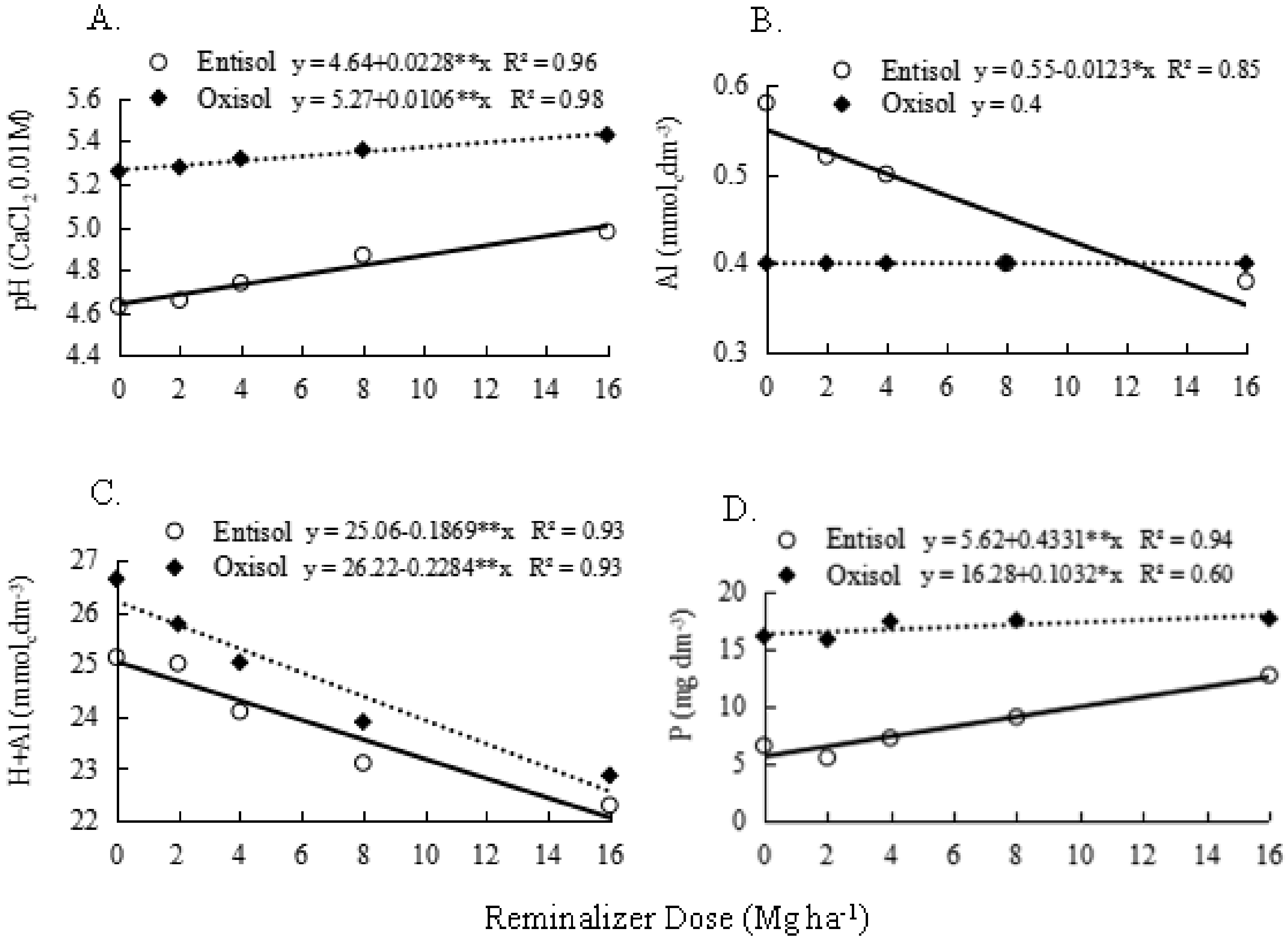
Variable	Factors	Rock: Basalt	Rock: Serpentinite	Soil: Entisol	Soil: Oxisol
Al ($mmol_c$ dm^{-3})	Soil: Entisol	0.59 Aa	0.38 Bb		
	Soil: Oxisol	0.12 Bb	0.58 Aa		
	Bioactivator: with				
	Bioactivator: without				
pH ($CaCl_2$)	Soil: Entisol	4.50 Bb	5.00 Ab		
	Soil: Oxisol	5.32 Ba	5.38 Aa		
	Bioactivator: with				
	Bioactivator: without				
H+Al ($mmol_c$ dm^{-3})	Soil: Entisol	23.17 Aa	19.94 Bb		
	Soil: Oxisol	24.86 Aa	23.90 Ba		
	Bioactivator: with			20.87 Bb	24.23 Aa
	Bioactivator: without			22.23 Aa	24.53 Aa
P (mg dm^{-3})	Soil: Entisol	10.64 Ab	4.58 Bb		
	Soil: Oxisol	17.96 Aa	15.53 Ba		
	Bioactivator: with				
	Bioactivator: without				
K ($mmol_c$ dm^{-3})	Soil: Entisol	0.92 Ab	1.04 Ab		
	Soil: Oxisol	4.54 Aa	4.46 Aa		
	Bioactivator: with	2.74 Ba	2.89 Aa		
	Bioactivator: without	2.73 Aa	2.61 Bb		

