SILVA, G. B. A.; PAIMEL, A. C. C.; MOTA, L. G.; AVELINO, A. C. D.; DUARTE, C. F. D.; CABRAL, C. H. A.; CABRAL, C. E. A. Effects of irrigation interval and water depth on limestone reactivity in Oxisol. **Revista de Agricultura Neotropical**, Cassilândia-MS, v. 13, n. 1, e9708, 2026. ISSN 2358-6303. DOI: https://doi.org/10.32404/rean.v13i1.9708.

Effects of irrigation interval and water depth on limestone reactivity in Oxisol

Gustavo Barbosa Alves Silva[1], Anna Cláudia Cardoso Paimel[1], Lucas Gimenes Mota[2], Anne Caroline Dallabrida Avelino[1], Camila Fernandes Domingues Duarte[1], Carla Heloisa Avelino Cabral[1], Carlos Eduardo Avelino Cabral[1]

[1] Universidade Federal de Rondonópolis, Rondonópolis, Mato Grosso, Brasil. E-mail: gustavo.barbosa@aluno.ufr.edu.br, annaccp34@gmail.com, anne@valloura.com.br, carla.cabral@ufr.edu.br, carlos.eduardocabral@hotmail.com, camila.duarte@ufr.edu.br
[2] New Mexico State University, Las Cruces, New Mexico, Estados Unidos. E-mail: lucasgm@nmsu.edu

Received: 03/07/2025; Accepted: 19/09/2025.

ABSTRACT

Owing to high aluminum levels, soil acidity limits agricultural productivity in tropical regions. Liming is essential for increasing the soil pH and neutralizing toxic aluminum, and its effectiveness depends on water availability from rainfall or irrigation. The objective of this study was to evaluate whether different irrigation intervals and depths modify the reactions of limestone applied in an Oxisol. The study was conducted in an agricultural greenhouse at Rondonópolis-MT, with 6 treatments, in a 3 × 2 factorial scheme, with three irrigation intervals (2, 5 and 10 days) and two irrigation depths (50 mm and 100 mm). The irrigation depths were divided into five applications according to the intervals described in the treatments. The variables evaluated were the soil pH; potential acidity (H^{+}+Al^{3+}); exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} contents; base saturation (V%); and cation exchange capacity (CEC). Analysis of variance and Tukey's test ($p<0.05$) were used. There was no significant interaction effect among the intervals and depths for the variables measured, except for the aluminum content and aluminum saturation. The 100 mm water depth increased the soil pH, base saturation, and calcium and magnesium contents by 5, 15, 13, and 10%, respectively, and reduced the potential acidity. Moreover, calcium saturation was greater in the 2-day interval, and magnesium saturation was greater in the 2- and 5-day intervals. The 100 mm depth, which was applied at intervals of 2 days, resulted in higher gravimetric moisture, which accelerated the limestone reaction. These results indicate that the 100 mm depth promoted greater availability of calcium, magnesium and base saturation in the soil, whereas the 50 mm depth resulted in fewer changes in these attributes.

Keywords: Soil acidity, Liming, Acidity correction, Aluminum neutralization, Soil moisture.

Efeitos do intervalo de irrigação e da lâmina hídrica na reatividade do calcário em latossolo

RESUMO

A acidez do solo, devido aos elevados teores de alumínio, limita a produtividade agrícola em regiões tropicais. A calagem é essencial para elevar o pH do solo e neutralizar o alumínio tóxico, sendo sua eficácia dependente da disponibilidade de água proveniente da chuva ou da irrigação. O objetivo deste estudo foi avaliar se diferentes intervalos e lâminas de irrigação modificam a reação do calcário aplicado em um Latossolo. O experimento foi conduzido em casa de vegetação agrícola em Rondonópolis, com 6 tratamentos, em esquema fatorial 3 × 2, avaliando três intervalos de irrigação (2, 5 e 10 dias) e duas lâminas de irrigação (50 mm e 100 mm). As lâminas foram divididas em cinco aplicações de acordo com os intervalos descritos nos tratamentos. As variáveis avaliadas foram pH do solo, acidez potencial (H^{+}+Al^{3+}), teores de Ca^{2+}, Mg^{2+} e Al^{3+} trocáveis, saturação por bases (V%) e capacidade de troca catiônica (CTC). Adotou-se análise de variância e teste Tukey ($p<0,05$). Não houve efeito significativo da interação entre intervalos e lâminas para as variáveis avaliadas, exceto para o teor de alumínio e saturação por alumínio. A lâmina de 100 mm aumentou em 5, 15, 13 e 10% o pH do solo, a saturação por bases e os teores de cálcio e magnésio, respectivamente, além de reduzir a acidez potencial. Ademais, a saturação por cálcio foi maior no intervalo de 2 dias, enquanto a saturação por magnésio foi maior nos intervalos de 2 e 5 dias. A lâmina de 100 mm, aplicada a cada 2 dias, resultou em maior umidade gravimétrica, acelerando a reação do calcário. Esses resultados indicam que a lâmina de 100 mm promoveu maior disponibilidade de cálcio, magnésio e saturação por bases no solo, enquanto a lâmina de 50 mm resultou em menores alterações nesses atributos.

