

# PLANT STIMULANT AS A STRATEGY TO REDUCE THE IMPACTS OF THERMAL STRESS ON SOYBEAN CROPS<sup>1</sup>

## ESTIMULANTE VEGETAL COMO ESTRATÉGIA PARA REDUZIR OS IMPACTOS DO ESTRESSE TÉRMICO NA CULTURA DA SOJA

Kássia Silveira Crivellaro<sup>2</sup>, Raquel Stefanello<sup>3</sup>, Sylvio Henrique Bidel Dornelles<sup>4</sup>,  
Luciane Almeri Tabaldi<sup>5</sup>, Lucas Augusto da Silva Gírio<sup>6</sup>, Anderson Cesar Ramos Marques<sup>7</sup>,  
Antonio Carlos Ferreira da Silva<sup>8</sup> e Ubirajara Russi Nunes<sup>9</sup>

### ABSTRACT

Agriculture has been increasingly affected by climate change, which compromises soybean production, especially due to thermal stress, responsible for reducing plant growth and productivity. Given this, this study evaluated the efficiency of a plant stimulant, applied in different concentrations, in mitigating the effects of thermal stress during the reproductive phase of soybeans. The experiment was conducted in a completely randomized block design in a 4 × 2 factorial arrangement (four doses of stimulant × two shading conditions) with subdivided plots. Physiological, biochemical, and yield parameters were analyzed. The results indicated that the stimulant reduced leaf temperature by up to 3.09 °C under high temperatures, promoting an increase in photosynthetic pigments and increasing the activity of antioxidant enzymes. This effect contributed to an increase in yield components, even under different shading conditions. The study demonstrates the potential of these sustainable tools to increase soybean resilience to abiotic stress and improve its productive performance.

**Keywords:** Bioinputs; Abiotic stress; *Glycine max* L.; Leaf Temperature.

### RESUMO

*A agricultura tem sido cada vez mais afetada pelas mudanças climáticas, que comprometem a produção de soja, especialmente devido ao estresse térmico, responsável por reduzir o crescimento e a produtividade das plantas. Diante disso, este estudo avaliou a eficiência de um estimulante vegetal, aplicado em diferentes concentrações,*

1 Trabalho de Pesquisa Técnico-Científica.

2 Bióloga, Mestre em Agrobiologia, Departamento de Biologia, Universidade Federal de Santa Maria (UFSM). E-mail: kassiascrivellaro@gmail.com. ORCID: <https://orcid.org/0009-0004-5745-3761>

3 Bióloga, Doutora em Agronomia, Departamento de Biologia, Universidade Federal de Santa Maria (UFSM). E-mail: raquelstefanello@yahoo.com.br. ORCID: <https://orcid.org/0000-0003-3079-2099>

4 Agrônomo, Doutor em Agronomia, Departamento de Biologia, Universidade Federal de Santa Maria (UFSM). E-mail: sylviobidel@gmail.com. ORCID: <https://orcid.org/0000-0002-1097-6176>

5 Bióloga, Doutora em Agronomia Departamento de Biologia, Universidade Federal de Santa Maria (UFSM). E-mail: lutabaldi@yahoo.com.br. ORCID: <https://orcid.org/0000-0002-3644-2543>

6 Agrônomo, Doutor em Agronomia, Departamento de Solos, Universidade Federal do Rio Grande do Sul (UFRGS). E-mail: lucasgirio@gmail.com. ORCID: <https://orcid.org/0000-0002-2383-9779>

7 Agrônomo, Doutor em Agronomia, Departamento de Biologia, Universidade Federal de Santa Maria (UFSM). E-mail: anderson.marques@ufsm.br. ORCID: <https://orcid.org/0000-0003-0866-8761>

8 Agrônomo, Doutor em Agronomia, Departamento de Biologia, Universidade Federal de Santa Maria (UFSM). E-mail: acfsilva2@uol.com.br. ORCID: <https://orcid.org/0000-0002-1050-1656>

9 Agrônomo, Doutor em Fitotecnia, Departamento de Fitotecnia, Universidade Federal de Santa Maria (UFSM). E-mail: russinunes@yahoo.com.br. ORCID: <https://orcid.org/0000-0002-7124-9204>

na mitigação dos efeitos do estresse térmico durante a fase reprodutiva da soja. O experimento foi conduzido em delineamento em blocos casualizados completos em um arranjo fatorial  $4 \times 2$  (quatro doses de estimulante  $\times$  duas condições de sombreamento) com parcelas subdivididas. Foram analisados parâmetros fisiológicos, bioquímicos e de rendimento. Os resultados indicaram que o estimulante reduziu a temperatura das folhas em até  $3,09\text{ }^{\circ}\text{C}$  sob altas temperaturas, promovendo um aumento nos pigmentos fotossintéticos e aumentando a atividade das enzimas antioxidantes. Esse efeito contribuiu para o aumento dos componentes de rendimento, mesmo sob diferentes condições de sombreamento. O estudo demonstra o potencial destas ferramentas sustentáveis para aumentar a resiliência da soja ao estresse abiótico e melhorar seu desempenho produtivo.

**Palavras-chave:** Bioinsumos; Estresse abiótico; *Glycine max* L.; Temperatura foliar.

## 1 INTRODUCTION

Global food security faces increasingly complex challenges, exacerbated by population growth and rapid urbanization. The current climate scenario poses unprecedented challenges to the Brazilian agricultural sector, with soybeans (*Glycine max* (L.) Merrill) being among the most affected crops. The intensification of climate change poses greater challenges to agricultural production and requires mitigation actions because these phenomena are associated with substantial productivity losses (Escobar *et al.*, 2020).

In Rio Grande do Sul, the increasing occurrence of abiotic stress, including prolonged droughts, heavy rains, and thermal stresses throughout the soybean cycle, is a growing concern (CONAB, 2024). To address these challenges, the Brazilian government launched the National Bioinputs Program (NBP) through Decree No. 10,375 on May 26, 2020 (Brasil, 2020). The program aims to stimulate environmentally responsible agricultural research and technology. Additionally, adopting agricultural practices that preserve natural resources in soybean production is essential to achieving the United Nations' goals of ensuring resilient production systems and promoting sustainable agriculture (ONU, 2022).

In this challenging scenario, the plant stimulant emerges as a promising alternative. Formulated with combinations of macro and micronutrients, microorganisms, and biologically active compounds, stimulants aim to optimize plant nutritional efficiency, strengthen stress resistance, and increase productivity (Baltazar *et al.*, 2021). Stimulants can regulate plant metabolic processes, facilitating adaptation to stress and inducing the synthesis of endogenous antioxidants to protect against oxidative damage caused by thermal stress (Tadele; Zerssa, 2023). However, few studies have explored their effectiveness in mitigating the effects of thermal stress.

The objective of this study was to evaluate the effectiveness of a plant stimulant applied at different concentrations in mitigating the effects of thermal stress on soybeans during the reproductive phase.

## 2 MATERIALS AND METHODS

The experiment was conducted during the 2022/2023 harvest season in Arroio Grande, Santa Maria, Rio Grande do Sul, Brazil (29°41'35.63"S, 53°41'46.51" W). According to the Brazilian Soil Classification System (Santos *et al.*, 2025), the soil is a typical sandy, eutrophic, haplic Planosol for this region. Biomonte Assessoria, Consultoria, Pesquisa e Desenvolvimento Rural Ltda. provided the experimental area.

The Brasmax Garra IPRO soybean cultivar was chosen for its widespread use in Rio Grande do Sul, as highlighted during the 43rd Southern Region Soybean Research Meeting (2023), and for its history of success on local properties, particularly in floodplain environments. This tall, indeterminate-growth cultivar is recommended for floodplain areas and irrigated locations, maximizing yields under these conditions. Sowing took place in November with 45 cm between rows and 14 seeds per linear meter.