*Means followed by the same uppercase letter in the row and lowercase in the column, within each attribute, do not differ significantly from each other (Tukey test, $p < 0.05$)



**, significant at $p \leq 0.01$ by the F-test

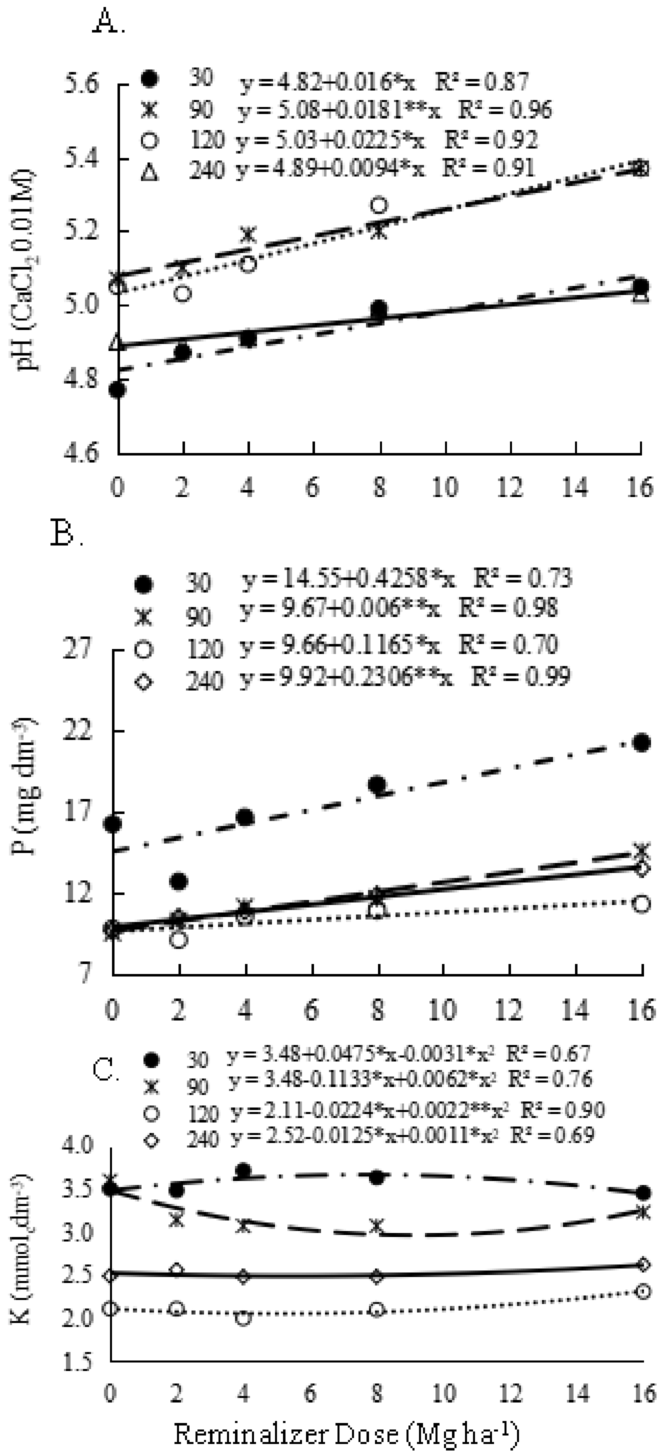
Figure 1. Effect of doses of basalt and serpentinite remineralizers on the pH in 0.01M $CaCl_2$ (A) and phosphorus (B) concentration



