Received: 30 August 2024 | Accepted: 22 October 2024

DOI: 10.1002/agg2.70008

Agrosystems, Geosciences & Environment OPEN ACCESS

ORIGINAL ARTICLE

Agrosystems

Limestone reaction in sandy soil: Rate effects, limestone type, moisture regime, and time

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Assigned to Associate Editor Larry Cihacek.

Funding information
Trijunção Farm, Grant/Award Number: 0369-Faped; Embrapa, Grant/Award Number: 30.18.00.022.00.00

Abstract

An experiment was conducted in the greenhouse facilities of Embrapa Maize and Sorghum to evaluate the limestone reaction in sandy soil based on rates, limestone type, effective calcium carbonate equivalent (ECCE), and moisture regime over time. A factorial design of $4 \times 2 + 3$ was adopted, consisting of four limestone rates with 76% ECCE (0, 1, 2, and 4 Mg ha^{-1}), two irrigation types (daily and monthly, simulating constant and intermittent moisture regime), and three additional treatments (three rates of "filler" limestone—99% ECCE—under monthly irrigation). Soil chemical characteristics were analyzed at 1, 2, 3, 6, and 12 months after treatment application. Soil fertility improved at the first month after treatment application, with emphasis on higher limestone rates, monthly moisture regime, and filler lime stone. The highest limestone rate did not increase the pH above 7.0. The recommended limestone rate was insufficient to elevate Ca + Mg levels to the adequate level for current production genotypes and systems, which demand higher standards. These outcomes reinforce the need for carrying out further studies and potential revision in liming recommendations for sandy soils.

1 | INTRODUCTION

Agriculture expansion has been witnessed over marginal areas presenting low agricultural aptitude for traditional production models worldwide. Sites presenting sandy soil texture are among these areas, such as those observed in Cerrado areas in Matopiba region, Brazil, which covers parts of Maranhão, Tocantins, Piauí, and Bahia states. This region is covered with sand-quartz sediments from the tertiary/quaternary, Areado, Urucuia, and Mata da Corda sandstone (Kangussu Donagemma et al., 2016). This environment is naturally fragile and requires appropriate management practices aimed at sustainability (Albuquerque Filho et al., 2020).

Among the primary limitations of these soils for plant cultivation are low fertility, low organic matter (OM) content, low water retention, and high acidity due to the presence of elements like aluminum (in its toxic form for root growth). Acidity is also observed in soil surface depth that, along with low calcium and magnesium rates, limit deeper root growth and, consequently, reduce water and nutrients' absorption (Borges et al., 2022). This process increases the risks posed by short drought periods to agricultural production systems.

Abbreviations: CEC, cation exchange capacity; ECCE, effective calcium carbonate equivalent; RLR, recommended lime rate.

Despite the observed limitations, these soil types have been incorporated into production processes; therefore, it is necessary enhancing and adjusting the technologies available to successfully establish agricultural production systems. In this context, the liming recommendations to correct soil acidity and provide nutrients such as calcium (Ca) and magnesium (Mg), aiming to improve plant growth conditions and to increase drought tolerance (Ca is a nutrient that stimulates root growth and Mg is fundamental in the process of photosynthesis), become essential to make these soils' agricultural use feasible.

Oftentimes, it is recommended to apply lower calcium doses in soils accounting for lower buffering, that is, with lower cation exchange capacity (CEC), due to lower clay and OM contents (Alvarez & Ribeiro, 1999; Sousa & Lobato, 2004). However, the successfully used liming levels by farmers in Central Brazil, Northern Minas Gerais State, Western Bahia State, and in other regions covered by sandy soils have been surprising, given the applied limestone doses (6–10 Mg ha^{-1} effective calcium carbonate equivalent [ECCE] 100% limestone), which are higher than the traditionally recommended ones. The use of doses higher than those in current recommendation methods began with clayey soils in Southern Minas Gerais State, where doses higher than 15 Mg ha^{-1} have been used in degraded pasture areas that have been turned into cropland sites. However, there are no studies or conclusive data to prove the suitability of the management method that has been adopted from farmers for sandy soils. Some studies have pointed the need of adopting from 9 to 15 Mg ha^{-1} for sandy soils in order to achieve a high yield in coverage areas (Moraes et al., 2023; Moreira et al., 2024; Oliveira et al., 2024; Singer, 2024).

Soil limestone reactions depend on this material's quality (equivalent CaO and MgO contents, particle size) and dose, on soil type, application method (surface or incorporation), rainfall intensity, and air and soil temperature (Esper Neto et al., 2019). Accordingly, it is possible to assume that limestone reaction in sandy soils is smaller than in clayey soils, because sandy soils have lower clay and OM contents. This sandy soil feature is translated into low soil buffering, low soil acidity buffering, weak Ca and Mg draining, besides limited water retention capacity (Bellingieri, 1983; Plese, 2000). Assumingly, these features limit limestone dilution, but literature lacks studies to prove this hypothesis in sandy soils.

Raij et al. (1982) conducted a liming experiment in maize (*Zea mays* L.) crops for 5 years in soil with 440 g kg^{-1} clay. They pointed out the relevance of analyzing Ca + Mg non-solubilized (residual). The analysis carried out 1 year after the application of 3, 6, and 9 Mg ha^{-1} limestone showed that 59%, 45%, 52%, and 67% of the Ca + Mg were within the non-solubilized fraction. Two years later, these values were 18%, 28%, and 33%, respectively; 5 years later, they were 8%, 6%, and 7%. Quaggio (2000) carried out a similar experiment in Clayey Dystrophic Purple Latosol, based on the following limestone doses: 0 to 12 Mg ha^{-1} limestone with 57% ECCE, and assessed the Ca and Mg non-solubilized fraction. These results pointed out that such a fraction got larger with the applied dose—it reached >50% at the doses of 10 and 12 Mg ha^{-1}. Total limestone reaction took place within 3 years. There was no deep Ca + Mg loss in soil profile, but they recorded approximately 20% after this time, on a yearly basis, in the top 60 cm layer.

Core Ideas

- High limestone rates with higher effective calcium carbonate equivalent benefit fertility in sandy soil under intermittent moisture.
- Optimal plant pH (5.5–6.5) achieved with low limestone rates; water pH stabilizes near 7.5 at high rates.
- Traditional limestone rates are insufficient to boost Ca and Mg for modern high-yield crops and systems.