The experimental design was in randomized blocks (RBD), in a  $4 \times 2$  factorial scheme, with subdivided plots and four replications. The main plots received four doses of stimulant (0; 13.3; 26.6; and 40 mL per plot), applied via spraying with a knapsack sprayer. Each experimental plot measured 2 m in width by 6 m in length, totaling 12 m<sup>2</sup>. The doses were expressed per plot, since applications were performed directly to each experimental unit under field conditions. The doses were defined based on the methodological approach adopted in studies with biostimulants in soybeans and adjusted to the experimental conditions of the present study (Meyer *et al.*, 2021; Prieto *et al.*, 2017). The control treatment (C) received only distilled water. The plant stimulant, which is classified as a liquid mineral and mixed fertilizer composed of plant polymers, nitrogen, phosphorus, zinc, copper, nickel, and magnesium, was applied at the phenological stage R1–R2, which is the beginning of flowering. The sub-plots were carried out with and without shading using a 75% shading net.

### 2.1 EVALUATION OF PHYSIOLOGICAL AND BIOCHEMICAL PARAMETERS AND PERFORMANCE COMPONENTS

To investigate the effects of thermal stress on soybeans, physiological, biochemical, and productive variables were evaluated during the period between phenological stages R1 and R8.

*Climatic Conditions:* Climatic conditions during the experimental period were evaluated based on data from the INMET (Brazilian National Institute of Meteorology) in the region where the study was conducted.

*Plant temperature in the upper third of the canopy:* Temperature measurements were taken with a UNIT-T® (model DSC 36) professional thermal imager in the middle portion of the canopy, specifically on the last trifoliate leaf. Temperature assessments were conducted between 11 a.m. and 12 p.m. at two-day intervals. Periodic adjustments were made according to local rainfall to ensure

data accuracy. Each treatment was evaluated on one plant per subplot, totaling 10 temperature measurements per treatment.

*Photosynthesis:* Photosynthesis measurements were taken after applying the plant stimulant treatments. Two plants from the central region of each subplot (with or without shading) were randomly selected. A Li-COR (IRGA) infrared gas analyzer was used to measure CO<sub>2</sub> assimilation (A -  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), stomatal conductance to water vapor (Gs -  $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ), and transpiration rate (E -  $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ). Measurements were taken in the middle third of the soybean plants, specifically on the last fully developed leaf. Evaluations were performed on a sunny day between 7:30 and 10:30 a.m.

*Photosynthetic pigments and enzymatic activity:* Leaf samples weighing 3 g were collected from the central region of each subplot (with or without shade cloth) for biochemical analysis. To evaluate antioxidant activity, the leaves were initially macerated in liquid nitrogen. Then, a 0.5 g sample was mixed with 3 mL of 0.05 M sodium phosphate (pH 7.8) buffer containing 1 mM EDTA and 2% (w/v) PVP for homogenization. The extract obtained was centrifuged at  $13000 \times g$  for 20 min at 4 °C, and the supernatant was used to measure enzyme activity and determine protein concentration. Guaiacol peroxidase (POD) activity was quantified using guaiacol as a substrate, according to the protocol described by Zeraik *et al.* (2008). For superoxide dismutase (SOD), quantification was performed by spectrophotometry, according to the method described by Giannopolitis and Ries (1977). For the extraction of total chlorophyll and carotenoids, the procedure described by Hiscox and Israelstan (1979) was followed, with quantification based on the equation by Lichtenthaler (1987). Fresh leaf samples (0.05 g) were incubated at 65 °C in dimethyl sulfoxide (DMSO) until complete extraction of the pigments. The absorbances of the extracted solutions were analyzed in a spectrophotometer at wavelengths of 663, 645, and 470 nm, corresponding to chlorophyll *a*, chlorophyll *b*, and carotenoids, respectively.

*Yield components:* The number of racemes and flowers in stages R2-R3, the number of pods in stages R7-R8, and the weight of one hundred grains (WHG) were evaluated according to the methodology of Musana *et al.* (2020) from five plants randomly selected per plot in an area of 5 m<sup>2</sup>.

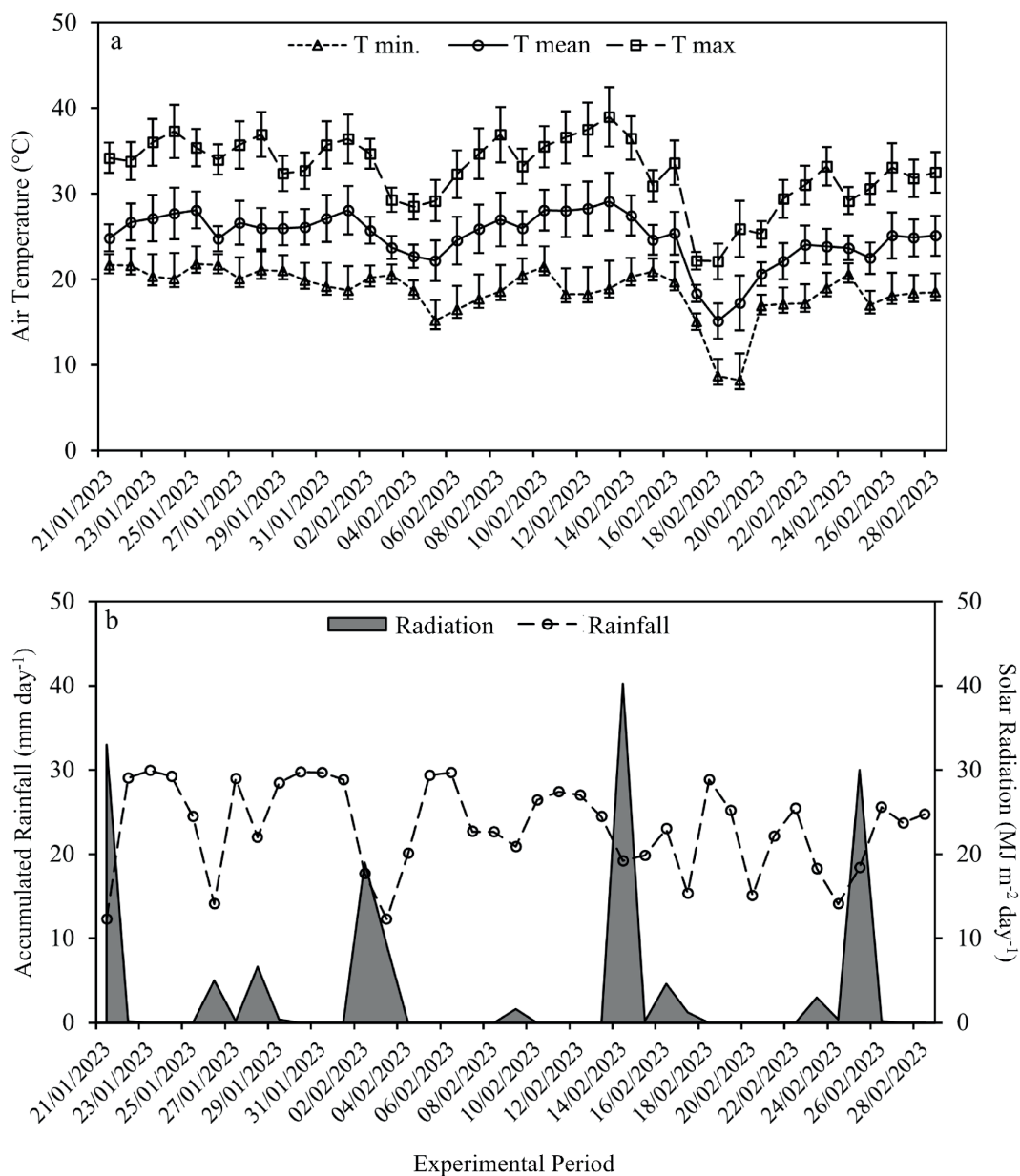
## 2.2 DATA ANALYSIS

Initially, the data were analyzed for normality of residuals and homogeneity of variances using the Shapiro-Wilk ( $p < 0.05$ ) and Bartlett's tests ( $p < 0.05$ ), which confirmed that the statistical assumptions were met. Then, the data were subjected to an analysis of variance (ANOVA) to determine the potential effects of the treatments and their interactions. When the F test detected a significant effect ( $p < 0.05$ ), complementary analyses were performed. These included applying the Scott-Knott multiple comparison test ( $p < 0.05$ ) to the shading factor and performing polynomial regression adjustments to the stimulant dose factor. These analyses and graphs were created using R software (R Core Team, 2022) and the ExpDes packages (Ferreira; Cavalcanti; Nogueira, 2021), Mass (Venables; Ripley, 2002), ggplot2 (Wickham, 2016) and cowplot (Wilke, 2020).