Palavras-chave: Acidez do solo, Calagem, Correção da acidez, Neutralização do alumínio, Umidade do solo.

1. Introduction

Soil acidity is a limiting factor for agricultural productivity, especially in tropical regions, where soils are naturally acidic and highly weathered (Fageria et al., 2008; Maraschin et al., 2020; Lisboa et al., 2021; Ribeiro et al., 2021; Chakraborty et al., 2024; Veloso et al., 2024; Shruthi et al., 2024). High levels of exchangeable aluminum (Al^{+3}), which is commonly found in dystrophic Oxisols, restrict root development in plants, thereby limiting water and nutrient uptake by plants (Kochian et al., 2004, Fageria et al., 2008). Moreover, low soil pH reduces nutrient availability through precipitation reactions, especially phosphorus, and increases the leaching of basic cations such as calcium, magnesium, and potassium (Fageria et al., 2008; Veloso et al., 2024).

These limitations help explain the low performance of crops grown in acidic soils that are not properly corrected (Veloso et al., 2024). The negative effects of acidity are even more pronounced in degraded production systems, where they contribute to reduced productivity and compromise system sustainability (Chakraborty et al., 2024). Aluminum toxicity in acidic soils affects nutrient dynamics not only by reducing phosphorus availability but also by decreasing calcium and magnesium uptake, impairing root elongation, and altering the balance of essential cations in the soil–plant system (Kochian et al., 2015; Lisboa et al., 2021). Such effects are particularly detrimental during the establishment phase of crops and pastures, as root system restriction compromises plant vigor and resilience.

The application of lime to acidic soils before plant growth is essential for neutralizing toxic aluminum, increasing the soil pH, and improving nutrient availability, all of which support pasture recovery and increased productivity (Fageria et al., 2008; Ribeiro et al., 2021; Veloso et al., 2024).

Moisture availability, whether from rainfall or irrigation, plays a crucial role in the dissolution of lime and the subsequent neutralization of soil acidity. The amount and frequency of water applied directly influence the efficiency and rate of these reactions, highlighting the importance of strategic water management under field conditions (Maraschin et al., 2020). In addition to promoting lime dissolution, the presence of soil water has a broader effect on the chemical dynamics of the system.

Soil water not only facilitates lime dissolution but also enhances ion diffusion in the soil solution, accelerating neutralization processes and the redistribution of calcium and magnesium throughout the profile (Dong et al., 2014). Consequently, the interaction between liming and the soil water regime may determine the effectiveness of acidity correction and the availability of nutrients for subsequent crop establishment.

Although it is well established that soil moisture significantly affects reactivity (Dong et al., 2014), studies that define the specific water requirements for this process are needed. Such information could support more flexible planning of the interval between liming and sowing, depending on the prevailing water regime. On the basis of this gap, we hypothesized that greater water availability, through greater irrigation depths and shorter intervals, would increase lime reactivity by accelerating its dissolution and soil acidity neutralization. Therefore, the objective of this study was to evaluate the effects of different irrigation depths and intervals on lime reactivity in an Oxisol.

2. Material and Methods

The experiment was conducted in a greenhouse at the Federal University of Rondonópolis (UFR), situated in the state of Mato Grosso, Brazil, at coordinates of 16°28' S latitude, 54°38' W longitude, and an elevation of 284 meters. A completely randomized design was adopted, arranged in a 3 × 2 factorial structure with four replicates, totaling 24 experimental units. The treatments combined three irrigation intervals (every 2, 5, and 10 days) with two irrigation depths (50 mm and 100 mm per treatment cycle).

