

Original Article

Use of *Trichoderma harzianum* on the performance of young *Inga laurina* (Sw.) Willd. (Fabaceae) plants in response to drought

Utilização de *Trichoderma harzianum* no desempenho de plantas jovens de *Inga laurina* (Sw.) Willd. (Fabaceae) em resposta à seca

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Abstract

Climate change is among the main causes of alterations in natural ecosystems, generating major impacts on native vegetation. Drought is considered one of the main threats to ecosystems under global climate change since it limits growth and the mobilization of carbohydrates, alters the photosynthetic rate, decreases productivity, and can cause higher rates of plant mortality. Studies have been using species of the fungus *Trichoderma* in the inoculation of plants under conditions of water stress, such as drought, however, its use in native tree plants is still scarce. Considering that *Inga laurina* (Sw.) Willd (Fabaceae) is a tree species found preferentially in humid or flooded regions and can be used in the recovery of degraded areas, the aim is to analyze the performance of young plants of *I. laurina*, inoculated and not inoculated with *Trichoderma harzianum* and kept in conditions of moderate drought and in pot capacity. After 21 days, we evaluated the length of the aerial part and root, the fresh and dry mass of the root, stem, and leaves, the number of leaves and the diameter of the collar, the total soluble carbohydrate content of the leaves and roots and the photosynthetic pigments in the leaves of the plants from each treatment. The results were statistically analyzed using the GraphPrim 8.0 statistical program. Plants kept in moderate drought, whether inoculated or not, showed no significant difference in terms of growth parameters. The chlorophyll *a*, chlorophyll *b*, total chlorophyll, and total carotenoid contents were lower in the plants under moderate drought as compared to the non-inoculated control plants, while the chlorophyll *a/b* ratio was higher in the inoculated plants. The content of total soluble carbohydrates was higher in the leaves of plants kept in moderate drought, with no significant difference observed in the roots of plants kept in the different treatments. When comparing leaves and roots for each treatment, there was a higher total soluble carbohydrate content in the roots, regardless of the treatment. Overall, there was a positive effect of *T. harzianum* in promoting growth and protecting *I. laurina*; the inoculated plants performed similarly to the plants in the control condition.

Keywords: growth, soluble carbohydrates, chlorophyll, carotenoids, wilt.

Resumo

As mudanças climáticas estão entre os principais causadores de alterações nos ecossistemas naturais, gerando grandes impactos na vegetação nativa. A seca é considerada uma das principais ameaças aos ecossistemas sob mudança climática global, pois limita o crescimento e da mobilização de carboidratos, altera a taxa fotossintética, diminui a produtividade e pode causar maior taxa de mortalidade das plantas. Estudos tem sido realizados utilizando espécies do fungo *Trichoderma* na inoculação de plantas mantidas em condições de estresse hídrico, como a seca, no entanto, o seu uso em plantas arbóreas nativas ainda é escasso. Considerando que *Inga laurina* (Sw.) Willd (Fabaceae) é uma espécie arbórea encontrada preferencialmente em regiões úmidas ou alagadas, podendo ser utilizada na recuperação de áreas degradadas, objetivou-se analisar o desempenho de plantas jovens de *I. laurina*, inoculadas e não inoculadas com *Trichoderma harzianum* e mantidas em condições de seca moderada e em capacidade de vaso. Ao final 21 dias avaliou-se o comprimento da parte aérea e da raiz, a massa fresca e seca da raiz, caule e folhas, o número de folhas e o diâmetro do coleto, o teor de carboidratos solúveis totais das folhas e raízes e dos pigmentos fotossintéticos das folhas das plantas de cada tratamento. Os resultados foram submetidos à análise estatística, através do programa estatístico GraphPrim 8.0. As plantas mantidas em seca moderada, seja inoculada ou não inoculada, não apresentaram diferença significativa quanto aos parâmetros de crescimento. Os teores de clorofila *a*, clorofila *b*, clorofila total e carotenoides totais foram inferiores nas plantas sob seca moderada quando comparadas às plantas controle não inoculadas, enquanto a razão clorofila *a/b* foi superior nas plantas inoculadas. O teor de carboidratos solúveis totais foi maior nas folhas de plantas mantidas em seca moderada, não se observando

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diferença significativa nas raízes das plantas mantidas nos diferentes tratamentos. Comparando folhas e raízes em cada tratamento, verificou-se maior teor de carboidratos solúveis totais nas raízes, independente do tratamento. No geral, houve ação positiva de *T. harzianum* na promoção do crescimento e proteção de *I. laurina*, no qual as plantas inoculadas apresentaram desempenho semelhante às plantas da condição controle.

