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Potassium silicate as an inducer of abiotic stress resistance in grain sorghum seeds[1]

Silicato de potássio como indutor de resistencia aos estresses abióticos em sementes de sorgo granífero

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ABSTRACT - Sorghum is an important crop that can absorb and accumulate abundant Si ranging, improving tissue tolerance to the water and salt stress and reducing sodium absorption. Thus, the objective was to verify the induction of resistance in germination and seedling growth of sorghum seeds to salt and water stress during germination due to treatment with silicon. Two experiments were carried out with seeds of two sorghum cultivars (EA03 and EA955) were solution of potassium silicate solutions at concentrations of 0, 0.3, 0.6, 0.9 and 1.2 g L^{-1}, in the first experiment and seeds were submitted to water stress using PEG 6000 (0, -0.2, -0.4, -0.6 and -0.8 MPa) in the second experiment were submitted to salt stress using NaCl (0, 75, 150 and 225 mM). Were analysed, germination, first germination count, shoot and root length, shoot to root ratio and seedling dry weight. The studied genotypes showed similar behavior when treated with potassium silicate. The presence of silicon in the treatment of seeds when exposed to salt stress has no effect on germination, but attenuates salinity damage related to seedling growth. Silicon attenuates the effects of water stress on sorghum seeds, by maintaining germination up to the potential of -0.6 Mpa, and providing better root development. However, the treatment with potassium silicate does not prevent the damage caused by high levels of water and salt stress, only attenuating its effects, thus, more studies are needed to better clarify the effects of Si on seeds.

Key words: *Sorghum bicolor.* Silicon. Water stress. Salt stress.

RESUMO - O sorgo é uma importante cultura que pode absorver e acumular Si em abundância, melhorando a tolerância do tecido aos estress hidríco e salino e reduzindo a absorção de sódio. Objetivou-se verificar a indução de resistência na germinação e no crescimento de mudas de sementes de sorgo ao sal e ao estresse hídrico durante a germinação devido ao tratamento com silício.Foram realizados dois experimentos com sementes de duas cultivares de sorgo (EA03 e EA955) em soluções de silicato de potássio na concentração de 0, 0,3 , 0,6, 0,9 e 1,2 g L^{-1}, no primeiro experimento e as sementes foram submetidas ao estresse hídrico utilizando PEG 6000 (0, -0,2, -0,4, -0,6 e -0,8 MPa) no segundo experimento foram submetidas ao estresse salino usando e NaCl (0, 75, 150 e 225 mM). Foram analisados a germinação, primeira contagem de germinação, comprimento da parte aérea e raiz, proporção parte aérea/raiz e massa seca de plântulas. Os genótipos estudados apresentaram comportamento semelhante quando tratados com silicato de potássio. A presença do silício no tratamento de sementes quando expostas ao estresse salino não tem efeito sobre a germinação, mas atenua a salinidade relacionada ao crescimento das mudas. O silício atenua os efeitos do estresse hídrico nas sementes de sorgo, mantendo a germinação até o potencial de -0,6 Mpa, e proporcionando melhor desenvolvimento radicular. No entanto, o tratamento com silicato de potássio não evita os danos causados pelos altos níveis de estresse hídrico e salino, apenas atenua seus efeitos, assim mais estudos são necessários para esclarecer melhor os efeitos do Si nas sementes.

Palavras-chave: *Sorghum bicolor.* Silício. Estresse hídrico. Estresse salino.

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INTRODUCTION

Water is essential for germination to occur, as it is directly or indirectly involved in all stages of germinative metabolism (MARCOS FILHO, 2015). Water stress at the start of imbibition can therefore to harm the sequence of germinative events in the seed during water absorption, leading to a delay and reduction in both the percentage and speed of germination (SARMENTO *et al.*, 2020).

In addition to water stress, salt stress also affects plants are mainly due to the osmotic and toxic effects of sodium (Na^+) and chloride (Cl^-) ions, reduced osmotic potential, and changes in nutrient uptake, leading slow down plant growth, mainly due to the energy expenditure required to absorb additional soil water and make biochemical adjustments (TAIZ *et al.*, 2017). In various species, germination and development are limited due to salt stress, leading to the need for morphological, anatomical, cellular, biochemical and molecular changes that vary with the species and the stage of plant development, in addition to varying with the type, duration and intensity of the stress (CHEN *et al.*, 2018).

One alternative for lessening the damage caused by water and salt stress is the use of attenuators such as silicon, since this element has several effects on plants, among them resistance to abiotic stresses (ROMA-ALMEIDA *et al.*, 2016). Most of the benefits of silicon are due to its being deposited on the cell wall beneath the leaf cuticle, in the form of amorphous silica ($SiO_2.nH_2O$) (FREITAS *et al.*, 2011), forming a cuticle-silica double layer that acts as a protective barrier, reducing water loss in the plant by evapotranspiration (RODRIGUES *et al.*, 2019). In their studies with Si nanoparticles as seed priming, Hussain *et al.* (2019) observed that Si stimulated the activity of antioxidant enzymes and reduced the concentration of ROS (reactive oxygen species), which positively impacted the growth of wheat plants.

Sorghum (*Sorghum bicolor* (L.) Moench) is a cereal which is cultivated around the world and which adapts to hot climates (PRAMONO *et al.*, 2018; VERMA *et al.*, 2017). Sorghum is an important crop that can absorb and accumulate abundant Si ranging from 2–3% dry weight in tissues, improving tissue tolerance and reducing Na^+ absorption (YIN *et al.*, 2016). Given the above, we work with the hypothesis that the silicon present in the potassium silicate when in contact with the seed will form a protective barrier, increasing the seed resistance to abiotic stresses. Thus, the objective was to verify the induction of resistance in germination and seedling growth of sorghum seeds to salt and water stress during germination due to treatment with silicon.

MATERIAL AND METHODS

The research was carried out at the Seed Analysis Laboratory of the Department of Plant Science at the Centre for Agricultural Sciences (CCA), Federal University of Ceara (UFC), Pici Campus, Fortaleza, Ceará.

