

## Increase in soil biological health through the application of the Rekal mineral soil treatment

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### Abstract

The agricultural sector is extremely socioeconomically relevant in Brazil. Agricultural production systems are dynamic, and they currently focus on plant production, with emphasis on sustainability and soil health aimed at ensuring the regenerative agriculture implementation by using natural inputs rather than chemical ones. The objective of the present study is to investigate the effects of Rekal soil remineralizer on the biological health of soils cultivated with soybeans in four experimental sites located in Goiás State under different soil conditions and agricultural management procedures. The experiment followed a randomized block design with four treatments, namely: the standard treatment with potassium chloride and three treatments based on increasing the remineralizer doses. Soil samples were collected before treatment application and after the crop cycle was over. The samples were used to assess soil biological health based on the BioAS methodology (*Empresa Brasileira de Pesquisa Agropecuária*), which includes physical, chemical, and biological indicators, with emphasis on the activity of enzymes  $\beta$ -glucosidase and arylsulfatase, organic matter content, and soil quality indices. According to the results, there was a significant increase in the activity of enzymes  $\beta$ -glucosidase and arylsulfatase, organic matter accumulation, and improved soil chemical and biological quality indices in comparison with the standard treatment (without Rekal remineralizer application). This finding points out that Rekal is a technological and sustainable alternative capable of both enhancing nutrient cycling and improving features related to soil fertility and resilience in soybean production systems.

**Keywords:** soy; soil remineralizer; BioAS; sustainable agriculture.

**Practical Application:** The use of remineralizers strengthens soil health and promotes sustainable agriculture.

## 1 INTRODUCTION

Agriculture depends on mineral fertilizers to preserve soil fertility and achieve favorable physical, chemical, and biological conditions for crop development. According to data from the Brazilian fertilizer sector, the country shows a high dependence on imported agricultural inputs, reinforcing the need for strategic alternatives to strengthen national agricultural sustainability (Associação Nacional para Difusão de Adubos [ANDA], 2023). Soil remineralizers that consist of mechanically reduced mineral materials are the most resilient and sustainable alternatives to achieve potential gradual macro- and micronutrient release, increase cation exchange capacity, improve water retention, and support soil microbiota. Furthermore, it helps achieve a more sustainable and efficient soil fertility (Santos et al., 2025; Serviço Geológico do Brasil, 2024; Theodoro et al., 2021).

These inputs also boost relevant soil biochemical and microbiological processes because they interact with roots

and microorganisms, and, consequently, accelerate weathering and release nutrients such as calcium, magnesium, silicon, and phosphorus, in addition to triggering the formation of secondary minerals that improve soil structure (Mendez et al., 2022). Despite response variations caused by the geological origin and grain size of the used rocks, the literature also shows their consistent impact on the availability of elements such as Ca, Mg, P, and K, as well as on increasing soil quality and biological health (Luchese et al., 2023; Ribeiro et al., 1999; Santos et al., 2024).

Soil quality is a multidimensional concept comprising physical, chemical, and biological features (BioAS). It assesses soil health based on the activity of enzymes arylsulfatase and  $\beta$ -glucosidase in combination with physical and chemical indicators. It stands out among methodologies developed to measure soil quality by allowing the sensitive detection of changes emerging from agricultural management (Mendes et al., 2020).

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Recent studies have shown that remineralizers work as multifunctional inputs that respond to corrective, fertilizing, and bio-stimulating functions that have a direct impact on both microbial activity and soil-plant system functioning (Martins et al., 2023). The association between the use of remineralizers and the application of methodologies sensitive to biological dynamics, such as BioAS, is a strategic update in soil quality assessments, since it leads to a clearer understanding of these inputs' effect on the fertility, resilience, and sustainability of agricultural ecosystems.

The aims of the present study were to verify the effects of Rekal soil remineralizer on the biological health of soils cultivated with soybeans in four experimental sites located in Goiás State under different soil conditions and agricultural management procedures in comparison with the standard treatment.

### 1.1 Relevance of the work

Research on remineralizers is essential to promoting more sustainable and resilient agriculture. These natural inputs improve soil fertility by providing a gradual and balanced release of nutrients, in addition to stimulating beneficial microbiota. Scientific studies ensure their efficiency and safety, guiding producers on best application practices. Investing in research strengthens innovation, reduces dependence on chemical inputs, mitigates environmental impacts, and contributes to food security. Therefore, advancing knowledge about remineralizers becomes strategic for agricultural production and the conservation of natural resources.

## 2 MATERIAL AND METHODS

Rekal was the soil remineralizer used in the experiment. It was extracted from, and processed in, Northern Goiás State, Vila Propício City, by Stracta Mineração Ltda. Four experimental sites were installed and, altogether, they formed a 25.92 ha experimental area located in commercial soybean sites in Santa Rita do Novo Destino, Mimoso de Goiás, and Niquelândia municipalities, Goiás State, based on features shown in Table 1.

Climate in the region is featured as an Aw type, according to the Köppen and Geiger (1928) climate classification system: hot and humid – 6 months of dry winter and 6 months of tropical weather, with yearly rainfall higher than 750 mm (it could reach 1800 mm).

Rekal preparation starts by finding the geological deposits and selecting the rock masses to be explored. The next stage lies in drilling and blasting procedures, which are followed by loading, transporting, and feeding the processing plant. Rekal production resembles that of limestone, and its process route includes primary and secondary crushing, and grinding. This is a purely physical processing method. The finished product is homogenized after the grinding stage to achieve a uniform particle-size distribution and minimal cohesion between granules. It is done in order to mitigate potential segregation during the stacking process.

Product batches were selected to be shipped to the experimental sites. Samples were collected from each batch for physicochemical analysis in a laboratory environment, as shown in Table 2.

All experimental sites were subjected to the same randomized block design, with four treatments and four repetitions. The following treatments were applied: standard (T1), which used KCl (potassium chloride) and made soil acidity correction through limestone application in the current year or in previous years, and the application of three different Rekal soil remineralizer doses (T2, T3, and T4), as shown in Table 3.

Initial soil sampling was performed prior to treatment application. Soil collections were outsourced and conducted by a company expert in precision agriculture. Samples were collected with the aid of rotary drills 0–10 cm down in the ground (BioAS methodology). They were taken to Embrapa BioAS Network Laboratory after collection (Exata Laboratory, Jataí-GO). This laboratory is qualified to carry out BioAS analyses. Soil health features (BioAS) observed prior to treatment application are available in Table 4.