The literature lacks studies focused on sandy soils and the dynamics of limestone reactions in the sandy soils in order to better understand associated processes and to determine the most suitable recommendations to these environments. The aim of this study was to assess limestone reactions in vessels due to liming rates, limestone type, moisture regime, and time spent after application in sandy soil.

2 | MATERIALS AND METHODS

The experiment was carried out in the greenhouse of Embrapa Maize and Sorghum, Sete Lagoas City, Minas Gerais State, Brazil, from April 2018 to May 2019. Soil collected from the 0–20 cm soil layer was used in the experiment. This soil was classified as Oxisol, with medium-sandy texture—it came from Trijunção Farm, which is located in the Western Bahia State Cerrado region. In October 2013, the area from where the soil was collected was treated with 1 Mg ha^{-1} of limestone and 1 Mg ha^{-1} of gypsum, incorporated to a depth of 20 cm. Soil chemical and physical attributes before the experiment's establishment were set based on methodologies described by Teixeira et al. (2017), namely, potential hydrogen (pH) H_2O = 5.1; phosphorus (P), potassium (K), and sulfur (S) = 2.3; 15.4, and 16.9 mg dm^{-3}; Ca, Mg, aluminium (Al), potential acidity (H + Al), and CEC = 0.9, 0.3, 0.0, 0.7, and 1.9 cmol$_c$ dm^{-3}; base saturation (BS) = 59%; boron (B), copper (Cu), iron (Fe), manganese (Mn), zinc (Zn) = 0.06, 2.6, 31.7, 0.4, and 4.4 mg dm^{-3}; OM, clay, silt, and sand = 8.7, 145, 10, and 845 g kg^{-1}, respectively.

The experiment was conducted in pots (capacity for 4 kg of soil) in a completely randomized design, with four repetitions, at factorial arrangement $4 \times 2 + 3$ (four rates of commercial limestone [0, 1 time the recommended lime rate (RLR), 2RLR, 40RLR] × 2 daily and monthly irrigation conditions [to simulate constant and intermittent moisture regimes] + 3 additional treatments [three doses of filler limestone under monthly irrigation]).

The characteristics of the commercial limestone, in rates, were as follows: calcium carbonate equivalent = 85.5%; neutralization potential = 88.8%; ECCE = 76%; CaO = 27.3%; MgO = 16.1%. This 76% ECCE limestone was finely ground to obtain the 99% ECCE filler limestone. Therefore, what differentiated one limestone from the other was the granulometry.

The pots capable to support 5 kg filled with 4 kg of soil were used and limestone rates were calculated through the method based on Al neutralization, and on Ca and Mg content increase (Alvarez & Ribeiro, 1999), considering the values of Y and $X = 2.0$ (Y is related to the soil texture and value of 1 is used for sandy textured soils (clay content < 15 dag kg^{-1}), value of 2 for medium textured soils (clay content 15–35 dag kg^{-1}), and value of 3 for heavy textured soils (clay content > 35 dag kg^{-1}). The value of X is determined on the basis of the crop Ca + Mg demand. For example, 2.0 is for most crops. Thus, the rates of 76% ECCE limestone corresponded to 0, 1, 2, and 4 Mg ha^{-1}, and to 0, 0.76, 1.52, and 3.04 Mg ha^{-1} for 99% ECCE limestone.

The soil was treated with fertilizer based on the demand for experiments carried out in pots in order to adjust the chemical fertility conditions (Novais et al., 1991). Irrigation with deionized water was performed right after treatment applications, in all pots, for 3 days (to keep 80% field capacity), for the initial 1-month incubation. The two irrigation treatments used were as follows: (1) constant moisture regime on a daily basis (daily moisture regime); (2) intermittent moisture regime only 3 days in 1 month; in this case, the pots did not get any irrigation for 27 consecutive days in 1 month (monthly moisture regime). In both cases, water amount during irrigation was adjusted in order to keep moisture equal to 80% of field capacity based on pots' weight.

Soil sampling from all pots was conducted at 1, 2, 3, 6, and 12 months after the experiment started, using a mini-core sampler. Routine chemical analyses were carried out: OM, pH, P, S, K, Ca, Mg, Al, H + Al, sum of basis (SB), CEC, BS, B, Cu, Fe, Mn, and Zn (Teixeira et al., 2017).

The data were checked for normality and submitted to three-way analysis of variance ($p < 0.05$), in which the treatment means were compared using the LSD test ($p < 0.05$) for soil moisture regime, and regression analysis ($p < 0.05$) for lime rate and time of reaction. When the interaction of factors was significant, the comparisons between treatments were made for each condition of rate, time of reaction, and moisture regime for the variables: pH, Ca, Mg, and V%. The additional treatments were compared with orthogonal contrasts ($p < 0.05$) for specific effects, such as the difference between lime sources in each rate or time.

The data obtained in all sampling periods (pH, P, K, Ca, Mg, V%, H + Al, BS, and CEC) were scaled and subjected to principal component analysis (PCA). Statistical analyses were performed in R software, version 4.2.3 (R Core Team, 2023), using the R packages ExpDes (Ferreira et al., 2022), ggbiplot (Vu, 2011), and gmodels (Warnes et al., 2018). Graphics were plotted in Sigmaplot, version 12.5 (SigmaPlot, 2006).

3 | RESULTS

The present study focused on introducing the results and discussions about crops' yield, Ca + Mg content, and soil pH, given the close association among these variables (Bossolani et al., 2021; Maraschin et al., 2020; Resende et al., 2016; Sako et al., 2016) and all attributes related to acidity (Al, H + Al, BS, and micronutrients), without neglecting the other variables, as P, K, S, and OM.

The soil pH was influenced according to all conditions of lime rate, moisture regime, and time of reaction (Table 1). The soil pH increased according to lime rate of 0–4 (Figure 1A,C,E), increasing from 5.19 to 5.81 in 30 days, 4.96 to 6.30 in 60 days, 5.03 to 6.60 in 90 days, 5.25 to 6.51 in 180 days, and from 5.81 to 6.76 in 365 days when monthly irrigated (Figure 1A). When soil was daily irrigated, the pH changed from 4.84 to 5.82 in 30 days, 5.27 to 6.54 in 60 days, 5.36 to 6.54 in 90 days, 5.84 to 6.95 in 180 days, and from 6.06 to 7.39 in 365 days (Figure 1C). With limestone ECCE99 monthly irrigated (0–4 RLR), the increases in soil pH were from 5.19 to 6.00 in 30 days, 4.96 to 6.84 in 60 days, 5.03 to 6.65 in 90 days, 5.25 to 6.92 in 180 days, and 5.81 to 6.95 in 365 days (Figure 1E). The lime rates for maximum soil pH were 3.30, 4.00, and 3.50 for limestone ECCE76 monthly irrigated, ECCE76 daily irrigated, and ECCE9, respectively, at time of 365 days, reaching soil pH of 6.75, 7.43, and 6.99 (Figure 1B,D,F).