Palavras-chave: crescimento, carboidratos solúveis, clorofila, carotenoides, murcha.

1. Introduction

Climate change is one of the main causes of alterations in natural ecosystems, impacting on native vegetation. Drought events due to a decrease in the amount and frequency of rainfall, deforestation, and global climate change, combined with high temperatures, generate major impacts on plant biodiversity, such as: growth limitation, changes in carbohydrate mobilization, changes in the photosynthetic rate, a drop in productivity, a higher mortality rate, among others (Zhang et al., 2004; Leite et al., 2022).

Drought is one of the main stress factors for plants in tropical forests (Leite et al., 2022) and is defined as the deficit of water available to plants, associated with reduced rainfall and increased evapotranspiration (Sarremejane et al., 2022), inducing morphophysiological changes in affected plants. Among the various defense mechanisms developed by plants are changes in stomatal regulation to maintain the difference between leaf water potential and soil potential during the drought period and prevent the loss of hydraulic function (Chen et al., 2010; Kumagai et al., 2015), through biochemical changes in the plant, which enable greater accumulation of osmotically active substances capable of regulating the amount of water in plant cells (Huang et al., 2023).

Stomatal changes caused by water stress, influenced by abscisic acid (ABA), directly interfere with the photosynthetic rate of plants, since stomatal closure to prevent water loss alters the rate of carbon dioxide uptake by the plant, which can cause a decrease in photosynthesis, reducing productivity, in addition to directly reflecting on carbon metabolism in plants subjected to drought (Kunjet et al., 2013; Duan et al., 2020). However, the accumulation and transport of non-structural carbohydrates between the different organs of the plant during water stress needs to be studied, as it still requires further clarification whether these carbohydrates are preferentially allocated to roots or aerial organs in response to drought (Huang et al., 2023).

The photosynthetic rate of plants is also influenced by the degradation of photosynthetic pigments caused by drought. Drought stress causes damage to photosystem complexes, reducing light capture efficiency and photosynthetic capacity, negatively affecting plant performance and survival (Leite et al., 2022).

As for the morphological changes shown by plants subjected to drought, the most noteworthy are lower shoot height, smaller stem diameter, fewer leaves, and lower dry mass, as well as an increase in total carbohydrate and proline content, as compared to plants kept at 100% pot capacity (Santos et al., 2022; Leite et al., 2022).

Tests with plants in soils inoculated with *Trichoderma* demonstrate the fungus's ability to promote significant

changes in the establishment and growth of plants under conditions of environmental stress (Kubiak et al., 2023). *Trichoderma* is a natural fungus and comprises more than 10,000 species, from the Hypocreaceae family that is part of the rhizosphere. It has conidiophores branched into spirals. The conidia are ellipsoidal to globose and green in color, with the presence of halos (Zhu and Zhuang, 2015; Zin and Badaluddin, 2020). This fungus is of economic importance and is used in agriculture as a biological control agent due to its antifungal power. In addition to combating phytopathogens, studies indicate that this genus has a fertilizing action and is capable of favoring the development of plants by increasing their growth, degrading toxic compounds (Zhdanova et al., 2000), altering the microbiota and rhizosphere and adsorbing nutrients in the soil (Zafra et al., 2015).

The interaction mechanism of the *Trichoderma* genus is complex and variable, depending on the species of fungus, the host plant involved and environmental factors. For this reason, several species of the genus are being described, with the most widely used species for the biofuel and agricultural industries being the strains *T. harzianum*, *T. atrovirida*, *T. viride*, *T. asperellum* and *T. virens*, among others (Pacheco-Trejo et al., 2022). Several studies have reported an improvement in the performance of cultivated plants and trees when inoculated with the *Trichoderma* fungus (Mahato et al., 2018; Kubiak et al., 2023). However, its use in seedlings of native tree species is still scarce.