### 3 RESULTS AND DISCUSSION

During the experimental period, climatic conditions were favorable for soybean development (Figure 1). The average air temperature was 24.9 °C, ranging from 23.2 to 39.0 °C, within the ideal range of 20 to 30 °C for the reproductive period (Floss, 2022; Zheng *et al.*, 2024). However, temperatures above this ideal range, especially during critical reproductive stages, can compromise grain filling, resulting in significant productivity losses (Kim *et al.*, 2026).

**Figure 1** - Air temperature: minimum (T min.), average (T avg.), and maximum (T max.) (a); accumulated precipitation (mm day<sup>-1</sup>) and global solar radiation (MJ m<sup>-2</sup> day<sup>-1</sup>) (b) during the experimental period (21/01/2023 to 28/02/2023).

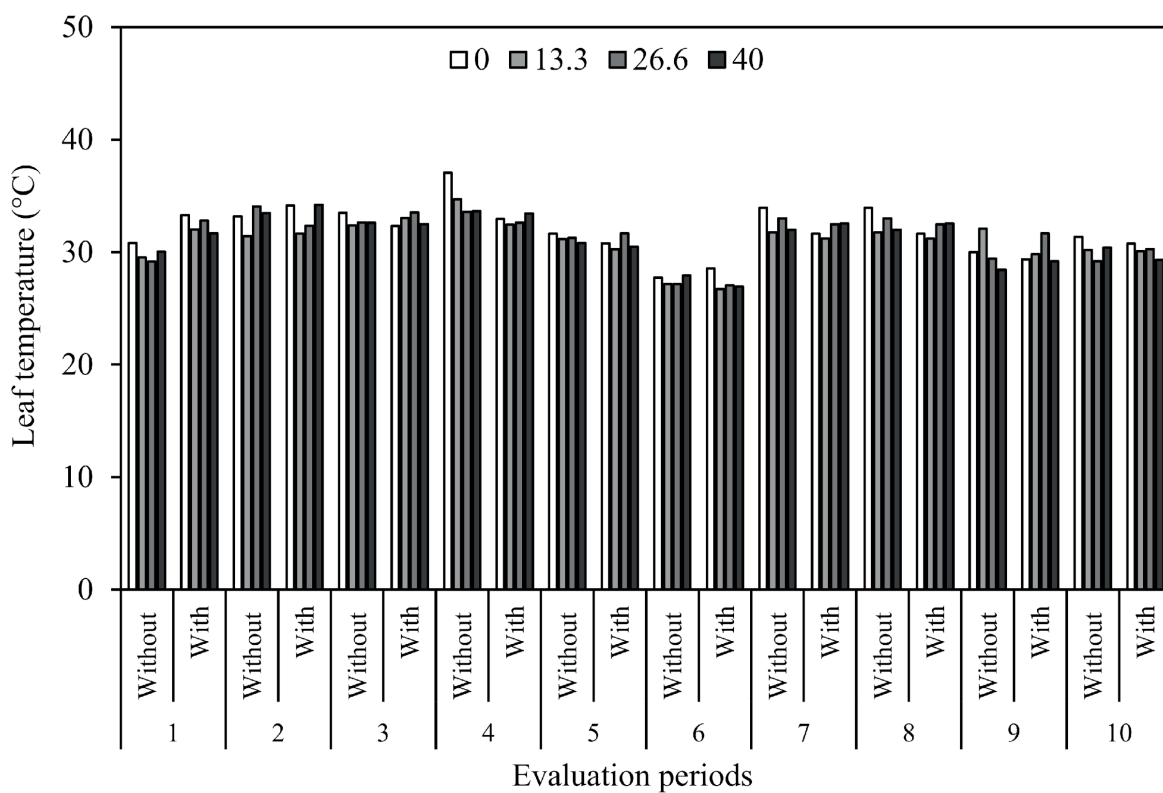


Source: INMET (2023)

The average solar radiation of  $23.2 \text{ MJ m}^{-2} \text{ day}^{-1}$  was sufficient for photosynthesis and biomass accumulation (Reis *et al.*, 2020; Raza *et al.*, 2021). However, the accumulated precipitation (155 mm) was lower than the 240 mm recommended by Radin, Schönhofen and Tazzo (2017) for an adequate crop yield in Rio Grande do Sul. However, the regularity of the precipitation maintained soil moisture, preventing water stress, as reflected by adequate leaf temperatures throughout the evaluations.

The average leaf temperature was  $31.45 \text{ }^{\circ}\text{C}$ . Without shading, temperatures ranged from  $31.04$  to  $32.42 \text{ }^{\circ}\text{C}$  between stimulant doses; with shading, they ranged from  $30.89$  to  $31.79 \text{ }^{\circ}\text{C}$  (Figure 2).

**Figure 2** - Average leaf temperature of soybean plants grown under four doses of stimulant (mL per plot) and two shading conditions: with shade cloth (no stress) and without shade cloth (with stress), over ten evaluation periods.



Source: Authors (2026)

In general, leaf temperature was higher in the absence of the plant stimulant (dose 0), particularly during the fourth evaluation period. The use of the product during this period resulted in a  $3.09 \text{ }^{\circ}\text{C}$  reduction in leaf temperature under unshaded conditions. During periods of high temperatures, the stimulant reduced leaf temperature; previous studies of similar products did not demonstrate this reduction (Repke *et al.*, 2022b). These products act on physiological mechanisms that favor thermal regulation and protect plants against abiotic stresses (Del Buono, 2021; Nawaz *et al.*, 2022; Johnson; Joel; Puthur, 2024).

This response is supported by Carillo *et al.* (2025), who report that biostimulants enhance plant cooling capacity by improving metabolic regulation and water use efficiency under stress conditions, contributing to greater thermal tolerance.

