

ARTICLE

Physiological responses, growth, and floral stem quality of *Heliconia* species treated with salicylic acid and kaolin under full-sun in a semi-arid condition

Respostas fisiológicas, crescimento e qualidade de hastes florais de espécies de *Heliconia* tratadas com ácido salicílico e caulim sob condições de pleno sol no semiárido

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Abstract

Tropical floriculture is an economically relevant activity, particularly for family farming, because of the high added value of cut flowers and the potential for rapid financial returns. Among tropical ornamentals, *Heliconia* species are valued for their diversity of colors and forms. However, cultivation under full-sun conditions in semi-arid regions exposes plants to high solar irradiance, which may constrain physiological performance and growth. This study evaluated the effects of foliar applications of salicylic acid (SA) and kaolin on the physiological responses, vegetative growth, and floral stem quality of *Heliconia bihai* cv. Lobster Claw Two, *Heliconia rostrata*, *Heliconia psittacorum* cv. Red Opal, and *Heliconia psittacorum* × *Heliconia spathocircinata* cv. Golden Torch grown under full-sun conditions in the Submiddle São Francisco Valley, Brazil. Treatments consisted of SA at 0, 100, 200, and 300 mg L⁻¹ and kaolin at 50 g L⁻¹, arranged in a randomized complete block design. Chlorophyll *a* fluorescence, photosynthetic pigments, membrane integrity, vegetative growth, and floral stem quality were evaluated. Foliar treatments modulated PSII photochemistry, photosynthetic pigment contents, and membrane integrity, with responses depending on species, treatment, and phenological phase. Among the evaluated species, *H. rostrata* showed the most consistent favorable physiological responses, particularly to kaolin and SA at 100 and 200 mg L⁻¹ during the reproductive phase. However, these physiological and biochemical responses were not consistently translated into improved vegetative growth or floral stem quality compared with the water control, with these traits remaining predominantly species-dependent. Overall, SA and kaolin induced species-specific physiological adjustments in *Heliconia* under full-sun semi-arid conditions, but no generalized beneficial effect was observed across the evaluated species, highlighting the importance of species-specific management when considering these compounds as photoprotective strategies.

Keywords: Chlorophyll fluorescence, membrane integrity, photosynthetic pigments, tropical floriculture.

Resumo

A floricultura tropical é uma atividade economicamente relevante, particularmente para a agricultura familiar, devido ao alto valor agregado das flores de corte e ao potencial de rápido retorno financeiro. Entre as ornamentais tropicais, as espécies de *Heliconia* são valorizadas pela diversidade de cores e formas. No entanto, o cultivo em condições de pleno sol em regiões semiáridas expõe as plantas à elevada irradiância solar, o que pode limitar o desempenho fisiológico e o crescimento. Este estudo avaliou os efeitos de aplicações foliares de ácido salicílico (AS) e caulim sobre as respostas fisiológicas, o crescimento vegetativo e a qualidade das hastes florais de *Heliconia bihai* cv. Lobster Claw Two, *Heliconia rostrata*, *Heliconia psittacorum* cv. Red Opal e *Heliconia psittacorum* × *Heliconia spathocircinata* cv. Golden Torch cultivadas em condições de pleno sol no Submédio do Vale do São Francisco, Brasil. Os tratamentos consistiram de AS nas concentrações de 0, 100, 200 e 300 mg L⁻¹ e caulim a 50 g L⁻¹, dispostos em delineamento em blocos casualizados. Foram avaliadas a fluorescência da clorofila *a*, os pigmentos fotossintéticos, a integridade de membranas, o crescimento vegetativo e a qualidade das hastes florais. Os tratamentos foliares modularam a fotoquímica do fotossistema II (FSII), os teores de pigmentos fotossintéticos e a integridade de membranas, com respostas dependentes da espécie, do tratamento e da fase fenológica. Entre as espécies avaliadas, *H. rostrata* apresentou as respostas fisiológicas favoráveis mais consistentes, particularmente ao caulim e ao AS nas concentrações de 100 e 200 mg L⁻¹ durante a fase reprodutiva. Entretanto, essas respostas fisiológicas e bioquímicas não se traduziram consistentemente em melhorias no crescimento vegetativo ou na qualidade das hastes florais em comparação com o controle com água, permanecendo essas características predominantemente dependentes da espécie. De modo geral, o AS e o caulim induziram ajustes fisiológicos específicos para cada espécie de *Heliconia* sob condições de pleno sol em ambiente semiárido, mas não foi observado efeito benéfico generalizado entre as espécies avaliadas, destacando a importância de um manejo específico para cada espécie ao considerar o uso desses compostos como estratégias fotoprotetoras.

Palavras-chave: Floricultura tropical, fluorescência da clorofila, integridade de membranas, pigmentos fotossintéticos.

Introduction

Heliconia species stand out in the tropical flower market due to the high ornamental value of their inflorescences, their wide diversity of shapes and colors, and their postharvest durability, characteristics that confer significant economic and cultural relevance. Although they are adapted to humid tropical regions, their commercial cultivation has traditionally been concentrated in areas with high relative humidity, water availability, and natural shading, conditions that favor vegetative growth and inflorescences production (Malakar et al., 2023). However, the growing demand for tropical

flowers has driven the expansion of cultivation to new production regions (Hernández-Chontal et al., 2025), including irrigated semi-arid areas such as the Submiddle São Francisco Valley. This region offers strategic advantages, including well-established irrigation infrastructure and favorable conditions for year-round production. Nevertheless, plant performance and flower stem quality depend on the interaction between genotype and growing conditions, particularly light intensity and temperature, which, when excessive, may impair the photosynthetic apparatus, vegetative growth, and productivity (Souza et al., 2023).