Seeds from two untreated sorghum cultivars (EA03 and EA955) were obtained from the Centre for Agricultural Sciences (CCA) of the Federal University of Ceara (UFC) from the 2015 and 2017 harvests respectively. For the treatments with silicon, as a source, the foliar fertiliser, Sifol®, composed of potassium silicate (12% silicon - Si and 15% potassium - K_2O), was used, the seeds were soaked for two hours (definition based on base in the soaking curve) in a solution, at concentrations of 0 (Control), 0.3, 0.6, 0.9 and 1.2 g L^{-1} de silicon (doses defined based on preliminary tests).

The seeds were taken from the solution and any excess removed by drying on paper towels. The seeds then were placed in a forced air circulation oven at 40 °C to dry for three hours until they reached 12% humidity (ULLMANN *et al.*, 2015).

Two experiments were carried out where in the first to simulate salt stress NaCl solutions were used to four salinity levels of 0 (control), 75, 150 and 225 mM. In the second experiment to simulate water stress, PEG 6000 solutions with potentials of 0 (control), -0.2, -0.4, -0.6 and -0.8 MPa were used. The concentrations of the solutions udes were defined by preliminary tests (unpublished results).

For both experiments the seeds were then submitted to the following analyses: Germination - 200 seeds were used, divided into four replications, and sown on three sheets of paper towelling (Germitest®) moistened with distilled water (tratament 0) or a solution of PEG 6000 or NaCl in concentrations described above, in the proportion of 2.5 times the weight of the dry paper, and then placed in a Biochemical Oxygen Demand (BOD) germinator at a temperature of 25 ºC, with 12 light and 12 dark photoperiod, end evaluation to ten days after sowing; First germination count - performed in conjunction with the germination test, with the evaluation being carried out at 4 days after sowing.

Were also analysed the shoot and root length - carried out together with the test for germination, where 10 days after sowing, shoot and root length (mm) in ten normal seedlings was measured with the aid of a ruler graduated in millimetres. The mean length was obtained by summing the results of each replication and dividing by the number of normal seedlings under evaluation (KRZYZANOWSKI; VIEIRA; FRANÇA-NETO, 1999); Shoot to root ratio - carried out together with the shoot and root length, by dividing the mean shoot length by the mean length of the primary roots; Seedling dry weight - 10 seedlings from each replication were placed in paper bags and left for 48 hours in a forced air circulation oven at 65 °C to constant weight. The dry matter was weighed on a precision balance (0.001 g) and the result divided by the number of seedlings.

For both experiments, the experimental design used was completely randomized, with a double factorial 5 x 4 (five doses of silicon x four levels of salt stress) in the first experiment and 5 x 5 (five doses of silicon x five levels of water stress) in the second, with four replicates of 50 seeds each, for two batches of sorghum seeds. The data were submitted to analysis of variance at a level of 5% significance, using the Sisvar® statistical software. The choice of models was based on statistical significance (F-test) and adjustment of the coefficient of determination (R^2). The Sigmaplot v12.5 software was used to represent the results graphically. The equations were performed using MatLab software to better fit the studied models.

RESULTS AND DISCUSSION

In the (Table 1) shows the summary of the analysis of variance where it is possible to observe that in saline stress for the EA03 genotype only germination did not show any interaction between the factors, whereas for EA955 there was no interaction for germination and root length. For water stress, both EA03 and EA955 showed no interaction in first germination count and seedling dry weight.

For first count, there was a significant interaction between the silicon treatments and salt stress (Figures 1A and 1B), it can be seen that the EA03 genotype (Figure 1A) maintained the percentage of seedlings above 90.7% from the concentration of 0.6 g L^{-1} Si, even at the highest levels of stress, whereas in concentrations 0 and 0.3 g L^{-1} Si, presented a reduction in the percentage of seedlings for 89.8% and 84.8% respectively. According to Lima *et al.* (2011), sorghum is a silicon accumulator, and this accumulation may have led to a recovery of the FC value with the increase in silicon level, since silicon provides greater biological capacity for seeds, to withstand stress conditions (TUNES *et al.*, 2014).

The EA955 genotype (Figure 1B) the treatments with silicon maintained the percentage first count around 60% at the highest salt level of stress (225 mM), while the untreated seeds had percentages of 34.03%. Sorghum and Sunflower Plants have the effect of Si-minimized salinity, by reducing the permeability of plasma and lipid membranes and keeping these membranes active for integrity and functionality (HURTADO *et al.*, 2021).

Table 1 - Summary of analysis of variance, by mean squares (MS), for first germination count (FGC), germination (G), shoot length (SL), root length (RL), shoot to root ratio (SRR), seedling dry weight (SDW) in seeds of two cultivars of sorghum (EA03 and EA955) treated with Si and subjected to salt and water stress

