Influence of silicon application on the growth of corn under conditions of water stress

Influência da aplicação de silício no crescimento do milho sob condições de estresse hídrico

Influencia de la aplicación de silicio en el crecimiento del maíz en condiciones de estrés hídrico

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ABSTRACT
The low availability of water in the soil is one of the precursors of stress in the plant, responsible for the decrease in growth and losses in crop productivity, by hindering the maintenance of essential metabolic processes. Many experimental results have demonstrated the effect of silicon (Si) as an attenuator of environmental stresses in plants. Thus, the objective of this research was to evaluate the growth of the corn crop subjected to water stress and the application of silicon in the semi-arid region of Alagoas. The experimental design used was in strips with four replications, schematized in subdivided plots. The culture was subjected to a combination of five water stress conditions (1, 4, 7, 10 and 13 days of intervals of irrigation) and two conditions of availability of Si (with and without Si). The following plant variables were analyzed: canopy height, stem diameter and leaf area index. It was found that the longer the irrigation interval, the lower the growth of plants. The application of Si provided higher rates of leaf area. The use of Si in plant fertilization in water deficit conditions is a viable alternative.

Keywords: Leaf Area Index, Irrigation Intervals, Silicate, Zea mays L.

RESUMO
A reduzida disponibilidade de água no solo é um dos precursores de estresse nas plantas, responsável pela diminuição do crescimento e de perdas na produtividade das mesmas, por dificultar a manutenção dos processos metabólicos essenciais. Muitos resultados experimentais têm demonstrado o efeito do silício (Si) como atenuador de estresses ambientais em plantas. Assim, objetivou-se com a presente pesquisa avaliar o crescimento da cultura do milho submetido ao estresse hídrico e à aplicação de silício no semiárido Alagoano. O delineamento experimental utilizado foi em faixas com quatro repetições, esquematizado em parcelas subdivididas. A cultura foi submetida a uma combinação de cinco condições de estresse hídrico (1, 4, 7, 10 e 13 dias de turno de rega) e duas condições de disponibilidade de Si (com e sem Si). Foram analisadas as seguintes variáveis da planta: altura do dossel, diâmetro do colmo e índice de área foliar. Constatou-se que quanto maior o intervalo de irrigação, menor foi o crescimento das plantas. A aplicação de Si proporcionou maiores índices de área foliar. O uso Si na fertilização de plantas em condições de déficit hídrico é uma alternativa viável.
Palavras-chave: Índice de Área Foliar, Turno de Rega, Silicato, Zea mays L.

RESUMEN
La reducida disponibilidad de agua en el suelo es uno de los precursores del estrés en la planta, responsable de la disminución del crecimiento y las pérdidas en la productividad de la misma, por dificultar el mantenimiento de los procesos metabólicos esenciales. Muchos resultados experimentales han demostrado el efecto del silicio (Si) como atenuador del estrés ambiental en las plantas. Así, se tuvo como objetivo con la presente investigación evaluar el crecimiento del cultivo del maíz sometido al estrés hídrico y a la aplicación de silicio en el semiárido Alagoano. El delineamiento experimental utilizado fue en bandas con cuatro repeticiones, esquematizado en parcelas subdivididas. El cultivo se sometió a una combinación de cinco condiciones de estrés hídrico (1, 4, 7, 10 y 13 días de turno de riego) y dos condiciones de disponibilidad de Si (con y sin Si). Se analizaron las siguientes variables de la planta: altura del dosel, diámetro del tallo y índice de área foliar. Se encontró que cuanto mayor era el intervalo de riego, menor era el crecimiento de las plantas. La aplicación de Si proporcionó mayores índices de área foliar. El uso de Si en la fertilización de plantas en condiciones de déficit hídrico es una alternativa viable.

Palabras clave: Índice de Área Foliar, Turno de Riego, Silicato, Zea mays L.

1 INTRODUCTION

The growth of the world's population and the consequent increase in demand for food is a recurring concern in the search for more productive and sustainable agricultural systems (Calicioglu et al., 2019). Water is a resource that determines and at the same time limits the development, and, consequently, the productivity of plants, since it constitutes the matrix and the environment where most of the biochemical processes essential to the life of plants occur (Lehninger, 2006).