When the soil received a daily soil moisture regime, it presented higher pH than when monthly irrigated in almost all conditions of lime rate and reaction time; for example, soil pH was 6.76 and 7.39 when monthly and daily irrigated, respectively, at rate of 4 RLR in 365 days (Figure 1A,C). The soil pH was affected by limestone type in general, but had little change in specific conditions (shown in Table S1). The limestone ECCE99 resulted in higher soil pH at rates of 1 and 2 RLR in 180 days, and at rates of 4 RLR in 90 days (Figure 1E).

The soil pH increased with time of application up to 365 days (Figure 1B,D,F), for example, the pH increased

TABLE 1 Three-way analysis of variance (ANOVA) p values ($\Pr > t$) for soil chemical properties according to recommended lime rate, time of reaction, and soil moisture regime.

	Pr > *t*							
Treatment	**OM**	**pH**	**P**	**S**	**K**	**Ca**	**Mg**	**H + Al**
Rate (R)	0.064	0.0001	0.0001	0.008	0.02	0.0001	0.0001	0.0001
Moisture (M)	0.034	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Time (T)	0.106	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
R × M	0.178	0.005	0.025	0.441	0.051	0.374	0.046	0.031
R × T	0.330	0.0001	0.073	0.003	0.327	0.055	0.0001	0.589
M × T	0.797	0.0001	0.0001	0.02	0.0001	0.0001	0.0001	0.0001
R × T × M	0.476	0.044	0.754	0.04	0.143	0.054	0.0001	0.297
	SB	**CEC**	**BS**	**B**	**Cu**	**Fe**	**Mn**	**Zn**
Rate (R)	0.0001	0.400	0.0001	0.0001	0.01	0.087	0.0001	0.005
Moisture (M)	0.0001	0.0001	0.146	0.0001	0.0001	0.138	0.0001	0.907
Time (T)	0.0001	0.0001	0.0001	0.044	0.0001	0.0001	0.001	0.0001
R × M	0.207	0.100	0.001	0.093	0.052	0.001	0.001	0.175
R × T	0.025	0.086	0.008	0.0001	0.561	0.563	0.137	0.693
M × T	0.0001	0.0001	0.006	0.114	0.638	0.776	0.613	0.134
R × T × M	0.016	0.029	0.039	0.108	0.167	0.055	0.064	0.504

Abbreviations: BS, base saturation; CEC, cation exchange capacity; OM, organic matter; SB, sum of basis.

from 5.19 to 5.81 at rate of 0 RLR and from 5.47 to 6.67 at rate of 2 RLR (Figure 1B). The times for maximum soil pH were reached in 250, 350, and 242 days for limestone ECCE76 monthly irrigated, ECCE76 daily irrigated, and ECCE99, respectively, at rate of 4 RLR, reaching soil pH of 7.05, 6.96, and 7.02 (Figure 1B,D,F). The soil daily irrigated showed higher soil pH than the monthly irrigated (Figure 1B,D), while few differences were observed between limestone source ECCE76 and ECCE99 (Figure 1B,D).

The Ca^{2+} content in soil changes according to the treatments in general, but not in specific interactions (Table 1). In general, the Ca^{2+} content increased with lime rate. The Ca^{2+} content increased from 1.63 to 2.36 $cmol_c\ dm^{-3}$ for the limestone ECCE76, and from 1.58 to 2.41 $cmol_c\ dm^{-3}$ for limestone ECCE99, reaching maximum Ca^{2+} content at the highest rate evaluated (4 RLR) (Figure 2A). The limestone ECCE99 resulted in higher Ca^{2+} content than limestone ECCE76 at rates of 2 and 4 RLR (Figure 2A). The Ca^{2+} content decreased according to time of reaction (30 to 365 days), from 2.21 to 1.66 $cmol_c\ dm^{-3}$ when daily irrigated and from 2.12 to 1.87 $cmol_c\ dm^{-3}$ when monthly irrigated (Figure 2B), where the daily irrigated resulted in lower Ca^{2+} content at 60, 180, and 365 days (Figure 2B).

The Mg^{2+} content had significant interaction of lime rate, moisture regime, and time of reaction (Table 1). The Mg^{2+} content increased according to lime rate of 0 to 4 RLR (Figure 3A,C,E), increasing from 0.78 to 1.08 $cmol_c\ dm^{-3}$ in 30 days, and from 0.62 to 0.89 $cmol_c\ dm^{-3}$ in 365 days when monthly irrigated (Figure 3A), while when soil was daily irrigated, the Mg^{2+} content increased from 0.76 to 1.10 in 30 days, and from 0.51 to 0.85 in 365 days (Figure 3B). The lime rates for maximum Mg^{2+} content were 3.2, 3.7, and 2.9 RLR for limestone ECCE76 monthly irrigated, ECCE76 daily irrigated, and ECCE9, respectively, at time of 60 days, corresponding to Mg^{2+} contents of 1.28, 1.18, and 1.46 $cmol_c\ dm^{-3}$ (Figure 3B,D,F).

Usually, the Mg^{2+} content was lower in soil daily irrigated than in monthly irrigated; for example, at rate of 4 RLR in 365 days, the Mg^{2+} contents were 0.85 and 0.94 $cmol_c\ dm^{-3}$ in daily and monthly irrigated, respectively (Figure 3A,C). The Mg^{2+} content was affected by limestone type in general but had little change in specific conditions (shown in Table S3). The limestone ECCE99 resulted in higher soil Mg^{2+} than ECCE76 at rate of 2 RLR in 180 days (0.83 vs. 0.67 $cmol_c\ dm^{-3}$), and at rate of 4 RLR in 90 days (1.16 vs. 1.02 $cmol_c\ dm^{-3}$) and 180 days (1.05 vs. 0.90 $cmol_c\ dm^{-3}$) (Figure 3E).