One of the native plants that has been used in the process of soil recovery through reforestation is *Inga laurina* (Sw.) Willd., a tree species belonging to the Fabaceae family, endemic to South America and Central America and found preferably in humid or flooded regions. It is considered hygrophilous, occupying areas of riparian forest, riverbanks, and coastal regions (Garcia and Bonadeu, 2020). Because it has considerable qualities for increasing biodiversity due to the attraction of animals that feed on its fruit and because it is endemic to a large part of Brazil, it can be easily used in projects to recover degraded areas. However, like most native species, it requires favorable conditions for its development, and water availability can be a determining factor for its establishment (Carvalho and Nakagawa, 2012).

The aim of this study was to verify the performance of *I. laurina* seedlings, inoculated and not inoculated with *T. harzianum*, under conditions of moderate drought and pot capacity.

2. Methodology

2.1. Obtaining *I. laurina* plants

Fruits of *I. laurina* were collected in Porto Rico, in the state of Paraná, Latitude: -22.7723, Longitude: -53.2675

22° 46' 20" South, 53° 16' 3" West, a tropical climate region with a dry season, according to the Köppen-Geiger climate classification: Aw. The seeds were removed from the fruit and their sarcotesta removed manually. The seeds were then sown in Styrofoam trays containing sand and Fertilizare substrate in a 2:1 ratio to produce seedlings.

The young plants were transferred seven days after emergence to black plastic bags measuring 10 cm x 15 cm, containing the same substrate used for the seedlings' emergence. The plants remained in the greenhouse for 15 days, being watered daily for acclimatization.

2.2. Conducting the experiment

After the acclimatization period, the plants were separated and kept in four treatments: control (C), with plants irrigated daily; inoculated control (IC) with plants irrigated and with soil added with *Trichoderma harzianum*; moderate drought (D), with plants irrigated every ten days; and inoculated moderate drought (ID), with plants irrigated every ten days and with soil inoculated with *T. harzianum*. For the control treatment, the plants were watered daily, and the amount of water was established based on maintaining the pot capacity. Moderate drought was estimated considering the moment when the plants (at least 50%) showed wilted leaves, and the plants were then watered with 60 mL of water every 10 days.

For inoculation with the *Trichoderma* strain, the commercial product Tricodermil, which contains *Trichoderma harzianum*, was used. A 2 mL solution was added to the soil at a dilution of 1.5×10^{10} on the first day of the experiment and repeated on day 10.

The experiment was conducted for 21 days, and 124 plants were used, with 31 plants assigned to each treatment.

2.3. Growth analysis

After 21 days of treatment, 10 plants from each treatment were used to assess the growth variables: height, root length, collar diameter, number of leaves, fresh and dry mass of roots, stems, and leaves.

Root height and length were obtained using a ruler graduated in mm, while the diameter of the collar was obtained using a digital caliper and measured in mm. The number of leaves was counted manually using the fully expanded leaves. The fresh mass of each organ was measured using a precision scale, after which the leaves, stem, and root were placed in paper bags, separately for each plant and treatment, and kept for 48 hours in a drying oven at 60 °C to obtain the dry mass.

2.4. Quantification of photosynthetic pigments

To quantify the photosynthetic pigments (chlorophyll *a*, *b*, total chlorophyll, and carotenoids), fully expanded leaves from the second and/or third node were used, collected from four plants from each treatment. The leaves were collected at the same time, according to the methodology described by Carvalho et al. (2022). Extraction was carried out using 80% acetone and quantification using a spectrophotometer (Spectrophotometer Shimadzu UV – 1201) at 470, 645 and 663 nm (Lichtenthaler and Wellburn, 1983) and 647 nm (Lichtenthaler and Buschmann, 2001) and the results are

expressed in mg g^{-1} MF. Wavelengths 663, 645 e 647 nm were used to quantify chlorophyll *a* and *b* contents. The wavelength of 470 nm was used to quantify carotenoid content. Chlorophyll contents were estimated according to the methodology described by Arnon (1949).