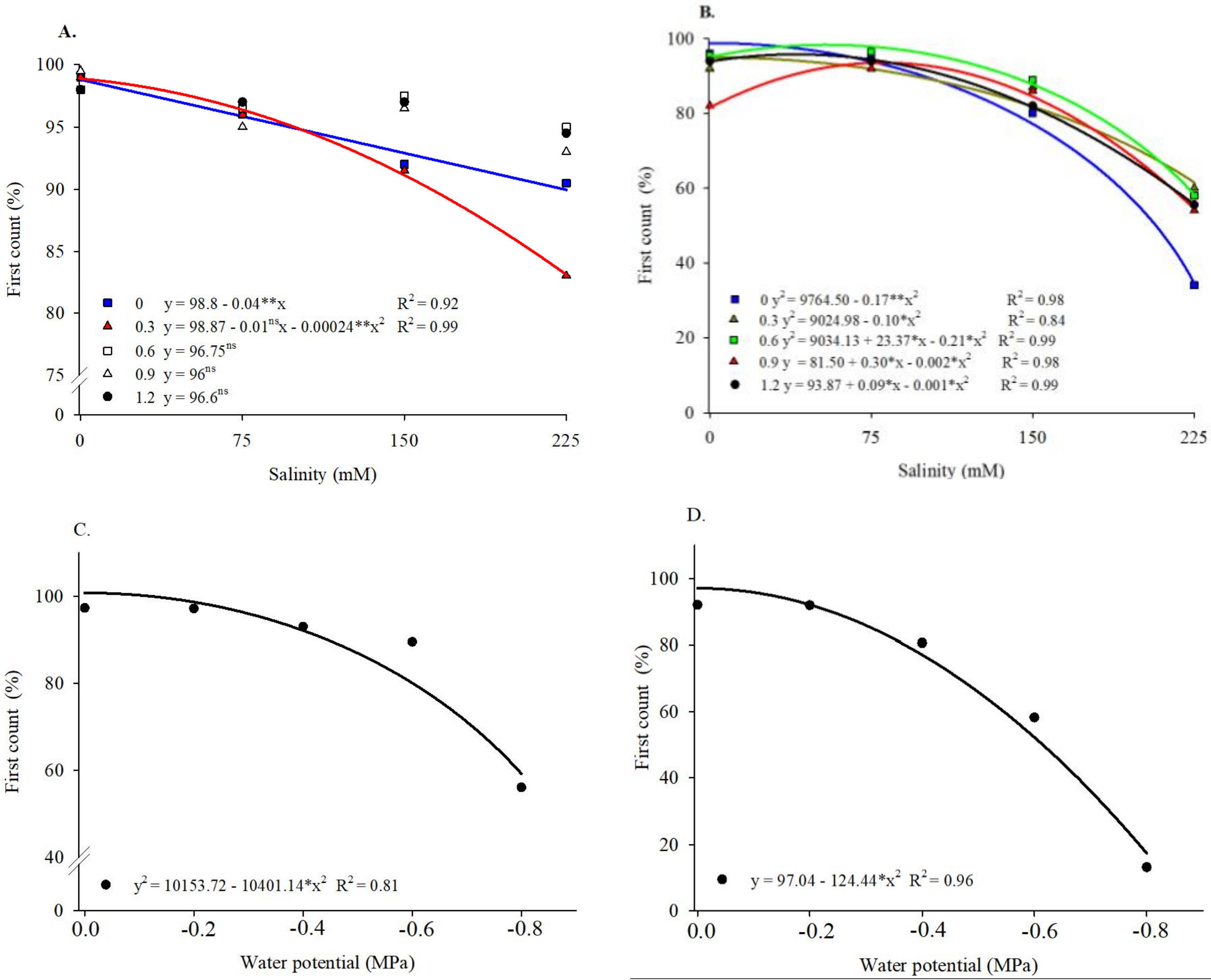
SALT STRESS							
SV	DF	MS					
		FGC	G	SL	RL	SRR	SDW
EA03							
STRESS	3	162.72**	15.92*	588.23**	476.84**	6.620**	147.33**
SI	4	54.92**	2.42^{ns}	3.37**	2.43^{ns}	8.15**	10.59**
STRESS*SI	12	34.26**	5.96^{ns}	2.88**	4.36**	8.19**	5.06**
Erro	60	12.62	4.55	0.58	1.48	0.89	0.86
CV (%)		3.73	2.19	7.21	8.40	93.01	8.87
EA955							
STRESS	3	7469.47**	2735.13**	599.41**	504.31**	0.41**	188.20**
SI	4	176.57**	69.92^{ns}	3.18**	10.62*	0.004^{ns}	4.59**
STRESS*SI	12	153.01**	35.92^{ns}	2.88**	3.28^{ns}	0.021*	6.16**
Erro	60	36.90	30.83	0.67	4.15	0.008	0.97
CV (%)		7.52	6.39	7.61	14.96	12.08	9.51
WATER STRESS							
SV	DF	MS					
		FGC	G	SL	RL	SRR	SDW
EA03							
STRESS	4	6062.9**	2158.56**	497.35**	45.62**	1.33**	76.94*

Continuation Table 1

SI	4	39.4^{ns}	77.36^{ns}	0.30^{ns}	9.77*	0.008^{ns}	32.55*
STRESS*SI	16	33.67^{ns}	92.31*	3.39*	11.02**	0.02**	36.06^{ns}
Erro	75	69.55	42.29	1.81	2.73	0.009	36.54
CV (%)		9.63	7.11	13.14	9.70	16.20	56.18
EA955							
STRESS	4	22008.44**	8258.96**	578.62**	180.59**	1.4**	203.05**
SI	4	306.64**	363.86**	2.05^{ns}	8.56*	0.006^{ns}	22.95**
STRESS*SI	16	103.71^{ns}	207.86**	4.64**	16.37**	0.04**	1.34^{ns}
Erro	75	59.85	56.08	1.03	3.18	0.006	0.95
CV (%)		11.52	9.29	10.75	12.01	13.09	9.99

SV - Source of variation; CV - Coefficient of variation; ns, * and ** Not significant, significant at 0.05 and 0.01, respectively, by the F test

Figure 1 - First germination count in seeds of sorghum EA03 (A and C) and EA955 (B and D) treated with Si and subjected to salt and water stress