The Mg^{2+} content in soil decreases with the increase of the time after application up to 365 days (Figure 3B,D,F), for example, the Mg^{2+} decreased from 0.78 to 0.62 $cmol_c\ dm^{-3}$ at rate of 0 RLR and from 1.08 to 0.89 $cmol_c\ dm^{-3}$ at rate of 2 RLR (Figure 3B). The soil daily irrigated showed lower Mg^{2+} content than the monthly irrigated (Figure 3B,D), while few differences were observed between limestone ECCE76 and ECCE99 (Figure 3B,D).

The BS was influenced by the interaction of lime rate, moisture regime, and time of reaction (Table 1). The BS increased according to the lime rate of 0 to 4 RLR, showing the highest levels at the rate of 4 RLR (Figure 4A,C,E). The BS increased from 54% to 72% in 30 days and from 51% to 72% in

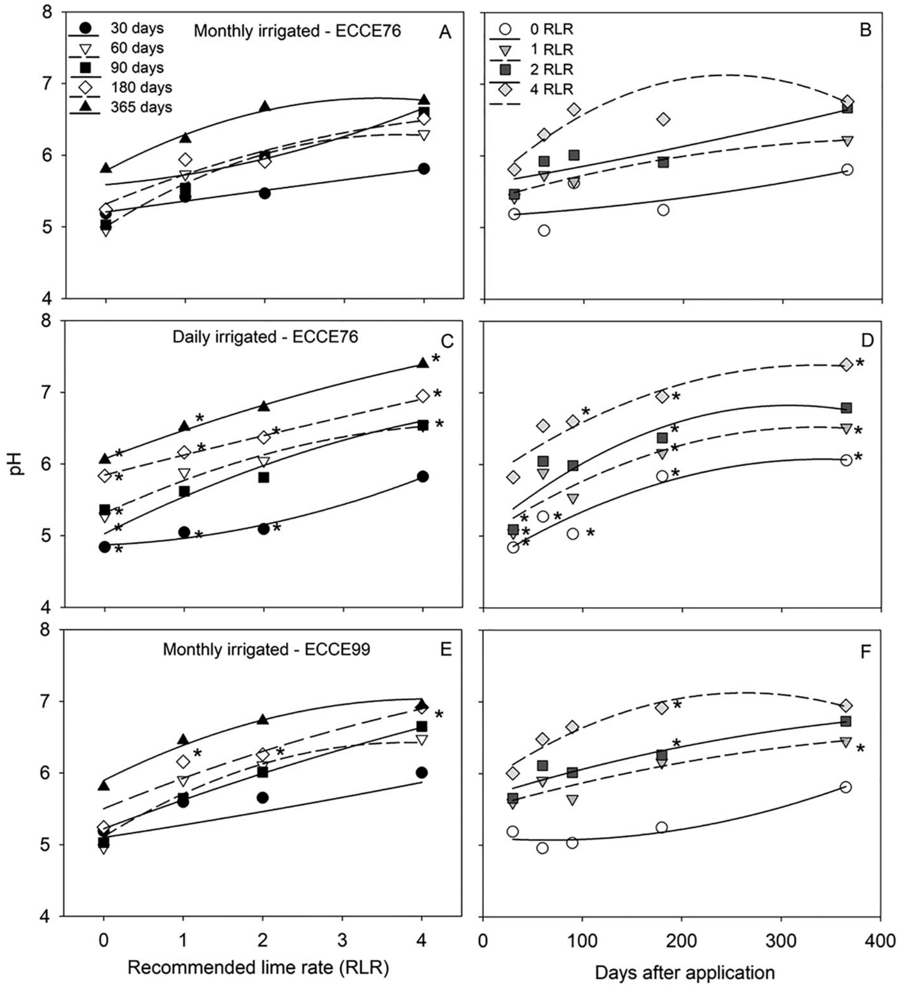

FIGURE 1 Change in soil pH according to lime rate (A, C, and E), time of reaction (B, D, and F), soil moisture regime, and limestone type. *Significant difference by LSD test ($p < 0.05$) between monthly (C and D) and daily irrigated (A and B), or between lime effective calcium carbonate equivalent (ECCE99) (E and F) and lime ECCE76 (A and B) in each lime rate or reaction time. Equation parameters are shown in Table S2.

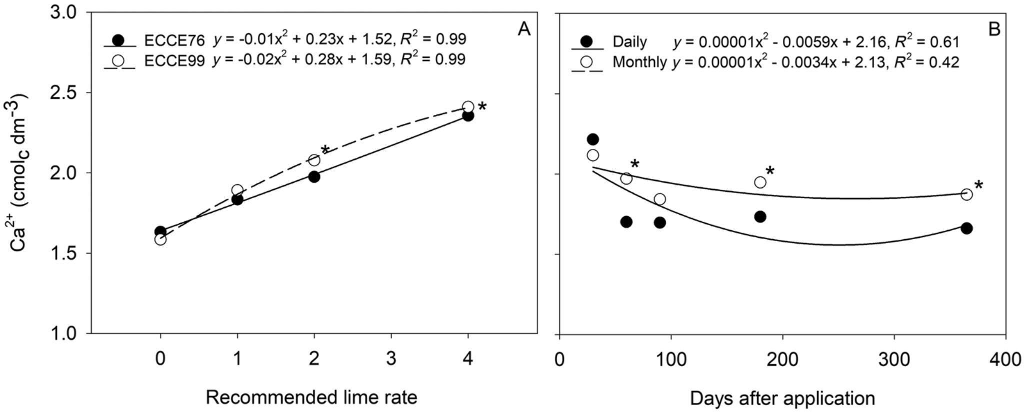

FIGURE 2 Change in Ca^{2+} content (exchangeable) in soil according to lime rate (A), time of reaction (B), limestone type and soil moisture regime. *Significant difference by LSD test ($p < 0.05$) between limestone effective calcium carbonate equivalent (ECCE99) and limestone ECCE76 (A) or between monthly and daily irrigated (B) in each lime rate or reaction time.