* and **, significant at $p \leq 0.05$ and $p \leq 0.01$ by the F-test, respectively

Figure 2. Values of pH in 0.01M $CaCl_2$ (A), aluminum - Al (B), potential acidity - H + Al (C), and phosphorus - P concentration (D) in the Entisol and Oxisol influenced by doses of remineralizers

less need for phosphate to saturate the positively charged and active sites in the specific adsorption. The highest pH values were verified at 90 and 120 days after soil incubation (Figure 3A), regardless of the remineralizer doses, showing that the studied remineralizers do not correct the soil pH in the short term. On the other hand, the highest P and K concentrations were obtained at 30 days after soil incubation, regardless of the studied doses (Figures 3B and 3C), indicating the importance



* and **, significant at $p \leq 0.05$ and $p \leq 0.01$ by the F-test, respectively

Figure 3. Effect of remineralizer doses on the pH in 0.01M $CaCl_2$ (A) and phosphorus (B) and potassium (C) concentrations at 30, 90, 120, and 240 days after soil incubation with the remineralizer and bioactivator

of plants in the system for absorbing these nutrients, thus avoiding losses by leaching and fixation.

Higher pH values reduce active acidity and aluminum (Figures 2B and 2C). Active acidity was reduced by 13.3 and 15.2% at the dose of 16 Mg ha^{-1} for the Oxisol and Entisol, respectively (Figure 2C). The reduction for aluminum was 6.7% in the Entisol (Figure 2B). Other authors have also reported the benefits of the gradual availability of nutrients over time by remineralizers (Grecco et al., 2013; Anda et al., 2015).

Aluminum concentration showed a decreasing linear adjustment as a function of incubation time, regardless of the soil class (Figure 4A) and type of remineralizer (Figure 5B). The highest reductions in the aluminum concentration were observed for the Oxisol (84%) and when using serpentinite (78%) at 240 days of incubation (Figures 4A and 5B, respectively). A higher aluminum neutralization/immobilization was observed due to the higher values of pH (Figure 4B) and organic matter in the Oxisol compared to the Entisol.

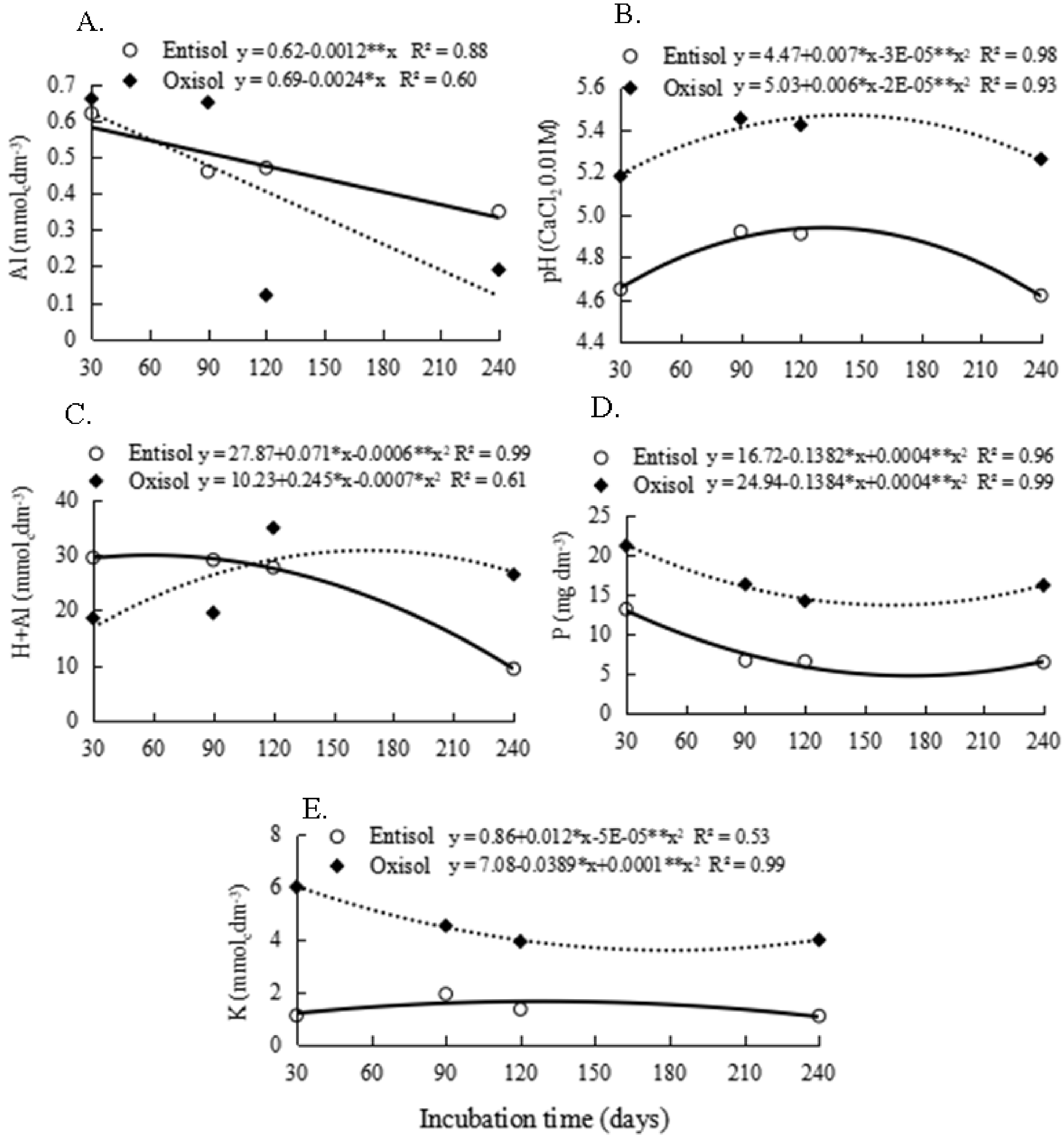
The values of pH and H+Al showed a quadratic adjustment as a function of the evaluation time, regardless of the soil class (Figures 4B and 4C), type of remineralizer (Figures 5A and 5C), and doses of remineralizers (Figure 6A).

