Interference Journal
ISSN 2009-3578
A2 QUALIS SUCUPIRA 2017-2020

Resposta de *Urochloa brizantha* cv. BRS Piatã a diferentes níveis de alumínio e à aplicação de silício

Daniel Pereira Gasparoto de Aguiar[1], Lara Oliveira Prestes Lourenço[2], Isabela Bazzo da Costa[3], Marcílio Félix[3], Rodolfo Cláudio Spers[3], Márcio José Segateli Spers[4], Francielli Biazi[1], Gabriela de Alcantara Dalevedo[1], Lucas Aparecido Gaion3[*]

https://doi.org/10.36557/2009-3578.2025v11n2p8453-8468
Artigo recebido em 6 de Outubro e publicado em 6 de Dezembro de 2025

ARTIGO ORIGINAL

RESUMO

O objetivo do presente estudo foi avaliar a resposta da forrageira *Urochloa brizantha* cv. BRS Piatã a diferentes níveis de alumínio (Al) e ao uso de silício (Si) como atenuador da toxicidade de Al. Para isso, plantas de *U. brizantha* foram cultivadas em vasos plásticos com capacidade de 2,5 L, preenchidos com solução nutritiva. Utilizou-se um delineamento inteiramente casualizado, em esquema fatorial 4 × 2, composto por quatro concentrações de Al (0, 2, 4 e 8 mmol L^{-1}) e aplicação ou não de Si. Foram empregadas quatro repetições por tratamento. Após 14 dias, as plantas foram coletadas para as seguintes avaliações: altura de planta, massa fresca e seca da parte aérea e das raízes, razão raiz/parte aérea, área foliar, número de perfilhos, extravasamento de eletrólitos, e acúmulo de Si e Al. Os dados foram submetidos à análise de regressão polinomial, aplicando-se modelos lineares e quadráticos para selecionar aquele com melhor ajuste. De modo geral, o Al acumulou-se tanto nas raízes quanto na parte aérea das plantas, reduzindo o crescimento de ambos os órgãos. Além disso, observou-se acentuado aumento no extravasamento de eletrólitos, indicando maior estresse oxidativo. Por outro lado, a aplicação de Si reduziu o acúmulo de Al e o extravasamento de eletrólitos, enquanto aumentou o crescimento tanto da parte aérea como das raízes. Dessa forma, conclui-se que, embora o Al cause danos severos à *U. brizantha*, a aplicação de Si foliar é um potencial mitigador desse estresse.

Palavras-chave: estresse abiótico, forrageira, nutrição de plantas, ciência do solo.

Response of *Urochloa brizantha* cv. BRS Piatã to different levels of aluminum and to silicon application

ABSTRACT

The aim of the present study was to evaluate the response of the forage *Urochloa brizantha* cv. BRS Piatã to different levels of aluminum (Al) and the use of silicon (Si) as an attenuator of Al toxicity. For this, plants of *U. brizantha* were cultivated in plastic pots with a capacity of 2.5 L filled with nutrient solution. A completely randomized design was used in a 4 x 2 factorial scheme consisting of four concentrations of Al (0, 2, 4, and 8 mmol L^{-1}) and application or non-application of Si. Four replications were used for each treatment. After 14 days, the plants were collected for the following evaluations: plant height, fresh and dry mass of shoot and roots, root/shoot ratio, leaf area, number of tillers, electrolyte extravasation, and accumulation of Si and Al. The data were submitted to polynomial regression analysis, applying linear and quadratic mathematical models to select the one with the best adjustment. In general, Al accumulated in both roots and shoots of plants, reducing the growth of both organs. In addition, there was a strong increase in electrolyte extravasation, indicating increased oxidative stress. On the other hand, the foliar application of Si reduced the accumulation of Al and the leakage of electrolytes while increasing the growth of both the shoot and the roots. Thus, it is concluded that, although Al causes severe damage to *U. brizantha*, the foliar application of Si is a potential mitigator of this stress.

Keywords: abiotic stress, forage, plant nutrition, soil science

Instituição afiliada – [1] Postgraduate student in Veterinary Medicine, University of Marília, Marília, São Paulo, Brazil.
[2] Undergraduate student in Agronomy, University of Marília, Marília, São Paulo, Brazil.
[3] Professor in the Postgraduate Program in Veterinary Medicine, University of Marília, Marília, São Paulo, Brazil.
[4] Postgraduate student in Animal Science, São Paulo State University, Botucatu, São Paulo, Brazil.

Autor correspondente: Lucas Aparecido Gaion lucas.gaion@yahoo.com.br

INTRODUÇÃO

Brazil has about 80 million hectares of pastures with some level of degradation, which represents 52.3% of Brazilian pastures (IBGE, 2019; Mapbiomas, 2021). Most of our pastures are located in low fertility soils, with high aluminum (Al) saturation (Buol 2009; Prado et al. 2012; Althaus et al. 2018). Al accumulates mainly in acid soils (<5), which causes the solubilization of Al, and so assumes the toxic form $[Al(H_2O)_6]^{3+}$ (Gupta; Gaurav and Kumar, 2013). When in high concentration, Al causes toxicity to cultivated plants. In these conditions, plants show symptoms, such as root and shoot growth retardation and reduction reducing the number of lateral roots as well as development of necrotic points in the root system, which can result in reduced productivity levels (Rahman and Upadhyaya, 2021). Actually, Al fundamentally impacts cellular structures such as the cell wall, plasma membrane and cytoskeleton (Vance et al., 2021). Thus, the collapse of these structures reduces root growth, which negatively affects the uptake of water and nutrients (Chahan et al., 2021).