In this context, plant regulators and photoprotective products have been investigated as strategies to improve plant response to high-irradiance conditions. Salicylic acid is a signaling molecule involved in plant responses to abiotic stress and has been associated with the regulation of physiological and antioxidant responses (Yang et al., 2023). Kaolin, in turn, acts as a reflective particle film (physical barrier) that reduces the amount of solar radiation absorbed by leaf surfaces and may alleviate the effects of excessive irradiance (Xavier et al., 2023). Because salicylic acid and kaolin act through distinct mechanisms, their comparative evaluation under the same growing conditions may provide complementary information on the responses of *Heliconia* species to high solar irradiance. However, the magnitude of these responses may vary among genotypes, as different genetic materials can exhibit distinct physiological strategies for acclimation to environmental conditions (Kochetova et al., 2022).

Despite the potential of these strategies, information remains limited on how different *Heliconia* genotypes respond to salicylic acid and kaolin when cultivated under full-sun conditions, particularly in semi-arid environments. Previous studies conducted under semi-arid conditions have demonstrated that the light environment affects the physiological and agronomic performance of *Heliconia*, both under different shading conditions and under high solar irradiance (Souza et al., 2016; Souza et al., 2023). In addition, kaolin, combined with boron and zinc, has shown potential to mitigate the effects of light stress in *Heliconias* grown under semi-arid conditions (Xavier et al., 2023). However, it remains unclear whether responses to salicylic acid and kaolin under the same growing conditions differ among *Heliconia* genotypes and whether treatment-induced changes in physiological and photochemical traits are accompanied by changes in vegetative growth, flower stem quality, and productivity.

Thus, integrating physiological and agronomic traits may provide a more comprehensive understanding of species-specific responses and support management strategies for tropical flower production under high-irradiance conditions. We hypothesized that *Heliconia* species differ in their responses to salicylic acid and kaolin under full-sun conditions, with these treatments mitigating the effects of high solar irradiance in a species-dependent manner. Therefore, this study aimed to evaluate the effects of salicylic acid and kaolin on the physiological performance, growth, and floral stem quality of different *Heliconia* species cultivated under full sun in the Submiddle São Francisco Valley, Brazil.

Material and Methods

The experiment was conducted from October 2024 to December 2025 in the Sub-middle São Francisco Valley region (9°19'16" S, 40°32'44" W, 387 m above sea level). According to the Köppen climate classification, the region has a BSh climate, characterized as hot semi-arid, with rainfall occurring predominantly from February to April. Meteorological data on air temperature, relative humidity, and global solar radiation were obtained from an automatic weather station (Davis Vantage Pro2), located approximately 1,600 m from the experimental area. During the experimental period, air temperature ranged from 15.3 to 37.0 °C, with a mean of 27.16 °C. Relative humidity ranged from 12.9% to 92.7%, with a mean of 53.81%, while mean daily global solar radiation was 22.54 MJ m⁻² day⁻¹. Cumulative rainfall during the experimental period was 378 mm. The soil of the experimental area had a sandy texture. At a depth of 20–40 cm, the particle-size distribution consisted of 87.75% sand, 4.55% silt, and 7.69% clay, with a soil bulk density of 1.61 g cm⁻³. Regarding soil fertility, the organic matter content was 3.0 g dm⁻³ (Walkley–Black method), pH (H₂O) was 5.37, electrical conductivity was 0.18 dS m⁻¹ (saturation paste extract), phosphorus content was 7.7 mg dm⁻³ (Mehlich⁻¹ method), calcium was 0.59 cmolc dm⁻³, magnesium was 0.09 cmolc dm⁻³, potassium was 0.14 cmolc dm⁻³, and sodium was 0.011 cmolc dm⁻³.

Planting was carried out on October 16, 2024. At planting, 2 L of organic compost (well-cured goat manure), 122.7 g of urea (61% N), 200 g of potassium chloride (KCl; 60% K₂O), 73.8 g of monoammonium phosphate (MAP; 9% N and 48% P), and 20 g of hydrated lime were incorporated into each planting hole (Segovia, 2020). Seedlings were planted in holes measuring 20 cm in width and 20 cm in depth, with one seedling per planting hole, using a spacing of 1.5 m between plants and 2.0 m between rows. Irrigation was performed using a microsprinkler system with a nominal flow rate of 55 L h⁻¹. Initially, irrigation was applied to raise the soil moisture to field capacity; subsequently, irrigation

management was based on crop evapotranspiration (ET_c), with irrigation intervals adjusted to the actual water demand of the plants, aiming to optimize water use.

The experimental design was a randomized complete block design in a 4 × 5 factorial arrangement, with four replications and one plant per experimental plot, totaling 80 experimental units. Each experimental plot consisted of a single plant due to the large size and clumping growth habit of *Heliconia*, as well as the 1.5 × 2.0 m spacing required for adequate plant development and to minimize interference among neighboring plants. The use of a single plant per experimental plot has also been adopted in previous field experiments with *Heliconia* (Souza et al., 2024). Within each block, the 20 treatment combinations were randomly assigned to the experimental plots through a random draw, with each treatment combination represented once per block. The first factor consisted of four *Heliconia* species: *H. bihai* cv. Lobster Claw Two, *H. rostrata*, *H. psittacorum* cv. Red Opal and *H. psittacorum* × *H. spathocircinata* cv. Golden Torch. The second factor consisted of five photoprotective foliar treatments: salicylic acid (SA) at concentrations of 0 mg L⁻¹ (water application), 100, 200, and 300 mg L⁻¹, and Surround® WP (95% w/w kaolin; median particle size of 1.4 µm) at a concentration of 50 g L⁻¹, based on Xavier et al. (2023).