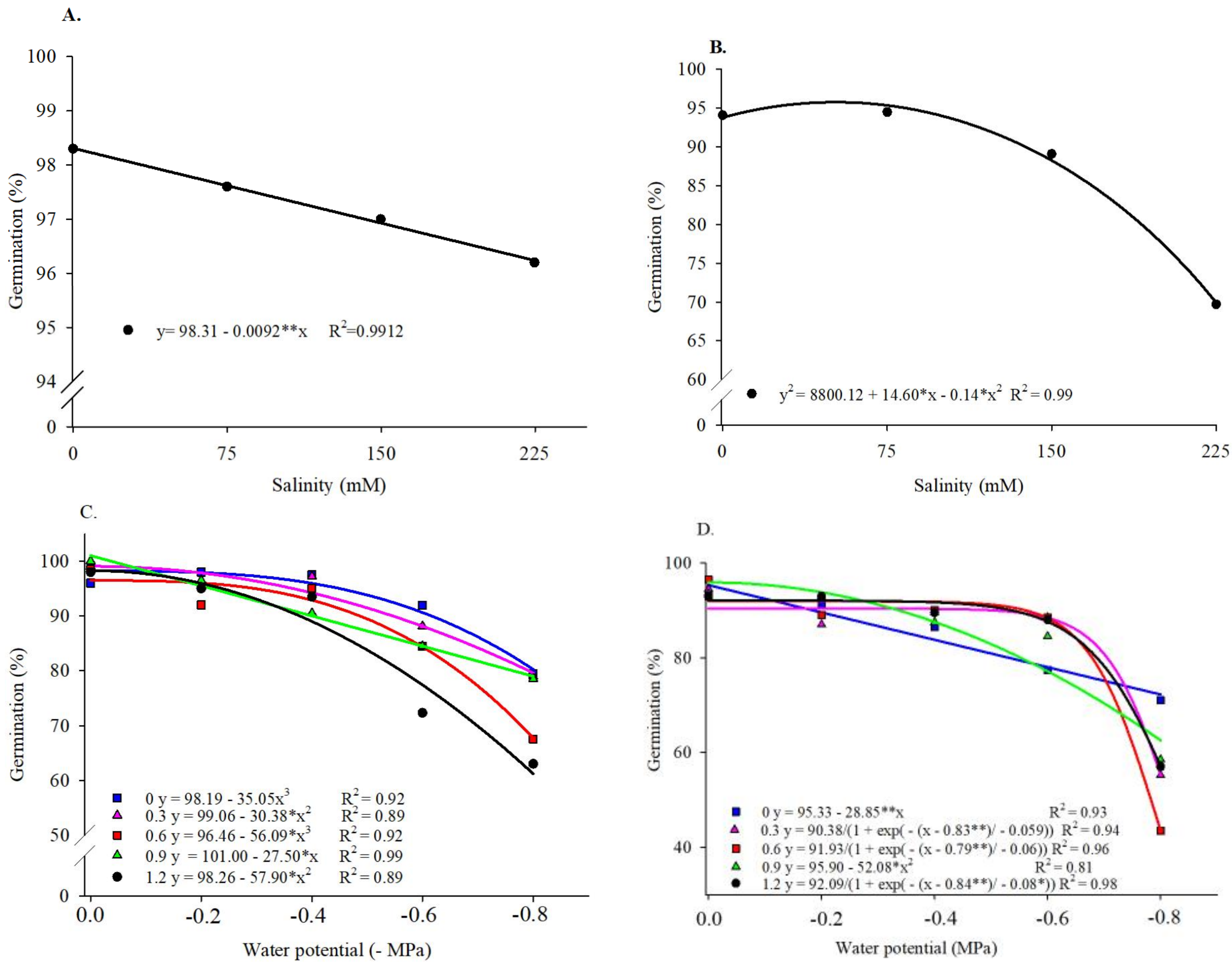
ns, * and ** Not significant, significant at 0.05 and 0.01, respectively, by the F test

When subjected to water stress, both genotypes showed a reduction in first germination count; in EA03 germination was close to 60.03% (Figure 1C), while in EA955 was from 17.39% (Figure 1D) in the less potential (-0.8 Mpa). Similar results were found by Pereira *et al*. (2012), with a reduction in the values for first germination count in seeds of *Urochloa decumbens* and *Urochloa ruziziensis* when subjected to water stress. This reduction may have been due to the prolongation of phase III, as described by Bewley and Black (1994); during this phase, the seed has a greater need for water, and PEG interferes with the viscosity of the water and solubility of the oxygen, which are necessary for germination (SARMENTO *et al*., 2020).

It was possible to see a reduction in germination in both genotypes with increasing salt concentrations, which for EA03 (Figure 2A) was around 2.06%, while for EA955 (Figure 2B), showed a greater reduction, with germination being below 73.42%. Coelho *et al.* (2014) point out that when certain levels of salinity do not affect germination, this may indicate a tolerance to salinityFrom this it can be inferred that EA03 has greater tolerance the salinity compared to EA955.

When subjected to water stress, the EA03 genotype (Figure 2C) maintained germination close to 90% up to the level of -0.4 MPa, whereas the EA955 genotype (Figure 2D) at seed treated with silicon maintained germination in between 88.5% and 77.15% in the potential of -0.6 MPa, with the untreated seeds at the same concentration having 78.02%. This behaviour may be due to a better response from the EA955 genotype to silicon accumulation compared to the EA03 genotype, since the greater the Si accumulation, the easier it is to verify the benefits it can bring, as the highest tolerance to salt stress (MIGLIORINI *et al.*, 2021).

Figure 2 - Seed germination in sorghum EA03 (A and C) and EA955 (B and D) treated with Si and subjected to salt and water stress



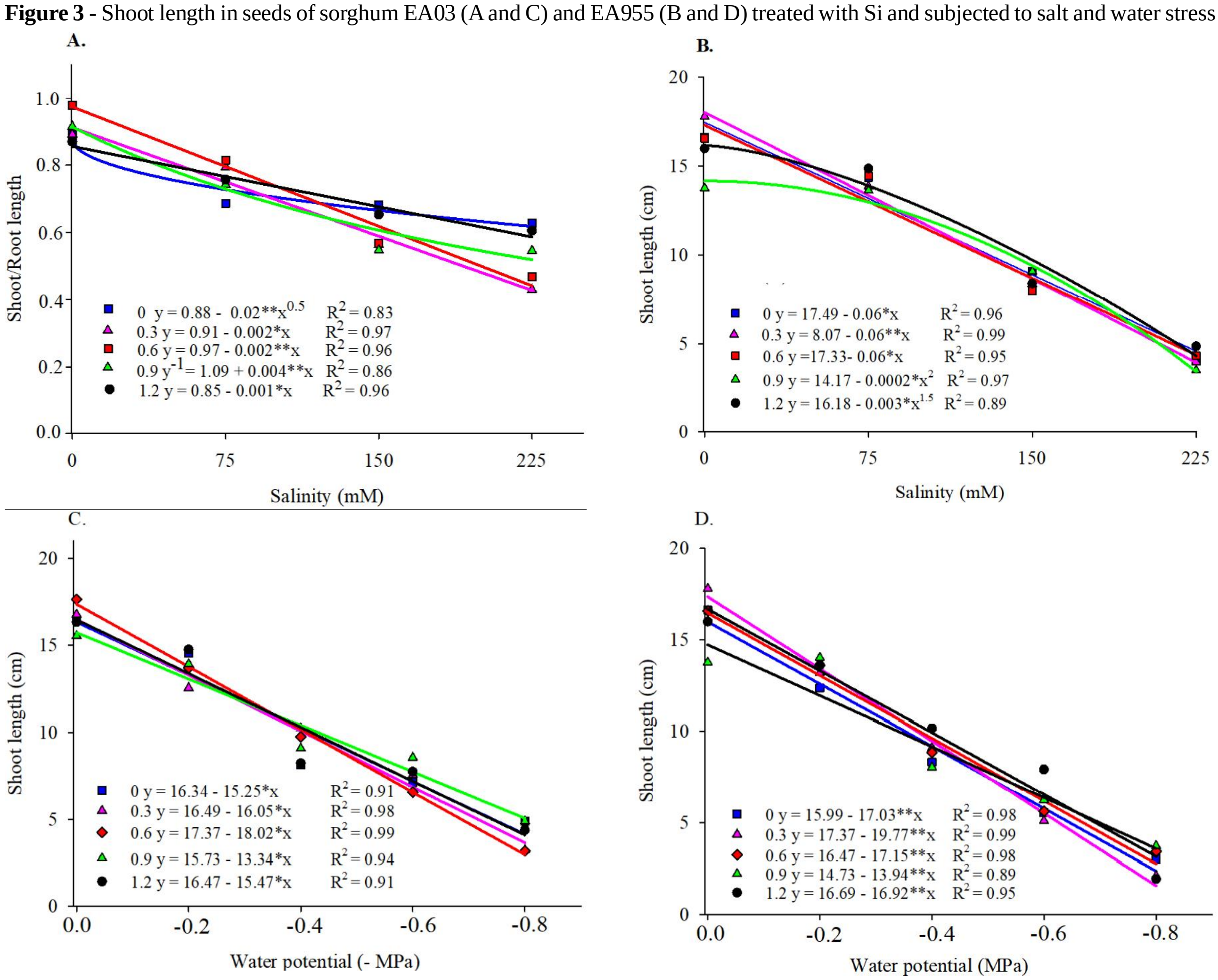
* and ** Not significant, significant at 0.05 and 0.01, respectively, by the F test