The maximum pH values (5.51 and 4.90) for the soil class were found at 155 and 120 days, and the values for H+Al were 31.74 and 29.97 $mmol_c$ dm^{-3} at 175 and 59 days for the Oxisol and Entisol, respectively (Figures 4B and 4C). Regarding the type of remineralizers, serpentinite contributes with higher pH and H+Al values compared to basalt (Figures 5A and 5C), with maximum estimated values of 5.3 and 5.1 at 127 and 135 days for pH and 29.18 and 26.85 at 108 and 119 days for H+Al for serpentinite and basalt, respectively. The highest estimated pH value (5.45) was obtained at the highest dose of remineralizers (Figure 6A).

These results suggest that remineralizers as soil correctives have low solubility, regardless of the soil class. Therefore, they should be added at least four months before sowing at the highest studied doses so that the soil is corrected to promote higher efficiency of water and nutrient absorption by plants at the cultivation time and obtain better crop yields.

The data fitted the polynomial model for P and K, regardless of the soil class (Figures 4D and 4E), type of remineralizer (Figures 5D and 5E), and doses of remineralizers (Figures 6B and 6C). The minimum concentrations for soil classes were 12.97 and 4.78 mg dm^{-3} both at 173 days for P and 3.30 and 1.58 $mmol_c$ dm^{-3} at 194 and 120 days for K for the Oxisol and Entisol, respectively (Figures 4D and 4E). The minimum concentrations for the type of remineralizers were 10.20 and 7.49 mg dm^{-3} at 167 and 189 days for P and 2.13 and 2.27 $mmol_c$ dm^{-3} at 222 and 164 days for K for basalt and serpentinite, respectively (Figures 5D and 5E). The interaction time of incubation x doses of remineralizers showed that the estimated levels of P were 7.77, 8.22, 9.91, 9.74, and 11.30 mg dm^{-3} at 173, 180, 157, 163, and 160 days, respectively, at doses of 0, 2, 4, 8, and 16 Mg ha^{-1} (Figure 6B), while the estimated levels for K were 2.24, 2.20, 2.0, 2.11, and 2.53 $mmol_c$ dm^{-3} at 218, 182, 180, 181, and 172 days, respectively, at doses of 0, 2, 4, 8, and 16 Mg ha^{-1} (Figure 6C).