Treatments were applied every 30 days, by foliar spraying, always in the morning, in an amount sufficient to completely wet the plants, and Tween 20 was added as a surfactant at 0.1% (v/v) to solutions. The first application was performed at 99 days after planting (DAP) (January 23, 2025), when the plants were already established in the field and exhibited uniform growth, and the last application was performed at 286 DAP (July 29, 2025), when the plants were at the full reproductive stage, totaling seven applications.

For physiological parameters, two evaluations were performed. The first evaluation was conducted on March 11, 2025 (146 DAP), corresponding to the vegetative phase of plant. The second evaluation was conducted on April 24, 2025 (190 DAP), corresponding to the reproductive phase. The same plant was used for both evaluations.

Chlorophyll *a* Fluorescence, Membrane Integrity and Photosynthetic Pigments

Chlorophyll *a* fluorescence was estimated using a portable fluorometer (PAR-FluorPen FP 110, Photon Systems Instruments). Measurements were performed in the morning on leaves previously dark-adapted using detachable leaf clips for a period of 30 minutes. The leaves were illuminated over a 4-mm diameter area using an array of six LEDs and a light pulse of 3000 µmol m⁻² s⁻¹. Initial fluorescence (F₀), maximum fluorescence (F_m), and variable fluorescence (F_v) values were recorded. Based on these parameters, the maximum quantum efficiency of photosystem II (PSII) (F_v/F_m), absorbed photon flux per reaction center (ABS/RC), electron transport flux per reaction center (ETo/RC), and energy dissipation per reaction center (Dio/RC) were calculated.

Membrane integrity was indirectly assessed through electrolyte leakage, estimated according to Blum and Ebercon (1981), with modifications adapted to the present study. The percentage of ionic leakage or electrolyte loss was calculated using Equation 1.

$$MI = (1 - C1/C2) \times 100 \quad (1)$$

where MI is membrane integrity (%), C1 is the initial electrical conductivity of the solution, and C2 is the final electrical conductivity of the solution.

The quantification of chlorophylls (*a*, *b*, and total) and carotenoids, expressed as mg g⁻¹ FW, was performed according to the methodology adapted from Lichtenthaler (1987). Pigment concentrations were calculated using Equations 2–5 for chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), total chlorophyll (Total Chl), and carotenoid content, respectively. The variables A663, A646, and A470 represent the absorbance values measured at wavelengths of 663, 646, and 470 nm, respectively.

$$\text{Chl } a = 12.25 \times A663 - 2.79 \times A646 \quad (2)$$

$$\text{Chl } b = 21.5 \times A646 - 5.1 \times A663 \quad (3)$$

$$\text{Total Chl} = \text{Chl } a + \text{Chl } b \quad (4)$$

$$\text{Carotenoid} = (1000 \times A470 - 1.82 \times \text{Chl } a - 85.02 \times \text{Chl } b) / 198 \quad (5)$$

Growth and Quality of Floral Stems

Vegetative growth was assessed based on the relative increment in plant height (PH, %), number of tillers per clump (NT, %), total leaf area per clump (TLA, %), and clump area (CA, %) between 98 and 190 DAP. At each of these evaluations, plant height, number of tillers, and total number of leaves (NL) per clump were recorded. Total leaf area was estimated according to Zucoloto et al. (2008) using Equation 6:

$$TLA = 0.5187 (W \times L \times NL) + 9,603.5 \quad (6)$$

where TLA is the estimated total leaf area, W and L are leaf width and length, respectively, and NL is the total number of leaves per clump. Clump area was estimated using Equation 7, considering the clump as an ellipse:

$$CA = (\pi \times L \times W) / 4 \quad (7)$$

where CA is the estimated clump area, L is the maximum clump length, and W is the maximum clump width measured perpendicular to the length.

Flowering began at 159 DAP. Floral stems were harvested when the inflorescences exhibited two to three open bracts, preferentially in the morning or late afternoon, when temperatures were milder. At harvest, floral stem quality was evaluated based on floral stem length (FSL, cm), stem diameter (SD, mm), inflorescence length (IL, cm), inflorescence width (IW, cm), and relative water content (RWC, %). FSL was measured from the base of the stem to the point of inflorescence insertion; SD was measured 20 cm below the inflorescence; IL was measured from the base to the apex of the inflorescence; and IW was measured at the point of greatest lateral expansion.

For RWC determination, a 20-cm stem segment was collected below the inflorescence and immediately weighed to obtain the fresh weight (FW). The segments were then immersed in water for 4 h to reach full turgidity and weighed to obtain the turgid weight (TW). Subsequently, the samples were dried in a forced-air circulation oven at 70 °C for 72 h and weighed to obtain the dry weight (DW). RWC was calculated using Equation 8:

$$RWC (\%) = [(FW - DW) / (TW - DW)] \times 100 \quad (8)$$

where FW is the fresh weight, TW is the turgid weight, and DW is the dry weight of the stem segment.

The data were initially subjected to the Shapiro-Wilk test to assess normality, and homogeneity of variances was also evaluated. The statistical model included species, foliar treatments, and their interaction, with blocks included according to the randomized complete block design. Variables that met the assumptions for parametric analysis were subjected to analysis of variance (ANOVA), and significant effects were followed by the Scott-Knott test at the 5% probability level using SISVAR software (Ferreira, 2014). This approach was used for maximum quantum efficiency of photosystem II (Fv/Fm), absorbed photon flux per reaction center (ABS/RC), electron transport flux per reaction center (ETo/RC), energy dissipation per reaction center (Dio/RC), membrane integrity (MI), chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), total chlorophyll (Total Chl), chlorophyll *a/b* ratio (Chl *a/b*), carotenoid content (CC), floral stem length (FSL), stem diameter (SD), inflorescence length (IL), inflorescence width (IW), and relative water content (RWC).