2.5. Total soluble carbohydrate analysis

For the quantification of total soluble carbohydrates in the roots and leaves, 100mg samples of the dry mass of the roots and leaves were obtained and the carbohydrate extracted with heated 80% ethanol. After grinding, the solution was centrifuged at 3000 rpm for 5 minutes. The supernatant was collected and transferred to beakers, and 2.5 mL of heated 80% ethanol was added to the residue, resuspended, and centrifuged for 5 minutes at 3000 rpm. This procedure was repeated 3 times and then the volume of the supernatant in the cylinder was adjusted to 25 mL with 80% ethanol, constituting the first carbohydrate extract for this analysis. From this extract, 5 mL was removed for evaporation and 3 mL of distilled water was added to the residue to obtain the aqueous extract. The total soluble carbohydrate content was determined from the reaction with anthrone (Clegg, 1956), and the concentration of total soluble carbohydrates was obtained from the standard curve and readings in a spectrophotometer at 620 nm. For the leaves, the alcoholic extract was depigmented using chloroform and then the procedures described above were carried out to obtain the aqueous extract.

2.6. Statistical analysis

The results obtained from the analysis of growth and physiological variables were subjected to prior normality analysis (Shapiro-Wilk test). After meeting the assumptions of normality, the data was submitted to analysis of variance, followed by the Tukey test to determine the differences between the treatments and the control, with the data considered significant if it showed $p < 0.05$.

3. Results

3.1. Growth and development

Growth analyses carried out 21 days after the start of the experiment indicated that the plants have mechanisms for resisting water stress. The young *I. laurina* plants showed visible adjustments in their metabolism to adapt to the drought. As for the action of *T. harzianum* on growth, the treatments show, albeit discreetly, that the fungus has a favorable factor for plant growth, development, and maintenance.

The mortality rate was 18% in treatment C and 10% in treatment CI, while mortality was 38% in treatment S and 30% in treatment SI, highlighting the protective action of *T. harzianum*. In addition to the mortality and survival rates, Figure 1 shows the recovery of the plants after the second application of the fungus.

The *I. laurina* plants showed no significant differences in terms of growth variables, according to Table 1 and Figure 2.



Figure 1. Plant regrowth after the second application of the fungus in the treatments. A: Inoculated control; B: Inoculated water stress.

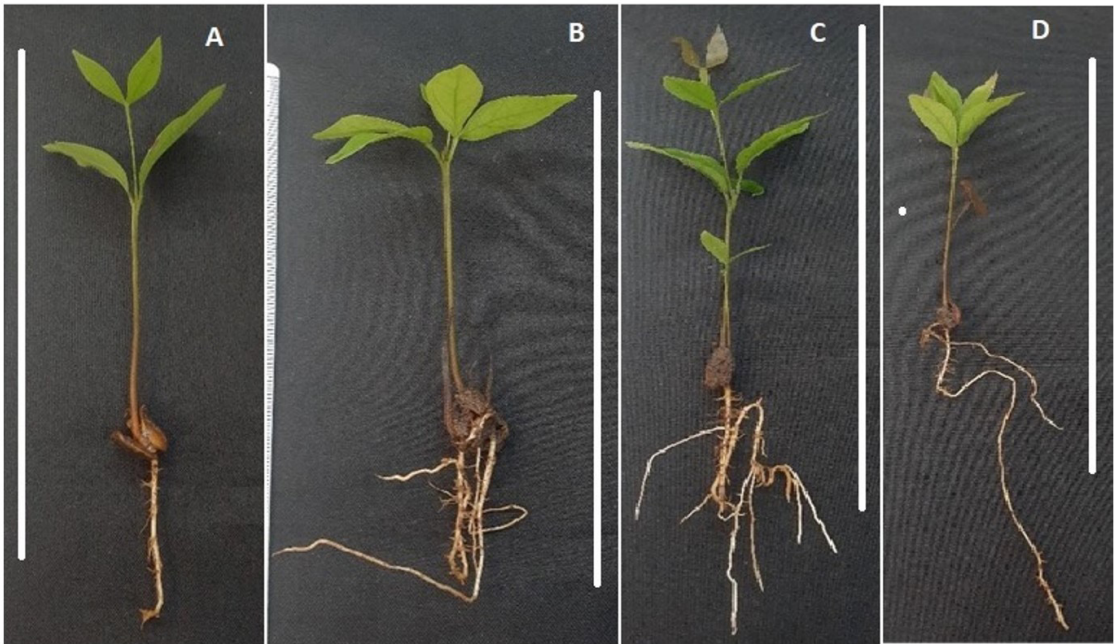


Figure 2. *Inga laurina* plants at the end of the experiments. A: Control; B: Stress; C: Inoculated control; D: stress inoculated.