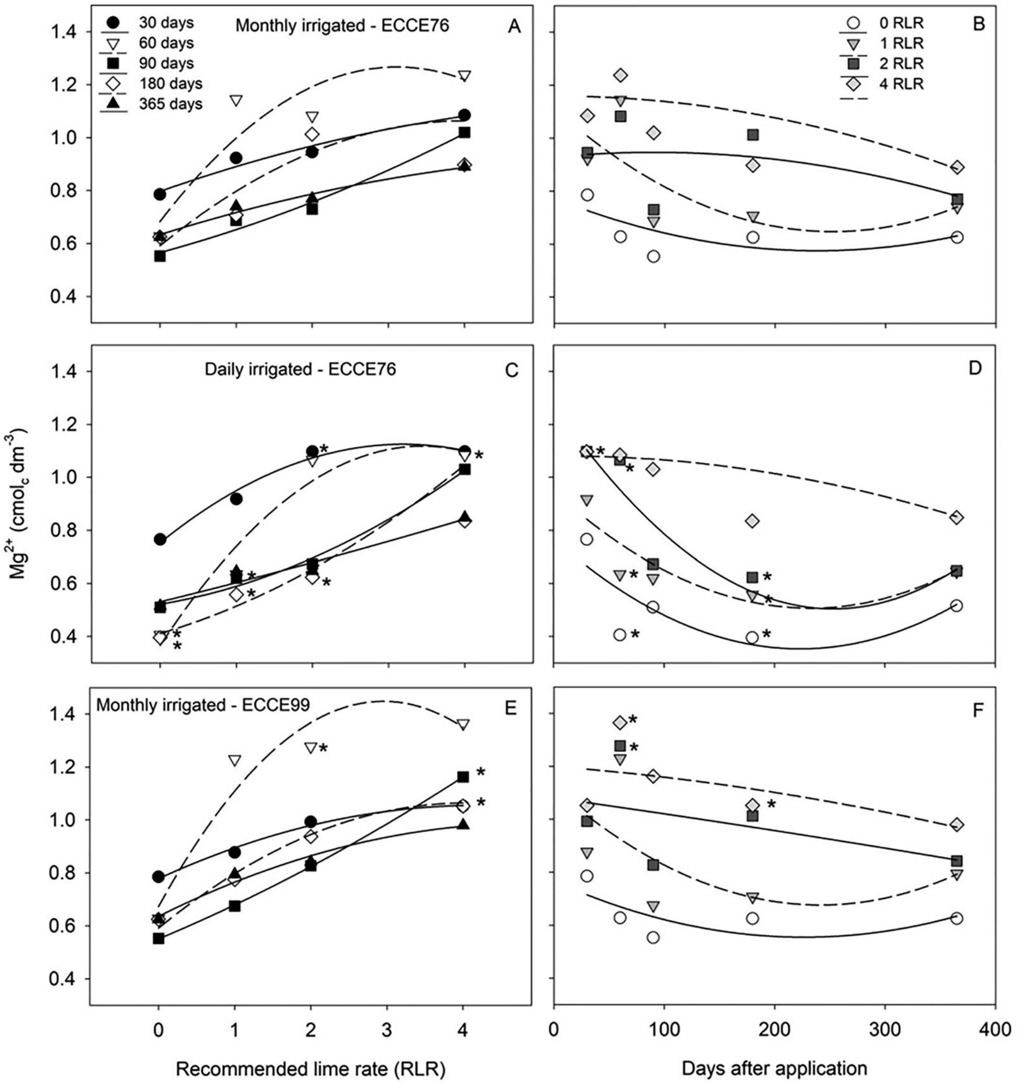

FIGURE 3 Change in Mg^{2+} content (exchangeable) in soil according to lime rate (A, C, and E), time of reaction (B, D, and F), soil moisture regime, and limestone type. *Significant difference by LSD test ($p < 0.05$) between monthly (C and D) and daily irrigated (A and B), or between limestone effective calcium carbonate equivalent (ECCE99) (E and F) and limestone ECCE76 (A and B) in each lime rate or reaction time. Equation parameters are shown in Table S3.

365 days when daily irrigated (Figure 4A), while when soil was monthly irrigated, the BS changed from 44% to 75% in 30 days and from 49% to 84% in 365 days (Figure 4C). Therefore, the soil moisture regime daily irrigated had lower BS than monthly. The exception was just for the rate of 4 RLR in 365 days, when the daily regime obtained higher BS than monthly one (Figure 4A,C). The BS was affected by limestone type (shown in Table S4); for example, the limestone ECCE99 resulted in higher BS than ECCE76, corresponding to BS of 83% and 72%, respectively, at rate of 4 RLR in 365 days (Figure 4E).

The BS had a small influence of the time of reaction (Figure 4B,D,F); for example, at rate of 4 RLR, the BS did not change for limestone ECCE76 in 365 days when monthly irrigated, but it increased from 75% to 84% when daily irrigated, and from 73% to 83% for limestone ECCE99 monthly irrigated (Figure 4B,D,F).

The other soil fertility properties (P, K, H + Al, SB, CEC, OM, Cu, Fe, Mn, and Zn) were differently affected by the treatments, showing the effect of one or more factors and/or the interaction of them (Table 1). The H + Al, P, S, and SB had significant effect of lime rate, reaction time, moisture, and limestone type (Table 2 and Table S5); for example, the P content increased from 146 to 172 mg dm^{-3} with lime rate increasing (0 to 4RLR); it decreased according to time after lime; the P content was higher when monthly irrigated than daily; and it was higher with limestone ECCE99 than ECCE76. The K content had a significant effect of lime rate, reaction time, and moisture but was not affected according to the limestone type. The CEC decreased from 5.4 to