These results show that the process of phosphorus fixation may have started after 30 days of soil incubation. Also, even with phosphate reacting with the soil throughout the incubation period (Figure 6B), this reaction forms

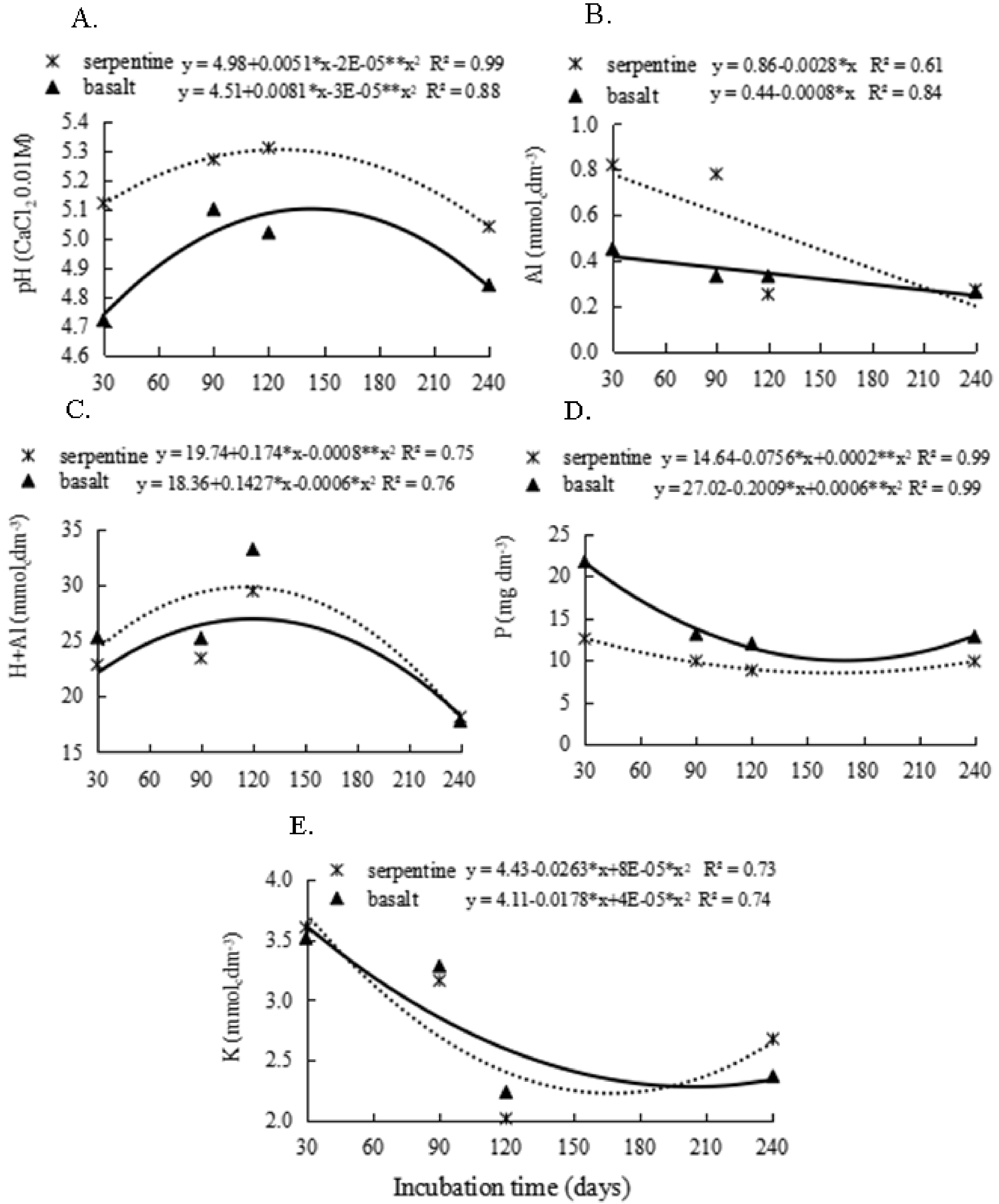


* and **, significant at p ≤ 0.05 and p ≤ 0.01 by the F-test, respectively

Figure 4. Aluminum (A), pH in 0.01M $CaCl_2$ (B), potential acidity - H + Al (C), phosphorus (D), and potassium (E) in the Entisol and Oxisol after incubation (days) with remineralizers and bioactivator

compounds with lower P availability for the plants. The data for K suggest the occurrence of dissolution reversal, with K reabsorption and/or mineral neoformation, forming compounds with lower solubility (Duarte et al., 2022). These results suggest different times of addition of remineralizers, depending on the purpose (acidity corrector or fertilizer).