For the variable, shoot length, there was interaction between treatments for both genotypes when subjected to both types of stress (Figure 3). There was a reduction in shoot length when subjected to salt stress in both genotypes even in the presence of treatments with silicon, were in the concentration of 225 mM the EA03 (Figure 3A) reach in between 3.37 and 5.56 cm, and EA955 (Figure 3B) in between 4.04 and 6.05 cm, whether the seeds are treated or not, such a reduction may occur due to the osmotic effects caused by the presence of salt, since according to Taiz *et al.* (2017), the first measurable effect of a reduction in water potential is the smallest growth, due to a reduction in cell expansion.

Figures 3C (EA03) and 3D (EA955) show the effects of water stress, where there was a reduction in shoot length in both genotypes, which remained below 5 cm,showing that despite having a significant effect, the presence of silicon did not prevent damage caused by water stress. This reduction may occur due to the water stress transmitted by the low water potential of the solutions used, this effect is described by Sonobe *et al*. (2011) in his studies with water stress in sorghum seeds, one of the effects being the reduction of water absorption and consequently lower cell expansion due to low cell turgor.

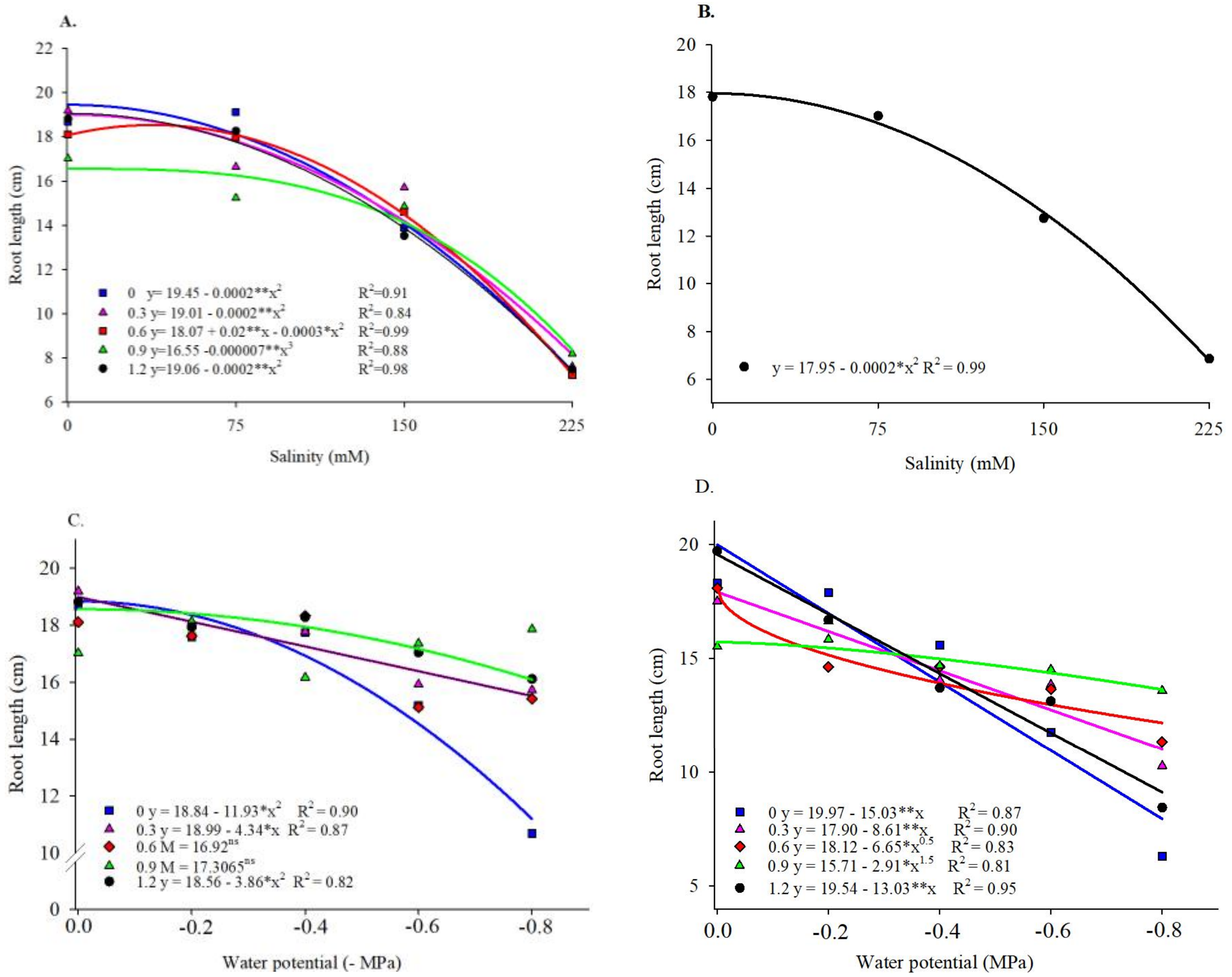
For the EA03 genotype at the highest level of salinity (225 mM), the concentration of 0.3 and 0.9 g L^{-1} of the Si presented the best values (8.88 and 8.86 cm), while at the other concentrations the values arrived to 7.38 cm. For EA955 with the increasing of salt concentacions the root lengthreduced from 18 to 7.82 cm; Thus, Si functioned as a mitigating factor for the EA03 genotype but did not present the same effect for the EA955 genotype, not preventing the damage caused by saline stress. Hurtado *et al.* (2021) in their studies observed that the benefits of silicon in sorghum plants, these benefits being due to Si decrease Na^+ absorption and increase nutrient absorption and use efficiency, favoring root production.