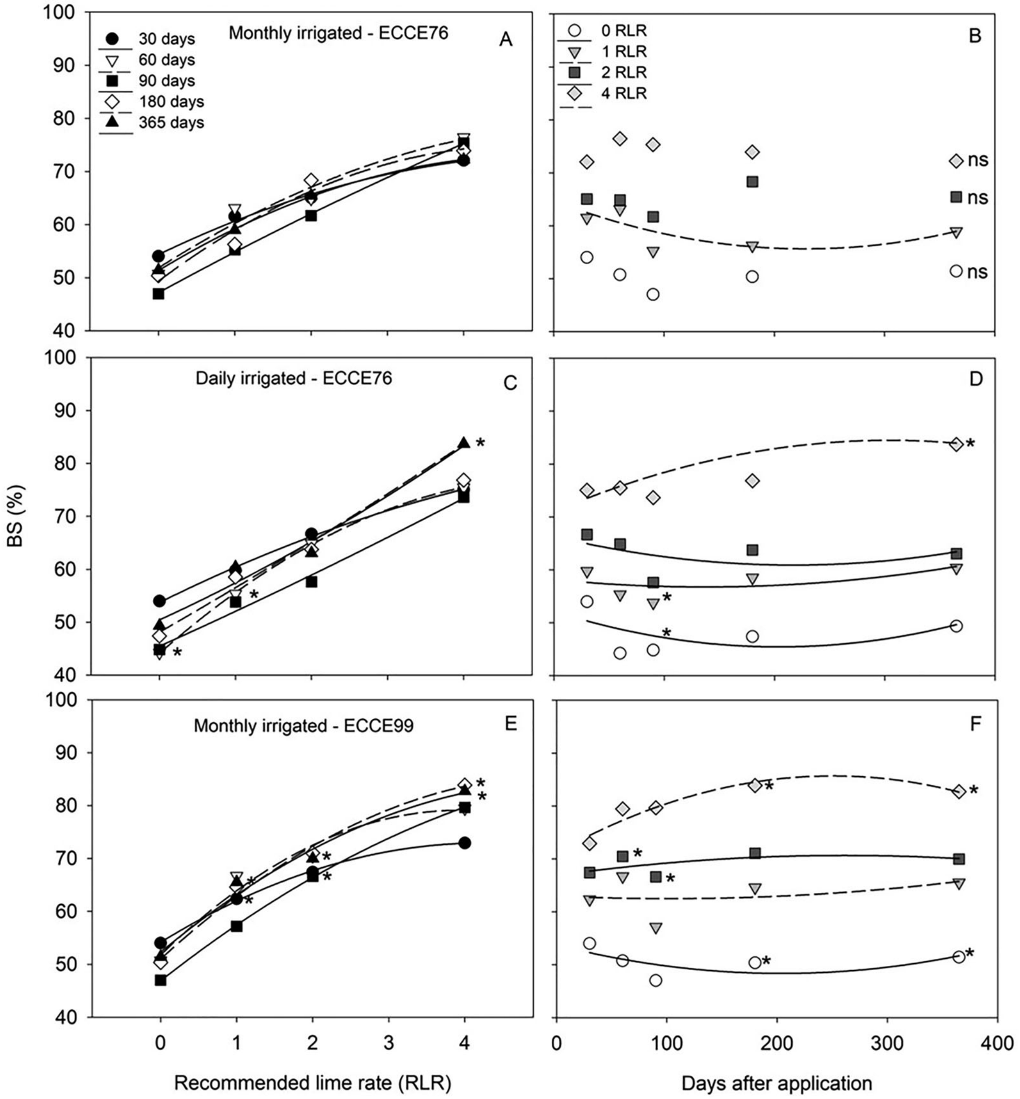

FIGURE 4 Change in base saturation (BS) in soil according to lime rate (A, C, and E), time of reaction (B, D, and F), soil moisture regime, and limestone type. *Significant difference by LSD test ($p < 0.05$) between monthly (C and D) and daily irrigated (A and B), or between limestone effective calcium carbonate equivalent (ECCE99) (E and F) and limestone ECCE76 (A and B) in each lime rate or reaction time. ns: no difference ($p < 0.05$) between times. Equation parameters are shown in Table S4.

4.2 $\text{cmol}_c\ \text{dm}^{-3}$ after 365 days of application, and it was higher when monthly irrigated than daily. The OM content was only influenced by soil moisture regime, but with small differences (0.91 and 0.88 g dm^{-3}) when daily irrigated and monthly, respectively (Table 2).

The micronutrients B, Cu, Mn, and Zn contents in soil increased according to the lime rate (0 to 4 RLR), while Fe had no significant effect. For example, the content of Zn increased from 5.5 to 6.1 mg dm^{-3}. The micronutrients increased with the time after liming; for example, Mn content increased from 4.7 to 5.3 mg dm^{-3} from 90 to 365 days. The content of B, Cu, and Mn were higher when monthly irrigated than daily, while the Zn content was the opposite. Limestone types did not affect micronutrient contents (Table 2).

The Pearson correlation was significant for most of the soil attributes, except OM content, which had a significant correlation with only P content (Table 3). The soil pH was negatively correlated with H + Al ($r = -0.87$) and K content ($r = -0.49$), and positively with BS ($r = 0.66$), Ca and Mg contents, with coefficients of 0.19, and 0.17, respectively.

In the PCA analysis, the two components explained 78.8% of the variance (Figure 5). The variables that most contributed to PC1 were SB, Mg, and Ca contents, which were positively correlated with each other; and in the PC2, the main contributors were pH and H + Al, which was negatively correlated (Figure 5).

TABLE 2 Change in content of soil chemical properties (P Mehlich 1, K, H + Al, sum of basis [SB], cation exchange capacity [CEC], organic matter—OM, S, B, Cu, Fe, Mn, and Zn) according to lime rate, time of reaction, soil moisture regime, and limestone type.

Treatment	P (mg dm^{-3})		K (mg dm^{-3})		H + Al (cmol$_c$ dm^{-3})		SB (cmol$_c$ dm^{-3})		CEC (cmol$_c$ dm^{-3})		OM (g dm^{-3})	
Recommended lime rate												
0	146	*	72.2	*	2.29	*	2.26	*	4.55	ns	0.92	ns
1	162		74.2		1.92		2.70		4.62		0.86	
2	165		77.8		1.65		2.98		4.64		0.90	
4	172		80.4		1.13		3.41		4.54		0.90	
Time of application (days)												
30	181	*	133.5	*	1.97	*	3.46	*	5.43	*	0.87	ns
60	169		77.9		1.78		2.94		4.73		0.90	
90	160		60.4		1.81		2.56		4.37		0.88	
180	156		58.6		1.62		2.62		4.23		0.94	
365	141		50.5		1.55		2.61		4.16		0.89	
Moisture regime												
Daily	156	b	68.6	b	1.69	b	2.97	b	4.39	b	0.91	a
Monthly	167	a	83.7	a	1.81	a	3.12	a	4.78	a	0.88	b
Limestone type												
ECCE76	167	b	83.7	ns	1.81	a	2.97	b	4.78	ns	0.88	ns
ECCE99	171	a	87.3		1.63	b	3.12	a	4.75		0.88	
Treatment	**S**		**B**		**Cu**		**Fe**		**Mn**		**Zn**	
	mg dm^{-3}											
Recommended lime rate												
0	13.3	*	0.46	*	1.56	*	36.2	ns	4.72	*	5.50	*
1	12.3		0.45		1.57		32.9		4.55		5.39	
2	18.4		0.52		1.54		35.2		4.73		5.43	
4	12.6		0.53		1.71		38.4		5.57		6.12	
Time of application (days)												
30	–		–		–		–		–		–	
60	–		–		–		–		–		–	
90	–		–		1.65	*	38.1	*	4.75	*	5.06	*
180	20.9	a	0.48	b	1.42		31.0		4.65		5.62	
365	7.4	b	0.50	a	1.70		37.9		5.28		6.15	
Moisture regime												
Daily	9.5	b	0.46	b	1.51	b	34.6	ns	4.61	b	5.62	a
Monthly	18.8	a	0.52	a	1.67	a	36.8		5.17	a	5.60	b
Limestone type												
ECCE76	18.8	ns	0.52	ns	1.67	ns	36.8	ns	5.17	ns	5.60	ns
ECCE99	18.2		0.53		1.64		36.7		5.20		5.51	

Abbreviations: CEC, cation exchange capacity; ECCE, effective calcium carbonate equivalent; OM, organic matter; SB, sum of basis.