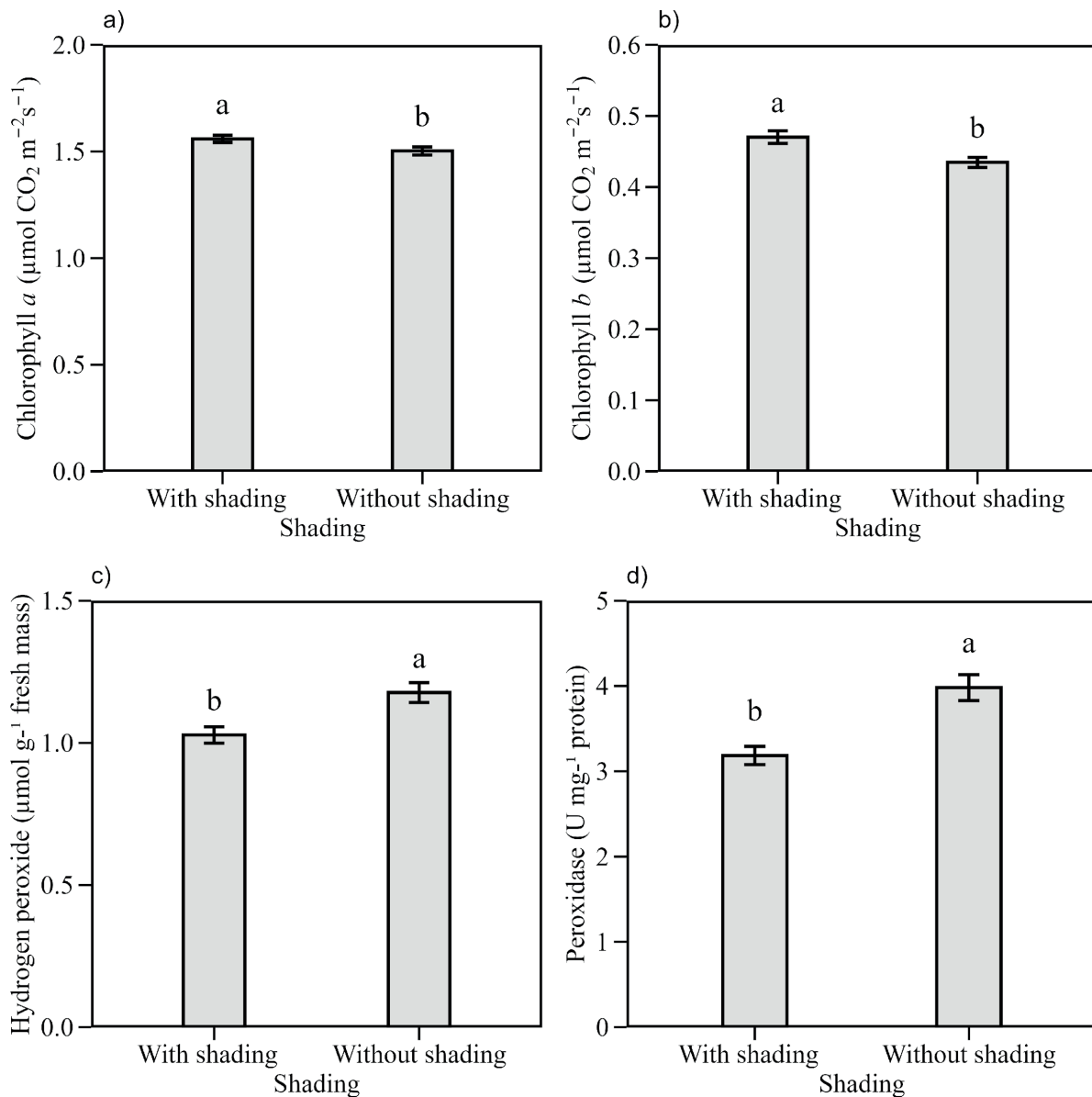
Some studies indicate that an increase of 1 °C in temperature reduces productivity by 1 to 6%, while an increase of 100 mm in precipitation is associated with a variation of 0.2 to 1% in soybean harvest (Silva *et al.*, 2023). Additionally, a 1 °C increase in the global average temperature would reduce wheat production by 6.0%, rice production by 3.2%, corn production by 7.4%, and soybean production by 3.1% (Zhao *et al.*, 2017). Therefore, it is plausible that the stimulant contributed to the reduction in leaf temperature since a 1 °C decrease can significantly impact the thermal comfort and physiological performance of plants, preventing damage caused by excessive heat. The results also highlight the importance of the environmental context. Under ideal conditions, the effects of the stimulant may be subtle, but in challenging environments, they are more evident.

The analysis of variance did not identify significant interactions between the doses and shading for the physiological variables. Furthermore, no significant effects of the doses or shading on net assimilation rate, stomatal conductance, transpiration, or water use efficiency were observed. Overall, the average values of these variables were 36.81  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  for net assimilation rate, 0.15  $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$  for stomatal conductance, 7.09  $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$  for transpiration, and 5.21  $\text{mol CO}_2 \text{ mol H}_2\text{O}^{-1}$  for water use efficiency.

The absence of significant stimulant effects may be associated with favorable environmental conditions and cultivar size, which provided natural shading and greater moisture retention. In contrast, studies conducted under stressful conditions reported positive effects of stimulants on soybeans, including increased  $\text{CO}_2$  assimilation, stomatal conductance, and photosynthetic efficiency. These results indicate greater carbon use capacity (Repke *et al.*, 2022a; Repke *et al.*, 2022b). These results reinforce the idea that the effects of the stimulant are more evident in pronounced environments.

No significant interaction between doses and shading was observed for pigments and biochemical variables. When analyzing the main effects, a significant effect of the doses was observed for chlorophyll *a* (Cl-*a*), total chlorophyll (Cl-Total), and carotenoids (CAR). A significant effect of the shading factor was observed for chlorophyll *a*, chlorophyll *b*, hydrogen peroxide content ( $\text{H}_2\text{O}_2$ ), and peroxidase enzyme activity (POD) (Figure 3). No significant effects of the studied factors were observed for superoxide dismutase (SOD), with an overall average of 267.75 ( $\text{U mg}^{-1}$  of protein) obtained throughout the experiment.

**Figure 3** - Chlorophyll *a* (a), chlorophyll *b* (b), hydrogen peroxide (c), and peroxidase (d) contents in soybean leaves grown under two shading conditions: with shading and without shading.



\*Means followed by the same letter are not different at 5% probability by the Scott-Knott test.

Source: Authors (2026)

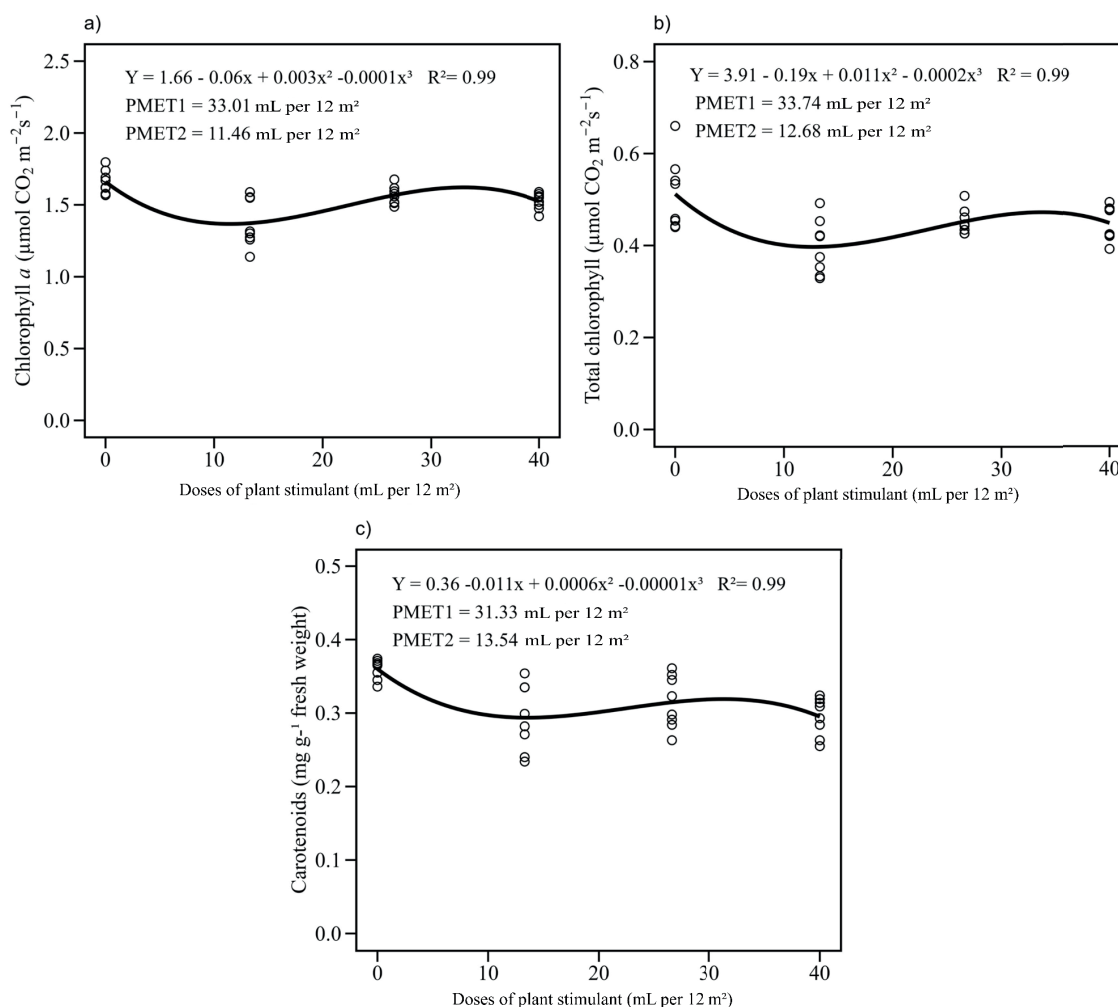
The results underscore the intricate relationship between environmental conditions and plant physiology, with the stimulant serving as a mediator. The positive influence of the doses on chlorophyll *a* (Cl-*a*), total chlorophyll (Cl-Total), and carotenoids suggests beneficial effects on photosynthesis and protection against oxidative stress. The increase in these variables in the shading treatments is explained by the reduction in light intensity, which favors greater chlorophyll synthesis and optimizes light absorption. This ensures adequate photosynthesis rates are maintained (Taiz; Zeiger, 2017; Shafiq *et al.*, 2021).