One of the main causes of stress in plants is water availability (Araújo Júnior et al., 2019). Plants can suffer damage from both excess and lack of water, with water deficit being the most common cause of stress in crops. The water deficit is defined by the lack of water in the soil for the demand of the crop, which leads to the absorption of water and some nutrients by the root system of the plant to be reduced, causing damage (Campos et al., 2021).
Silicon (Si), physiologically, is not an essential element to plants, but it is a beneficial element for their growth and development, and the absorption, transport and accumulation of the element are indispensable to plants (Gaur et al., 2020). The element is actively absorbed and transported to plant organs such as leaf, stem and stem, which subsequently precipitates and is associated with the stiffening of the cell wall and then the benefits are achieved, such as greater resistance to biotic and abiotic factors, which usually cause physiological and yield losses (Cassel et al., 2021).

When the Si accumulates under the cuticle of the leaf, a double layer is formed that creates an extra barrier to prevent water loss, which can reduce transpiration and increase the structural reinforcements that alter the photosynthetic rate to increase the water use efficiency (Rea et al., 2022). The supply of Si contributes to maintaining the water content in the leaf tissue and reducing the damage caused by the water deficit, providing greater mass production (Teixeira et al., 2020).

The cultivation of corn in the region of the Semi-arid region of Alagoas is essential for subsistence agriculture, however, due to the irregularities of rainfall and the stress caused by the water deficit, the crop has low productivity in relation to the national average. Faced with scenarios of climate change, it is necessary to study and develop techniques and technologies aimed at the management of crops of socioeconomic importance and the availability of technological information for the irrigating producer to increase the water use efficiency.

Thus, the objective of this study was to evaluate the growth of the corn crop subjected to water stress and the application of silicon in the semi-arid region of Alagoas.

2 MATERIAL AND METHODS

The research was conducted in the experimental area of the Instituto Federal de Alagoas - Campus Piranhas. The climate classification of the region according to Köppen is of the BSh type, very hot climate, semi-arid, steppe type, with a rainy season centered in the months of March to July. The average annual rainfall in the region is 492 mm (Santos et al., 2017).
The experimental design used was in strips with four replications, schematized in subdivided plots. The plots were treated with five intervals of irrigation (TR of 1, 4, 7, 10 and 13 days) and the subplots treated with and without the application of water-soluble potassium silicate (7.3% of Si and 17% of K2O and density of 1.41 g cm\(^{-3}\)). The subplots in each block were composed of five rows of 6.0 m in length spaced at 0.70 m, and the useful area was composed of the central 3.0 m of the three middle lines.

Soil preparation was carried out with ploughing. The planting was carried out in manually open grooves, in which 2 seeds were placed every 0.3 m and 0.7 m of spacing between the planting lines. Feroz Viptera 3 hybrid corn seeds were used, with high productive potential and resistance to cartridge caterpillar and glyphosate. The roughing was carried out in phase 1 with the help of pruning shears, when the plants had the four definitive leaves, leaving a stand of 47,619 plants ha\(^{-1}\).

The fertilization was applied according to the recommendations of Cavalcanti et al. (2008) and Coelho (2006) considering a level of grain productivity of 10 t ha\(^{-1}\) and the chemical characteristics of the soil. Three applications of silicate fertilization via foliar were carried out, the first and the second application at a dose of 0.5 L ha\(^{-1}\), in phases V4 and V6 of the culture, and potassium silicate was used as a source. The third application was carried out in the culture laying phase (VT), in which the dose of 1 L ha\(^{-1}\) was applied, as recommended by the manufacturer.

The irrigation was carried out with dripping tapes. In the first 20 days all treatments were irrigated daily in order to keep the humidity close to field capacity (FC), from this period (21 DAP), the treatments with irrigation intervals were applied. The irrigation management was carried out by monitoring soil moisture through tensiometers installed in each subplot at depths of 20 and 40 cm, respecting the limit of water storage in the soil, as presented in the Table 1.
Table 1. Physical characterization attributes of the soil of the experimental area.