For the relative increment in plant height (PH), number of tillers (NT), total leaf area per clump (TLA), and clump area (CA), which did not meet the assumptions for parametric analysis, data transformation was initially attempted. When the assumptions were not met after transformation, the Aligned Rank Transform (ART) method was applied using the ARTTool package in R, preserving the factorial structure of the experiment. Significant main effects detected by the ART analysis were followed by pairwise comparisons with Tukey adjustment at the 5% probability level using the emmeans package in R.

Results and Discussion

For the chlorophyll *a* fluorescence parameters during the vegetative phase, significant effects of species and foliar treatment were observed

for the maximum quantum efficiency of PSII (Fv/Fm), whereas ETo/RC was significantly affected only by species (Table 1). No significant effects were detected for ABS/RC or Dio/RC. No significant species $\times$ foliar treatment interaction was observed for any of the chlorophyll fluorescence parameters evaluated during this phase.

Across species and foliar treatments, Fv/Fm values ranged from 0.60 to 0.66 (Table 1), remaining below the range of 0.75-0.83 reported for non-stressed plants (Guidi et al., 2019). Reduced Fv/Fm reflects a decrease in the maximum photochemical efficiency of PSII and is commonly associated with photoinhibitory conditions (Xia et al., 2023; Kardiman et al., 2025). Under high irradiance, the amount of absorbed light energy may exceed the capacity for photochemical utilization, increasing excitation pressure on PSII and favoring photoinhibition (Chen et al., 2023). Considering that the *Heliconia* species were cultivated under full-sun conditions and exposed to high solar radiation throughout the experimental period, the reduced Fv/Fm values observed here are consistent with photoinhibitory pressure associated with the high-irradiance environment.

Among the species, *H. bihai* exhibited the highest Fv/Fm (0.66), differing significantly from *H. rostrata*, Red Opal, and Golden Torch (0.60-0.62) (Table 1). This response indicates that *H. bihai* maintained higher maximum photochemical efficiency of PSII during the vegetative phase, suggesting a lower degree of photoinhibition under the prevailing high-irradiance conditions. When averaged across species, 100 and 300 mg L⁻¹ SA resulted in the highest Fv/Fm values (0.65), differing significantly from kaolin, water control and 200 mg L⁻¹ SA. This response suggests that specific SA concentrations contributed to maintaining PSII photochemical efficiency under experimental conditions.

For ETo/RC, *H. bihai* and cv. Golden Torch showed significantly higher values (0.79 and 0.73, respectively) than *H. rostrata* and Red Opal (0.69 and 0.64, respectively) (Table 1). Higher ETo/RC indicates greater electron transport flux per active PSII reaction center and suggests differences among genotypes in the organization and functioning of the photosynthetic apparatus under high-irradiance conditions. These genotype-dependent responses may reflect distinct strategies for managing excitation energy and maintaining PSII functionality under environmental stress (Swoczyna et al., 2022; Kochetova et al., 2022).

A significant species $\times$ foliar treatment interaction was observed for membrane integrity (MI) and all photosynthetic pigment variables, including chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), total chlorophyll (Total Chl), carotenoid content, and the Chl *a/b* ratio during the vegetative phase (Table 1). Therefore, the significant interactions were further examined by comparing foliar treatments within each species and species within each foliar treatment (Fig. 1), allowing the identification of species-specific responses to salicylic acid concentrations and kaolin.

For membrane integrity (MI), the effects of foliar treatments differed among species (Fig. 1A). No significant differences among treatments were observed for *H. bihai* cv. Lobster Claw Two and Golden Torch. In *H. rostrata*, the water control resulted in the highest MI, whereas kaolin and 100 mg L⁻¹ SA showed intermediate values, and the lowest MI was observed with 200 and 300 mg L⁻¹ SA. In contrast, Red Opal showed higher MI with kaolin and all SA concentrations compared with the water control. Comparisons among species within each foliar treatment further revealed that MI did not differ among species under kaolin and 100 mg L⁻¹ SA. Under the water control, Red Opal showed lower MI than the other species. At 200 mg L⁻¹ SA, Lobster Claw Two and Red Opal showed higher MI than *H. rostrata* and Golden Torch, whereas at 300 mg L⁻¹ SA, *H. rostrata* showed lower MI than the other species.

The contrasting responses of *H. rostrata* and Red Opal reinforce the species- and concentration-dependent effects of the foliar treatments on membrane stability. Notably, differences among species varied according to the treatment applied, further supporting the significant species $\times$ foliar treatment interaction. In *H. rostrata*, the reduction in MI at 200 and 300 mg L⁻¹ SA indicates that increasing SA concentration did not improve membrane stability under the experimental conditions. Conversely, in Red Opal, both kaolin and SA treatments resulted in higher membrane integrity than the water control. Salicylic acid has been associated with the maintenance of membrane stability under abiotic stress, including reductions in electrolyte leakage (Mendonça et al., 2022). However, the contrasting responses observed among *Heliconia* species indicate that this effect cannot be generalized and may depend on SA concentration.

Foliar treatments significantly affected chlorophyll contents within all species, with responses varying according to pigment and species (Fig. 1B-D). In *H. bihai* cv. Lobster Claw Two, 300 mg L⁻¹ SA resulted in the highest Chl *a*, Chl *b*, and Total Chl contents, whereas the lowest values occurred with 200 mg L⁻¹ SA for Chl *a* and Total Chl and with 100 mg L⁻¹ SA for Chl *b*. In *H. rostrata*, 200 mg L⁻¹ SA consistently resulted in the highest chlorophyll contents, not differing from kaolin for Chl *a* and Total Chl; 300 mg L⁻¹ SA generally produced intermediate values, while the water control and 100 mg L⁻¹ SA showed the lowest values.