Table 1. Growth parameters of young *Inga laurina* plants kept in the control, inoculated control, stress, and inoculated stress treatments.

Trat/Par	H (cm)	RL (cm)	NL	CD (mm)	TDM (g)	WC (%)
C	8.29±0.35a	10.19±1.25a	4.87±0.77a	0.36±0.02a	0.19±0.02a	71.46±3.15a
CI	8.24±0.72a	12.69±1.78a	6.25±0.41a	0.37±0.02a	0.22±0.03a	69.73±2.28a
S	7.71±0.55a	9.70±0.66a	4.87±0.55a	0.34±0.03a	0.21±0.02a	62.40±1.31a
SI	8.75±0.24a	9.72±0.79a	5.00±0.53a	0.40±0.03a	0.17±0.02a	62.29±2.90a
Média	8.25	10.57	5.25	0.37	0.20	66.98
p	0.7193	0.2619	0.2834	0.3318	0.5263	0.3799

Mean ± standard error; H (height); RL (root length); NL (number of leaves); CD (collar diameter); TDM (total dry mass); WC (water content).

3.2. Analysis of chlorophyll *a*, *b*, total, and carotenoid content

I. laurina plants from the Control treatment had higher chlorophyll *b*, total chlorophyll, and total carotenoid contents, as shown in Figure 3. Plants kept in the Control and Inoculated Control treatments did not differ in terms of chlorophyll *a*, chlorophyll *a/b* ratio and total chlorophyll/carotenoid ratio (Figure 3A, 3C, 3E). There was also no significant difference in the ratio of chlorophyll *a/b* and the total chlorophyll/carotenoid ratio between plants from the Control inoculated treatment and the drought Inoculated treatment. Plants from the drought treatment

had lower total chlorophyll content compared to the control treatments (Figure 3D). Plants from the Control inoculated treatment did not differ from the drought Inoculated treatment in terms of total chlorophyll *a*, *b*, and carotenoids (Figure 3A, 3B and 3F).

3.3. Analysis of total soluble carbohydrates in roots and leaves

The results obtained from the carbohydrate analysis show that the plants kept in moderate drought without inoculation had a higher total soluble carbohydrate content (Figure 4 - A), while the leaves of the other treatments did not differ from