Therefore, many studies have been carried out to find alternatives for stress attenuation by Al (Shetty and Prakash, 2020; Ranjan et al. 2021b; Sousa Junior et al. 2022). Mainly because in many regions, the use of soil conditioner, which can raise soil pH and neutralize toxic Al, is still limited, especially due to difficulties in accessing the area or lack of awareness of farmers (Moreira et al., 2018). Currently, it has been pointed out that several substances can have a mitigating effect on Al stress, for example, hormones, nutrients, secondary messengers and beneficial elements such as silicon (Si) (Chen et al., 2019; Wang et al., 2019; Rahman and Upadhyaya, 2021; Ranjan et al., 2021a,b).

Among these, Si is widely known as a beneficial element, increasing plant tolerance to various biotic and abiotic stresses (Zargar et al., 2019; Mostofa et al., 2021; Ranjan et al., 2021b). Regarding the attenuation of stress by Al, Si primarily could reduce the binding efficiency of Al to the cell wall by the formation of the Si-Al complex (Rahman and Upadhyaya, 2021). In addition, Si acts by activating antioxidant enzymes, especially superoxide dismutase (SOD), which leads to a reduction in the oxidative stress of plants exposed to Al (Vega et al., 2019; Rahman and Upadhyaya, 2021). In sugarcane, the addition of potassium silicate (2 mmol L^{-1}) to the nutrient solution reduced the absorption of Al by the plants and its transport to the shoot and, thus, restored the normal growth of the plants (Sousa Junior et al., 2022). Furthermore, the use of Si tends to increase the biosynthesis of lignin and phenolic compounds, which confers greater tolerance to plants (Vega et al., 2019; Sousa Junior et al., 2022).

Therefore, it is of great importance to study the interference of toxicity by Al in forage production, especially the negative effect of Al on grasses of the genus *Urochloa* since they stand out for being the most used as a forage source in the feeding of the national cattle herd (Silva Filho et al., 2014). Among the species of the genus *Urochloa*, *U. brizantha* stands out, originally from Africa and present in the national market for more than 30 years (Jank et al., 2014; Schultze-Kraft, 2020). *U. brizantha* has characteristics such as resistance to leafhoppers, high forage production and good regrowth capacity (EMBRAPA, 2015), which characterizes it as an excellent alternative species for forage production.

However, in Brazil, most of the territories destined for forage production are characterized by low fertility and have problems with the high acidity and toxicity caused by Al, these factors negatively affect crop production and yield (Dias-Filho, 2014). Therefore, the high concentration of Al has an important impact on the Brazilian agriculture and livestock sector, as it directly affects the metabolic and physiological processes of crops. Soils in Brazilian territory have a pH ranging between 3.7 and 5.5 and Al is the predominant cation in more than a third of soils with a pH lower than 5.5 (Abreu Júnior et al., 2003).

In view of the above, our objective with the present work was to evaluate the effect of the application of Si as an attenuator of stress by Al in plants of *U. brizantha* cv. BRS Piatã.

METODOLOGY

The experiment was carried out in a greenhouse belonging to the Agriculture Sector of the University of Marilia. For this, seeds of *Urochloa brizantha* cv. BRS Piatã were sown in phenolic foam trays. After germination, when the plants were about 5 cm tall, 15 days after sowing (DAS), they were transplanted into plastic pots with a capacity of 2.5 L filled with Clark's nutrient solution (1975). For that, the plants were fixed in polystyrene plates to allow the immersion of the root system in the nutrient solution. In the first week, the nutrient solution with 50% of its ionic strength was used. The plants were grown under natural light with a photoperiod of 12/12 h (light/dark), mean temperature of 25.5/18.8 ºC (day/night), and relative humidity of 62.2 ± 18.

At 21 DAS, the plants began to receive a nutrient solution with 100% of the ionic strength and treatments with different concentrations of Al were added to the nutrient solution (0, 2, 4 and 8 mmol L^{-1}), using hydrated aluminum sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$). To ensure aluminum availability, the pH of the solution was measured daily and maintained at 4.5, being changed every five days. In addition, the nutrient solution was constantly aerated using an air pump (Sunsun Aco-001). From 21 DAS, every seven days, the plants treated with silicon received silicon foliar sprays at a dose of 0.84 g L^{-1}. Si was applied in the form of potassium silicate (Si= 168 g L^{-1}; K_2O= 210 g L^{-1}; d= 1.4 g L^{-1}). Control plants were sprayed with potassium chloride to balance the potassium supply to the plants.