Figure 3 - Shoot length in seeds of sorghum EA03 (A and C) and EA955 (B and D) treated with Si and subjected to salt and water stress



* and ** Not significant, significant at 0.05 and 0.01, respectively, by the F test

Figure 4 - Root length in seeds of sorghum EA03 (A and C) and EA955 (B and D) treated with Si and subjected to salt and water stress



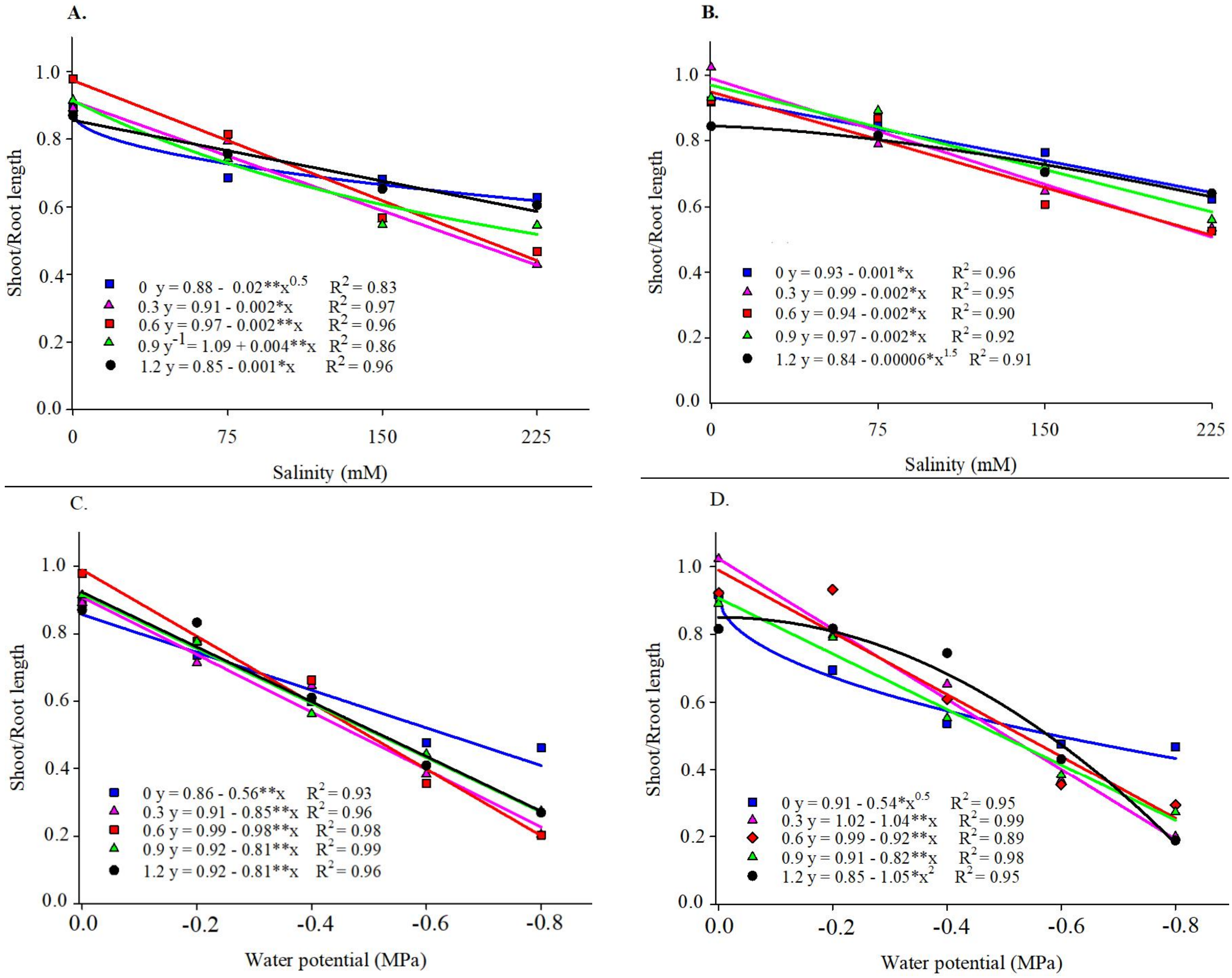
ns, * and ** Not significant, significant at 0.05 and 0.01, respectively, by the F test

When subjected to water stress, the seeds of both genotypes showed a reduction in root length. In EA03 (Figure 4C) at the lowest water potential (-0.8 MPa), the treated seeds at all concentrations of silicon remained superior to those of treatment 0 (11.2 cm), and at a concentration of 0.9 g L^{-1} Si the roots achieved 18 cm. In the potential -0.8 Mpa the EA955 genotype (Figure 4D), apresented the root length close to 7.9 cm in the treatment 0, while in the treatment with 0.9 g L^{-1} Si it came close to 13.62 cm in the concentration of the -0.8 Mpa, thereby showing that the EA955 genotype may be more sensitive to water stress than the EA03 genotype. Avila *et al.* (2020) they also observed the positive effects of Si on sorghum plants, where it mitigated the effects of the water deficit, thus providing greater tolerance to drought.