In *H. psittacorum* cv. Red Opal, 300 mg L⁻¹ SA resulted in the highest Chl *a*, Chl *b*, and Total Chl contents. For Chl *a* and Total Chl, kaolin, the water control, and 200 mg L⁻¹ SA did not differ, whereas 100 mg L⁻¹ SA resulted in the lowest values; for Chl *b*, the water control and 100 and 200 mg L⁻¹ SA did not differ, while kaolin resulted in the lowest value. In *H.*

psittacorum × *H. spathocircinata* cv. Golden Torch, 100 and 200 mg L⁻¹ SA resulted in the highest Chl *a* and Total Chl contents, while 200 mg L⁻¹ SA alone resulted in the highest Chl *b* content (Fig. 1B-1D).

Comparisons among species within each foliar treatment further evidenced the interaction. For Chl *a* and Total Chl, *H. rostrata* showed the highest values under kaolin, whereas *H. rostrata* and Red Opal showed the highest values under the water control. At 100 mg L⁻¹ SA, Golden Torch showed the highest Chl *a* and Total Chl contents, while at 200 mg L⁻¹ SA, *H. rostrata* showed the highest values. Conversely, at 300 mg L⁻¹ SA, Lobster Claw Two and Red Opal showed higher Chl *a* and Total Chl contents than *H. rostrata* and Golden Torch. For Chl *b*, differences among species were absent under the water control and 300 mg L⁻¹ SA, whereas under kaolin and 200 mg L⁻¹ SA, *H. rostrata* and Golden Torch showed the highest values (Fig. 1B-1D).

Table 1. Summary of the analysis of variance for maximum quantum efficiency of photosystem II (Fv/Fm), absorbed photon flux per reaction center (ABS/RC), electron transport flux per reaction center (ETo/RC), energy dissipation per reaction center (Dio/RC), membrane integrity (MI), chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), total chlorophyll (Total Chl), chlorophyll *a/b* ratio (Chl *a/b*) and carotenoid content (CC) in *Heliconia* species subjected to foliar treatments with salicylic acid (SA) and kaolin during the vegetative phase (146 DAP).

Source of variation	Fv/Fm -	ABS/RC -	ETo/RC -	Dio/RC -	MI (%)	Chl <i>a</i> (mg g ⁻¹ FW)	Chl <i>b</i> (mg g ⁻¹ FW)	Total Chl (mg g ⁻¹ FW)	Chl <i>a/b</i> -	CC (mg g ⁻¹ FW)
Species (A) ("F")	3.01 *	0.45 ns	4.52 **	0.79 ns	4.08 *	93.13 **	38.24 **	120.57 **	4.00 *	17.05 **
HLC	0.66 a	3.38	0.79 a	1.15	80.20 a	405.60 c	134.70 b	540.30 c	3.20 a	98.49 b
HR	0.60 b	3.40	0.69 b	1.36	76.94 b	568.03 a	185.67 a	753.70 a	3.18 a	125.31 a
HRO	0.62 b	3.19	0.64 b	1.23	78.53 b	418.72 c	143.95 b	562.67 c	3.05 a	91.61 b
HGT	0.62 b	3.29	0.73 a	1.25	80.15 a	442.83 b	175.99 a	618.86 b	2.75 b	94.05 b
Foliar treatments (B) ("F")	2.69 *	2.03 ns	1.13 ns	2.08 ns	2.36 ns	70.01 **	27.48 **	82.99 **	11.52 **	6.67 **
Kaolin	0.61 b	3.36	0.73	1.33	79.80	502.66 b	148.34 b	651.00 b	3.54 a	106.98 a
0 mg L ⁻¹ SA	0.62 b	3.20	0.67	1.21	80.72	399.87 d	137.72 b	539.60 c	2.97 b	91.66 b
100 mg L ⁻¹ SA	0.65 a	3.39	0.75	1.19	78.61	386.11 d	141.62 b	527.73 c	3.20 b	94.53 b
200 mg L ⁻¹ SA	0.60 b	3.61	0.68	1.46	72.27	446.59 c	185.03 a	631.62 b	2.46 c	100.19 b
300 mg L ⁻¹ SA	0.65 a	3.01	0.73	1.05	77.37	558.78 a	185.68 a	744.46 a	3.06 b	118.47 a
Species x Foliar treatments (A x B) ("F")	1.14 ns	0.57 ns	1.08 ns	0.69 ns	4.57 **	60.44 **	18.10 **	68.95 **	9.58 **	9.07 **
C.V. (%)	8.32	16.51	16.75	29.57	3.77	6.51	9.62	5.46	13.20	14.07

HLC = *Heliconia bihai* cv. Lobster Claw Two; HR = *Heliconia rostrata*; HRO = *Heliconia psittacorum* cv. Red Opal; HGT = *Heliconia psittacorum* × *Heliconia spathocircinata* cv. Golden Torch. Values are expressed as means. Within each factor, means followed by different letters in the same column differ according to the Scott-Knott test ($p \leq 0.05$). ns = not significant; * and ** indicate significance at the 5 and 1% probability levels, respectively; C.V. = coefficient of variation.