Similar responses have been reported by Carillo *et al.* (2025), who highlight that biostimulants act through metabolic regulation, enhancing antioxidant activity and contributing to the mitigation of oxidative damage, particularly under environmental stress conditions such as variations in light and temperature.

Shaded plants showed greater pigment accumulation, a mechanism associated with maximizing light capture and antioxidant protection (Hu; Ding; Zhu, 2020; Sun *et al.*, 2022; Taiz; Zeiger, 2017). Additionally, temperature influences the physiological regulation of plants, and shading creates a favorable microclimate. This is evidenced by reduced oxidative stress, as shown by lower H<sub>2</sub>O<sub>2</sub> concentrations and peroxidase activity (Figure 3). These results align with studies on *Ascophyllum nodosum*-based biostimulants, which enhance photosynthetic pigments and mitigate oxidative stress (Cordeiro *et al.*, 2024).

Analysis of the stimulant doses revealed cubic responses for chlorophyll a (Cl-a), chlorophyll b (Cl-b), and carotenoids, with maximum technical efficiency occurring at doses between 31.33 and 33.74 mL per plot (12 m<sup>2</sup>) and minimum efficiency occurring at doses between 11.46 and 13.54 mL per plot (12 m<sup>2</sup>) (Figure 4). This evidence demonstrates the relationship between dose and physiological effect.

**Figure 4** - Chlorophyll a (a), chlorophyll b (b), and carotenoid (c) contents of soybean leaves grown under four doses of plant stimulant: 0, 13.3, 26.6, and 40 mL per plot (12 m<sup>2</sup>). PMET1: point of maximum technical efficiency; PMET2: point of minimum technical efficiency.



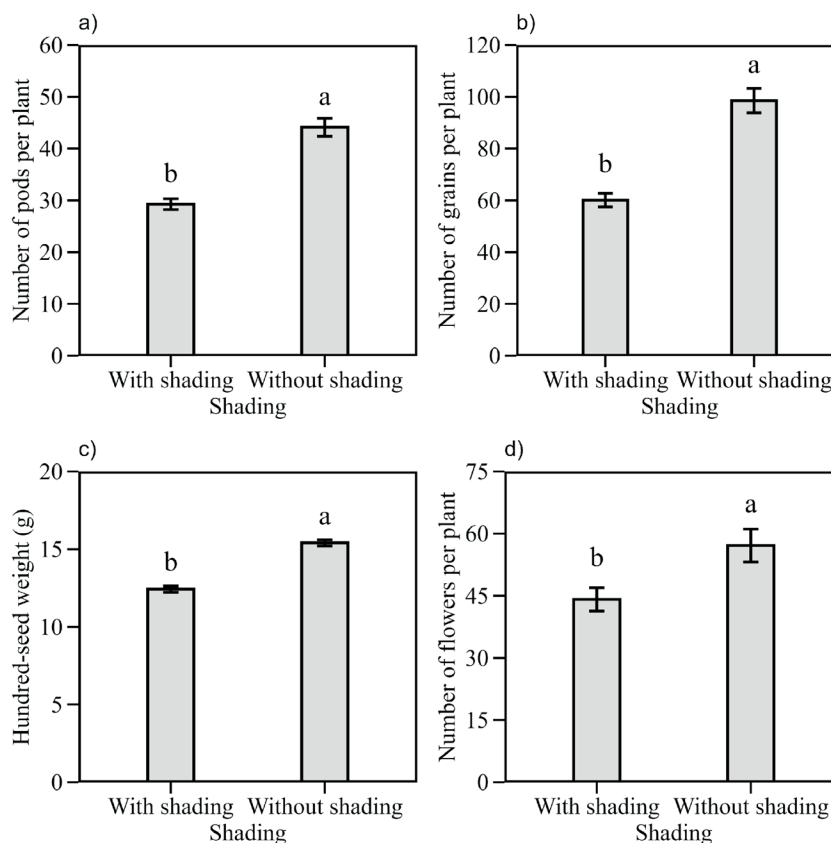
Source: Authors (2026)

No interaction between doses and shading was observed for yield components. However, the number of pods (NPP), grains (NGP), and flowers per plant (NF) increased with higher doses. These results underscore the significance of plant nutrition in relation to environmental conditions in determining crop yield.

Productive performance is associated with the presence of macro- and micronutrients in the stimulant (N, Mg, P, K, Zn, Cu e Ni), which are essential for processes such as protein synthesis, photosynthesis, energy metabolism, osmotic regulation, stomatal control, enzyme activation, disease resistance, vegetative growth, and stress tolerance (Ye; Tian; Jin, 2022; Wang *et al.*, 2022; Castro *et al.*, 2020; Tian *et al.*, 2021; Ahmed *et al.*, 2023; Floss, 2022; Taiz; Zeiger, 2017; Stanton *et al.*, 2022; Guirola-Céspedes; González-Suárez; Ley-Chong, 2023). Additionally, plant stimulants favor phytohormone production and reduce oxidative stress, promoting balanced growth and higher yields (Floss, 2011; Johnson; Joel; Puthur, 2024).

Plants grown without shading had a higher number of pods, grains, and flowers (Figure 5), which confirms the importance of light for yield (Lopes; Lima, 2015; Wu *et al.*, 2025). Greater energy availability favors the allocation of carbohydrates to reproductive structures, increasing productivity (Xu *et al.*, 2024). However, although shading increases the content of photosynthetic pigments, this does not necessarily translate into greater photosynthetic efficiency (Timpmann; Rätsep; Freiberg, 2023).

**Figure 5** - Number of pods per plant (a), number of grains per plant (b), hundred-grains weight (c), and number of flowers per plant (d) in soybeans grown under two shading conditions.



\*Means followed by the same letter are not different at 5% probability by the Scott-Knott test.

Source: Authors (2026)

The biochemical adaptations of plants in response to shading, such as increased antioxidant production and adjustments to optimize light capture, demonstrate the complexity and adaptability of plant response mechanisms to environmental conditions (Yang *et al.*, 2018; Fan *et al.*, 2019; Rahimi *et al.*, 2021). Thus, the results of these productive variables emphasize the importance of considering not only the amount of light, but also how plants respond biochemically to variations in light under adverse conditions.