Thus, a completely randomized design was used in a 4 x 2 factorial scheme, consisting of four levels of Al (0, 2, 4 and 8 mmol L^{-1} of Al^{3+}) and presence or absence of foliar Si. Four replications were used for each treatment, consisting of a pot containing one plant.

After 14 days under the conditions described (35 DAS), the plants were collected, washed with distilled water, detergent (0.1%) and acid solution (0.3%) and separated into shoots and root systems. Initially, the leaf area was obtained by scanning the leaves and subsequent analysis of the images using the Quant software (Vale et al., 2003). For electrolyte extravasation analysis, five discs from the leaf blade of the middle third of the plant were collected from each plant. Then, the discs were placed in Petri dishes containing 20 mL of deionized water for 90 min at 25 °C and the initial electrical conductivity (Xi) of the samples was then measured. Subsequently, they were submitted to 80 °C for 90 min in a drying oven and, after cooling, the final conductivity (Xf) was measured. The percentage of electrolyte leakage was calculated by the formula: [(Xi/Xf) x 100].

Then, the number of tillers of the plants was counted, and the height of the plants was measured using a graduated ruler. The fresh mass of shoot and root system was determined using an analytical balance (Bel S203H). Afterwards, the shoot and the root system were packed in paper bags and placed in an oven with forced air circulation at 65 °C until reaching constant mass, and then the dry mass was measured. From the shoot biomass, the Si concentration was determined according to the method proposed by Korndörfer et al. (2004). Based on the Si content and the shoot dry mass, the Si accumulation in the plants was calculated. In addition, Al concentration was determined in shoots and roots, following the method suggested by Wang and Wood (1973).

The results were submitted to polynomial regression analysis, applying linear and quadratic mathematical models to select the one with the best fit to the data.

RESULTS

The increase in the concentration of Al in the nutrient solution reduced the shoot fresh mass of the *Brachiaria* plants, that is, the maximum applied dose (8 mmol L^{-1}) caused a reduction of 42% in the accumulation of shoot fresh mass in comparison to the plant control (Figure 1a). Furthermore, the foliar application of Si was able to recover part of the vegetative growth of the plants, especially at the lowest Al concentration (Figure 1a). Indeed, at the concentration of 2 mmol L^{-1} of Al, the application of Si increased the vegetative growth of the shoot by 29%, while at the concentration of 8 mmol L^{-1} of Al the application of Si increased the growth by 20% (Figure 1a). When plants were grown in the presence of Al, we observed a reduction of up to 31% (at 8 mmol L^{-1} of Al) in root fresh mass when compared to the control condition (Figure 1b). On the other hand, the application of Si was not very efficient in mitigating the negative effects of Al on the root system, although Si increased the fresh mass of roots by 12% in control plants (Figure 1b).

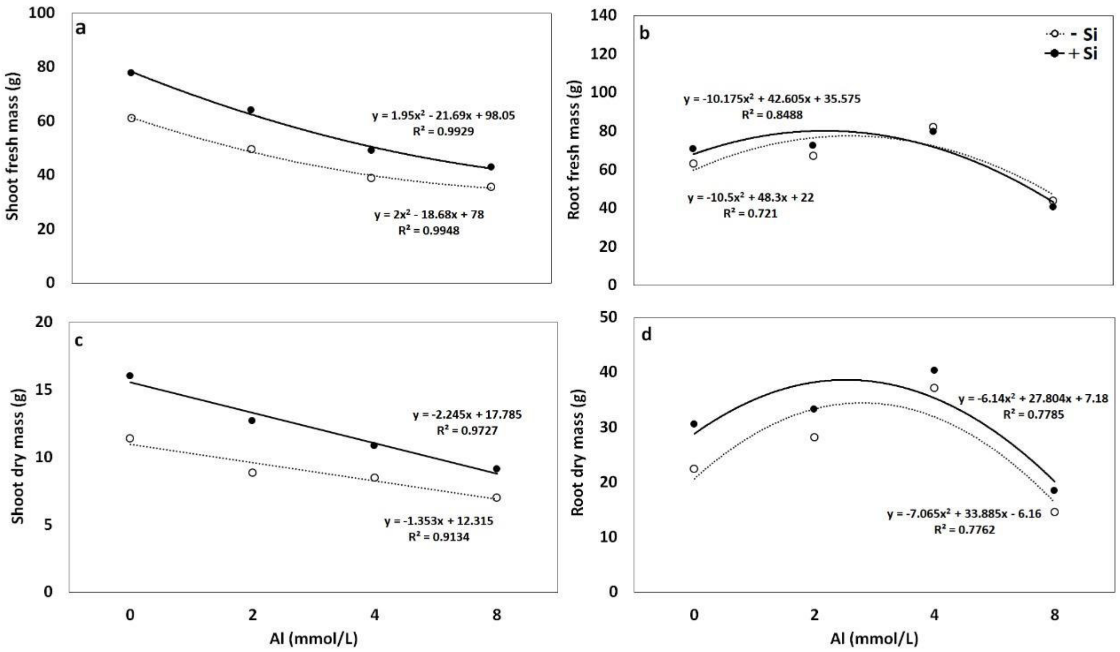

Figure 1. Shoot fresh mass (a), root fresh mass (b), shoot dry mass (c) and root dry mass (d) of plants of *Urochloa brizantha* cv. BRS Piatã cultivated in nutrient solution with doses of aluminum (Al) and silicon (Si) foliar. Control plants received neither Al nor Si.