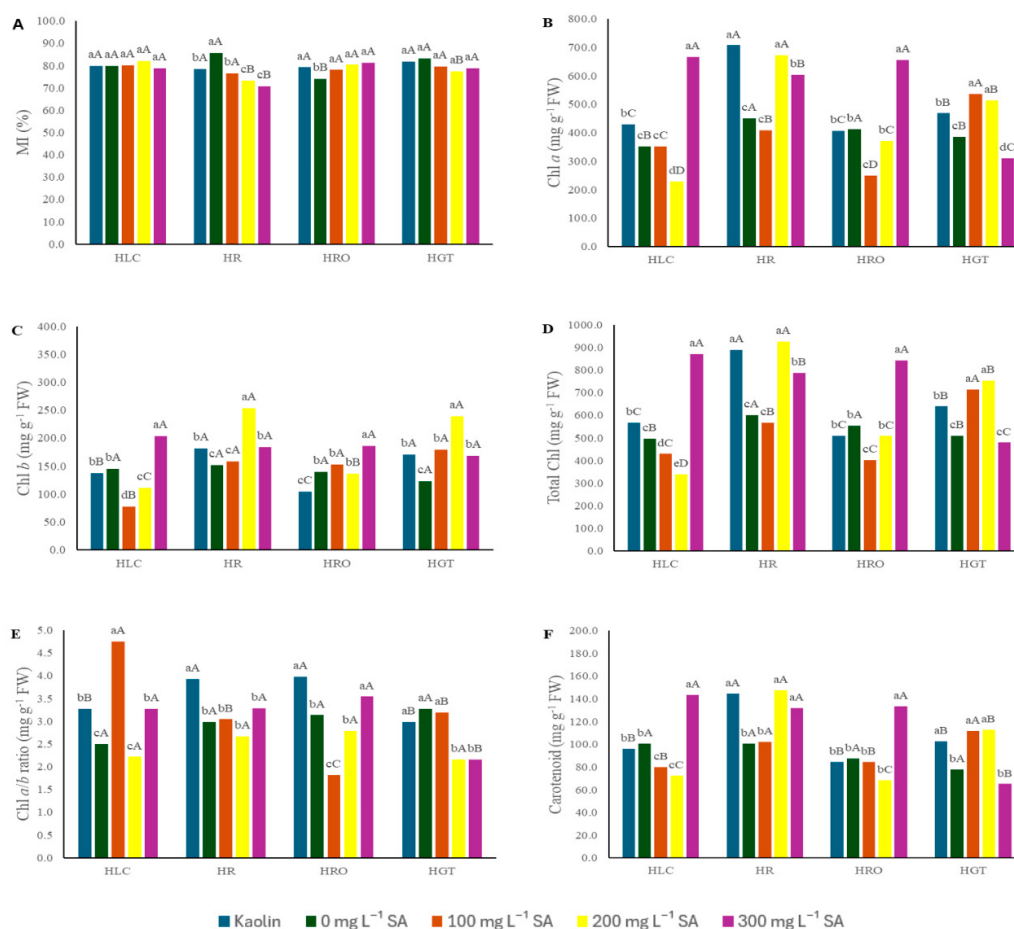


Fig. 1. Membrane integrity (MI) (A), chlorophyll *a* (Chl *a*) (B), chlorophyll *b* (Chl *b*) (C), total chlorophyll (Total Chl) (D), Chl *a/b* ratio (E), and carotenoid content (F) of *Heliconia* species subjected to foliar treatments with salicylic acid (SA) and kaolin during the vegetative phase (146 DAP). Means followed by the same lowercase letter within each species and the same uppercase letter within each foliar treatment do not differ according to the Scott-Knott test ($p \leq 0.05$). HLC = *Heliconia bihai* cv. Lobster Claw Two; HR = *Heliconia rostrata*; HRO = *Heliconia psittacorum* cv. Red Opal; HGT = *Heliconia psittacorum* × *Heliconia spathocircinata* cv. Golden Torch.

Comparisons among species within each foliar treatment further evidenced the interaction. For Chl *a* and Total Chl, *H. rostrata* showed the highest values under kaolin, whereas *H. rostrata* and Red Opal showed the highest values under the water control. At 100 mg L⁻¹ SA, Golden Torch showed the highest Chl *a* and Total Chl contents, while at 200 mg L⁻¹ SA, *H. rostrata* showed the highest values. Conversely, at 300 mg L⁻¹ SA, Lobster Claw Two and Red Opal showed higher Chl *a* and Total Chl contents than *H. rostrata* and Golden Torch. For Chl *b*, no differences among species were observed under the water control or 300 mg L⁻¹ SA. Under kaolin and 200 mg L⁻¹ SA, *H. rostrata* and Golden Torch showed the highest values, whereas at 100 mg L⁻¹ SA, *H. rostrata*, Red Opal, and Golden Torch showed higher values than Lobster Claw Two (Fig. 1B-1D).

Overall, the shifts in chlorophyll contents both among treatments within species and among species within treatments demonstrate that chlorophyll responses were species- and concentration-dependent. The highest chlorophyll contents were generally associated with 300 mg L⁻¹ SA in *H. bihai* cv. Lobster Claw Two and *H. psittacorum* cv. Red Opal, whereas 200 mg L⁻¹ SA was associated with higher chlorophyll contents in *H. rostrata* and *H. psittacorum* × *H. spathocircinata* cv. Golden Torch. Salicylic acid has been associated with the regulation of physiological and antioxidant responses under abiotic stress, which may contribute to the maintenance of photosynthetic pigments by limiting chlorophyll degradation under stressful conditions (Yang et al., 2023; Elsis et al., 2024). However, the contrasting responses among species and SA concentrations indicate that the effects of SA on chlorophyll content cannot be generalized across *Heliconia* species.