<table>
<thead>
<tr>
<th>Z</th>
<th>Ds</th>
<th>FC</th>
<th>WP</th>
<th>AWC</th>
<th>MW</th>
<th>Granulometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
<td>g cm⁻³</td>
<td>cm⁻³ cm⁻³</td>
<td>cm⁻³ cm⁻³</td>
<td>mm</td>
<td>mm</td>
<td>---</td>
</tr>
<tr>
<td>0 – 20</td>
<td>1.66</td>
<td>0.208</td>
<td>0.143</td>
<td>12.84</td>
<td>9.84</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>20 – 40</td>
<td>1.62</td>
<td>0.168</td>
<td>0.095</td>
<td>14.65</td>
<td>10.72</td>
<td>Loamy sand</td>
</tr>
</tbody>
</table>

Z = Soil depth; Ds = Soil density; FC = Field capacity; WP = Wilting point; AWC = Available water capacity and MW = Minimum water stored in the soil.

Throughout the growth and development of the crop, the following biometric variables were analyzed: leaf area index (LAI), canopy height and stem diameter, measured fortnightly from 30 days after planting (DAP). Five plants were marked in the useful area of the subplots, randomly chosen, for biometric analyses. The LAI was calculated by Equation 1:

\[
LAI = \frac{LA \times NP}{\varepsilon \times H}
\]

In which:

- LA - is the leaf area (m²);
- NP - is the number of plants in the counting line;
- \(\varepsilon\) - is the average spacing between lines (m); and
- H - is the length of the counting line of the plants (m).

The leaf area was determined by the equation \(LA = L \times W \times 0.75 \times (N+2)\), according to the methodology of Hermann and Câmara (1999), in which L is the length of the "leaf +3" (m); W is the width of the "leaf +3" (m); 0.75 is the shape correction factor of the corn leaves; and N is the number of photosynthetically active leaves.

The data obtained were submitted to analysis of variance by the F test (p<0.05 and p<0.01), and with significance in the qualitative factor, they were subjected to the comparison of means test, Tukey's test (p<0.05), and the quantitative factor was subjected to polynomial regression in the analysis of variance, decomposing the degrees of freedom into regression components. For this, the statistical program Sisvar version 5.8 was used (Ferreira, 2019). The model that best fitted the data was determined based on the following criteria: the highest value of the coefficient of determination (\(R^2\)); significance
of the parameters of fitting equation (p<0.05); non-significant effect of the regression deviation; and biological explanation of the evaluated treatments by each variable.

3 RESULTS AND DISCUSSIONS

According to the analysis of variance all growth variables showed a significant difference for the water stress factor (intervals of irrigation), at the level of 1% probability by the Fisher test (Table 2). For the silicon variation factor (application or non-application), there was a significant difference only for the variables stem diameter (SD) and leaf area index (LAI) at 5 and 1% probability, respectively. Regarding the interaction of these factors, only the canopy height (CH) showed a significant difference.

Table 2. Summary of the analysis of variance for the variables of canopy height (CH), stem diameter (SD) and leaf area index (LAI) as a function of the factors water stress (intervals of irrigation - TR), silicon (with and without application) and age (days after planting) in the crop of corn grown in the semi-arid region of Alagoas.