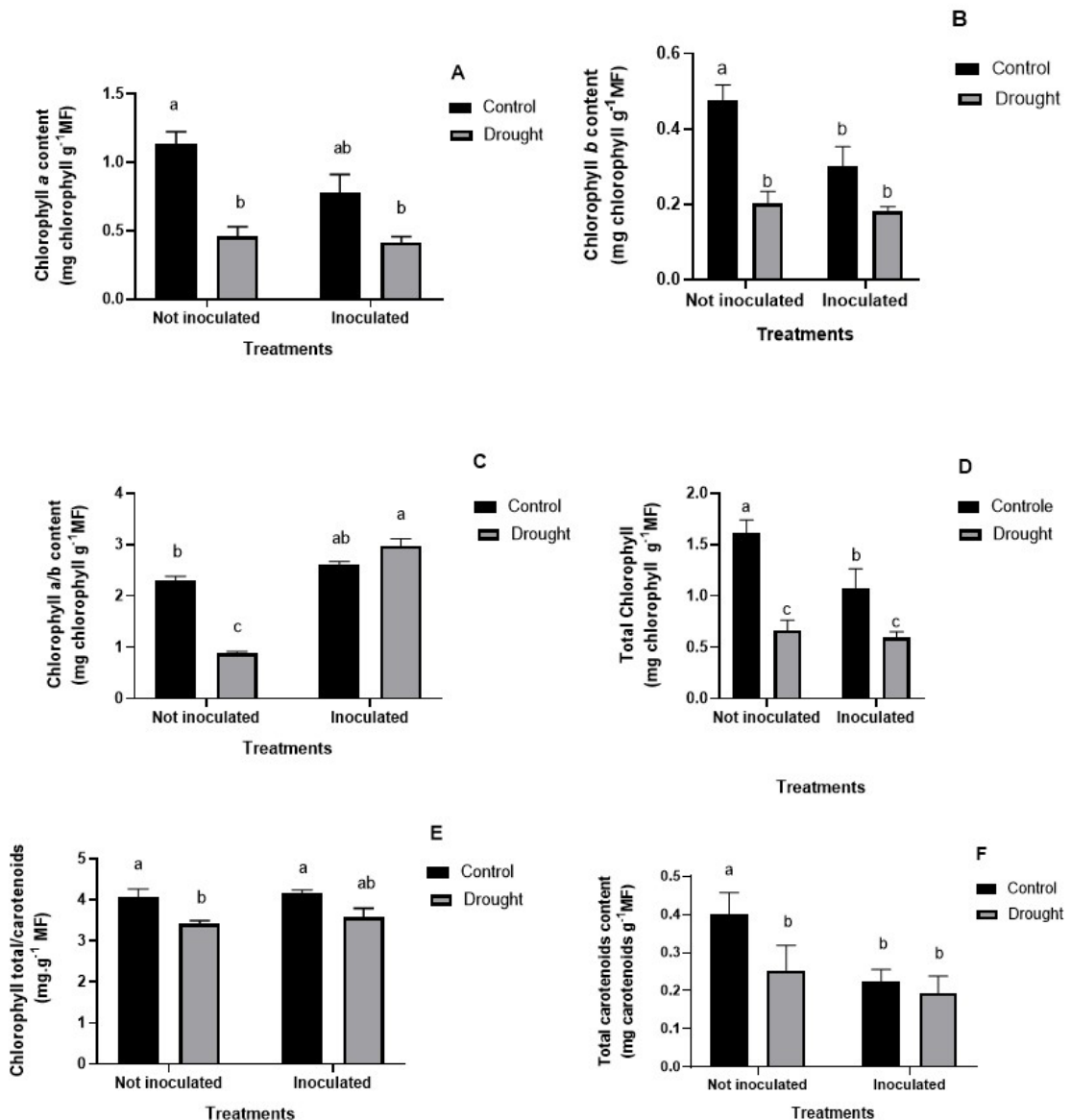


Figure 3. Chlorophyll *a* (A), chlorophyll *b* (B), chlorophyll *a/b* ratio (C), total chlorophyll content (D), total chlorophyll/carotenoid ratio (E), and total carotenoids (F) in *Inga laurina* (Sw.) Willd leaves, kept in treatments C, IC, D, and ID. Equal letters do not differ by Tukey's test ($p < 0.05$).

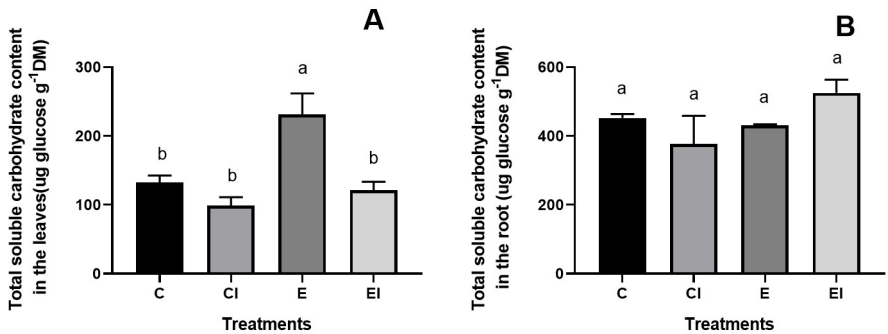


Figure 4. Total soluble carbohydrate content in the leaves (A) and roots (B) of *Inga laurina* (Sw.) Willd, kept in treatments C, IC, D, and ID. Equal letters do not differ by Tukey's test ($p < 0.05$).