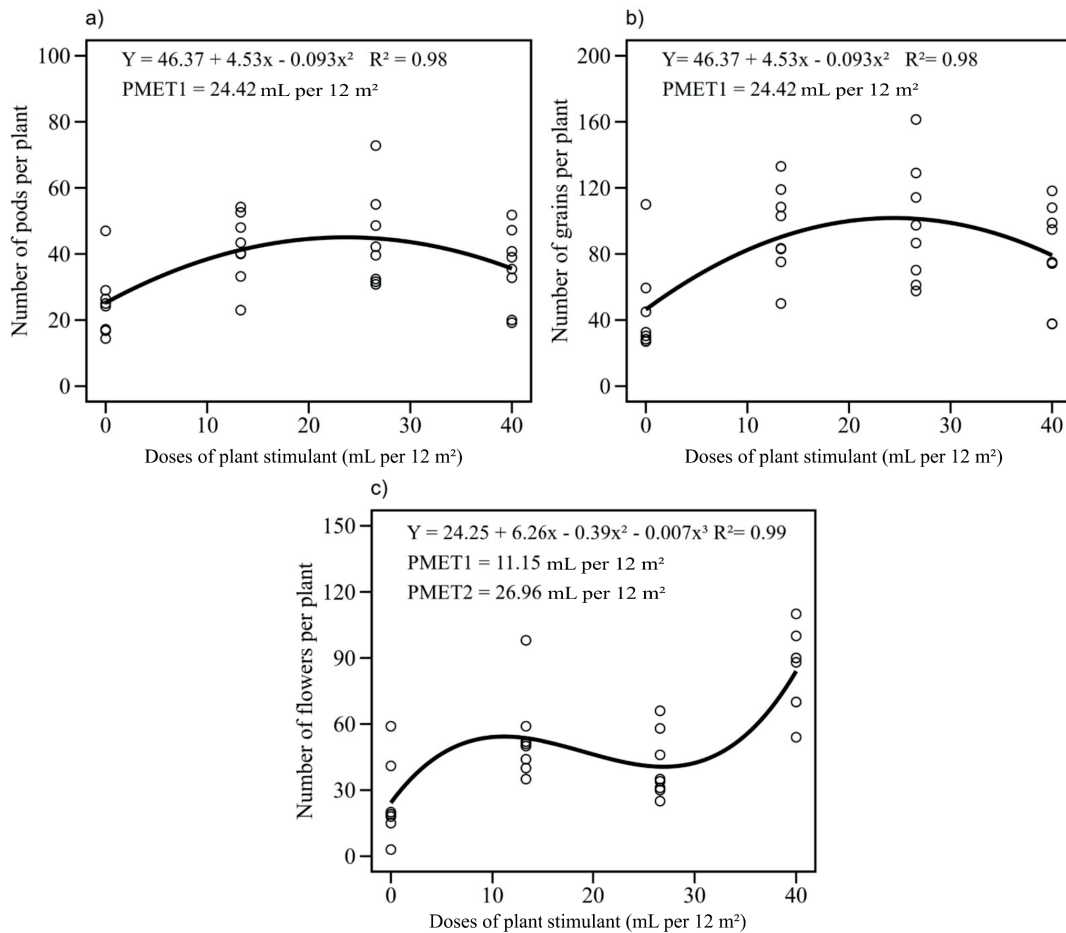
Plants grown under high light intensity are more efficient at converting solar energy into biomass. In the long term, when exposed to low light conditions, they adapt by increasing antioxidant production and adjusting gene expression to increase the number and size of photosynthetic antennae. This allows them to capture more light and compensate for the lower availability of solar energy (Folta; Carvalho, 2015; Paradiso; Proietti, 2021).

Shading can also reduce transpiration rates, affecting water and nutrient absorption. This can result in lower biomass accumulation and consequently reduced crop productivity (Gong *et al.*, 2015; Li *et al.*, 2024). Conversely, full sun exposure increases photosynthesis and biomass production in legumes, favoring reproductive development and higher yields (Mitache *et al.*, 2024). These findings align with previous research emphasizing the importance of light in regulating photosynthesis and plant development. Light availability is a critical factor that can limit or promote plant growth and influence nutrient use efficiency (Wu *et al.*, 2025).

Plant height did not vary between treatments (1.34 m). This can be attributed to the ability of soybeans to maintain a stable height under different conditions by prioritizing the allocation of resources to reproductive organs in response to different light levels and doses. Hormonal regulation, including gibberellin and auxin levels, plays a crucial role in maintaining plant height regardless of environmental variations (Lopes; Lima, 2015; Floss, 2022; Ma; Freitas; Dias, 2022).

When analyzing the influence of shading alone, superior productivity was observed in plants grown in full sun (without shading) (Figure 6). Soybean plants exposed to direct sunlight had a higher number of pods, grains, hundred-grain weight, and flowers per plant. These results align with previous research emphasizing the importance of light in regulating photosynthesis and plant development. Full light increases photosynthetic efficiency and influences the synthesis of growth hormones, such as auxins and gibberellins, which promote cell division and the development of reproductive organs (Souza *et al.*, 2022; Wei; Wang; Yu, 2023).

**Figure 6** - Number of pods per plant (a) and number of grains per plant (b) in soybeans grown under four doses of plant stimulant: 0, 13.3, 26.6, and 40 mL per plot (12 m<sup>2</sup>). PMET1: maximum point; PMET2: minimum point.



Source: Authors (2026)

The absence of significant interaction between the doses and shading indicates that these factors influence soybean productivity components independently. The condition without shading was more favorable for production, and different stimulant doses adjusted productivity by varying the number of reproductive organs.

According to the literature, temperatures above 30 °C during the reproductive phase of legumes result in flower abortion, pollen and ovule infertility, compromised fertilization, and reduced seed filling. This reflects a significant drop in grain productivity (Sher *et al.*, 2024; Mehmood *et al.*, 2025). In the present study, greater flower maintenance was visually observed with the use of the stimulant, suggesting that it contributes to heat resilience.

When analyzing the influence of doses on the variables number of pods per plant and number of grains per plant, quadratic responses were observed with increasing doses, reaching maximum technical efficiency values of 23.66 and 24.42 mL per plot (12 m<sup>2</sup>), respectively (Figure 6). For the number of flowers, the response to doses was cubic, with maximum and minimum efficiency points at 11.15 and 26.96 mL per plot (12 m<sup>2</sup>), respectively.

High doses can result in nutritional imbalances or toxicity, reducing yield; this explains the quadratic and cubic models observed (Rouphael; Colla, 2020). Thus, the positive effects of the stimulant are associated with the action of nutrients and modulation of physiological and biochemical processes that confer greater tolerance to thermal stress.

Despite the consistent results, further research is needed to better understand how the plant stimulant works, particularly under severe thermal stress conditions. The observed responses indicate high product efficiency and suggest that positive effects can be achieved with lower doses, a hypothesis to be evaluated in future studies. Additionally, integrating plant stimulants with beneficial microorganisms can enhance plant tolerance to thermal stress.

## 4 CONCLUSIONS

This study demonstrates the potential of plant stimulants to increase the resilience and productivity of soybeans, particularly in scenarios involving abiotic stress. Under high temperatures, a reduction of up to 3 °C in leaf temperature was observed, and under more stable conditions, a reduction of about 1 °C was observed. These reductions optimize plant development. This decrease positively impacts photosynthetic capacity, biochemical variables, antioxidant activity, and chlorophyll and pigment content, resulting in improved crop productivity, which underscores the relevance of these stimulants for soybean production.

The results suggest that the stimulant is a promising tool for managing soybeans in adverse climatic conditions and contributes to food security and sustainable production. Additionally, the results reinforce the effectiveness of using this tool to prepare plants for stressful events and mitigate the effects of thermal stress, ensuring significant productivity benefits in the face of climate change.

## REFERENCES

- AHMED, N. *et al.* The power of magnesium: unlocking the potential for increased yield, quality, and stress tolerance of horticultural crops. **Frontiers in Plant Science**, Lausanne, v. 14, 2023. DOI: <https://doi.org/10.3389/fpls.2023.1285512>
- BALTAZAR, M. *et al.* Recent advances in the molecular effects of biostimulants in plants: an overview. **Biomolecules**, Basel, v. 11, n. 8, 1096, 2021. DOI: <https://doi.org/10.3390/biom11081096>
- BRASIL. **O Programa Nacional de Bioinsumos**. Brasília, DF: Ministério da Agricultura e Pecuária, 2020. Disponível em: <https://www.gov.br/agricultura/pt-br/assuntos/inovacao/bioinsumos/o-programa>. Acesso em: 21 jan 2026.
- CARILLO, P. Can biostimulants enhance plant resilience to heat and water stress in the Mediterranean hotspot? **Plant Stress**, v. 16, p. 100802, 2025. DOI: <https://doi.org/10.1016/j.stress.2025.100802>

CASTRO, C. *et al.* **Magnésio: manejo para o equilíbrio nutricional da soja.** Londrina: Embrapa Soja, 2020. 54 p.

COMPANHIA NACIONAL DE ABASTECIMENTO. **Acompanhamento da safra brasileira de grãos: 9º levantamento - safra 2023/24.** Brasília, DF: CONAB, 2024. Disponível em: <https://www.conab.gov.br/info-agro/safras/graos/boletim-da-safra-de-graos>. Acesso em: 21 jan 2026.