<table>
<thead>
<tr>
<th>SV</th>
<th>DF</th>
<th>CH</th>
<th>SD</th>
<th>LAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block</td>
<td>3</td>
<td>1.03**</td>
<td>50.25ns</td>
<td>1.76**</td>
</tr>
<tr>
<td>Water Stress (W)</td>
<td>4</td>
<td>7.41**</td>
<td>248.12**</td>
<td>14.13**</td>
</tr>
<tr>
<td>Silicon (S)</td>
<td>1</td>
<td>0.01ns</td>
<td>49.50*</td>
<td>1.28**</td>
</tr>
<tr>
<td>Age (A)</td>
<td>7</td>
<td>7.02**</td>
<td>162.87**</td>
<td>58.90**</td>
</tr>
<tr>
<td>W x S</td>
<td>4</td>
<td>0.32**</td>
<td>4.30ns</td>
<td>0.07ns</td>
</tr>
<tr>
<td>W x A</td>
<td>28</td>
<td>0.09**</td>
<td>14.47**</td>
<td>0.11**</td>
</tr>
<tr>
<td>S x A</td>
<td>7</td>
<td>0.00ns</td>
<td>22.36ns</td>
<td>0.99ns</td>
</tr>
<tr>
<td>CV W (%)</td>
<td></td>
<td>15.45</td>
<td>17.85</td>
<td>26.01</td>
</tr>
<tr>
<td>CV S (%)</td>
<td></td>
<td>6.75</td>
<td>13.76</td>
<td>25.33</td>
</tr>
<tr>
<td>Média geral</td>
<td></td>
<td>1.9</td>
<td>23.8</td>
<td>1.36</td>
</tr>
</tbody>
</table>

SV: Source of variation; DF: Degrees of freedom; CV: Coefficient of variation; ns: not significant; ** and *: significant at 1 and 5%, respectively, by Fisher’s test.

Source: Authors

For the factor age of plants (A), the analysis of variance showed that there was a significant difference between the treatments applied for all growth variables evaluated
at 1% probability (Table 2), and that this factor showed significant interaction only with water stress, also at 1% probability on all growth variables.

A quadratic response is observed for the canopy height (CH) of the plants treated with the application of Si, in which the highest height (2.41 m) was obtained with 1 day of irrigation interval (Figure 1A). The plants treated without the application of Si showed a linear reduction in the CH as a function of the intervals of irrigation. It is observed that the maximum CH obtained by the plants without the application of Si was 1.97 m obtained with the application of 1 day irrigation interval and the lowest height was 1.19 m obtained with 13 days of irrigation intervals. The unfolding of intervals of irrigation within the application or not of silicon (Figure 1A) showed a significant difference for the application of silicon only in the treatment with 1 day of irrigation interval. For the other intervals of irrigation (4, 7, 10 and 13 days) there was no difference between the application or not of silicon in the plants.
Figure 1. Effect of the interaction of water stress factors (intervals of irrigation) and application of silicon on the height of the canopy (A) and isolated effect of these factors on the diameter of the stem (B) and the leaf area index (C) in the culture of corn grown in the semi-arid region of Alagoas.

The stem diameter (SD) showed a decreasing linear effect as the intervals of irrigation increased (Figure 1B). It is observed that the plants that received water daily had larger SD, with an average of 26.3 mm, while the plants that received water every 13 days had smaller SD with an average of 20.8 mm. This difference between the lowest and highest level of water stress is 79%. According to the average comparison test (Figure 1B), the plants treated with the application of silicon showed a higher average of SD.
compared to the plants treated without the application of the nutrient, with a difference of 0.78 mm.

The plants irrigated daily showed higher averages of LAI, compared to the plants of the other treatments, with an average of 1.9 (Figure 1C). This represents an increase of 140.5% in relation to the treatment of a higher level of water stress (13 days of irrigation intervals), which had an average of 0.79. The linear regression model indicates a 95% correlation between water stress levels and the LAI, indicating that the LAI depends on intervals of irrigation. According to Tukey's test, there was a significant difference at 5% probability between the averages of treatments with and without silicon for the LAI (Figure 2C). The LAI of the plants treated with the application of silicon was higher compared to the plants treated without the application of the element, with averages of 1.4 and 1.3, respectively.

Nilahyane et al. (2020) studying the performance of corn grown in a semi-arid region under conditions of water limitation, found that the water deficit negatively affected the growth of plants by decreasing the canopy height, and consequently, reducing the accumulation of biomass. Bukhari et al. (2021) observed a reduction in agronomic parameters in the wheat crop due to water stress, however, fertilization with Si showed a higher growth rate. On the other hand, Neri (2009) found that the application of silicon in corn cultivars did not affect the height of the plants.