Regarding the shoot dry mass, we verified a linear reduction with the increase of the Al concentration (Figure 1c). In fact, there was a 39% reduction in dry mass when compared plants under the highest Al dose (8 mmol L^{-1}) and the control condition (0 mmol L^{-1}). The application of foliar Si attenuated the negative effects of Al, increasing the dry mass of the shoot by 43 and 30%, respectively, at the lowest and highest Al concentration (Figure 1c). In turn, the dry mass of the roots was drastically affected by the increase of Al in the nutrient solution, reducing from 22.4 g to 14.6 g (35% reduction), when compared to the control condition and the concentration of 8 mmol L^{-1} of Al (Figure 1d). Unlike the root fresh mass, the application of Si proved to be efficient in improving the accumulation of dry mass in the roots, that is, even at the highest concentration of Al, Si increased the accumulation of carbon in the roots by 26% (Figure 1d).

Al reduced plant height when compared to the control condition, so the concentration of 8 mmol L^{-1} caused a 55% reduction in plant height (Figure 2a). The application of Si restored part of the plant growth, especially in the concentration of 2 mmol L^{-1} of Al; 70% increase; and in the concentration of 8 mmol L^{-1} of Al; increase of

33% (Figure 2a). The number of tillers was little affected by Al in the nutrient solution (Figure 2b). The application of Si increased the number of tillers on the plants, however, increasing the Al content in the nutrient solution linearly reduced the number of tillers (Figure 2b).

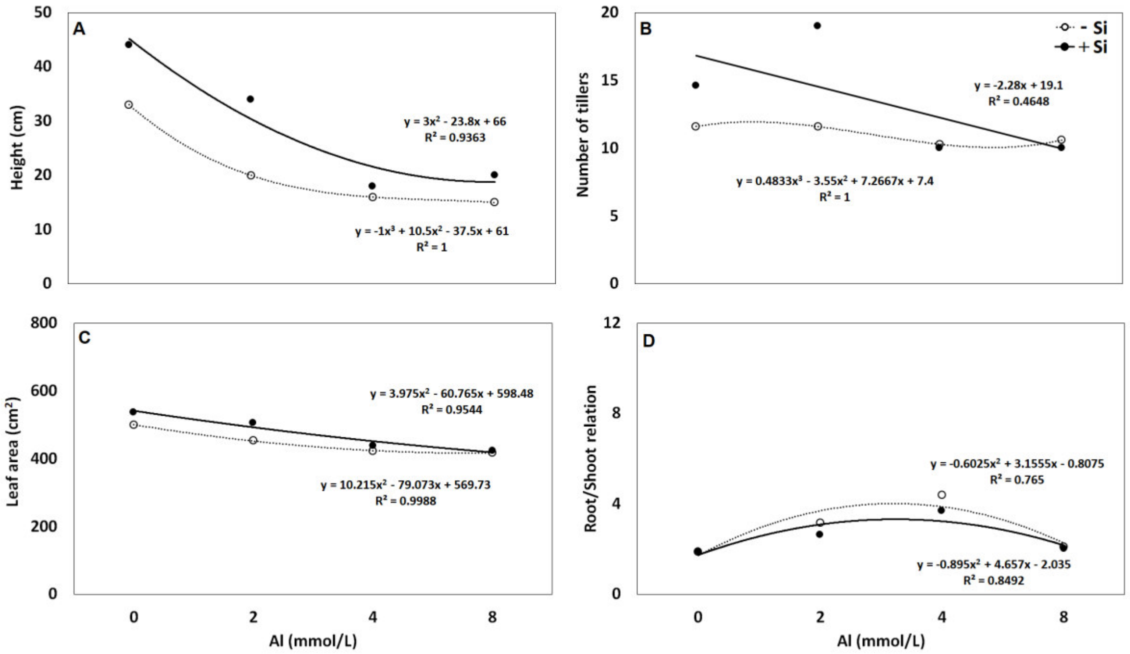

Figure 2. Height (a), number of tillers (b), leaf area (c) and root/shoot ratio (d) of plants of *Urochloa brizantha* cv. BRS Piatã cultivated in nutrient solution with doses of aluminum (Al) and silicon (Si) foliar. Control plants received neither Al nor Si.

Leaf area was reduced by 17% at the highest Al concentration (8 mmol L^{-1}) compared to the control condition (Figure 2c). In the control condition, the application of Si increased the leaf area of the plants in 7%, while in the concentration of 8 mmol L^{-1}, the Si provided an increase of only 1% of the leaf area of the plants (Figure 2c). Initially, Al concentrations of 2 and 4 mmol L^{-1} provided an increase in the ratio between roots and shoots, however, the concentration of 8 mmol L^{-1} of Al caused a reduction in the ratio between roots and shoots (Figure 2d). The application of Si proved to be inefficient in terms of increasing the relationship between the root and the shoot (Figure 2d).