The interpretation range suggested by Souza & Lobato (2004) for P in both soils remained the same at 173 days after the addition of remineralizers, that is, high concentration for the Oxisol and very low for the Entisol, demonstrating that the doses of remineralizers could not guarantee the P concentration within the sufficiency range in soils with very low levels, as in the Entisol. It can be explained by the strong affinity of P with the surface of soil colloids and the reaction with aluminum and iron ions (Alovisi et al., 2020), which results in P adsorption and precipitation, in addition to the low P_2O_5 supply from remineralizers, providing 0.6 and 0.02% P_2O_5 for basalt and serpentinite powder, respectively. These values are much lower than the amounts of P added via soluble fertilizers. The interpretation range for K in the Entisol changed from low to adequate, according to Souza & Lobato (2004).

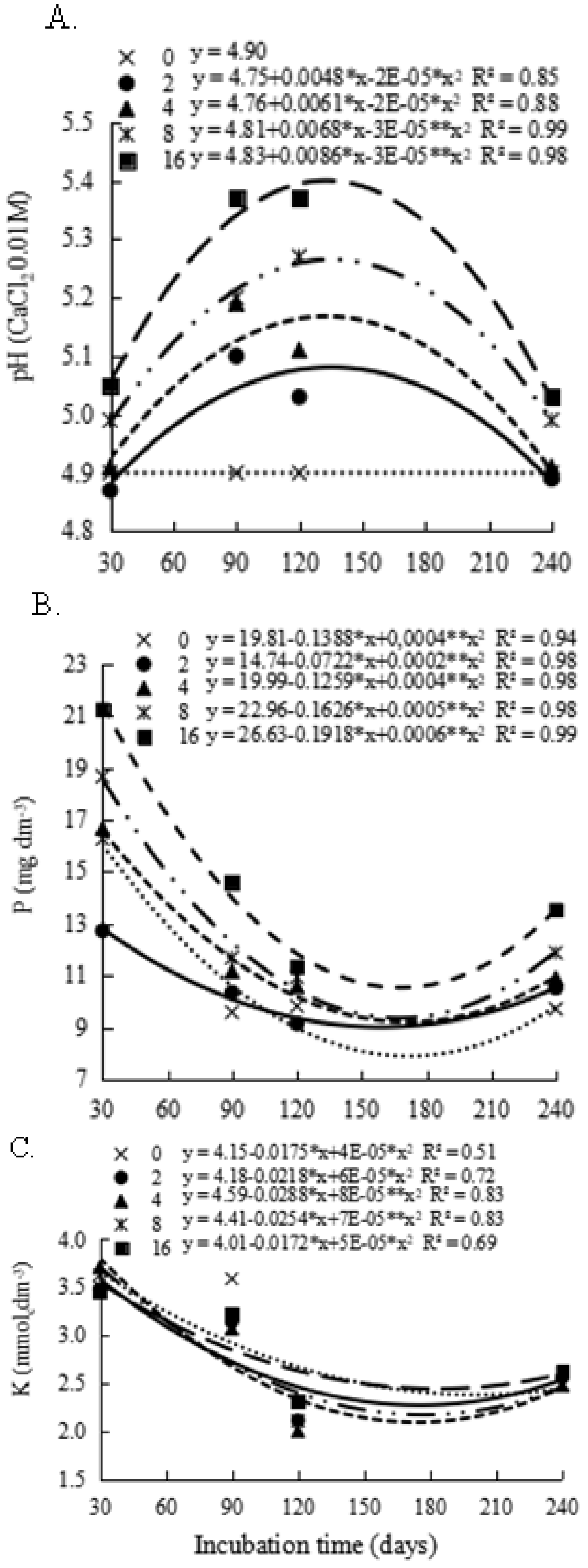


* and **, significant at $p \leq 0.05$ and $p \leq 0.01$ by the F-test, respectively

Figure 5. Effect of the interaction of soil incubation time with remineralizers (basalt and serpentinite) for pH in 0.01M $CaCl_2$ (A), aluminum (B), potential acidity - H + Al (C), phosphorus (D), and potassium (E) in the analyzed soils