For each irrigation depth, five applications were performed using volumes of 10 mm or 20 mm per event, resulting in cumulative totals of 50 mm and 100 mm, respectively, for each experimental unit. Each unit consisted of a PVC pot measuring 20 cm in diameter and 20 cm in height, filled with soil as characterized below.

The soil used in the experiment was classified as an Oxisol (Typic Hapludox) according to the USDA Soil Taxonomy (Soil Survey Staff, 2014), corresponding to a *Latossolo Vermelho distrófico* in the Brazilian Soil Classification System (Santos et al., 2018), with a clayey texture.

It was collected from a native Cerrado area at a depth of 0–20 cm. Following collection, the soil was air-dried and sieved through a 4 mm mesh to ensure uniformity and to remove coarse materials and plant residues.

A representative soil sample was subjected to chemical analysis and particle size composition (Table 1). Soil collection and analyses were performed following the methodologies described by Teixeira et al. (2017).

Table 1. Chemical and particle size characterization of the red Oxisol.

pH	P*	K	Ca	Mg	Al	H	CEC	V	m	Sand	Silt	Clay
$CaCl_2$	mg dm^{-3}		$cmol_c$ dm^{-3}					%		g kg^{-1}		
4.2	2.5	56	0.5	0.2	0.9	4.3	6.0	12.9	54.0	595	125	280

*Mehlich-1 method; CEC: cation exchange capacity; V: base saturation; m: aluminum saturation.

Then, the sieved soil was transferred to the pots (experimental unit) at approximately 5.0 kg per pot, and the amount of limestone necessary to increase the soil base saturation to 60% was incorporated. The dolomitic limestone used for soil correction had the following characteristics: a CaO content of 31%, a MgO content of 21%, a total neutralizing power (TNP) of 107.0%, a reactivity of 80.4%, and a relative total neutralizing power (RTNP) of 86.0%.

Immediately after the incorporation of limestone, the first irrigation was applied at depths of 10 and 20 mm. The volume of water per pot was calculated considering the surface area of the soil in the container and the depth to be applied (10 mm = 180 mL and 20 mm = 360 mL). Five irrigations were performed according to the intervals proposed in the treatments (Table 2). In addition, the gravimetric moisture of the soil was quantified before irrigation and after each irrigation, according to Teixeira et al. (2017).

To verify the water percolation potential under the highest irrigation depth, the maximum water-holding capacity of the soil was determined.

Table 2. Schedule of irrigation and collection of soil samples for chemical analysis.

Irrigation interval	Incorporation of limestone	Days after incorporation of limestone 4	8	10	12	15	20	25	30	40	45
2	💧	💧	💧	💧	💧						⚗
5	💧			💧		💧	💧	💧			⚗
10	💧			💧			💧		💧	💧	⚗

💧: moment when soil moisture was raised to the maximum water retention capacity. ⚗: Soil collection for chemical and particle size analysis.

To verify the soil moisture at the maximum water-holding capacity, soil-filled pots equipped with drainage holes at the bottom were placed in trays containing water up to two-thirds of the pot height and left until the soil pores reached saturation through capillary rise from the water entering via the drainage holes. Capillary irrigation ensures uniform filling of all the soil pores, unlike surface irrigation, which may create preferential flow paths along the pot walls. After pore saturation, identified by the presence of a water layer on the soil surface, the pots were removed from the trays and allowed to drain. When water ceased to flow from the drainage holes, the pots were weighed, corresponding to the soil's maximum water-holding capacity. The initial gravimetric soil moisture and maximum soil water capacity were 5.88% and 32%, respectively.

Forty-five days after the first irrigation, soil samples were collected from each pot for the following chemical analyses: pH in $CaCl_2$ solution (Teixeira et al., 2017), exchangeable cations (calcium, magnesium and aluminum), and potential acidity (Cunha et al., 2017). On the basis of these analyses, the sorptive complex of the soil was estimated (Teixeira et al., 2017), allowing for the determination of the cation exchange capacity (CEC), aluminum saturation (m), sum of bases (SB), base saturation (V) and calcium and magnesium saturation (Teixeira et al., 2017).