The experimental sites were subjected to the no-till soybean system, and their plantings were over 5 years old, except for

**Table 1.** Name and location of the experimental sites.

Name	City	Water regime	Coordinates	Altitude
São Luiz II Farm	Santa Rita do Novo Destino-GO	Irrigated	14°50'50.69" S and 49°04'54.24" W	536
São Luiz II Farm	Santa Rita do Novo Destino-GO	Rainfed	14°51'02.38" S and 49°05'09.62" W	527
Lago Farm	Mimoso de Goiás-GO	Rainfed	15°01'33.39" S and 48°20'42.65" W	725
Canada Farm	Niquelândia-GO	Rainfed	14°50'22.09" S and 48°38'28.62" W	588

**Table 2.** Physicochemical features of the Rekal soil remineralizer used in the experimental sites.

Rekal	Analytical data						
	CaO			MgO		K <sub>2</sub> O	
	Sum of oxides	Retained on the sieves					
	2.00 mm	0.85 mm	0.30 mm				
São Luiz II Farm – Irrigated	16.51	8.82	2.68	68.81	0.32	8.75	21.48
São Luiz II Farm – Rainfed	16.93	8.76	2.65	67.24	0.41	8.52	21.41
Lago Farm	16.67	7.78	2.48	64.82	0.60	9.06	21.26
Canada Farm	16.75	9.61	2.20	57.73	0.00	11.40	23.42

**Table 3.** Experimental treatments used for Rekal remineralizer assessment conducted in four experimental sites in comparison with using K<sub>2</sub>O in a soluble source (potassium chloride).

São Luiz II Farm – Irrigated site		
Treatments	Remineralizer doses as a K <sub>2</sub> O supplier	Amount of K <sub>2</sub> O supplied by the soluble source (KCl)
T1	0 kg.ha <sup>-1</sup>	100.00 kg.ha <sup>-1</sup>
T2	4662.81 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
T3	8817.11 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
T4	11944.58 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
São Luiz II Farm – Rainfed site		
Treatments	Remineralizer doses as a K <sub>2</sub> O supplier	Amount of K <sub>2</sub> O supplied by the soluble source (KCl)
T1	0 kg.ha <sup>-1</sup>	100.00 kg.ha <sup>-1</sup>
T2	2068.74 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
T3	3621.90 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
T4	5463.24 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
Lago Farm		
Treatments	Remineralizer doses as a K <sub>2</sub> O supplier	K <sub>2</sub> O amount supplied by the soluble source (KCl)
T1	0 kg.ha <sup>-1</sup>	150.00 kg.ha <sup>-1</sup>
T2	3312.42 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
T3	5813.27 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
T4	8228.09 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
Canada Farm		
Treatments	Remineralizer doses as a K <sub>2</sub> O supplier	K <sub>2</sub> O amount supplied by the soluble source (KCl)
T1	0 kg.ha <sup>-1</sup>	100.00 kg.ha <sup>-1</sup>
T2	3223.82 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
T3	4417.76 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>
T4	7122.24 kg.ha <sup>-1</sup>	0 kg.ha <sup>-1</sup>

Canada Farm, which was under 3 years old. Soil management and crop practices were different in the experimental sites. Each of the experimental fields adopted different methods: a different soil management; liming; planting; pest, disease and invasive plant control; and other crop practices based on its needs and implemented technology level.

The following variables were assessed to identify differences between the standard treatment (potassium chloride + limestone) and the use of Rekal remineralizer in improving soil health features: the activity of enzymes β-glucosidase and arylsulfatase, soil organic matter (SOM) content (g.dm<sup>3</sup>), clay content (%), soil quality index (FertBio SQI), chemical soil quality index (Chemical SQI), and soil nutrient cycling, storage, and supply function. The analyses were performed at Embrapa BioAS Network Laboratory after the end of the crop cycle, with soil samples collected 0–10 cm down in the ground, according to the BioAS methodology (Laboratório Exata, Jataí-GO).

The variables were subjected to analysis of variance (ANOVA) at 5% significance level. Subsequently, the Tukey test (5%) was performed with variables that were significant at the F test in order to compare the means. Final soil balance analyses (final analysis minus initial analysis) were performed to assess soil health improvement; the outcomes were expressed as a percentage.

### 3 RESULTS AND DISCUSSION

The analyzed parameters include enzyme activity (aryl-sulfatase and β-glucosidase), SOM, clay fraction, soil quality indices (SQIs) (FertBio SQI, Biological SQI, and Chemical SQI), and nutrient cycling, storage, and supply. Table 5 provides the summary results recorded for the ANOVA applied to these parameters, which allowed for observing significant differences between treatments.

**Table 4.** Mean soil chemical and physical analysis results per treatment recorded before the installation of the four experimental sites.

Exp. site	Treat.	Arylsulfatase	β-glucosidase	Soil Organic Matter	Clay	FertBio	Biological	Chemical	Nutrient Cycling	Nutrient Storage	Nutrient Supply
Lago Farm	T1	113.67	116.00	32.00	47.67	0.84	0.87	0.82	0.87	0.83	0.82
	T2	108.33	117.00	29.00	47.67	0.81	0.86	0.78	0.86	0.79	0.77
	T3	100.00	110.67	29.00	46.83	0.80	0.84	0.78	0.84	0.81	0.76
	T4	95.67	108.00	30.00	43.50	0.82	0.86	0.80	0.86	0.88	0.73
Canada Farm	T1	21.00	53.33	20.67	35.33	0.68	0.47	0.78	0.47	0.77	5.91
	T2	28.67	57.67	21.00	34.33	0.68	0.54	0.75	0.54	0.79	8.53
	T3	21.67	59.67	22.00	38.00	0.68	0.48	0.78	0.48	0.77	4.58
	T4	25.67	50.33	21.33	35.33	0.67	0.49	0.75	0.49	0.79	9.30
São Luiz Farm (irrigated)	T1	53.00	87.33	20.33	32.67	0.82	0.78	0.83	0.78	0.79	0.87
	T2	52.00	88.67	20.33	34.33	0.81	0.77	0.84	0.77	0.77	0.91
	T3	50.67	86.00	20.00	34.33	0.79	0.75	0.81	0.75	0.75	0.88
	T4	54.33	91.33	19.67	32.67	0.82	0.81	0.82	0.81	0.78	0.87
São Luiz Farm (rainfed)	T1	56.33	66.00	20.33	37.67	0.74	0.68	0.77	0.68	0.71	0.83
	T2	55.33	67.67	19.67	37.67	0.74	0.68	0.77	0.68	0.69	0.85
	T3	58.67	65.33	20.67	36.00	0.77	0.70	0.81	0.70	0.76	0.86
	T4	62.67	63.33	22.00	37.67	0.77	0.70	0.81	0.70	0.77	0.85

Source: Exata Laboratory, Jataí-GO.