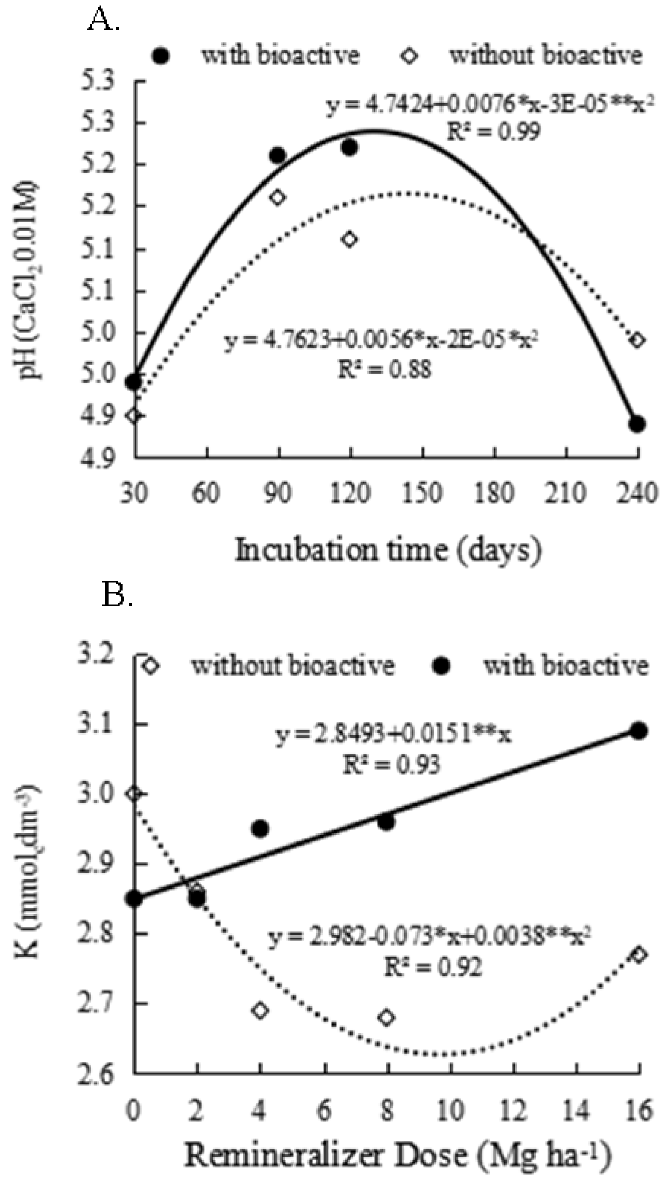
Estimated maximum pH values of 5.2 and 5.1 were observed at 127 and 140 days, respectively, with and without the bioactivator (Figure 7A). A minimum estimated value of 2.63 $mmol_c$ dm^{-3} was found for K at the dose of 9.63 Mg ha^{-1} without a bioactivator and a linear increase in the K concentration in the soil was observed with the use of the bioactivator (Figure 7B).

Therefore, the use of the bioactivator reduced the reaction time of the remineralizers in the soil from 140 to 127 days, with an increase in pH, and favored a linear



* and **, significant at p ≤ 0.05 and p ≤ 0.01 by the F-test, respectively

Figure 6. Effect of the interaction between soil incubation time and doses of remineralizers (0, 2, 4, 8, and 16 Mg ha^{-1}) for values of pH in 0.01M $CaCl_2$ (A) and concentrations of phosphorus (B) and potassium (C)



* and **, significant at p ≤ 0.05 and p ≤ 0.01 by the F-test, respectively

Figure 7. Effect of the interaction of incubation time of soils with and without the bioactivator for pH in 0.01M $CaCl_2$ (A) and effect of the interaction of remineralizer doses with and without the bioactivator for potassium concentration in the soil (B)

increase in K availability. However, the interpretation range of K in the soil suggested by Souza & Lobato (2004) remained the same.

Conclusions

1. Increasing doses of remineralizers (basalt and serpentinite) favored an increase in pH, P, and K and a reduction in Al and H+Al in both soils (Entisol and Oxisol).
2. Remineralizers have the potential to raise soil pH in the long term, requiring periods of at least 120 days to obtain the desired results.
3. P and K concentrations are reduced with an increase in the contact time of the remineralizers with the soils.
4. The bioactivator reduced the reaction time of the remineralizers and favored an increase in K availability.