*Significant difference ($p < 0.05$) between lime rates or between times of reaction; equation parameters are shown in Table S4. Different lowercase letters mean significant difference ($p < 0.05$) between moisture regimes or between limestone types. ns: no significant ($p < 0.05$).

4 | DISCUSSION

It was possible to observe liming residual effect on the field in 2013, even at the 0-limestone rate. This effect was expected, as liming is reported to modify soil characteristics regardless of the sampling time (Caires et al., 2000).

Several studies have shown soil pH increase due to limestone doses' application within a certain time interval (Augusti et al., 2023; Caires et al., 2000, 2004; Rheinheimer

TABLE 3 Matrix of Pearson correlation coefficients between soil chemical properties.

Variables	**Pearson coefficient**									
	pH	**P**	**K**	**Ca**	**Mg**	**H + Al**	**SB**	**CEC**	**BS**	**OM**
pH	–									
P	−0.20*	–								
K	−0.49*	0.45*	–							
Ca	0.19*	0.29*	0.62*	–						
Mg	0.17*	0.37*	0.61*	0.87*	–					
H + Al	−0.87*	0.10	0.22*	−0.47*	−0.43*	–				
SB	0.10	0.36*	0.71*	0.97*	0.95*	−0.39*	–			
CEC	−0.57*	0.44*	0.88*	0.61*	0.61*	0.39*	0.69*	–		
BS	0.66*	0.11	0.20*	0.79*	0.76*	−0.89*	0.76*	0.06	–	
OM	0.08	−0.22*	−0.13	−0.08	−0.13	−0.03	−0.11	−0.14	−0.03	–

Abbreviations: BS, base saturation; CEC, cation exchange capacity; OM, organic matter; SB, sum of basis.
*Significant at $p < 0.05$.

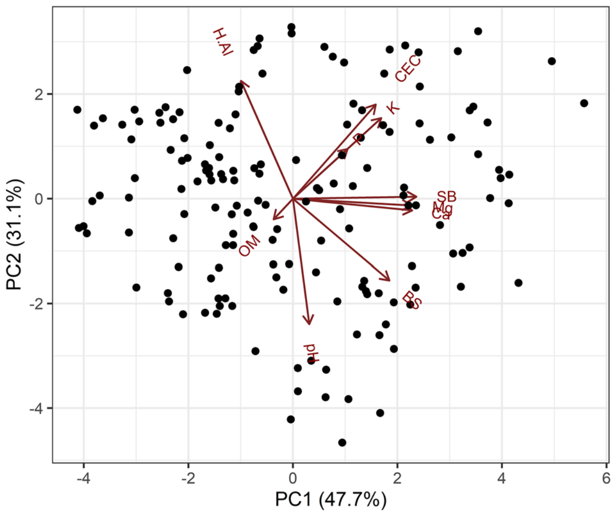

FIGURE 5 Principal components analysis of soil chemical properties according to lime rate (0, 1, 2, and 4), time of reaction (30, 60, 90, 180, and 365 days), soil moisture regime (daily and monthly irrigated), and limestone type (effective calcium carbonate equivalent [ECCE76] and ECCE99). Soil attributes: pH, organic matter (OM), K, P, Ca, Mg, H + Al, sum of basis (SB), base saturation (BS), and cation exchange capacity (CEC).

et al., 2000), just as herein observed. Results showed that lower limestone rates in sandy soils, despite the short period of 30-day limestone application, were enough to reach the ideal pH for plant growth (5.5–6.5) (Cherian & Arnepalli, 2015). This outcome was expected given these soils' low buffering power, which only recorded 145 g kg^{-1} clay and 8.7 g kg^{-1} OM in the present study.

Different from the expectations, the daily irrigation regime under constant moisture led to lower soil pH values than those recorded under monthly irrigation and intermittent moisture regime (Figure 1A,B,C,D). One hypothesis assumingly meeting this outcome lies on the fact that constant moisture inhibited the limestone reaction due to the self-liming effect. This effect is caused by constant water saturation, which is similar to what is observed in flooded crops. In other words, one of the main impacts of water blade application on the soil lies on natural pH correction by the course of reduction reactions. It happens due to lack of soil O_2 and to consequent changes in microbial metabolism (from aerobic to anaerobic), whose reduction reactions in composites consume H^+ (this phenomenon is known as soil self-liming) (Marchesan et al., 2019).

No matter the conditions, it is important highlight that most soil pH values did not exceed 7.0 in low sandy soil buffering capacity, even with applied rates up to four times higher than the traditional recommendations (Figure 1). Several sandy soil pH and liming data have shown that these values do not lead to rates as high as those mentioned in the literature. The application of much higher doses (from 10 to 20 Mg ha^{-1}) led to maximum pH 7.5 (Esper Neto et al., 2019; Goulding, 2016; Viana et al., 2023). This outcome is also explained by the fact that there is stabilized limestone reaction under low soil acidity buffering and weak Ca and Mg draining, which leads to chemical balance. It is so because calcium carbonate solubility drops down drastically from pH 6.0 onward and, similarly, the limestone reaction in the soil also drops (Allen & Hossner, 1991).

Esper Neto et al. (2019) assessed different limestone doses in sandy soil (120 g kg^{-1} clay) and found maximum pH, H_2O value = 5.94, with dose of 5.25 Mg ha^{-1} in the 0–10 cm soil layer, as well as maximum soybean yield (2,929 kg ha^{-1}) at the dose of 4.6 Mg ha^{-1} limestone. It is worth pointing out that the dose recommended by the base-saturation method would be 2.0 Mg ha^{-1}, based on soil chemical features prior to experiment installation.