**Table 5.** Summary of the analysis of variance applied to variables found through BioAS about the activity of enzymes arylsulfatase and  $\beta$ -glucosidase, Soil Organic Matter, Clay, FertBio SQI, Biological SQI, Chemical SQI, and Nutrient Cycling, Storage, and Supply as Rekal remineralizer dose functions (T2, T3, and T4) in comparison with the standard treatment (T1) (potassium chloride [KCl] and agricultural limestone) in four experimental sites (Lago, Canada, São Luiz [rainfed], and São Luiz II [irrigated] farms).

		Mean square – Lago Farm									
Variation source	gl	Arylsulfatase	$\beta$ -glucosidase	SOM	Clay	FertBio SQI	Biological SQI	Chemical SQI	Nutrient Cycling	Nutrient Storage	Nutrient Supply
Treatment	3	7.220 <sup>NS</sup>	121.030*	3.560*	3.850 <sup>NS</sup>	0.001*	0.000 <sup>NS</sup>	0.003*	0.000 <sup>NS</sup>	0.006**	0.002 <sup>NS</sup>
Block	3	320.890	305.160	8.170	0.500	0.000	0.001	0.000	0.006	0.000	0.000
Error	9	62.000	35.020	2.390	5.980	0.000	0.000	0.000	0.000	0.000	0.011
CV (%)	---	9.25	5.61	5.52	4.99	2.73	3.92	3.37	3.66	3.25	4.76
		Mean square – Canada Farm									
Variation source	gl	Arylsulfatase	$\beta$ -glucosidase	SOM	Clay	FertBio SQI	Biological SQI	Chemical SQI	Nutrient Cycling	Nutrient Storage	Nutrient Supply
Treatment	3	72.999*	237.741*	8.111*	14.667 <sup>NS</sup>	0.001 <sup>NS</sup>	0.003 <sup>NS</sup>	0.003*	0.004 <sup>NS</sup>	0.006 <sup>NS</sup>	0.006*
Block	3	88.888	209.388	0.722	44.667	0.000	0.001	0.000	0.001	0.008	0.000
Error	9	24.222	76.302	0.722	12.444	0.000	0.002	0.000	0.002	0.003	0.009
CV (%)	---	16.92	13.62	4.45	9.16	3.91	8.82	2.37	8.82	9.14	3.91
		Mean square – São Luiz II Farm (irrigated)									
Variation source	gl	Arylsulfatase	$\beta$ -glucosidase	SOM	Clay	FertBio SQI	Biological SQI	Chemical SQI	Nutrient Cycling	Nutrient Storage	Nutrient Supply
Treatment	3	140.444*	241.481*	2.481 <sup>NS</sup>	9.481 <sup>NS</sup>	0.001 <sup>NS</sup>	0.004 <sup>NS</sup>	0.002 <sup>NS</sup>	0.004 <sup>NS</sup>	0.003 <sup>NS</sup>	0.000 <sup>NS</sup>
Block	3	8.666	230.722	2.667	18.167	0.001	0.002	0.000	0.005	0.005	0.000
Error	9	34.889	31.019	0.741	14.019	0.002	0.020	0.001	0.002	0.007	0.000
CV (%)	---	8.69	4.50	3.96	10.12	4.95	5.49	5.15	5.49	10.69	0.78
		Mean square – São Luiz II Farm (rainfed)									
Variation source	gl	Arylsulfatase	$\beta$ -glucosidase	SOM	Clay	FertBio SQI	Biological SQI	Chemical SQI	Nutrient Cycling	Nutrient Storage	Nutrient Supply
Treatment	3	169.037*	372.148*	2.777 <sup>NS</sup>	1.000 <sup>NS</sup>	0.006*	0.013*	0.004*	0.013*	0.008 <sup>NS</sup>	0.001 <sup>NS</sup>
Block	3	146.888	17.388	0.722	1.166	0.000	0.005	0.000	0.005	0.000	0.000
Error	9	78.519	39.463	2.278	13.833	0.001	0.003	0.001	0.003	0.003	0.000
CV (%)	---	15.59	7.08	6.68	9.24	4.53	7.01	4.70	7.01	7.06	3.16

\*: \* Significant at 1% probability; \* Significant at 5% probability; NS – non-significant; CV – Coefficient of variation.

SOM: soil organic matter; SQI: soil quality indices; NS: non-significant; CV: Coefficient of variation. Significant at 5% probability; \*\* Significant at 1% probability.

Results in Table 5 evidence statistically significant differences ( $p < .05$ ) in the activity of enzyme  $\beta$ -glucosidase, SQIs (FertBio SQI and Chemical SQI), and organic matter content. Enzyme  $\beta$ -glucosidase played a core role in carbohydrate mineralization and organic matter cycling, which had a direct impact on carbon availability for the soil microbiota. According to this finding, appropriate management practices can exert a positive influence on these parameters (Nannipieri et al., 2003).

Indices FertBio SQI and Chemical SQI, which encompass biological and chemical indicators, also showed a significant increase, and this suggests that the adopted management improved overall soil quality, created more favorable conditions for microbial activity, and increased nutrient availability (Bünemann et al., 2018). The herein recorded increased organic matter content reinforced this result and highlighted the relevance of strategies aimed at increasing the provision of organic compounds that are essential for soil fertility and agricultural production sustainability (Lal, 2020).

Furthermore, nutrient storage presented significant differences. This finding highlights that the management helped

retain essential soil nutrients. Therefore, this outcome is likely associated with the interaction among organic matter content, cation exchange capacity, and microbial activity (Medeiros et al., 2024).

On the other hand, parameters such as the activity of enzyme arylsulfatase, clay fraction, biological SQI, and nutrient cycling and supply did not show significant variations, which indicates these features' higher stability or lower sensitivity to the adopted management practices. This finding corroborated previous studies on the resistance of certain indicators to environmental variations (Wallenstein & Burns, 2011).

Table 6 presents the mean values recorded for the activity of the enzyme  $\beta$ -glucosidase, SOM, SQIs (FertBio SQI and Chemical SQI), and nutrient storage and cycling as Rekal remineralizer dose functions in comparison with the standard treatment (T1). These data allowed for assessing the effect of the remineralizer on soil chemical, biological, and enzymatic quality indices in the irrigated system at Lago Farm.

According to the mean results recorded for Lago Farm (Table 6), the Rekal remineralizer application had a positive influence on several soil quality-related parameters. The activity

of the enzyme  $\beta$ -glucosidase increased from 97.67, in the standard treatment (T1), to 109.33, in T3 and T4. This finding points out that higher remineralizer doses boost carbohydrate mineralization and carbon availability for the soil microbiota, which favors nutrient cycling (Nannipieri et al., 2003).