There was a reduction in the shoot to root ratio with the increase in salt stress, where for EA03 (Figure 5A) the greatest reductions were seen at concentrations of 0.3 and 0.6 g L^{-1} Si with 0.41 and 0.43 respectively, whereas for EA955 (Figure 5B), the lowest values for this ratio are found at concentrations of 0.3 and 0.6 g L^{-1} Si with 0.47 and 0.51 respectively, these reductions in the shoot to root ratio may indicate that at these Si concentrations the seedlings were able to prioritise root growth to the detriment of shoot growth. This increase is explained by Taiz *et al.* (2017), where under water or saline stress conditions there is a greater reduction in the size of the shoot and a greater number of assimilated can be allocated for root growth.

Just as for salt stress, water stress (Figures 5C and 5D) also led to a reduction in the shoot to root ratio, where for the EA03 genotype (Figure 5C) the greatest reduction in the ratio (0.2) was seen at a concentration of 0.6 g L^{-1} Si, with the genotype EA955 (Figure 5D) showing the greatest reduction at a concentration of 1.2 g L^{-1}. Similar results were found by Kappes *et al.* (2010) in maize seed

Figure 5 - Shoot to root ratio in seeds of sorghum EA03 (A and C) and EA955 (B and D) treated with Si and subjected to salt and water stress



* and ** Not significant, significant at 0.05 and 0.01, respectively, by the F test

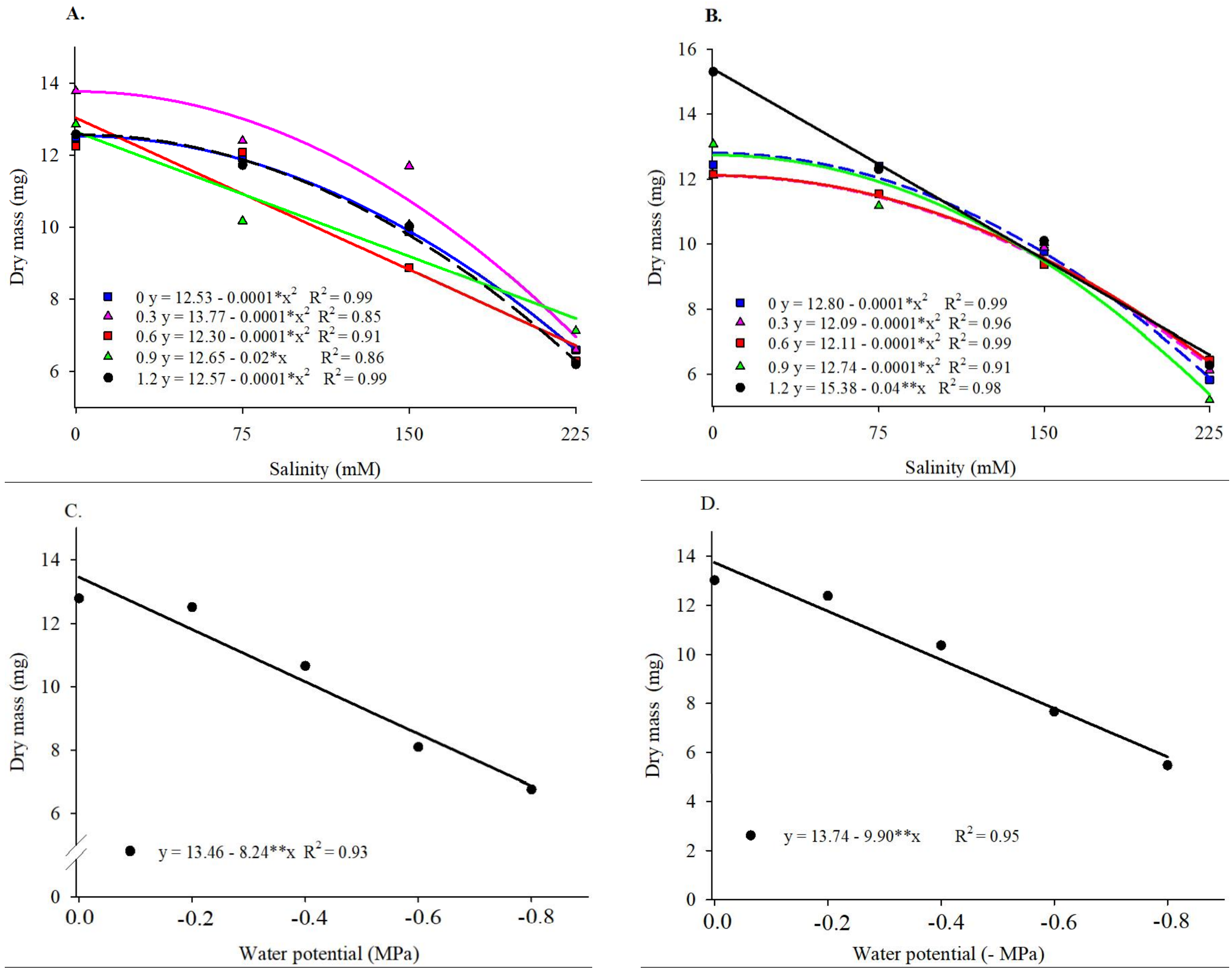
subjected to water stress, where they point out that root growth is closely linked to the that of the shoots, and that the shoot to root ratio is of great importance in determining productive potential.

A reduction can be seen in the variable, total dry weight, for both the EA03 genotype (Figure 6A) and for the EA955 genotype (Figure 6B), with EA03 showing the best values for dry weight at a concentration of 0.9 g L^{-1} Si (8.1mg) at the highest level of salinity (225 mM). Moraes *et al.* (2011) saw an increase in sugar cane dry weight, at a concentration of 40 g L^{-1} potassium silicate, this increase may have occurred due to silicon accumulation.

For EA955 at the same concentration saline (255 mM), the value for total dry weight in all the silicon treatments was around 7.6 mg, this reduction may reflect the reduced size of the seedling, as seen in previous variables. Korndörfer *et al.* (2010), also found no increase in dry weight in *Brachiaria brizantha* ‘Marandu’ or *Panicum maximum* ‘Mombasa’ at increasing concentrations of Si.