The statistical model used was as follows:

$$Y_{ijk} = \mu + I_i + L_j + (I \times L)_{ij} + e_{ijk}$$

Yijk: Observed value for each experimental unit; μ: Overall average; I_i: Effect of irrigation intervals; Lj: Effect of irrigation depths; $(I \times L)_i$j: Interaction between factors; $e_i$jk: Experimental error associated with the sampling unit.

The data were analyzed via analysis of variance (ANOVA) to assess the effects of the factors and their interactions. When significant differences were detected, the means were compared via Tukey's test at the 5% probability level ($p<0.05$). All the statistical analyses were performed via SISVAR software, version 5.7.

3. Results and Discussion

There was no significant interaction effect ($p<0.05$) between the irrigation interval and depth for any of the evaluated variables (Table 3). However, both factors, when analyzed independently, influenced most soil chemical attributes, except for the aluminum content and aluminum saturation (m), which remained unaffected.

Compared with longer intervals, the shortest irrigation interval (2 days) significantly increased the soil pH and base saturation (V) ($p<0.05$). The soil pH reached 5.17 at the 2-day interval, representing increases of 2.2% and 2.8% over the 5-day (5.06) and 10-day (5.03) intervals, respectively (Figure 1a). Similarly, the V% was 52% at 2 days, whereas reductions of 5.8% and 7.7% were observed at 5 and 10 days (49% and 48%), respectively (Figure 1b). These results indicate that greater irrigation frequency favored limestone dissolution and reactivity, accelerating the neutralization of soil acidity and increasing base saturation.

Exchangeable cations also responded positively to shorter irrigation intervals (Figure 1C and 1D). For Mg^{2+}, the 2-day interval reached 1.30 $cmol_c\ dm^{-3}$, an increase of 10.2% and 17.1% compared with 5 days (1.18 $cmol_c\ dm^{-3}$) and 10 days (1.11 $cmol_c\ dm^{-3}$), respectively (Figure 1C). The same pattern was observed for Ca^{2+}, with a value of 1.25 $cmol_c\ dm^{-3}$ at 2 days, which was 10.6% greater than that of the 5-day interval (1.13 $cmol_c\ dm^{-3}$) and 16.8% greater than that of the 10-day interval (1.07 $cmol_c\ dm^{-3}$) (Figure 1d). These findings suggest that shorter irrigation intervals increase Ca^{2+} and Mg^{2+} availability in the soil, likely due to improved carbonate solubilization and cation mobility, resulting in greater effectiveness of soil acidity correction (He et al., 2024; Kumar et al., 2023; Fadl et al., 2024).

Table 3. Synthesis of the analysis of variance and standard error of the mean for the effects of irrigation interval and depth on soil chemical attributes.

Variable	Intervals (I)	Depths (D)	I x D	SEM
pH ($CaCl_2$)	0.0030	<0.0001	0.7915	0.0209
Ca^{+2} ($cmol_c\ dm^{-3}$)	0.0007	0.0001	0.9297	0.0217
Ca (%)	0.0013	<0.0001	0.2861	0.3171
Mg^{+2} ($cmol_c\ dm^{-3}$)	0.0032	0.0028	0.5545	0.0272
Mg (%)	0.0065	<0.0001	0.7959	0.4150
H+Al ($cmol_c\ dm^{-3}$)	0.0566	<0.0001	0.0626	0.0315
Al^{+3} ($cmol_c\ dm^{-3}$)	0.3874	0.3306	0.3874	0.0058
m (%)	0.3874	0.3306	0.3874	0.2651
SB ($cmol_c\ dm^{-3}$)	0.0012	0.0004	0.7916	0.0469
CEC ($cmol_c\ dm^{-3}$)	0.0699	0.0993	0.0979	0.0464
V (%)	0.0017	<0.0001	0.6061	0.6629

SB: sum of bases; CEC: cation exchange capacity; V: base saturation; SB: sum of bases; P values indicate the level of statistical significance obtained via analysis of variance (ANOVA) for the main effects (irrigation interval and irrigation depth) and their interaction (intervals*depths). Significance was considered at the level of 5% ($p<0.05$). SEM: standard error of the mean.