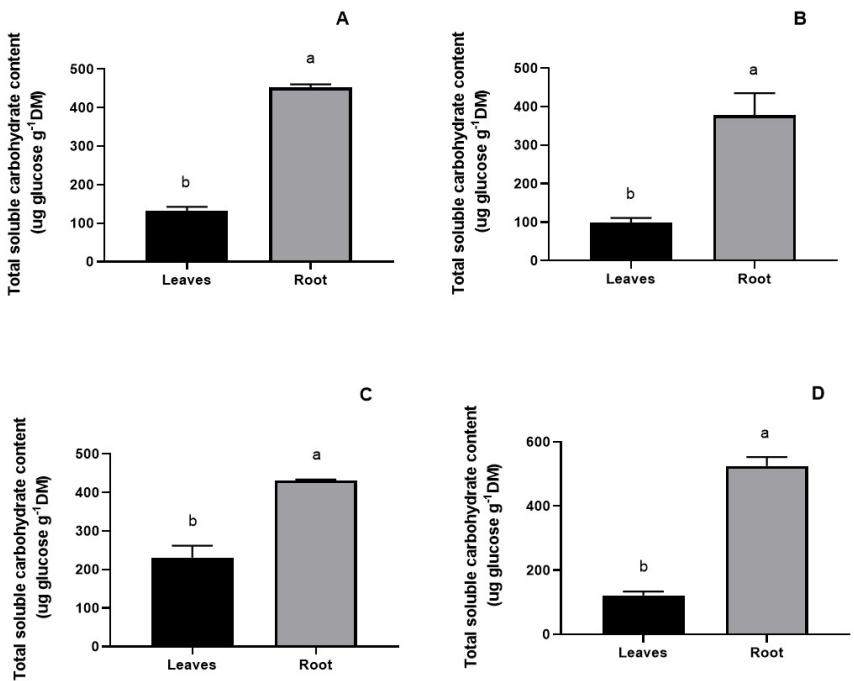


Figure 5. Total soluble carbohydrate content in the leaves and roots of *Inga laurina*, kept in treatments C (A), IC (B), D (C), and ID (D). Equal letters do not differ by the t-test ($p < 0.05$).

each other. The total soluble carbohydrate content in the roots did not differ between treatments (Figure 4 - B).

In all treatments, there was a greater accumulation of total soluble carbohydrates in the roots than in the leaves (Figure 5). However, the soluble carbohydrate content in the leaves was found to be increased as compared to the roots of plants kept in moderate drought (Figure 5C). However, the soluble carbohydrate content in the roots of plants in the control condition (non-inoculated and inoculated) was approximately 350% higher than in the

leaves (Figure 5 A and 5B), while the soluble carbohydrate content in the roots of plants under drought was 190% higher than in the leaves (Figure 5 C). In the stressed and inoculated plants, the soluble carbohydrate content in the roots was approximately 430% higher than in the leaves (Figure 5 D). In addition, the proportion of total soluble carbohydrate content obtained in the leaves of stressed plants was 1.75, 2, and 1.89 times higher than that found in the leaves of plants from the Control, Inoculated Control, and Inoculated Drought treatments, respectively.

4. Discussion

4.1. Growth

In recent years, there have been climatic events associated with water stress, such as periods of prolonged drought, which can influence plant tolerance to stress. Environmental variations can trigger different physiological responses (Pacheco-Trejo et al., 2022), including greater tolerance to water stress, which makes a plant more resistant to dry environments, ensuring greater plasticity over time to withstand water variations in the environment (Bello et al., 2022) and making it possible to occupy new locations with different climatic conditions (Garcia and Bonadeu, 2020). Perhaps for this reason, there was no significant difference in the growth variables of the *I. laurina* plants kept in the different treatments (Figure 2). In addition, when analyzing the interaction between plants and the fungus, the variation that exists in each plant and in the interaction of each individual with *T. harzianum* must be taken into account (De Palma et al., 2019).

The second application of *T. harzianum* in the IC and ID treatments 10 days after the start of the experiment made the protective and growth-promoting action in *I. laurina* evident, as the plants recovered more quickly from the water stress and it was also possible to see the presence of regrowth with the emergence of new leaves (Figure 1). Llorens et al. (2020) indicate that *T. harzianum* can also be used for biopriming in native species, inducing a faster response to drought when observing the more effective recovery process after the second application of the fungus (Pacheco-Trejo et al., 2022).