The significant species × foliar treatment interaction for the Chl *a/b* ratio was characterized by contrasting treatment responses among species (Fig. 1E). In *H. bihai* cv. Lobster Claw Two, 100 mg L⁻¹ SA resulted in the highest Chl *a/b* ratio, followed by kaolin and 300 mg L⁻¹ SA, whereas the water control and 200 mg L⁻¹ SA showed the lowest values. In *H. rostrata*, kaolin resulted in the highest Chl *a/b* ratio, while the water control and all SA concentrations did not differ. In *H. psittacorum* cv. Red Opal, kaolin and 300 mg L⁻¹ SA did not differ and resulted in the highest ratios, followed by the water control and 200 mg L⁻¹ SA, whereas 100 mg L⁻¹ SA resulted in the lowest value. In *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, kaolin, the water control, and 100 mg L⁻¹ SA did not differ and resulted in higher Chl *a/b* ratios than 200 and 300 mg L⁻¹ SA. Comparisons among species within each foliar treatment further showed that *H. rostrata* and Red Opal had higher Chl *a/b* ratios than Lobster Claw Two and Golden Torch under kaolin (Fig. 1E). No differences among species were observed under the water control or 200 mg L⁻¹ SA. At 100 mg L⁻¹ SA, Lobster Claw Two showed the highest ratio, followed by *H. rostrata* and Golden Torch, while Red Opal showed the lowest value. At 300 mg L⁻¹ SA, Golden Torch showed a lower ratio than the other species.

Changes in the Chl *a/b* ratio indicate adjustments in the organization of the photosynthetic apparatus, particularly in the relative investment in light-harvesting complexes and reaction centers. Light-harvesting proteins bind both Chl *a* and Chl *b*, whereas reaction-center proteins predominantly bind Chl *a*; therefore, the Chl *a/b* ratio can be used as an indicator of the relative abundance of light-harvesting complexes in relation to reaction centers (Gjindali and Johnson, 2023). The contrasting responses both

among treatments within species and among species within treatments reinforce the species-dependent nature of this response and suggest adjustments in chlorophyll composition and light-harvesting organization rather than a uniform response of the photosynthetic apparatus. The variation in pigment contents observed in the present study is consistent with Leite et al. (2023), who also reported differences in photosynthetic pigment contents among *Heliconia* species under contrasting cultivation conditions, reinforcing the influence of species and growing environment on pigment responses.

The significant species $\times$ foliar treatment interaction for carotenoid content was characterized by contrasting treatment responses among species (Fig. 1F). In *H. bihai* cv. Lobster Claw Two, 300 mg L⁻¹ SA resulted in the highest carotenoid content, whereas kaolin and the water control did not differ, and 100 and 200 mg L⁻¹ SA showed the lowest values. In *H. rostrata*, kaolin and 200 and 300 mg L⁻¹ SA did not differ and resulted in higher carotenoid contents than the water control and 100 mg L⁻¹ SA. In *H. psittacorum* cv. Red Opal, 300 mg L⁻¹ SA resulted in the highest carotenoid content, whereas the remaining treatments did not differ from each other. In *H. psittacorum* $\times$ *H. spathocircinata* cv. Golden Torch, kaolin and 100 and 200 mg L⁻¹ SA did not differ and resulted in higher carotenoid contents than the water control and 300 mg L⁻¹ SA.

Comparisons among species within each foliar treatment further evidenced this interaction. Under kaolin, *H. rostrata* showed higher carotenoid content than the other species, whereas no differences among species were observed under the water control. At 100 mg L⁻¹ SA, *H. rostrata* and Golden Torch showed higher carotenoid contents than Lobster Claw Two and Red Opal. At 200 mg L⁻¹ SA, *H. rostrata* showed the highest carotenoid content, followed by Golden Torch, while Lobster Claw Two and Red Opal showed the lowest values. Conversely, at 300 mg L⁻¹ SA, Golden Torch showed lower carotenoid content than the other species (Fig. 1F).

Carotenoids play an important role in photoprotection under excess irradiance by participating in the dissipation of excess excitation energy and the quenching of reactive oxygen species, thereby contributing to the protection of the photosynthetic apparatus against photo-oxidative damage (Xavier et al., 2023; Souza et al., 2024). In the present study, the contrasting responses both among treatments within species and among species within treatments demonstrate that carotenoid adjustments were species- and concentration-dependent. While 300 mg L⁻¹ SA resulted in the highest carotenoid content in *H. bihai* cv. Lobster Claw Two and *H. psittacorum* cv. Red Opal, 200 mg L⁻¹ SA was among the treatments associated with higher carotenoid content in *H. rostrata*, whereas 100 and 200 mg L⁻¹ SA and kaolin were associated with higher contents in Golden Torch. These contrasting responses indicate that adjustments in the carotenoid pool in response to foliar treatments cannot be generalized across *Heliconia* species.

Overall, the species- and treatment-dependent changes in photosynthetic pigment contents observed during the vegetative phase may reflect physiological adjustments to the high-irradiance environment rather than direct evidence of improved PSII performance. Similarly, Approbato et al. (2023) reported adjustments in chlorophyll content in

Panicum maximum while PSII photochemistry remained unaffected, suggesting that changes in pigment composition may be part of the acclimation of the photosynthetic apparatus to environmental conditions.

During the reproductive phase (190 DAP), significant species $\times$ foliar treatment interactions were observed for Fv/Fm, ABS/RC, DIO/RC, MI, Chl *a*, Chl *b*, Total Chl, Chl *a/b* ratio, and carotenoid content (Table 2). In contrast, ETo/RC was not affected by the species $\times$ foliar treatment interaction, although significant main effects of both species and foliar treatments were detected.