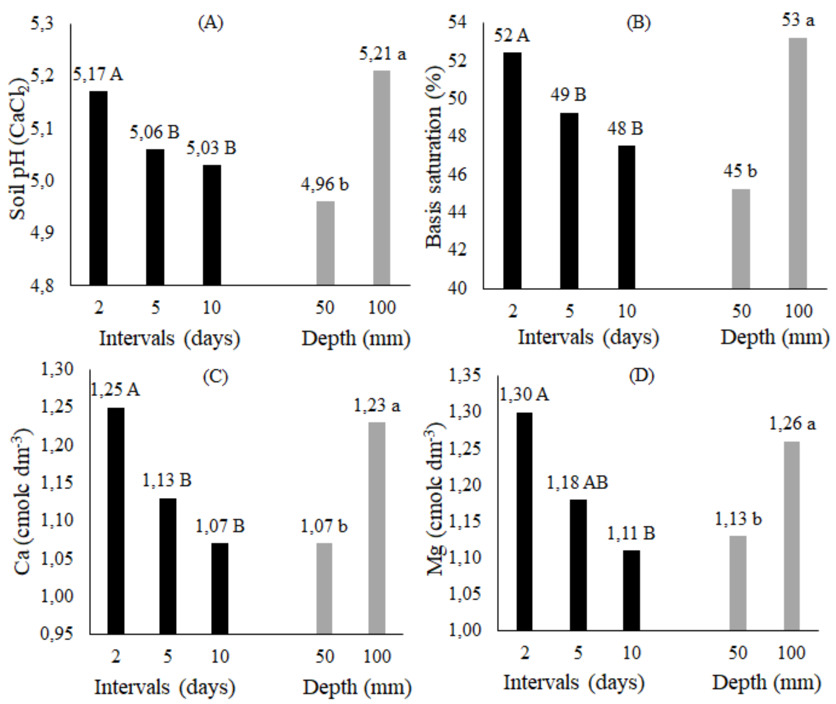

Figure 1. Influence of irrigation intervals and irrigation depths on soil chemical properties: soil pH ($CaCl_2$) (A); basis saturation (B); exchangeable Mg^{2+} (C); exchangeable Ca^{2+} (D). Means followed by the same letter do not differ according to Tukey's test at 5% probability (uppercase letters compare irrigation intervals; lowercase letters compare irrigation depths).

Potential acidity (H^{+}+Al^{3+}) was not influenced by the irrigation interval but decreased at depths less than 100 mm (Table 4). Even so, the values remained low and stable across the treatments. Similarly, the cation exchange capacity (CEC) showed no significant response to either factor, with an average value of 5.0 $cmol_c$ dm^{-3}. This behavior is expected in balanced Oxisols and reflects the stability of the total exchangeable charges at pH 7.0 (Bernardi et al., 2018). In such soils, the irrigation interval alone may not be sufficient to provoke changes in the CEC or potential acidity, unlike in soils with more extreme conditions (Costa et al., 2024; Fadl et al., 2024).

The 100 mm irrigation depth also increased the sum of exchangeable bases (SBs) and significantly increased Ca and Mg saturation ($p<0.05$). While Ca saturation was also greater under the 2-day interval, Mg saturation remained unaffected by interval changes.

Notably, the treatment combining the 100 mm depth with a 2-day interval was the only one that surpassed the soil's maximum water retention capacity (Figure 2), creating conditions favorable for accelerated limestone dissolution and cation exchange reactions.

The soil pH was influenced by both the irrigation depth and interval. The highest pH values occurred at greater depths and shorter intervals, likely because the increase in soil moisture exceeds the retention capacity, which facilitates limestone reactions. This finding reinforces the importance of water availability in enhancing lime effectiveness, accelerating pH correction, and improving soil chemical conditions (Pauletti et al., 2014). Consequently, irrigation management can play a pivotal role in reducing the necessary waiting period between liming and sowing.

Table 4. Effects of irrigation intervals and irrigation depths on soil attributes.

Variable	Irrigation interval (days)			Depth (mm)	
	2	5	10	50	100
Al^{+3}	0.00 A	0.01 A	0.00 A	0.00 a	0.00 a
H+Al	2.38 A	2.48 A	2.52 A	2.66 a	2.26 b
SB	2.63 A	2.41 A	2.27 A	2.30 b	2.58 a
CEC	5.02 A	4.90 A	4.80 A	4.96 a	4.85 a
Ca (%)	24.85 A	23.18 B	22.47 B	21.60 b	25.40 a
Mg (%)	25.85 A	24.20	23.23 B	22.75 b	26.08 a

Means followed by the same uppercase letter in the columns (irrigation intervals) and lowercase letter in the columns (irrigation depths) do not differ according to Tukey's test at 5% probability ($p<0.05$). SB: sum of bases; CEC: cation exchange capacity.