The organic matter content ranged from 27.33 to 29.33, and it was higher in T4. It is possible assuming that the organic matter increased due to the remineralizer's application, since it helps improve fertility, soil structure, and water retention, in addition to favoring the biological activity (Lal, 2020).

The means recorded for SQIs (FertBio SQI and Chemical SQI) ranged from 0.75 to 0.80 and from 0.73 to 0.80, respectively. The highest mean value was observed in T4. This finding points toward a soil-quality improvement trend linked to remineralizer application, which has a positive effect on integrated chemical and biological features (Bünemann et al., 2018).

Mean nutrient storage values ranged from 0.74 to 0.82, and the highest value was recorded for T4. Therefore, the Rekal remineralizer application helps in the retention of essential nutrients. This presumably occurs because of the organic matter/cation exchange capacity interaction, which allows for greater nutrient availability to plants (Medeiros et al., 2024).

Table 7 shows the mean values recorded for the activity of enzymes arylsulfatase and  $\beta$ -glucosidase, SOM, Chemical SQI, and nutrient inputs as Rekal remineralizer dose functions in comparison with the standard treatment (T1). These results allowed for analyzing the remineralizer's impact on both soil fertility and enzyme activity at Canada Farm.

The mean results recorded for Canada Farm have shown that the Rekal remineralizer application had a positive influence on some soil quality parameters, whereas other parameters remained relatively stable (Table 7).

The activity of the enzyme arylsulfatase ranged from 23.67, in the standard treatment (T1), to 32.67, in T2. This finding highlights that remineralizer application can boost the mineralization of sulfated compounds, and it increases sulfur availability for plants, which is an essential nutrient for protein synthesis and plant growth (Wallenstein & Burns, 2011).

The activity of the enzyme  $\beta$ -glucosidase increased from 54.00 to 71.33, and this suggests that intermediate Rekal remineralizer doses can lead to higher carbohydrate decomposition and carbon supply to the soil microbiota, thereby strengthening nutrient cycling (Nannipieri et al., 2003). The SOM content ranged from 17.33 to 20.67, and the highest value recorded for this variable was observed in T3. This outcome shows that remineralizer application helps improve soil fertility, structure, and water retention capacity, in addition to stimulating the biological activity (Lal, 2020).

The Chemical SQI showed relatively stable means, which ranged from 0.69 to 0.75. This finding suggests that remineralizer treatments keep soil chemical quality at levels similar to those of the standard treatments, without major changes in it. On the other hand, nutrient supply means range from 0.76 to 0.84, and it points out that the Rekal remineralizer application favors the availability of essential nutrients, mainly at intermediate doses, which can boost plant growth (Medeiros et al., 2024).

Table 8 presents the mean values recorded for the activity of enzymes arylsulfatase and  $\beta$ -glucosidase as Rekal remineralizer dose function in comparison with the standard treatment (T1). These data allowed for assessing the effect of the remineralizer on soil biological, chemical, and enzymatic quality indices under irrigated conditions at São Luiz II Farm.

The mean results recorded for São Luiz II Farm (irrigated) have shown that the Rekal remineralizer application has an

**Table 6.** Mean values recorded for the activity of the enzyme  $\beta$ -glucosidase, Soil Organic Matter, Clay, FertBio SQI, Chemical SQI, and Nutrient Cycling and Storage as Rekal remineralizer dose functions (T2, T3, and T4) in comparison with the standard treatment (T1) (potassium chloride [KCl] and agricultural limestone) at Lago Farm.

Treatment	$\beta$ -glucosidase	SOM	FertBio SQI	Chemical SQI	Nutrient Cycling	Nutrient Storage
T1	97.67 <sup>b</sup>	27.33 <sup>b</sup>	0.76 <sup>ab</sup>	0.75 <sup>ab</sup>	0.76 <sup>b</sup>	0.74 <sup>b</sup>
T2	105.67 <sup>ab</sup>	28.00 <sup>ab</sup>	0.76 <sup>ab</sup>	0.75 <sup>ab</sup>	0.79 <sup>b</sup>	0.77 <sup>ab</sup>
T3	109.33 <sup>a</sup>	27.33 <sup>ab</sup>	0.75 <sup>b</sup>	0.73 <sup>b</sup>	0.79 <sup>a</sup>	0.74 <sup>b</sup>
T4	109.33 <sup>a</sup>	29.33 <sup>a</sup>	0.80 <sup>a</sup>	0.80 <sup>a</sup>	0.78 <sup>ab</sup>	0.82 <sup>a</sup>

SOM: soil organic matter; SQI: soil quality indices. \*Means followed by the same letter in the column did not differ from each other in the Tukey test at 5% significance. Source: Elaborated by the authors.

**Table 7.** Mean values recorded for the activity of enzymes arylsulfatase and  $\beta$ -glucosidase, Soil Organic Matter, Chemical SQI, and Nutrient Supply as Rekal remineralizer dose functions in comparison with the standard treatment (potassium chloride [KCl] and agricultural limestone) at Canada Farm.

Treatments	Arylsulfatase	$\beta$ -glucosidase	SOM	Chemical SQI	Nutrient Supply
T1	23.67 <sup>c</sup>	54.00 <sup>c</sup>	17.33 <sup>c</sup>	0.74 <sup>a</sup>	0.84 <sup>a</sup>
T2	32.67 <sup>a</sup>	68.67 <sup>ab</sup>	18.67 <sup>bc</sup>	0.69 <sup>b</sup>	0.76 <sup>b</sup>
T3	27.67 <sup>b</sup>	71.33 <sup>a</sup>	20.67 <sup>a</sup>	0.75 <sup>a</sup>	0.84 <sup>a</sup>
T4	32.33 <sup>a</sup>	62.33 <sup>b</sup>	19.67 <sup>ab</sup>	0.73 <sup>a</sup>	0.78 <sup>ab</sup>

SOM: soil organic matter; SQI: soil quality indices. \*Means followed by the same letter in the column did not differ from each other in the Tukey test at 5% significance. Source: Elaborated by the authors.

impact on soil enzymatic activity (Table 8). The activity of the enzyme arylsulfatase ranged from 59.67, in the standard treatment (T1), to 73.67, in the T2 treatment, and it suggests that the remineralizer can boost the mineralization of sulfated compounds and favor sulfur availability for plants, which is an essential nutrient for protein synthesis and plant growth (Wallenstein & Burns, 2011). The enzyme  $\beta$ -glucosidase presented means ranging from 123.33 to 133.00, and the highest value was observed for T2. This finding points out that intermediate remineralizer doses lead to higher carbohydrate decomposition and carbon supply to the soil microbiota, thereby strengthening nutrient cycling (Nannipieri et al., 2003).