CORDEIRO, E. C. N. *et al.* Can *Ascophyllum nodosum* extract application before or at drought stress trigger different metabolic adaptation responses in soybean plants? **Journal of Applied Phycology**, Dordrecht, v. 36, p. 2283-2293, 2024. DOI: <https://doi.org/10.1007/s10811-024-03231-z>

DEL BUONO, D. Can biostimulants be used to mitigate the effect of anthropogenic climate change on agriculture? It is time to respond. **Science of the Total Environment**, Amsterdam, v. 751, 141763, 2021. DOI: <https://doi.org/10.1016/j.scitotenv.2020.141763>

ESCOBAR, N. *et al.* Spatially-explicit footprints of agricultural commodities: Mapping carbon emissions embodied in Brazil's soy exports. **Global Environmental Change**, v. 62, e102067, 2020. <https://doi.org/10.1016/j.gloenvcha.2020.102067>

FAN, Y. *et al.* Soybean (*Glycine max* L. Merr.) seedlings response to shading: leaf structure, photosynthesis and proteomic analysis. **BMC Plant Biology**, London, v. 19, 34, 2019. DOI: <https://doi.org/10.1186/s12870-019-1633-1>

FERREIRA, E. B.; CAVALCANTI, P. P.; NOGUEIRA, D. A. **ExpDes.pt: pacote Experimental Designs.** R package version 1.2.2, 2021. Disponível em <https://cran.r-project.org/web/packages/ExpDes.pt/ExpDes.pt.pdf>. Acesso em 02 jul 2024.

FLOSS, E. L. **Fisiologia das plantas cultivadas: o estudo do que está por trás do que se vê.** 5. ed. Passo Fundo: Universidade de Passo Fundo, 2011.

FLOSS, E. L. **Maximizando o rendimento da soja: ecofisiologia, nutrição e manejo.** 3. ed. Passo Fundo: Aldeia Sul; Passografic, 2022.

FOLTA, K. M.; CARVALHO, S. D. Photoreceptors and control of horticultural plant traits. **HortScience**, Washington, DC, v. 50, n. 9, p. 1274-1280, 2015. DOI: <https://doi.org/10.21273/HORTSCI.50.9.1274>

GIANNOPOLITIS, C. N.; RIES, S. K. Superoxide dismutases: I. Occurrence in higher plants. **Plant Physiology**, Bethesda, v. 59, n. 2, p. 309-314, 1977. DOI: <https://doi.org/10.1104/pp.59.2.309>

GONG, W. Z. *et al.* Tolerance vs. avoidance: two strategies of soybean (*Glycine max*) seedlings in response to shade in intercropping. **Photosynthetica**, Dordrecht, v. 53, n. 2, p. 259-268, 2015. DOI: <https://doi.org/10.1007/s11099-015-0103-8>

GUIROLA-CÉSPEDES, C.; GONZÁLEZ-SUÁREZ, E.; LEY-CHONG, N. Design of a chemical plant to obtain phosphoric acid based on the study of the need for phosphate products in Cuba. **Chemical Technology**, Santiago de Cuba, v. 43, n. 2, p. 406-420, 2023. Disponível em: <https://tecnologiaquimica.uo.edu.cu/index.php/tq/article/view/5350>. Acesso em: 21 jul. 2025.

HISCOX, J. D.; ISRAELSTAM, G. F. A method for the extraction of chlorophyll from leaf tissue without maceration. **Canadian Journal of Botany**, Ottawa, v. 57, p. 1332-1334, 1979. DOI: <https://doi.org/10.1139/b79-163>

HU, S.; DING, Y.; ZHU, C. Sensitivity and responses of chloroplasts to heat stress in plants. **Frontiers in Plant Science**, Lausanne, v. 11, 375, 2020. DOI: <https://doi.org/10.3389/fpls.2020.00375>

JOHNSON, R.; JOEL, J. M.; PUTHUR, J. T. Biostimulants: the futuristic sustainable approach for alleviating crop productivity and abiotic stress tolerance. **Journal of Plant Growth Regulation**, v. 43, p. 659-674, 2024. DOI: <https://doi.org/10.1007/s00344-023-11144-3>

KIM, Kyung-Hee *et al.* Climate-resilient soybean: integrated breeding strategies for mitigating drought and heat stress. **Agriculture**, v. 16, n. 4, p. 445, 2026. DOI: <https://doi.org/10.3390/agriculture16040445>

LICHTENTHALER, H. K. Chlorophylls and carotenoids: pigments of photosynthetic biomembranes. **Methods in Enzymology**, San Diego, v. 148, p. 350-382, 1987. DOI: [https://doi.org/10.1016/0076-6879\(87\)48036-1](https://doi.org/10.1016/0076-6879(87)48036-1)

LI, Y. *et al.* Shade tolerance in wheat is related to photosynthetic limitation and morphological and physiological acclimations. **Frontiers in Plant Science**, v. 15, p. 1465925, 2024. DOI: <https://doi.org/10.3389/fpls.2024.1465925>

LI-COR BIOSCIENCES. **Model LI-6400 Portable Photosynthesis System: operator's manual**. Lincoln, 2024. Disponível em: <https://www.licor.com/env/support/LI-6400/manuals.html>

LOPES, N. F.; LIMA, M. G. S. **Fisiologia da produção**. Viçosa, MG: Editora UFV, 2015.

MA, Y.; FREITAS, H.; DIAS, M. C. Strategies and prospects for biostimulants to alleviate abiotic stress in plants. **Frontiers in Plant Science**, v. 13, 2022. DOI: <https://doi.org/10.3389/fpls.2022.1024243>

MEHMOOD, M. *et al.* Effect of high temperature on pollen grains and yield in economically important crops: a review. **Planta**, v. 261, p. 141, 2025. DOI: <https://doi.org/10.1007/s00425-025-04714-0>

MEYER, F. R. *et al.* Foliar spraying of a seaweed-based biostimulant in soybean. **Revista Caatinga**, Mossoró, v. 34, n. 1, p. 99-107, 2021. DOI: <https://doi.org/10.1590/1983-21252021v34n111rc>

- MITACHE, M. *et al.* Exploring the impact of light intensity under speed breeding conditions on the development and growth of lentil and chickpea. **Plant Methods**, v. 20, p. 30, 2024. DOI: <https://doi.org/10.1186/s13007-024-01156-9>
- MUSANA, R. F. *et al.* Growth and yield performance of common bean (*Phaseolus vulgaris* L.) as influenced by plant density at Nyagatare, east Rwanda. **African Journal of Food, Agriculture, Nutrition and Development**, v. 20, n. 4, p. 16249-16261, 2020. DOI: <https://doi.org/10.18697/ajfand.92.18700>
- NAWAZ, F. *et al.* Biostimulants as regulators of stress metabolites to enhance drought and salinity stress tolerance in plants. In: KAMMAR, P.; NAGAR, S. (eds.). **Biostimulants for crop production and sustainable agriculture**. 1. ed. Oxfordshire: CABI Publishing, 2022. p. 17-40. DOI: <https://doi.org/10.1079/9781789248098.0017>
- ONU. **Os 17 objetivos de desenvolvimento sustentável no Brasil**. 2022. Disponível em: <https://brasil.un.org/pt-br/sdgs>. Acesso em: 17 set. 2024.
- PARADISO, R.; PROIETTI, S. Light quality manipulation to control plant growth and photomorphogenesis in greenhouse horticulture: the state of the art and the opportunities of modern LED systems. **Journal of Plant Growth Regulation**, v. 41, p. 742-780, 2022. DOI: <https://doi.org/10.1007/s00344-021-10337-y>
- PRIETO, C. A. *et al.* Bioestimulante, biofertilizante e inoculação de sementes no crescimento e produtividade da soja. **Revista de Agricultura Neotropical**, Cassilândia-MS, v. 4, n. 2, p. 1-8, 2017. DOI: <https://doi.org/10.32404/rean.v4i2.1167>
- R CORE TEAM. **R: a language and environment for statistical computing**. Vienna, Austria: R Foundation for Statistical Computing, 2022.
- RADIN, B.; SCHÖNHOFEN, A.; TAZZO, I. F. Impacto da quantidade e frequência de chuva no rendimento da soja. **Agrometeoros**, Passo Fundo, v. 25, n. 1, p. 19-26, 2017. DOI: <https://doi.org/10.31062/agrom.v25i1.26263>
- RAHIMI, M. *et al.* Antioxidant gene expression analysis and evaluation of total phenol content and oxygen-scavenging system in tea accessions under normal and drought stress conditions. **BMC Plant Biology**, v. 21, p. 494, 2021. DOI: <https://doi.org/10.1186/s12870-021-03275-0>
- RAZA, M. A. *et al.* Compact maize canopy improves radiation use efficiency and grain yield of maize/soybean relay intercropping system. **Environmental Science and Pollution Research**, v. 28, p. 41135-41148, 2021. DOI: <https://doi.org/10.1007/s11356-021-13541-1>
- REIS, L. *et al.* Influence of climate variability on soybean yield in Matopiba, Brazil. **Atmosphere**, v. 11, n. 10, e1130, 2020. DOI: <https://doi.org/10.3390/atmos11101130>