In Figure 3, we can see that as the Al concentration increases, there is also an increase in electrolyte leakage in a linear form (Figure 3). On the other hand, the application of Si reduced electrolyte leakage by 11%, even at the highest Al concentration (Figure 3). At the concentration of 2 mmol L^{-1} of Al, the application of Si reduced electrolyte leakage by 33% (Figure 3).

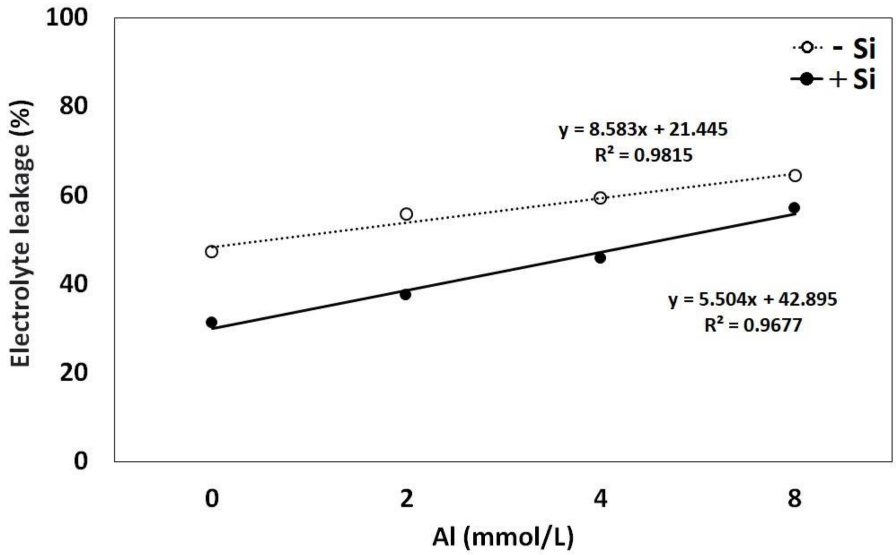

Figure 3. Electrolyte extravasation from plants of *Urochloa brizantha* cv. BRS Piatã cultivated in nutrient solution with doses of aluminum (Al) and silicon (Si) foliar. Control plants received neither Al nor Si.

The accumulation of Si was little influenced by the concentration of Al in the nutrient solution and was practically insignificant in plants not treated with Si (Figure 4a). On the other hand, the concentration of Al in the shoot increased in response to the increase in the concentration of Al in the nutrient solution, starting from 0.06 g kg^{-1} in the absence of Al and reaching 1.27 g kg^{-1} in the concentration of 8 mmol L^{-1} of Al (Figure 4b). Interestingly, the foliar application of Si drastically reduced the accumulation of Al in the shoot of the plants (Figure 4b). Indeed, the application of Si reduced the accumulation of Al in about 37% when the plants were cultivated under 8 mmol L^{-1} of Al (Figure 4b). The root system showed the highest accumulation of Al, reaching 2.6 g kg^{-1} of Al (Figure 4c). Similar to the Al accumulation in the shoot, the application of Si foliar minimized the accumulation of Al in the roots of *U. brizantha* plants. Thus, plants treated with Si showed a maximum Al accumulation of 1.21 g kg^{-1} at a concentration of 2 mmol L^{-1} of Al (Figure 4c).