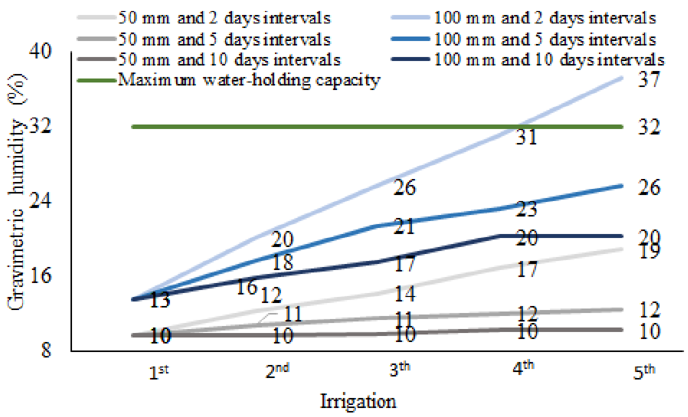

Figure 2. Gravimetric soil moisture immediately after irrigation.

Although the irrigation interval did not significantly alter variables such as Al^{3+}, H^{+} +Al^{3+} and CEC (Table 4), it did influence Ca^{2+} saturation, indicating that shorter intervals may contribute modestly to cation exchange dynamics (Table 4). Nonetheless, overall moisture availability from deeper irrigation appears to be the more dominant factor (Table 4; Figure 1). In terms of calcium and magnesium contents, even with variations across treatments, all values remained above the minimum thresholds required for the establishment of forage grasses, which are 0.7 and 0.5 $cmol_c$ dm^{-3}, respectively (Van Raij et al., 1996).

This suggests that under field conditions, even modest improvements in soil Ca and Mg through irrigation and liming can provide sufficient nutrition for pasture implantation. In support of this, previous studies reported increased forage yield with low to moderate Ca levels when combined with nitrogen fertilization (Silveira e Monteiro, 2007; 2011) and no consistent response to calcium applied via silicates (Santana et al., 2015; Silva et al., 2016), emphasizing that high Ca levels are not always needed to meet the needs of tropical forage species.

The effectiveness of soil acidity correction is influenced not only by the soil moisture level but also by the evaluation period after incubation, since between 60 and 180 days after application, lime reactivity is not significantly affected when the soil moisture varies from 20% to 80% of the soil saturation capacity (Calonego et al., 2012). In this study, forty-five days after limestone application, the larger blade associated with a shorter interval between irrigations favored greater changes in soil characteristics.

Overall, the results suggest that while the irrigation interval plays a minor role under the conditions studied, the irrigation depth has a substantial influence on the efficiency of limestone reactions in Oxisols. These findings support the integration of water management strategies with soil amendment practices, especially in regions relying on rainfall, to optimize liming efficiency and improve soil chemical conditions for pasture establishment.

4. Conclusions

The 100 mm irrigation depth significantly improved the soil pH, base saturation, and calcium and magnesium contents, with a 17.64% increase in base saturation. It also reduced potential acidity, maintaining stable levels across irrigation intervals. Although the CEC remained unaffected, the 100 mm depth enhanced calcium and magnesium saturation. The 2-day irrigation interval, combined with the 100 mm depth, resulted in higher soil moisture, promoting better nutrient availability and potentially enhancing pasture growth.

Authors' Contribution

Conceptualization: Gustavo Barbosa Alves Silva, Carlos Eduardo Avelino Cabral. Methodology: Gustavo Barbosa Alves Silva, Anne Caroline Dallabrida Avelino, Carlos Eduardo Avelino Cabral. Statistical analysis: Carlos Eduardo Avelino Cabral. Investigation: Gustavo Barbosa Alves Silva, Anna Cláudia Cardoso Paimel. Data curation: Gustavo Barbosa Alves Silva, Carlos Eduardo Avelino Cabral. Writing - original draft preparation: Gustavo Barbosa Alves Silva, Anne Caroline Dallabrida Avelino, Anna Claudia Cardoso Paimel, Carlos Eduardo Avelino Cabral. Writing - review and editing: Lucas Gimenes Mota, Anne Caroline Dallabrida Avelino, Carla Heloisa Avelino Cabral, Camila Fernandes Domingues Duarte, Carlos Eduardo Avelino Cabral. Visualization: Lucas Gimenes Mota, Camila Fernandes Domingues Duarte, Carlos Eduardo Avelino Cabral. Supervision: Carla Heloisa Avelino Cabral. All authors read and approved the final version of the manuscript.