- REPKE, R. A. *et al.* Alleviation of drought stress in soybean by applying a biostimulant based on amino acids and macro- and micronutrients. **Agronomy**, v. 12, n. 10, art. 2244, 2022b. DOI: <https://doi.org/10.3390/agronomy12102244>
- REPKE, R. A. *et al.* Increased soybean tolerance to high temperature through biostimulant based on *Ascophyllum nodosum* (L.) seaweed extract. **Journal of Applied Phycology**, v. 34, p. 3205-3218, 2022a. DOI: <https://doi.org/10.1007/s10811-022-02821-z>
- REUNIÃO DE PESQUISA DE SOJA DA REGIÃO SUL, 43, 2023. **43ª Reunião de Pesquisa de Soja da Região Sul**. Disponível em: <https://www.editoragazeta.com.br/43a-reuniao-de-pesquisa-de-soja-da-regiao-sul/>. Acesso em: 15 dez 2025.
- ROUPHAEL, Y.; COLLA, G. Biostimulants in agriculture. **Frontiers in Plant Science**, v. 11, e40, 2020. DOI: <https://doi.org/10.3389/fpls.2020.00040>
- SANTOS, H. G. dos *et al.* **Sistema Brasileiro de Classificação de Solos (SiBCS)**. 6. ed. rev. e ampl. Brasília, DF: Embrapa, 2025. 393 p.
- SHAFIQ, I. *et al.* Crop photosynthetic response to light quality and light intensity. **Journal of Integrative Agriculture**, v. 20, n. 1, p. 4-23, 2021. DOI: [https://doi.org/10.1016/S2095-3119\(20\)63227-0](https://doi.org/10.1016/S2095-3119(20)63227-0)
- SHER, A. *et al.* Heat stress effects on legumes: challenges, management strategies and future insights. **Plant Stress**, v. 13, e100537, 2024. DOI: <https://doi.org/10.1016/j.stress.2024.100537>
- SILVA, D. S. *et al.* Temperature effect on Brazilian soybean yields, and farmers' responses. **International Journal of Agricultural Sustainability**, v. 21, n. 1, e2173370, 2023. DOI: <https://doi.org/10.1080/14735903.2023.2173370>
- SOUZA, A. P. de *et al.* Soybean photosynthesis and crop yield are improved by accelerating recovery from photoprotection. **Science**, v. 377, n. 6608, p. 851-854, 2022. DOI: <https://doi.org/10.1126/science.adc9831>
- STANTON, C. *et al.* Zinc in plants: integrating homeostasis and biofortification. **Molecular Plant**, v. 15, n. 1, p. 65-85, 2022. DOI: <https://doi.org/10.1016/j.molp.2021.12.008>
- SUN, T. *et al.* Plant carotenoids: recent advances and future perspectives. **Molecular Horticulture**, v. 2, n. 3, p. 1-21, 2022. DOI: <https://doi.org/10.1186/s43897-022-00023-2>
- TADELE, K. T.; ZERSSA, G. W. Biostimulants and phytohormones improve productivity and quality of medicinal plants under abiotic stress. In: Husen, A.; Iqbal, M. (eds). **Medicinal plants**. Singapore: Springer, 2023. p. 335-362. DOI: [https://doi.org/10.1007/978-981-19-5611-9\\_13](https://doi.org/10.1007/978-981-19-5611-9_13)
- TAIZ, L.; ZEIGER, E. **Fisiologia vegetal**. 6. ed. São Paulo: Artmed, 2017.

- TIAN, X.-Y. *et al.* Physiological and molecular advances in magnesium nutrition of plants. **Plant Soil**, v. 468, p. 1-17, 2021. DOI: <https://doi.org/10.1007/s11104-021-05139-w>
- TIMPMANN, K.; RÄTSEP, M.; FREIBERG, A. Enhancing solar spectrum utilization in photosynthesis: exploring exciton and site energy shifts as key mechanisms. **Scientific Reports**, v. 13, 22299, 2023. DOI: <https://doi.org/10.1038/s41598-023-49729-3>
- VENABLES, W. N.; RIPLEY, B. D. **Modern applied statistics with S**. 4. ed. New York: Springer, 2002.
- WANG, R. *et al.* Nitrogen improves plant cooling capacity under increased environmental temperature. **Plant Soil**, v. 472, p. 329-344, 2022. DOI: <https://doi.org/10.1007/s11104-021-05244-w>
- WEI, Y.; WANG, S.; YU, D. The role of light quality in regulating early seedling development. **Plants**, v. 12, n. 14, e2746, 2023. DOI: <https://doi.org/10.3390/plants12142746>
- WICKHAM, H. **ggplot2: elegant graphics for data analysis**. New York: Springer-Verlag, 2016.
- WILKE, C. O. **gowplot: streamlined plot theme and plot annotations for ggplot2**. R package, version 1.1.1. 2020.
- WU, W. *et al.* The role of light in regulating plant growth, development and sugar metabolism: a review. **Frontiers in Plant Science**, v. 15, e1507628, 2025. DOI: <https://doi.org/10.3389/fpls.2024.1507628>
- XU, Y. *et al.* Variability in soybean yield responses to elevated atmospheric CO<sub>2</sub>: insights from non-structural carbohydrate remobilisation during seed filling. **Plant Physiology and Biochemistry**, v. 213, e108802, 2024. DOI: <https://doi.org/10.1016/j.plaphy.2024.108802>
- YANG, F. *et al.* Effect of interactions between light intensity and red-to-far-red ratio on the photosynthesis of soybean leaves under shade condition. **Environmental and Experimental Botany**, v. 150, p. 79-87, 2018. DOI: <https://doi.org/10.1016/j.envexpbot.2018.03.008>
- YE, J. Y.; TIAN, W. H.; JIN, C. W. Nitrogen in plants: from nutrition to the modulation of abiotic stress adaptation. **Stress Biology**, v. 2, n. 4, p. 1-14, 2022. DOI: <https://doi.org/10.1007/s44154-021-00030-1>
- ZERAIK, A. E. *et al.* Development of a spot test for monitoring peroxidase activity in a purification procedure. **Química Nova**, v. 31, n. 4, p. 731-734, 2008. DOI: <https://doi.org/10.1590/S0100-40422008000400003>
- ZHAO, C. *et al.* Temperature increase reduces global yields of major crops in four independent estimates. **Proceedings of the National Academy of Sciences of the United States of America**, v. 114, n. 35, p. 9326-9331, 2017. DOI: <https://doi.org/10.1073/pnas.1701762114>
- ZHENG, H. *et al.* Optimal sowing time to adapt soybean production to global warming with different cultivars in the Huanghuaihai Farming Region of China. **Field Crops Research**, v. 312, p. 109386, 2024. DOI: <https://doi.org/10.1016/j.fcr.2024.109386>