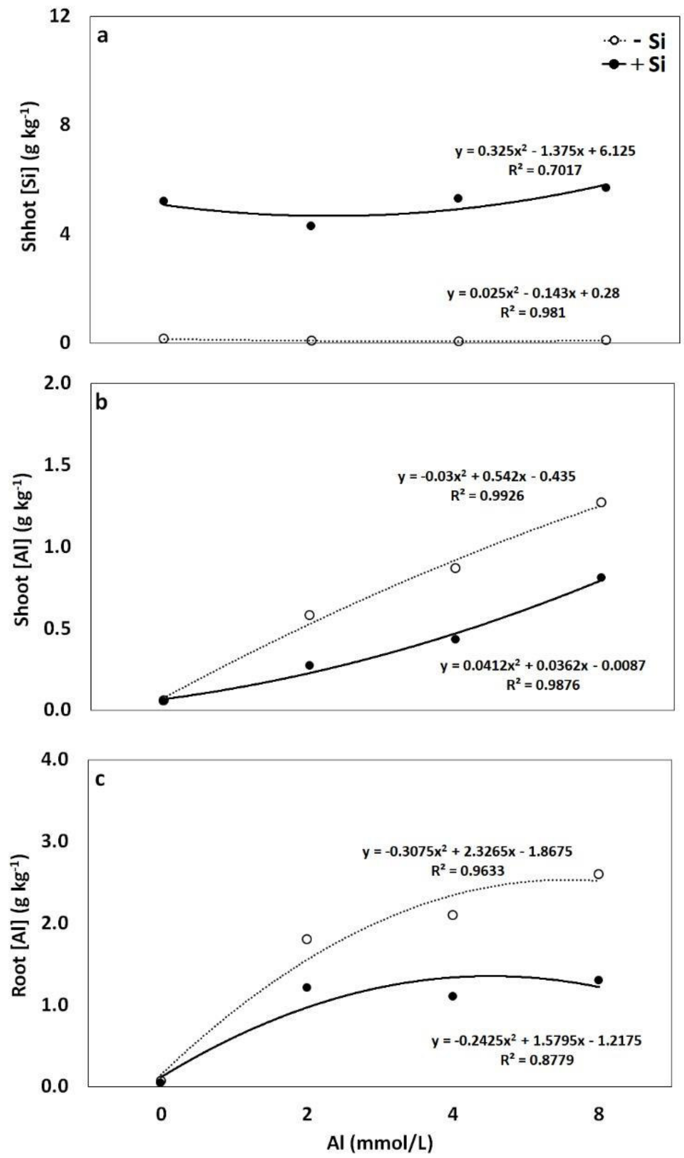

Figure 4. Accumulation of silicon (Si) in the shoot (a), accumulation of aluminum (Al) in the shoot (b) and roots (c) of plants of *Urochloa brizantha* cv. BRS Piatã cultivated in nutrient solution with doses of Al and Si foliar. Control plants received neither Al nor Si.

DISCUSSION

Most Brazilian soils, especially those located in the Cerrado, are acidic, which causes Al solubilization (Buol, 2009; Bueno et al., 2013). The available Al, in its toxic form of $[Al(H_2O)_6]^{3+}$, can be absorbed by plants, causing numerous negative impacts on their morphology and physiology (Yadav et al., 2021). In fact, absorbed Al causes disruption of cellular components such as cell wall, plasma membrane and cytoskeleton (Vance et al., 2021). In this way, cellular collapse negatively impacts the physiological metabolism of the plant, reducing ion absorption, increasing oxidative stress and altering photosynthetic activity (Fan et al., 2022). Finally, these effects result in lower vegetative growth and lower crop productivity.

In fact, in this work we observed a severe reduction in the growth parameters of both the shoot and the root system of *U. brizantha* plants exposed to different Al concentrations (Figures 1 and 2). For example, shoot dry mass showed a linear reduction in response to increasing Al concentration in the nutrient solution (Figure 1c). On the other hand, the dry mass of roots and the relationship between roots and shoots showed a reduction only in the highest concentration of Al (8 mmol L^{-1}) (Figure 1d). Indeed, several studies have reported that low doses of Al can stimulate root growth (Lenoble et al., 1996; Clune and Copeland, 1999; Sun et al., 2020). For example, canola plants (*Brassica napus* var. *napus* L.) showed greater root growth with 40 µM Al in the nutrient solution and strong root growth inhibition from 60 µM Al (Clune and Copeland, 1999). The authors hypothesized that the complex dynamics of Al in the nutrient solution may have increased the bioavailability of some ions and thus stimulated root growth. In some cases, such as for tea plants, Al is even essential for root emergence and growth (Sun et al., 2020).

In turn, Si is widely known as a beneficial element capable of mitigating several stressful conditions of both biotic and abiotic nature (Mostofa et al., 2021). As for Al stress, Si has been shown to be effective in minimizing the negative effects of Al toxicity. Indeed, the application of foliar Si on the leaves of *U. brizantha* induced recovery of at least part of the vegetative growth of the plants (Figures 1 and 2). For example, we observed more expressive results for shoot fresh and dry mass and plant height that increased at the level of 20, 30 and 33% with Si application, even at the highest Al concentration (Figures 1 and 2).

The improvement in growth by the application of Si is primarily associated with a reduction in the efficiency of Al binding to the cell wall by the formation of the Si-Al complex, which would result in lower absorption of this element by the plant (Rahman and Upadhyaya, 2021). In fact, plants treated with Si showed Si accumulation in the shoot and lower Al accumulation both in the shoot and in the root system (Figure 4). In addition, Si acts by activating antioxidant enzymes, especially superoxide dismutase (SOD), which leads to a reduction in the oxidative stress of plants exposed to Al (Vega et al., 2019; Rahman and Upadhyaya, 2021). *U. brizantha* plants showed a linear increase in electrolyte leakage with increasing Al concentration in the nutrient solution (Figure 3). On the other hand, when plants received Si, they exhibited a reduction in electrolyte leakage of the order of 33 and 11%, respectively, at the lowest (2 mmol L^{-1}) and highest (8 mmol L^{-1}) Al concentration (Figure 3).

CONCLUSION

Based on the data presented, we can conclude that Al, even at the lowest concentration used (2 mmol/L), is already sufficient to cause toxicity to *U. brizantha* plants. In addition, Si acts as an attenuator of Al stress, partially recovering plant growth, reducing both oxidative stress and Al accumulation in shoots and roots.