Bibliographic References

Bernardi, A.C.C., Bueno, J.O.A., Laurenti, N., Santos, K.E.L., Alves, T.C. 2018. Effect of liming and variable-rate fertilizers on soil chemical attributes and production costs of intensively managed Tanzania grass pasture. Brazilian Journal of Biosystems Engineering, 12(4), 368–385. https://doi.org/10.18011/bioeng2018v12n4p368-382

Calonego, U.C., Mora, V.S., Santos, C.H., Oliveira, L. 2012. Calagem e escarificação em solo incubado com diferentes umidades. Colloquium Agrariae, 8(2), 46–56. https://doi.org/10.5747/ca.2012.v08.n2.a078

Costa, F.H.R., Sousa, G.G., Lima, J.M.P., Almeida, M.S., Sousa, H.C., Gomes, S.P., Cruz Filho, E.M., Azevedo, B.M. 2024. Frequencies of irrigation in millet crop under salt stress. Brazilian Journal of Agricultural and Environmental Engineering, 28(3), e272197. https://doi.org/10.1590/1807-1929/agriambi.v28n3e272197

Chakraborty, N., Das, A., Pal, S., Roy, S., Sil, SK, Adak, M.K., Hasanuzzaman, M. 2024. Explorando os Mecanismos de Tolerância ao Alumínio em Plantas com Referência ao Arroz e Arabidopsis: Uma Revisão Abrangente das Adaptações Genéticas, Metabólicas e Fisiológicas em Solos Ácidos. Plants, 13(13), 1760. https://doi.org/10.3390/plants13131760

Cunha, J.M., Gaius, D.C., Campos, M.C.C., Soares, M.D.R., Silva, D.M.P., Lima, A.F.L. 2017. Physical attributes and soil carbon stock in areas of Terra Preta Archaeological in the Amazon. Environment & Water Magazine, 12(2), 263–281. https://doi.org/10.4136/ambi-agua.18907

Dong, Y., Cai, M., Zhou, J.B. 2014. Effects of moisture and carbonate additions on CO_2 emission from calcareous soil during closed–jar incubation. Journal of Arid Land, 6(1), 37–43. https://doi.org/10.1007/s40333-013-0195-6

Fadl, M.E., Sayed, Y.A., El-Desoky, A.I., Shams, E.M., Zekari, M., Abdelsamie, E.A., Drosos, M., Scopa, A. 2024. Irrigation practices and their effects on soil quality and soil characteristics in drylands: a comprehensive geomatic analysis. Soil Systems, 8(2), 52. https://doi.org/10.3390/soilsystems8020052

Fageria, N.K., Baligar, V.C. 2008. Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production. Advances in Agronomy, 99, 345–399. https://doi.org/10.1016/S0065-2113(08)00407-0

He, H., Li, D., Wu, Z., Wu, Z., Hu, Z., Yang, S. 2024. Assessment of the straw and biochar application on greenhouse gas emissions and yield in paddy fields under intermittent and controlled irrigation patterns. Agriculture, Ecosystems & Environment, 359, 108745. https://doi.org/10.1016/j.agee.2023.108745

Kochian, L.V., Piñeros, M.A., Liu, J., Magalhaes, J.V. 2015. Plant adaptation to acid soils: the molecular basis for crop aluminum resistance. Annual Review of Plant Biology, 66, 571–598. https://doi.org/10.1146/annurev-arplant-043014-114822

Kumar, J., Chawla, R., Katiyar, D., Chouriya, A., Nath, D., Sahoo, S., Ali, A., Singh, B.V. 2023. Optimizing irrigation and nutrient management in agriculture through artificial intelligence implementation. International Journal of Environment and Climate Change, 13(10), 4016–4022. https://doi.org/10.9734/ijecc/2023/v13i103077