Although the increase in the activity of the enzyme  $\beta$ -glucosidase was less significant in T3 and T4, according to the results, Rekal remineralizer application maintains or increases the enzymatic activity, mainly under irrigated conditions, which favors essential biogeochemical processes for soil fertility. Altogether, these outcomes suggest that using remineralizers in irrigated systems helps improve the enzymatic activity, achieving higher nutrient availability and preserving soil health at sustainable levels for agricultural production.

Table 9 shows the mean values recorded for the activity of enzymes arylsulfatase and  $\beta$ -glucosidase, FertBio SQI, Biological SQI, Chemical SQI, and Nutrient Cycling as Rekal remineralizer dose functions compared with the standard treatment (T1). These results allowed for analyzing the soil enzymatic activity response to remineralizer application in a dryland system at São Luiz II Farm.

The mean values recorded at São Luiz II Farm (rainfed) pointed out that the Rekal remineralizer application has a positive influence on several soil quality-related parameters (Table 9). The activity of the enzyme arylsulfatase increased from 50.67, in the standard treatment (T1), to 66.00, in T4, and this finding

suggests that higher remineralizer doses boost the mineralization of sulfated compounds, increase sulfur availability, and help amino acids and protein synthesis in plants (Wallenstein & Burns, 2011). The activity of the enzyme  $\beta$ -glucosidase ranged from 80.00 to 100.00, and the highest value recorded for this variable was observed in T4, which indicates that the remineralizer leads to higher carbohydrate decomposition and carbon supply to the soil microbiota, besides reinforcing nutrient cycling (Nannipieri et al., 2003).

SQIs also improved due to the application of higher remineralizer doses. FertBio SQI ranged from 0.73 to 0.82, the biological SQI ranged from 0.67 to 0.79, and the Chemical SQI ranged from 0.76 to 0.84. The highest value recorded for this variable was observed in T4. According to these results, the Rekal remineralizer favors an integrated improvement in soil health by benefiting both its biological and chemical features (Bünemann et al., 2018).

Finally, the cycling nutrients presented means ranging from 0.67 to 0.79, and the highest value was recorded for T4, which suggests that the Rekal remineralizer enhances the availability of essential nutrients for plants. It is assumingly explained by the organic matter/microbial activity stimulus (Medeiros et al., 2024).

Figure 1 presents the final soil balance, expressed as a percentage, recorded for variations between the final analysis and the initial analysis, based on different soil features observed at Lago Farm. It took into consideration the Rekal remineralizer-based treatments (T2, T3, and T4) in comparison with the standard treatment (T1).

The activity of enzymes arylsulfatase and  $\beta$ -glucosidase decreased in all treatments, mainly in T1, which presented arylsulfatase decrease close to 25–30% and arylsulfatase reduction close to 15%. Rekal-based treatments (T2–T4) recorded a lower decrease, and this finding points out that the remineralizer application helped reduce enzymatic activity loss. Assumingly, it happened due to the provision of nutrients and substrates for the soil microbiota, which maintain mineralization and carbon cycling processes (Nannipieri et al., 2003; Wallenstein & Burns, 2011).

The SOM and clay contents presented a negative balance in all treatments, which highlights soil carbon consumption throughout the cultivation cycle, whereas the clay fraction remained mostly stable or showed a slight increase in T3 and T4. These findings indicate that the remineralizer doses do not change soil texture, but they can influence the retention of nutrients associated with the fine fraction (Lal, 2020).

**Table 8.** Mean values recorded for enzymes arylsulfatase and  $\beta$ -glucosidase as Rekal remineralizer dose functions (T2, T3, and T4) in comparison with the standard treatment (T1) (potassium chloride [KCl] and agricultural limestone) at São Luiz II Farm (irrigated).

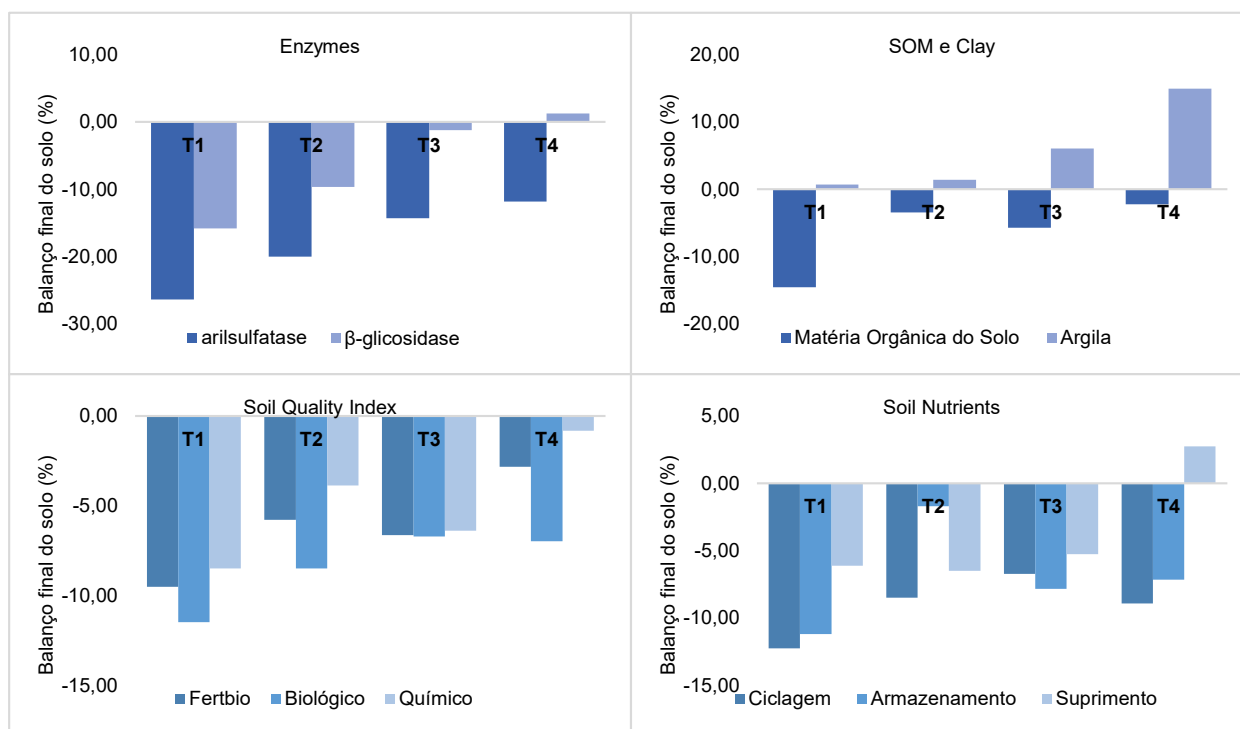
Treatments	Arylsulfatase	$\beta$ -glucosidase
T1	59.67 <sup>b</sup>	124.33 <sup>b</sup>
T2	73.67 <sup>a</sup>	133.00 <sup>a</sup>
T3	69.67 <sup>ab</sup>	123.33 <sup>b</sup>
T4	69.00 <sup>ab</sup>	124.00 <sup>b</sup>

\*Means followed by the same letter in the column did not differ from each other in the Tukey test at 5% significance. Source: Elaborated by the authors.