REFERENCES

ABREU JÚNIOR, C.H.; MURAOKA, T.; LAVORANTE, A. F. Relationship between acidity and chemical properties of Brazilians soils. **Scientia Agricola**, v.60, p.337-343, 2003. https://doi.org/10.1590/S0103-90162003000200019

ALTHAUS, D.; GIANELLO, C.; TEDESCO, M. J.; DA SILVA, K. J.; BISSANI, C. A.; FELISBERTO, R. Natural fertility and metals contents in soils of Rio Grande do Sul (Brazil). **Revista Brasileira de Ciências do Solo**, v.42, p.1-15, 2018. https://doi.org/10.1590/18069657rbcs201604182018

BUENO, M. L.; NEVES, D. R. M.; SOUZA, A. F.; OLIVEIRA JUNIOR, E.; DAMASCENO JUNIOR, G. A.; PONTARA, V.; LAURA, V. A.; RATTER, J. A. Influence of edaphic factors on the floristic composition of an area of cerradão in the Brazilian central-west. **Acta Botanica Brasileira**, v.27, p.445-455, 2013. https://doi.org/10.1590/S0102-33062013000200017

BUOL, S. W. Soils and agriculture in central-west and north Brazil. **Scientia Agricola**, v.66, p.697-707, 2009. https://doi.org/10.1590/S0103-90162009000500016

CHEN, J.; DUAN, R-X; HU, W-J.; ZHANG, N-N.; LIN, X-Y.; ZHANG, J-H.; ZHENG, H-L. Unravelling calcium-alleviated aluminium toxicity in *Arabidopsis thaliana*: Insights into regulatory mechanisms using proteomics. **Journal of Proteomics**, v.199, p.15-30, 2019. https://doi.org/10.1016/j.jprot.2019.02.013

CLARK, R.B. Characterization of phosphatase of intact maize roots. **Journal of Agricultural and Food Chemistry**, v.23, p.458-460, 1975. https://doi.org/10.1021/jf60199a002

CLUNE, T.S.; COPELAND, L. Effects of aluminium on canola roots. **Plant and Soil**, v.216, p.27-33, 1999. https://doi.org/10.1023/A:1004789014255

DIAS-FILHO, M. B. Diagnóstico das pastagens no Brasil. **Empresa Brasileira de Pesquisa Agropecuária**, 402, p.36, 2014. ISSN 1983-0513

EMBRAPA. **Soluções tecnológicas**. Embrapa, 2015. Available from: https://www.embrapa.br/busca-de-solucoes-tecnologicas/-/produto-servico/863/brachiaria-brizanthacv-marandu

FAN, J.; CHEN, K.; XU, J.; ABM, K.; CHEN, Y.; CHEN, L.; YAN, X. Physiological effects induced by aluminium and fluoride stress in tall fescue (*Festuca arundinacea* Schreb). **Ecotoxicology and Environmental Safety**, v.231, 2022, 113192. https://doi.org/10.1016/j.ecoenv.2022.113192

GUPTA, N.; GAURAV, S. S.; KUMAR, A. Molecular basis of aluminium toxicity in plants: a review. **American Journal of Plant Sciences**, v.4, p.21-37, 2013. https://doi.org/10.4236/ajps.2013.412A3004

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Censo da agropecuária**. Rio de Janeiro: IBGE, 2019.

JANK, L.; BARRIOS, S. C.; VALLE, C. B. do; SIMEÃO, R. M.; ALVES, G. F. The value of improved pastures to Brazilian beef production. **Crop and Pasture Science**, v.65, p.1132-1137, 2014. https://doi.org/10.1071/CP13319

KORNDÖRFER, G. H.; PEREIRA, H. S.; NOLLA, A. **Análise de silício: Solo, planta e fertilizante**. Uberlândia, Brazil: UFU, 2004.

LENOBLE, M. E., BLEVINS, D. G.; MILES, R. J. Prevention of aluminium toxicity with supplemental boron. II. Stimulation of root growth in an acidic, high-aluminium subsoil. **Plant, Cell and Environment**, v.19, p.1143-1148, 1996. https://doi.org/10.1111/j.1365-3040.1996.tb00429.x

MOREIRA, M. A. L.; FREITAS JUNIOR, M. de; TOLOI, R. C. O transporte rodoviário no brasil e suas deficiências. **Revista Fatec**, v.4, p.1-13, 2018. ISSN 2359-182X

MOSTOFA, M. G.; RAHMAN, M. M.; ANSARY, M. M. U.; KEYA, S. S.; ABDELRAHMAN, M.; MIAH, M. G.; TRAN, L-S. P. Silicon in mitigation of abiotic stress-induced oxidative damage in plants. **Critical Reviews in Biotechnology**, v.41, p.918-934, 2021. https://doi.org/10.1080/07388551.2021.1892582

PRADO, R. B.; BENITES, V. M.; POLIDORO, J. C.; GONÇALVES, C. E.; NAUMOV, A. Mapping soil fertility at different scales to support sustainable Brazilian agriculture. **International Journal of Biological, Biomolecular, Agricultural, Food and Biotechnological Engineering**, v.6, p.137-146, 2012. https://doi.org/10.5281/zenodo.1076684

Projeto MapBiomas – **Coleção 6 da Série Anual de Mapas de Cobertura e Uso de Solo do Brasil**. Available from: https://mapbiomas.org/estatisticas. Acessed on: September 22th, 2022.