Literature Cited

Anda, M. Shamshuddin, J.; Ishak, C. Improving chemical properties of a highly weathered soil using finely ground basalt rocks. Catena, v.124, p.147-161, 2015. https://doi.org/10.1016/j.catena.2014.09.012

Alovisi, A. M. T.; Cassol, C. J.; Nascimento, J. S.; Soares, N. B.; Silva Junior, I. R.; Silva, R. S. da; Silva, J. A. M. da. Soil factors affecting phosphorus adsorption in soils of the Cerrado, Brazil. Geoderma Regional, v.22, p.1-7, 2020. https://doi.org/10.1016/j.geodrs.2020.e00298

Alovisi, A. M. T.; Rodrigues, R. B.; Alovisi, A. A.; Tebar, M. M.; Villalba, L. A.; Muglia, G. R. P.; Palhano, M. S.; Tokura, L. K.; Cassol, C. J.; Silva, R. S.; Tokura, W. I.; Gning. A.; Kai, P. M. Uso do pó de rocha basáltica como fertilizante alternativo na cultura da soja, Research, Society and Development, v.10, p.1-12, 2021. https://doi.org/10.33448/rsd-v10i6.15599

Arif, M.; Hussain, N.; Yasmeen, A. Influence of bio-stimulant and potassium sources on the productivity of cotton. The Journal of Animal & Plant Sciences, v.29, p.1643-1653, 2019.

Bates, D.; Maechler, M.; Bolker, B. Walker, S.; Fitting linear mixed effects models using lme4. Journal of Statistical Software, v.67, p.1-48, 2015.

Claessen, M. E. C. Manual de métodos de analise de solo. 2.ed. Rio de Janeiro: EMBRAPA-CNPS, 1997. 212p.

CONAB - Companhia Nacional de Abastecimento. Indicadores de agropecuária. 2019. https://www.conab.gov.br/Conabweb/download/pdf

Duarte, L. M.; Xavier, L. V.; Rossati, K. F.; Oliveira, V. A.; Schimicoscki, R. S.; Ávila Neto, C. N.; Mendes, G. O. Potassium extraction from the silicate rock Verdete using organic acids. Scientia Agricola, v.79, p.1-8, 2022. https://doi.org/10.1590/1678-992X-2020-0164

Fontana, A.; Pereira, M. G.; Santos, J. J. S.; Donagemma, G. K.; Santos, O. A. Q. Capacidade de adsorção de fósforo em solos de textura arenosa com fertilidade construída. Revista Agrogeoambiental, v.13, p.606-614, 2021. https://doi.org/10.18406/2316-1817v13n320211639

Freire, J. C.; Ribeiro, M. A. V.; Bahia, V. G.; Lopes, A. S.; Aquino, L. E. Resposta do milho em casa de vegetação a níveis de água em solos da região de Lavras-MG. Revista Brasileira de Ciência do Solo, v.4, p.5-8, 1980.

Grecco, M. F.; Bamberg, A. L.; Bergmann, M.; Sander, A.; Toniolo, J. A.; Silveira, C. A. P.; Martinazzo, R. Liberação de nutrientes por fonolitos da suíte alcalina passo da capela. In: Simpósio Sul Brasileiro de Geologia, Porto Alegre, RS. 2013. http://www.alice.cnptia.embrapa.br/alice/handle/doc/963952

Krahl, L. L.; Valadares. L. F.; Sousa-Silva, J. C.; Marchi, G.; Martins. E. S.; Dissolution of silicate minerals and nutrient availability for corn grown successively. Pesquisa Agropecuária Brasileira, v.57, p.1-13, 2022. https://doi.org/10.1590/S1678-3921.pab2022.v57.01467

Penergetic. Resultados Oficiais Penergetic. 2017. https://issuu.com/araunah_agro/docs/1_revista_official_results_penerget

R Core Team. R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing, 2017. https://www.r-project.org/

Santos, H. G. dos; Jacomine, P. K. T.; Anjos, L. H. C. dos; Oliveira, V. A. de; Lumbreras, J. F.; Coelho, M. R.; Almeida, J. A. de; Araujo Filho, J. C. de; Oliveira, J. B. de; Cunha, T. J. F. Sistema brasileiro de classificação de solos. 5.ed. Brasília: EMBRAPA, 2018.

Sousa, D. M. G.; Lobato, E. Cerrado correção e adubação. 2.ed. Brasília: Embrapa Informação Tecnológica, 2004. 416p.

Theodoro, S. H.; Sander, A.; Barbano, D. F. M.; Almeida, G. R. Rochas basálticas para rejuvenescer solos intemperizados. Revista Liberato, v.22, p.1-120, 2021. https://doi.org/10.31514/rliberato.2021v22n37.p45

United States Soil Survey Staff. Keys to soil taxonomy. 12.ed. Lincoln: USDA-NRC, 2014, 360p.