**Table 9.** Mean values recorded for the activity of enzymes arylsulfatase and  $\beta$ -glucosidase, FertBio SQI, Biological SQI, Chemical SQI, and Nutrient Cycling as Rekal remineralizer dose functions (T2, T3, and T4) in comparison with the standard treatment (T1) (potassium chloride [KCl] and agricultural limestone) at São Luiz II Farm (rainfed).

Treatments	Arylsulfatase	$\beta$ -glucosidase	FertBio SQI	Biological SQI	Chemical SQI	Nutrient Cycling
T1	50.67 <sup>b</sup>	80.00 <sup>b</sup>	0.73 <sup>b</sup>	0.67 <sup>b</sup>	0.76 <sup>b</sup>	0.67 <sup>b</sup>
T2	55.67 <sup>ab</sup>	93.33 <sup>ab</sup>	0.77 <sup>ab</sup>	0.74 <sup>ab</sup>	0.79 <sup>ab</sup>	0.74 <sup>ab</sup>
T3	55.00 <sup>ab</sup>	81.33 <sup>b</sup>	0.76 <sup>ab</sup>	0.68 <sup>b</sup>	0.81 <sup>ab</sup>	0.68 <sup>b</sup>
T4	66.00 <sup>a</sup>	100.00 <sup>ab</sup>	0.82 <sup>a</sup>	0.79 <sup>a</sup>	0.84 <sup>a</sup>	0.79 <sup>a</sup>

SQI: soil quality indices. \*Means followed by the same letter in the column did not differ from each other in the Tukey test at 5% significance. Source: Elaborated by the authors.



SOM: soil organic matter; SQI: soil quality indices.

**Figure 1.** Final soil balance (final analysis minus initial analysis – result expressed in percentage) regarding the activity of enzymes arylsulfatase and  $\beta$ -glucosidase, Soil Organic Matter, Clay, FertBio SQI, Biological SQI, Chemical SQI, and Nutrient Cycling, Storage, and Supply as Rekal remineralizer dose functions (T2, T3, and T4) in comparison with the standard treatment (T1) (potassium chloride [KCl] and agricultural limestone) at Lago Farm.

SQIs (FertBio SQI, Biological SQI, and Chemical SQI) recorded a negative balance in all treatments, and T4 accounted for the lowest percentage loss. This outcome suggests that higher remineralizer doses help preserve soil health, in spite of nutrient extraction by plants and organic mineralization (Bünemann et al., 2018).

Soil nutrient cycling and storage values showed a percentage decrease in all treatments, whereas nutrient supply presented a slight increase in T4. This finding points out that the Rekal remineralizer can mitigate essential nutrient losses and maintain some nutrient availability for plant uptake, mainly at higher doses (Medeiros et al., 2024).

Figure 2 depicts the final soil balance recorded for enzymatic, physical, biological, chemical, and nutritional parameters at Canada Farm. The aim of this assessment lay in highlighting how different Rekal remineralizer doses work in comparison with the standard-treatment management procedures (KCl and limestone).

The activity of enzymes arylsulfatase and  $\beta$ -glucosidase showed a significant increase, mainly in T3. Increase was close to 27 and 20%, respectively, which suggests higher microbial activity and soil metabolism stimulus.

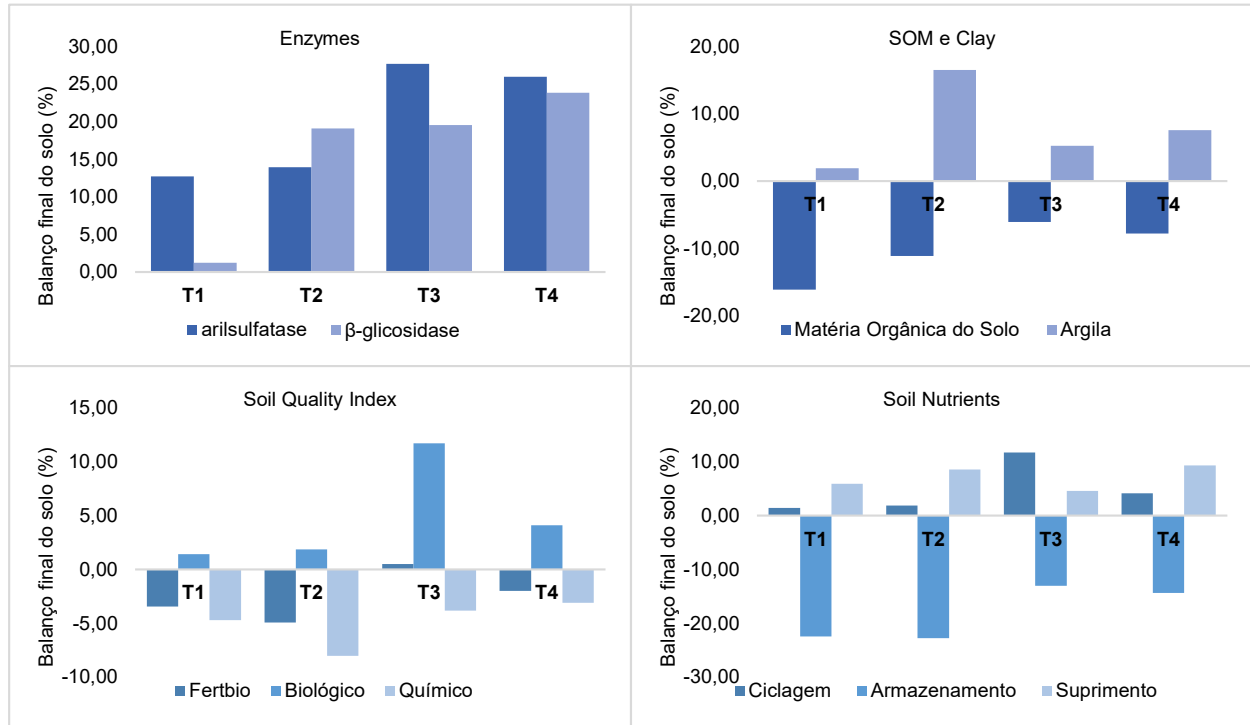
All treatments showed SOM decrease, which highlights carbon consumption throughout the cycle. However, the clay fraction showed a consistent increase, mainly in T2. This finding can be related to higher aggregate stability and fine particle retention due to the remineralizer application.