4.2. Photosynthetic pigments

In general, the plants kept in condition C had higher levels of chlorophyll *a*, chlorophyll *b*, total chlorophyll, and total carotenoids (Figure 3). However, analyzing the chlorophyll *a/b* ratio, the inoculated plants, whether IC or ID, showed a higher chlorophyll *a/b* ratio (Figure 3C) as compared to treatments C and D. The same was verified for the total chlorophyll/carotenoids ratio (Figure 3E). An increase in the chlorophyll *a/b* ratio reflects an increase in the ratio between the reaction center of photosystem II (PSII) and the amount of the light-harvesting complex of photosystem II (LHCII) (Zhen et al., 2019), which indicates an improvement in the rate of utilization of light energy (Liu et al. 2022) with the application of the inoculant. Thus, inoculation allowed a higher chlorophyll *b* content, thus avoiding the photooxidation of chlorophyll *a*. The reduction in chlorophyll content in drought-stressed plants indicates protection against photo-oxidative damage under conditions of water stress (Hung et al., 2020). This occurred in inoculated and non-inoculated plants under drought, reducing the chlorophyll *a* content (Fig. 3A).

4.3. Total soluble carbohydrates in roots and leaves

Plants in the D treatment had a higher total soluble carbohydrate content in the leaves compared to the other treatments (C, IC, and ID), which indicates an accumulation of osmotically active sugars due to the lower water availability of the substrate (Araújo and

Deminicis, 2009), providing a gradient of water potential in plants under water stress. However, the content of total soluble carbohydrates in the leaves of plants kept in the ID treatment did not differ from the content found in plants in the C and IC conditions (Figure 4A), indicating that inoculation with the *T. harzianum* fungus ensured that the plants performed similarly to the control even under drought conditions. In plants kept under conditions of water variation, the accumulation of soluble carbohydrates in the leaves occurs due to the impairment of phloem transport and, consequently, the transport of nutrients in the plant. There is also a reduction in the photosynthetic rate due to damage to photosystem II caused by drought, as well as a reduction in stomatal expansion, growth, and conductance (Araújo and Deminicis, 2009; Ferner et al., 2012).

The total soluble carbohydrate content in the roots did not differ across treatments. However, when comparing the soluble carbohydrate content found in the leaves and roots in each treatment, we observed that the roots had a higher soluble carbohydrate content in all treatments. Thus, the soluble carbohydrate content in the roots of plants under conditions C and IC was approximately 350% higher than that found in the leaves, while the soluble carbohydrate content obtained in the roots of plants under drought was 190% higher than that observed in the leaves. In the plants under the ID condition, such content was approximately 430% higher in the roots than in the leaves, indicating that inoculation with *T. harzianum* provided greater transport of photoassimilates from leaves to roots.

The mobilization and presence of carbohydrates are important for maintaining the plant's metabolic activities (Drew, 1997; Peng et al., 2018). In addition, it was found that the proportion of total soluble carbohydrate content present in the leaves of plants under stress is higher than that found in plants from the C, IC, and ID treatments, indicating that there was proportionally a greater accumulation of soluble carbohydrates in the leaves of plants under drought compared to the other treatments, which helps to reduce the water potential in the leaves, providing a gradient of water potential in the plant, which is important for increasing the efficiency of water absorption by the plant under conditions of water deficit. Huang et al. (2023) observed that soluble sugars are preferentially distributed in roots, especially fine roots, to maximize water absorption. However, the accumulation of osmotically active compounds, such as soluble sugars in the leaves, helps with drought tolerance (Nascimento et al., 2019). Camisón et al. (2020) related the reduction in starch content in the leaves of *Castanea sativa* Mill. to the higher content of soluble sugars in these leaves in response to water deficit. Thus, an increase in the soluble sugar content of leaves can contribute to drought resistance. In situations such as water stress, plants can alter their metabolism in response to the period of drought. To this end, tree species can mobilize compounds that alter their water potential, stomatal dynamics, organic solutes and the amount of photosynthetic pigments (Frosi et al., 2017), providing a greater capacity to acquire water and maintain water status and metabolic activities.

5. Conclusion

Morphological and biochemical analyses showed that *T. harzianum* had a positive effect on the performance of *I. laurina* under water stress, with a greater accumulation of total soluble carbohydrates and a higher chlorophyll *a/b* ratio. Thus, the addition of *T. harzianum* to *I. laurina* planting can ensure greater plant tolerance to environments with water variations, making the use of this native species in the recovery and reforestation of degraded areas more efficient, increasing biodiversity in different biomes.

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