For water stress (Figures 6C and 6D), results similar to those for salt stress were found where there was also a reduction in dry weight, there was, however, no difference between the treatments with silicon, for both EA03 (Figure 6C) and EA955 (Figure 6D) showing a dry weight of around 6.8 and 5.8 mg respectively in concentration of the -0.8 Mpa. Sonobe *et al.* (2011) in their studies with Si in sorghum they also observed a reduction in root and shoot dry mass of sorghum plants subjected to water stress, however Si had a significant effect on the plantlets increasing dry mass.

Figure 6 - Dry weight in seedlings of sorghum EA03 (A and C) and EA955 (B and D) treated with Si and subjected to salt and water stress



* and ** Not significant, significant at 0.05 and 0.01, respectively, by the F test

CONCLUSIONS

1. The studied genotypes showed similar behavior when treated with potassium silicate. The presence of silicon in the treatment of seeds when exposed to salt stress has no effect on germination, but attenuates salinity damage related to seedling growth;
2. Silicon attenuates the effects of water stress on sorghum seeds, by maintaining germination up to the potential of -0.6 Mpa, and providing better root development;
3. However, the treatment with potassium silicate does not prevent the damage caused by high levels of salt and water stress, only attenuating its effects, thus, more studies are needed to better clarify the effects of Si on seeds.

REFERENCES

AVILA, R. G. *et al.* Silicon supplementation improves tolerance to water deficiency in sorghum plants by increasing root system growth and improving photosynthesis. **Silicon**, v. 12, p. 2545-2554, 2020.

BEWLEY, J. D.; BLACK, M. **Seeds**: physiology of development and germination. 2. ed. New York: Springer, 1994. 445 p.

CHEN, D. *et al.* How does silicon mediate plant water uptake and loss under water deficiency? **Frontiers In Plant Science**, v. 9, p. 1-7, 2018.

COELHO, D. S. *et al.* Germination and initial growth of varieties of forage sorghum under saline stress. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 18, n. 1, p. 25-30, 2014.

FREITAS, L. B. *et al.* Foliar fertilization with silicon in maize. **Revista Ceres**, v. 58, n. 2, p. 262-267, 2011.

HURTADO, A. C *et al.* Silicon alleviates sodium toxicity in sorghum and sunflower plants by enhancing ionic homeostasis in roots and shoots and increasing dry matter accumulation. **Silicon**, v. 13, p. 475-486, 2021.

HUSSAIN, A. *et al.* Seed priming with silicon nanoparticles improved the biomass and yield while reduced the oxidative stress and cadmium concentration in wheat grains. **Environmental Science and Pollution Research**, v. 26, p. 7579-7588, 2019.

KAPPES, C. *et al*. Germination, seed vigor and seedling growth of corn on hidric stress conditions. **Scientia Agraria**, v. 11, n. 2, p. 125-134, 2010.

KORNDÖRFER, P. H. *et al.* Effect of silicon fertilizer on forage grasses and soil chemical characteristics. **Pesquisa Agropecuária Tropical**, v. 40, n. 2, p. 119-125, 2010.

KRZYZANOWSKI, F. C.; VIEIRA, R. D.; FRANÇA-NETO, J. B. (ed.). **Vigor de sementes**: conceitos e testes. Brasília: ABRATES, 1999. 218 p.

LIMA, M. de A. *et al*. Aplicação de silício em milho e feijão-de-corda sob estresse salino. **Revista Ciência Agronômica**, v. 42, n. 2, p. 398-403, 2011.

MARCOS FILHO, J. **Fisiologia de sementes de plantas cultivadas**. 2. ed. Londrina: ABRATES, 2015. 660 p.

MIGLIORINI, P. *et al.* Quality of calcium and magnesium silicate coated *Phaseolus vulgaris* seeds. **Colloquium Agrariae**, v. 17, p. 56-65, 2021.

MORAES, W. B. *et al*. Application of potassium silicate and leaf growth of sugarcane. **Revista Brasileira de Ciências Agrárias**, v. 6, n. 1, p. 59-64, 2011.

PEREIRA, M. R. R. *et al.* Influência do estresse hídrico e salino na germinação de *Urochloa decumbens* e *Urochloa ruziziensis*. **Bioscience Journal**, v. 28, n. 4, p. 537-545, 2012.

PRAMONO, E. *et al.* Seed yield of various genotypes of sorghum (*Sorghum bicolor* L. Moench) harvested from intercropping with cassava (*Manihot utilisima* L.) compared to monoculture and ratoon. **Journal of Agricultural Science**, v. 1, p. 1-12, 2018.

RODRIGUES, L. A. *et al.* Coating seeds with silicon enhances the corn yield of the second crop. **Revista Caatinga**, v. 32, n. 4, p. 897-903, 2019.

ROMA-ALMEIDA, R. C. C. *et al*. Efeito da aplicação de silicato de cálcio e de cinza de casca de arroz sobre a incidência de fungos associados a manchas em sementes de arroz irrigado. **Summa Phytopathologica**, v. 42, n. 1, p. 73-78, 2016.

SARMENTO, E. C. S. *et al.* Physiological potential of sorghum seeds under discontinuous hydration and water deficiency conditions. **Revista Ciência Agronômica**, v. 51, n. 4, p. 1-11, 2020.

SONOBE, K. *et al.* Effect of silicon application on sorghum root response to water stress. **Journal of Plant Nutrition**, v. 34, p. 71-82, 2011.

TAIZ, L. *et al*. **Fisiologia vegetal**. 4. ed. Porto Alegre: Artmed, 2017. 819 p.

TUNES, L. V. M. *et al.* Qualidade fisiológica, sanitária e enzimática de sementes de arroz irrigado recobertas com silício. **Revista Ceres**, v. 61, n. 5, p. 675-685, 2014.

ULLMANN, R. *et al.* Physiological quality of sweet sorghum seeds dried under different conditions of air. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 19, n. 1, p. 64-69, 2015.

VERMA, R. *et al.* Characterization of sorghum germplasm for various qualitative traits. **Journal of Applied and Natural Science**, v. 9, p. 1002-1007, 2017.

YIN, L. *et al.* Silicon-mediated changes in polyamines participate in silicon-induced salt tolerance in *Sorghum bicolor* L. **Plant, Cell & Environment**, v. 39, p. 245-258, 2016.