SQIs showed heterogeneous behavior. The FertBio index was negative in T1 and T2, but it increased by approximately 12% in T3, which indicates that the intermediate remineralizer application was more effective in boosting integrated soil fertility and biology. The Biological SQI also showed a higher increase in T3, whereas the Chemical SQI recorded negative variations in most treatments, except for T4.

There was a sharp decline in soil nutrient cycling in all treatments, mainly in T1. This outcome stresses high nutrient export by crops. On the other hand, nutrient storage and supply indicators pinpointed a significant increase in Rekal-based treatments, mainly in T3, which recorded an increase of over 10% in storage, which suggests better nutrient retention and gradual availability.

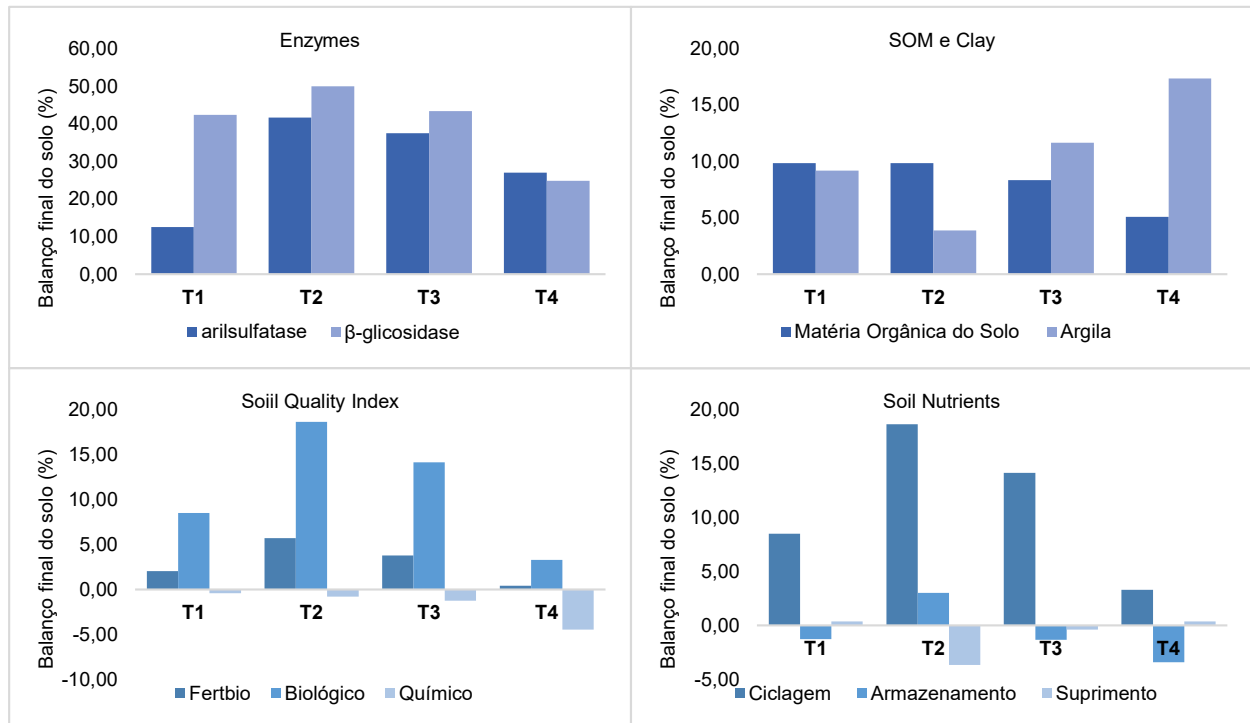
Figure 3 presents the final soil balance recorded at São Luiz II Farm (irrigated), including the data of arylsulfatase and  $\beta$ -glucosidase enzymes, organic matter, clay fraction, SQIs, and nutrient parameters. This analysis allowed for a better understanding of how the Rekal remineralizer influences soil quality and dynamics under irrigated conditions.

A significant increase in soil enzyme activity was observed in all treatments under irrigation at São Luiz II Farm, mainly in T2 and T3, which recorded an increase of over 40% for  $\beta$ -glucosidase and arylsulfatase. According to the results, the Rekal remineralizer application contributed to both the microbial activity and the organic matter decomposition potential. These findings point toward improved nutrient cycling processes.



SOM: soil organic matter; SQI: soil quality indices.

**Figure 2.** Final soil balance (final analysis minus initial analysis – results expressed in percentage) regarding the activity of enzymes arylsulfatase and  $\beta$ -glucosidase, Soil Organic Matter, Clay, FertBio SQI, Biological SQI, Chemical SQI, and Nutrient Cycling, Storage, and Supply as Rekal remineralizer dose functions (T2, T3, and T4) in comparison with the standard treatment (T1) (potassium chloride [KCl] and agricultural limestone) at Canada Farm.



SOM: soil organic matter; SQI: soil quality indices.

**Figure 3.** Final soil balance (final analysis minus initial analysis – results expressed in percentage) regarding the enzymes arylsulfatase and  $\beta$ -glucosidase, Soil Organic Matter, Clay, FertBio SQI, Biological SQI, Chemical SQI, and Nutrient Cycling, Storage, and Supply as Rekal remineralizer dose functions (T2, T3, and T4) in comparison with the standard farm (T1) (potassium chloride [KCl] and agricultural limestone) at São Luiz II Farm (irrigated).

SOM increased in all treatments, ranging from 5 to 10%, with emphasis on T1 and T2. The clay fraction increased in all treatments, mainly in T4, which reached approximately 17%. This finding can be related to improved structural stability and aggregation due to the mineral additions.

The SQIs recorded positive responses, mainly in the biological component, which showed an increase close to 20% in T2 and over 10% in T3. The FertBio index also recorded significant gains that had a strong impact on T1, T2, and T3. On the other hand, the Chemical SQI showed fluctuations close to zero or slightly negative ones. This finding suggests that the remineralizer's chemical contribution was quite indirect; it was observed through biological and physical effects rather than through an immediate increase in nutrient availability.