The leaf area index determines the interception of light, being an important parameter in the evaluation of crop growth and yield. Soumya et al. (2020), studying the application of Si in rice cultivation, observed an increase in the leaf area index of plants in relation to plants without availability of the element. Badawy et al. (2021) observed that the application of Si increased the LAI in rice plants in conditions of environmental stress. The accumulation of Si in plant tissues provides better structure and architecture of plants, increasing contact with sunlight, which in turn, increases photosynthetic rates resulting in greater growth and production of biomass.

Silicon has shown a beneficial effect on plant growth and development (Ma and Yamaji, 2008). The increase in the height of corn plants may be linked to the greater
accumulation of dry matter, caused by the role that silicon plays in cellular metabolism, being responsible for the activation of important enzymes (Correa et al., 2005).

There is a logistical response for the CH of corn plants with a difference between the levels of water stress as a function of the days after planting (DAP) (Figure 2). Plants treated with water availability showed greater growth of CH compared to plants treated with water restriction. The maximum height of the plants treated with 1 day of irrigation interval was 2.53 m at 135 DAP. For this treatment, the exponential increase in the CH of the plants occurred up to 75 DAP, and subsequently, the tendency to stability is observed. Plants treated with the highest level of water deficit (13 days of irrigation interval) had a maximum height of 1.62 m at 135 DAP and a tendency to growth stability started at 60 DAP.

Figure 2. Effect of the interaction of the age of the plants (days after planting - DAP) and levels of water stress on the canopy height (CH) in the crop of corn grown in the semi-arid region of Alagoas (the levels of water stress E1, E2, E3, E4 and E5 correspond to the irrigation intervals of 1, 4, 7, 10 and 13 days, respectively).

SD showed a reduction as a function of water stress levels and DAP (Figure 3). According to the regression analysis, this reduction was linear for intervals of irrigation 1, 4 and 7 days, while for intervals of irrigation of 10 and 13 days, the response was
quadratic. The plants treated with the 1 day of irrigation interval had a higher SD at 30 DAP (29.66 mm), while the plants treated with the highest level of water stress (13 days of irrigation interval) had a maximum SD at 71.66 DAP (22.61 mm).

Figure 3. Effect of the interaction of the age of the plants (days after planting - DAP) and levels of water stress on the stem diameter (SD) in the culture of corn grown in the semi-arid region of Alagoas (the levels of water stress E1, E2, E3, E4 and E5 correspond to the irrigation intervals of 1, 4, 7, 10 and 13 days, respectively).

There is an exponential response for the LAI with a difference between the levels of water stress as a function of DAP (Figure 4), in which the increase in water restriction caused a reduction in the LAI of plants. The maximum LAI of the plants treated with 1 day of irrigation interval was 4.24 observed at 59 DAP, while for the plants treated with 13 days of irrigation interval the maximum LAI was 2.38, observed at 58 DAP.
Plant growth is strongly influenced by the interaction of the environment with the genetics of the species (Gardner et al., 2010). Therefore, the variation in the growth parameters of plants with the same genetic material indicates that environmental conditions have more strongly influenced the response on growth. Subaedah et al. (2021) studying the effect of harvest time on the growth of sweet corn varieties, observed a higher plant height at 75 DAP, with an average of 1.62 m. Yang et al. (2020) evaluating plant height and stem diameter in a semi-arid region, observed stable growth of sweet corn from 70 to 91 DAP, respectively.

This reduction in plant growth due to water deficit is observed due to interruption or delay of expansion and cell division, which causes a decrease in leaf and stem growth well before water stress becomes severe to the point of causing the stomata and a decrease in photosynthesis (Duarte, 2012; Fatima et al., 2019). Báez et al. (2020) observed that soybean plants subjected to severe water deficit presented lower heights, compared to plants treated without water deficit. Melo et al. (2018), studying corn genotypes subjected...
to water deficit, found lower plant height compared to genotypes grown in an environment without water deficit.

4 CONCLUSIONS

Water stress negatively affected canopy height, stem diameter and leaf area index in the corn crop.

Fertilization with silicon attenuated the deleterious effects of water stress on the diameter of the stem and on the leaf area index.

The use of silicon as a water stress mitigator is feasible, especially in semi-arid regions, where dry farming is practiced.
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