RAHMAN, R.; UPADHYAYA, H. Aluminium toxicity and its tolerance in plant: a review. **Journal of Plant Biology**, v.64, p.101-121, 2021. https://doi.org/10.1007/s12374-020-09280-4

RANJAN, A.; SINHA, R.; BALA, M.; PAREEK, A.; SINGLA-PAREEK, S. L.; SINGH, A. K. Silicon-mediated abiotic and biotic stress mitigation in plants: Underlying mechanisms and potential for stress resilient agriculture. **Plant Physiology and Biochemistry**, v.163, p.15-25, 2021a. https://doi.org/10.1016/j.plaphy.2021.03.044

RANJAN, A.; SINHA, R.; LAL, S. K.; BISHI, S. K.; SINGH, A. K. Phytohormone signalling and cross-talk to alleviate aluminium toxicity in plants. **Plant Cell Reports**, v.40, p.1331-1343, 2021b. https://doi.org/10.1007/s00299-021-02724-2

SCHULTZE-KRAFT, R.; PETERS, M.; WENZL, P. A historical appraisal of the tropical forages collection conserved at CIAT. **Genetic Resources**, v.1, p.51-68, 2020. https://doi.org/10.46265/genresj.KZEW5023

SHETTY, R.; PRAKASH, N. B. Effect of different biochars on acid soil and growth parameters of rice plants under aluminium toxicity. **Scientific Reports**, v.10, 12249, 2020. https://doi.org/10.1038/s41598-020-69262-x

SILVA FILHO, A., MOUSQUER, C., CASTRO, W., SIQUEIRA, J., OLIVEIRA, V., MACHADO, R. Desenvolvimento de *Brachiaria brizantha* cv. marandu submetido a diferentes doses de ureia. **Revista Brasileira de Higiene e Sanidade Animal**, v.8, p.172-188, 2014. ISSN 1981-2965

SOUSA JUNIOR, G. S.; HURTADO, A. C.; SOUZA JUNIOR, J. P. de; PRADO, R. M.; DOS

SANTOS, D. M. M. Nutritional and structural role of silicon in attenuating aluminum toxicity in sugarcane plants. **Silicon**, v.14, p.5041-5055, 2022. https://doi.org/10.1007/s12633-021-01294-y

SUN, L.; ZHANG, M.; LIU, X.; MAO, Q.; SHI, C.; KOCHIAN, L.V.; LIAO, H. Aluminium is essential for root growth and development of tea plants (*Camellia sinensis*). **Journal of Integrative Plant Biology**, v.62, p.984-997, 2020. https://doi.org/10.1111/jipb.12942

VALE, F. X. R. do; FERNANDES-FILHO, E. I.; LIBERATO, J. R. Q. **A software plant disease severity assessment**. In: 8th International Congress of Plant Pathology. New Zealand. Anais, p. 105, 2003.

VANCE, W.; PRADEEP, K.; STRACHAN, S. R.; DIFFEY, S.; BELL, R. W. Novel sources of tolerance to aluminium toxicity in wild cicer (*Cicer reticulatum* and *Cicer echinospermum*) collections. **Frontiers in Plant Science**, v.12, 678211, 2021. https://doi.org/10.3389/fpls.2021.678211

VEGA, I.; NIKOLIC, M.; PONTIGO, S.; GODOY, K.; MORA, M. L. L.; CARTES, P. Silicon improves the production of high antioxidant or structural phenolic compounds in barley cultivars under aluminum stress. **Agronomy**, v.9, 388, 2019. https://doi.org/10.3390/agronomy9070388

WANG, C.; WOOD, F.A. A modified aluminon reagent for the determination of aluminum after HNO_3–H_2SO_4 digestion. **Canadian Journal of Soil Science**, v.53, p.237-239, 1973. https://doi.org/10.4141/cjss73-035

WANG, H.; JI, F.; ZHANG, Y.; HOU, J.; LIU, W.; HUANG, J.; LIANG, W. Interactions between hydrogen sulphide and nitric oxide regulate two soybean citrate transporters during the alleviation of aluminium toxicity. **Plant, Cell & Environment**, v.42, p.2340-2356, 2019. https://doi.org/10.1111/pce.13555

YADAV, V.; ARIF, N.; KOVAC, J.; SINGH, V. P.; TRIPATHI, D. K.; CHAUHAN, D. K.; VACULIK, M. Structural modifications of plant organs and tissues by metals and metalloids in the environment: A review. **Plant Physiology and Biochemistry**, v.159, p.100-112, 2021. https://doi.org/10.1016/j.plaphy.2020.11.047.

ZARGAR, S. M.; MAHAJAN, R.; BHAT, J. A.; NAZIR, M.; DESHMUKH, R. Role of silicon in plant stress tolerance: opportunities to achieve a sustainable cropping system. **3 Biotech**, v.9, n.73, 2019. https://doi.org/10.1007/s13205-019-1613-z