The nutrient cycling indicator showed substantial gains in all treatments, mainly in T2 (approximately 19%) and T3 (14%). This outcome points out that the remineralizer helped nutrient flow into both the microbial biomass and the organic matter. Nutrient storage and supply remained almost stable. There were only small positive or negative variations, which reinforced the hypothesis that the main remineralizer effect lies in improving soil biological and physical dynamics, in the short term.

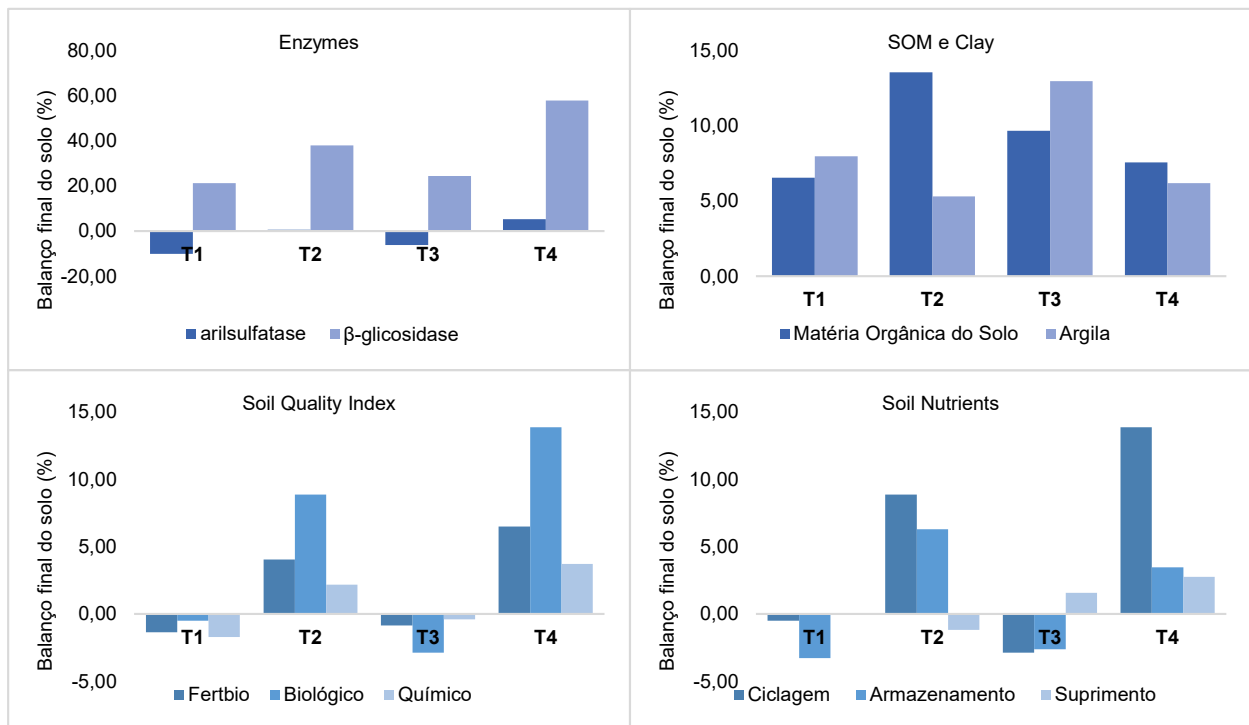
Figure 4 shows the final soil balance recorded at São Luiz II Farm (rainfed) based on enzymatic, physical, biological, and nutritional indicators. The comparison between the standard management and the different Rekal remineralizer doses aims at identifying their effects on soil quality maintenance and improvement.

Soil enzyme responses managed under a dryland system at São Luiz II Farm differed from those in the irrigated area. A significant increase in the activity of the enzyme  $\beta$ -glucosidase was observed, mainly in T4, which was followed by T2 and T3. On the other hand, the enzyme arylsulfatase showed discrete or negative values, just as in T1 and T3. This finding suggests that its activity can be more sensitive to limited moisture conditions commonly faced in dryland farming.

SOM increased in all treatments, and such an increase ranged from 6 to 13%. Treatments T2 and T3 recorded a remarkable increase. Clay content also increased, mainly in T3, approaching 13%, and this can point toward improved aggregate stability and fine particle retention.

The SQI presented the most significant response since it reached almost 14% in T4 and values higher than 8% in T2. The FertBio index followed this trend, and T4 also recorded a remarkable improvement (> 6%). The chemical component showed gains ranging from slightly negative values to rates higher than 3%, which suggests that the remineralizer acts more as a biological and physical improvement inducer than as an immediate source of available nutrients, in the short term.

The nutrient storage indicator was the most responsive one. It recorded a significant increase in T4 (approximately 14%) and significant values in T2 (approximately 9%). Nutrient cycling showed small positive variation only in T2 and T4, whereas nutrient supply remained positive in all treatments, although its magnitude was lower than 4%. According to these results,



SOM: soil organic matter; SQI: soil quality indices.

**Figure 4.** Final soil balance (final analysis minus initial analysis – results expressed in percentage) regarding the activity of enzymes arylsulfatase and  $\beta$ -glucosidase, soil organic matter (SOM), clay fraction, FertBio SQI, Biological SQI, Chemical SQI, and Nutrient Cycling, Storage, and Supply as Rekal remineralizer dose function (T2, T3, and T4) in comparison with the standard treatment (T1) (potassium chloride (KCl) and agricultural limestone) at São Luiz II Farm (rainfed).

the effects of remineralizer in a rainfed system are more evident for nutrient storage and stock stability because of the gradual release of mineral elements and their positive influence on organic matter.

The results have shown that the use of the Rekal remineralizer instead of the conventional standard adopted in most Brazilian agricultural areas has a direct impact on soil biological health gains. Although soil collection was performed after the crop cycle, the recorded effects were significant for the variables of interest. The current study broadened our knowledge on soil health and effectively reinforced the relevance of implementing sustainable management practices to efficiently ensure soil physical, chemical, and biological quality and, consequently, to provide alternatives to traditional chemical cultivation systems in Brazil.

#### 4 CONCLUSIONS

- I. Rekal remineralizer application leads to consistent soil biological health and fertility improvements expressed by the increased activity of enzymes arylsulfatase and  $\beta$ -glucosidase, organic matter content, and chemical and biological quality indices.
- II. Rekal remineralizer application boosted nutrient cycling and helped increase SQIs (FertBio SQI, Biological SQI, and Chemical SQI) by strengthening the quality of the soil-plant system.
- III. The Rekal remineralizer application showed increases in soil health variables in different production contexts. Therefore, it emerged as a sustainable and efficient alternative to the exclusive use of soluble fertilizers in soybean production.

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