Liao, P., Huang, S., Zeng, Y., Shao, H., Zhang, J., Groenigen, K.J. 2021. Liming increases yield and reduces grain cadmium concentration in rice paddies: a meta-analysis. Plant and Soil, 465(1–2), 157–169. https://doi.org/10.1007/s11104-021-05004-w

Lisboa, L.A.M., Pires, D.A.A., Muniz, J.A., Andrade, L.M.B., Sousa, D.M.G., Sousa, H.H.F., Santos, D.R. 2021. *Urochloa brizantha* cultivated in aluminum-toxic soil: changes in plant growth and ultrastructure of root and leaf tissues. Tropical Grasslands – Forrajes Tropicales, 9(1), 23–33. https://doi.org/10.17138/tgft(9)23-33

Maraschin, L., Scaramuzza, J.F., Vieira, C.R. 2020. Limestone incubation and the chemical characteristics of soils with different textures. Nativa, 8(1), 43–51. https://doi.org/10.31413/nativa.v8i1.6908

Pauletti, V., Pierri, L., Ranzan, T., Barth, G., Motta, A.C.V. 2014. Long-term effects of gypsum and limestone application in the no-tillage system. Brazilian Journal of Soil Science, 38(2), 495–505. https://doi.org/10.1590/S0100-06832014000200014

Ribeiro, A.C., Guimarães, P.T.G., Alvarez, V.V.H. 2021. Recommendation for the use of correctives and fertilizers in Minas Gerais: 5th approach. Viçosa, MG: CFSEMG.

Santana, C.S., Santos, L.S., Morais, G., Fernandes, L.A., Geraseev, L.C. 2015. Produtividade e valor nutritivo do capim-andropogon adubado com silicato de cálcio e magnésio. Animal Industry Bulletin, 72(4), 290–297. http://dx.doi.org/10.17523/bia.v72n4p290

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M.R., Almeida, J.A., Araujo Filho, J.C., Oliveira, J.B., Cunha, T.J.F. 2018. Sistema Brasileiro de Classificação de Solos. 5. ed. rev. e ampl. Brasília, DF: Embrapa.

Shruthi, P., Nagabovanalli, B.P., Dhumgond, P., Goiba, P.K., Laxmanarayanan, M. 2024. The benefits of gypsum for sustainable management and utilization of acid soils. Plant and Soil, 504, 5–28. https://doi.org/10.1007/s11104-024-06907-0

Silva, J.L., Ribeiro, K.G., Herculano, B.N., Pereira, O.G., Pereira, R.C., Soares, L.F.P. 2016. Dry matter production and structural and bromatological characteristics of *Brachiaria* and *Panicum* cultivars. Brazilian Animal Science, 17(3), 342–348. https://doi.org/10.1590/1089-6891v17i332914

Silveira, C.P., Monteiro, F.A. 2007. Morphogenesis and biomass production of Tanzania grass fertilized with nitrogen and calcium. Brazilian Journal of Animal Science, 36(2), 335–342. https://doi.org/10.1590/S1516-35982007000200009

Silveira, C.P., Monteiro, F.A. 2011. Influence of nitrogen and calcium fertilization on the morphological and productive characteristics of Tanzania grass roots grown in nutrient solution. Brazilian Journal of Animal Science, 40(1), 47–52. https://doi.org/10.1590/S1516-35982011000100007

Soil Survey Staff. 2014. Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. 12th ed. Washington, DC: USDA-NRCS.

Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G. 2017. Manual de métodos de análise de solo. 3. ed. Brasília, DF: Embrapa.

Van Raij, B., Cantarella, H., Quaggio, J.A., Furlani, A.M.C. 1996. Recomendações de adubação e calagem para o estado de São Paulo. 2. ed. Campinas, SP: Instituto Agronômico; Fundação IAC. (boletim técnico, 100).

Veloso, C.A.C., Carvalho, E.J.M., Silveira Filho, A. 2024. Dynamics of soil fertility in agrosilvopastoral systems in the Northeast region of the state of Pará. Brazilian Journal of Animal and Environmental Research, 7(4), e75229. https://doi.org/10.34188/bjaerv7n4-084

Volpe, E., Marchetti, M.E., Macedo, M.C.M., Rosa Junior, E.J. 2008. Renewal of degraded pasture with liming, fertilization, and legume intercropped in Quartzarenic Neosol. Acta Scientiarum. Agronomy, 30(1), 131–138. https://doi.org/10.4025/actasciagron.v30i1.1162