Christensen et al. (2022) carried out long-term research (since 1942) with sandy soil (42 g kg^{-1} clay), and liming and phosphorus application (starting in 1942 and 1944, respectively). They found maximum pH of 7.1 at the highest limestone dose (of 12 Mg ha^{-1} limestone), as well as maximum barley (*Hordeum vulgare*) yield at the 6.4 Mg ha^{-1} limestone application. This study reinforces results in other research, according to which pH does not increase so much and doses to achieve the best yield rates are quite higher than the traditionally recommended ones for this soil type. There was a Mn and P availability drop at a pH higher than 7.0.

Tiritan et al. (2016) applied varying limestone rates in medium-clayey texture soil (192 g kg^{-1} clay) and assessed them for 6, 12, and 18 months after liming application. After these experimental times were over, soil pH reached 5.3, and the highest limestone rate was achieved (5.7 Mg ha^{-1}—this rate was calculated in order to increase BS to 70%). However, this value decreased in the long-term assessment.

With respect to limestone reaction, results have shown that limestone rates reached the lower ideal pH limit for plant growth (pH H_20 5.5) from the 30th day on, after 99% ECCE limestone application, mainly under the monthly moisture regime (Figure 1B,D,F). However, pH was not expected to decrease overtime once there were no plants or other acidifying source. Viana et al. (2023) inferred that simple models, or polynomial quadratic equations, often present flaws at the time to reproduce soil real response to liming, just as when they point toward pH decrease after dosage increase, after reaching the maximum limit.

Just as expected, limestone rates significantly increased soil-exchangeable Ca + Mg. Values close to those demanded by more productive genotypes and systems (2.7 to 5.2 $cmol_c$ dm^{-3}) (Resende et al., 2016; Sako et al., 2016) were only recorded under the highest limestone rate (Table 1; Figures 2A and 3A,C,E).

Regarding reaction time, studies focused on planting system based on the straight surface application of four limestone application (0, 2, 4, and 6 Mg ha^{-1}) found that lime often increases Ca + Mg contents in soil up to the depth of 10 cm, within the first 12 months. From this time onward, pH and BS values have decrease (Caires et al., 2000), and it evidences the maximum action of limestone in the first crop year after the application.

Lower Ca and Mg values based on limestone application time (Figures 2B and 3B) can be explained just as it was justified for pH, since the research did not assess a cultivated plant. It is so because of likely having the self-liming effect with limestone re-precipitation, and because the adjusted model may not be the most appropriate for the herein assessed phenomenon (Viana et al., 2023).

Maraschin et al. (2020) assessed the liming system based on the incubation method applied to two soil types, with different textures: one was sandy (640 g kg^{-1} clay) and the other had medium-texture (273 g kg^{-1} clay). They used 10 limestone rates ranging from 0 to 20 Mg ha^{-1}. They observed that the chemical variables were related to soil texture and to limestone dose after 40-day incubation. The pH $CaCl_2$ values ranged from 3.70 to 6.90 in medium textured soil and from 4.10 to 6.81 in sandy soil, at doses ranging from 0.0 and 20.0 Mg ha^{-1}, respectively. The Ca and Mg contents increased as limestone doses also increased, and they reached maximum values of 3.05 and 2.25 $cmol_c$ dm^{-3}, respectively, in medium texture soil, and 4.15 and 3.10 $cmol_c$ dm^{-3} in sandy soil. BS ranged from 8.5% to 98.2% in medium texture soil and from 7.2% to 93.7% in sandy soil.

It is possible observing that the medium texture soil recorded the lowest CEC, buffering capacity, and Ca and Mg draining values; thus, limestone application led to the lowest values recorded for Ca, Mg, and BS variables than the sandy soil. If one extrapolates this finding to sandy soils with lower buffering capacity, one can observe some limitations to reach higher Ca and Mg values, mainly at lower limestone rates, for example. It is so, because this condition is little stimulated and quickly inhibits the reaction, a fact that contrasts the most clayey environments.

Results like those recorded by Maraschin et al. (2020) and the ones in the current study reinforce the need of conducting further studies and likely reviews of liming recommendations set for sandy soils. According to them, indications about the need for liming can be estimated through different methods, even if they are not related to each other; most of these methods do not match all soil types. They also pointed out that the lowest limestone rates (up to 4 Mg ha^{-1}) did not allow increasing Ca and Mg contents to levels appropriate to plants in the assessed soils.

Using limestone as finer granulometry leads to a faster reaction in the soil, since it increases Ca and Mg availability. Besides reducing adverse impacts linked to acidity, such as H + Al, it can be quite important in sandy soils. Results in the present study corroborate studies such as those by Viadé et al. (2011), Govindasamy et al. (2017), and Ratke et al. (2018, 2021).

Overall, and in opposition to other reports in the literature (Boaretto et al., 2022; Fageria & Baligar, 2008; Suganya et al., 2020), there was no decrease in micronutrients' availability due to liming. Moreira et al. (2017) and Moreira et al. (2024) reinforced this finding, according to which soil micronutrients' contents were little related to these same contents in plants. Soil nutrients were little affected by limestone applications, but there was no reduction in plants, at all, and it often did not cause a deficiency. The aforementioned authors also suggest that Melhich-1 extractant May not be properly assessing soil micronutrients' availability.

Accordingly, the presented results suggest the need for adjustments in liming recommendations set for sandy soils and for more intense production systems. Therefore, more research related to the subject and involving more greenhouse and field experiments must be carried out.

AUTHOR CONTRIBUTIONS

Flávia Cristina dos Santos: Conceptualization; methodology; project administration; supervision; writing—original draft; writing—review and editing. **Álvaro Vilela de Resende**: Conceptualization; supervision; writing—review and editing. **Johnny Rodrigues Soares**: Data curation; formal analysis; software. **João Hebert Moreira Viana**: Conceptualization; supervision. **Monna Lysa Teixeira Santana**: Supervision; visualization; writing—review and editing. **Silvino Guimarães Moreira**: Supervision; writing—review and editing. **Manoel Ricardo de Albuquerque Filho**: Conceptualization; data curation; supervision; writing—review and editing.

ACKNOWLEDGMENTS

The authors are grateful to Trijunção Farm (Trijunção Project), grant number 0369-Faped and Embrapa for the research support and financing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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How to cite this article: Santos, F. C., Resende, Á. V., Soares, J. R., Viana, J. H. M., Santana, M. L. T., Moreira, S. G., & Albuquerque Filho, M. R. d. (2024). Limestone reaction in sandy soil: Rate effects, limestone type, moisture regime, and time. *Agrosystems, Geosciences & Environment*, *7*, e70008. https://doi.org/10.1002/agg2.70008