For Fv/Fm, the effect of foliar treatments differed among species during the reproductive phase (Fig. 2A). In *H. bihai* cv. Lobster Claw Two and *H. psittacorum* cv. Red Opal, Fv/Fm did not differ among foliar treatments. In *H. rostrata*, kaolin and 100 and 200 mg L⁻¹ SA did not differ and resulted in higher Fv/Fm values than the water control and 300 mg L⁻¹ SA. In *H. psittacorum* $\times$ *H. spathocircinata* cv. Golden Torch, kaolin, the water control, and 200 mg L⁻¹ SA did not differ and resulted in higher Fv/Fm values than 100 and 300 mg L⁻¹ SA. Comparisons among species within each foliar treatment (Fig. 2A) showed no differences under kaolin or the water control. At 100 mg L⁻¹ SA, Golden Torch showed lower Fv/Fm than the other species; at 200 mg L⁻¹ SA, Red Opal and Golden Torch showed lower values than Lobster Claw Two and *H. rostrata*; and at 300 mg L⁻¹ SA, *H. rostrata* and Golden Torch showed lower values than Lobster Claw Two and Red Opal.

For ABS/RC, foliar treatments did not result in significant differences within *H. bihai* cv. Lobster Claw Two, *H. rostrata*, or *H. psittacorum* cv. Red Opal (Fig. 2B). In *H. psittacorum* $\times$ *H. spathocircinata* cv. Golden Torch, 100 and 300 mg L⁻¹ SA resulted in higher ABS/RC values than kaolin, the water control, and 200 mg L⁻¹ SA. Comparisons among species (Fig. 2B) showed no differences under kaolin or 200 mg L⁻¹ SA. Under the water control, Red Opal showed lower ABS/RC than the other species. At 100 mg L⁻¹ SA, Golden Torch showed higher ABS/RC than the other species, whereas at 300 mg L⁻¹ SA, *H. rostrata* and Golden Torch showed higher values than Lobster Claw Two and Red Opal.

For DIO/RC, foliar treatments did not differ within *H. bihai* cv. Lobster Claw Two or *H. psittacorum* cv. Red Opal (Fig. 2C). In *H. rostrata*, kaolin and 100 and 200 mg L⁻¹ SA resulted in lower DIO/RC values than the water control and 300 mg L⁻¹ SA. In *H. psittacorum* $\times$ *H. spathocircinata* cv. Golden Torch, 100 and 300 mg L⁻¹ SA resulted in higher DIO/RC values than kaolin, the water control, and 200 mg L⁻¹ SA. Comparisons among species (Fig. 2C) within each foliar treatment showed no differences under kaolin, the water control, or 200 mg L⁻¹ SA. At 100 mg L⁻¹ SA, Golden Torch showed higher DIO/RC than the other species. At 300 mg L⁻¹ SA, Golden Torch showed the highest DIO/RC, followed by *H. rostrata*, whereas Lobster Claw Two and Red Opal showed the lowest values.

For ETo/RC, the species $\times$ foliar treatment interaction was not significant. *H. rostrata* showed the highest mean value (0.96) when averaged across foliar treatments, whereas the other species formed a lower-value group (0.80-0.84). Regarding foliar treatments, kaolin and 100 and 200 mg L⁻¹ SA resulted in higher ETo/RC values (0.88-0.91) than the water control and 300 mg L⁻¹ SA (Table 2).

Table 2. Summary of the analysis of variance for maximum quantum efficiency of photosystem II (Fv/Fm), absorbed photon flux per reaction center (ABS/RC), electron transport flux per reaction center (ETo/RC), energy dissipation per reaction center (Dio/RC), membrane integrity (MI), chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), total chlorophyll (Total Chl), chlorophyll *a/b* ratio (Chl *a/b*) and carotenoid content (CC) in *Heliconia* species subjected to foliar treatments with salicylic acid (SA) and kaolin during the reproductive phase (190 DAP).

Source of variation	Fv/Fm -	ABS/RC -	ETo/RC -	Dio/RC -	MI (%)	Chl <i>a</i> (mg g ⁻¹ FW)	Chl <i>b</i> (mg g ⁻¹ FW)	Chl Total (mg g ⁻¹ FW)	Chl <i>a/b</i> -	CC (mg g ⁻¹ FW)
Species (A) ("F")	11.00 **	8.99 **	4.83 **	13.85 **	12.49 **	113.38 **	12.49 **	84.25 **	2.50 ns	112.04 **
HLC	0.69 a	2.92 a	0.83 b	0.92 b	70.93 c	551.11 c	202.90 b	754.01 c	2.81	120.82 b
HR	0.67 a	3.09 b	0.96 a	1.01 b	79.48 a	690.65 a	273.82 a	964.47 a	2.64	155.44 a
HRO	0.69 a	2.71 a	0.80 b	0.84 b	76.91 b	524.52 d	226.20 b	750.73 c	2.51	112.76 c
HGT	0.61 b	3.38 c	0.84 b	1.33 a	75.24 b	580.67 b	221.52 b	802.20 b	3.14	117.62 b
Foliar treatments (B) ("F")	5.62 **	5.05 **	2.68 *	6.81 **	0.20 ns	43.53 **	1.73 ns	24.59 **	1.94 ns	18.28 **
Kaolin	0.71 a	2.67 a	0.91 a	0.78 a	75.01	550.72 c	234.77	785.49 c	2.43	120.43 b
0 mg L ⁻¹ SA	0.65 b	3.07 b	0.81 b	1.07 b	76.37	566.19 c	230.61	796.80 c	2.66	122.29 b
100 mg L ⁻¹ SA	0.66 b	3.19 b	0.88 a	1.14 b	75.44	538.72 c	211.48	750.21 d	3.17	118.34 b
200 mg L ⁻¹ SA	0.68 a	2.92 a	0.91 a	0.94 a	75.50	619.96 b	232.35	852.32 b	2.76	134.38 a
300 mg L ⁻¹ SA	0.63 b	3.27 b	0.77 b	1.21 b	75.89	658.10 a	246.34	904.45 a	2.84	137.75 a
Species x Foliar treatments (A x B) ("F")	2.17 *	2.13 *	0.58 ns	2.88 **	1.89 **	16.87 **	5.72 **	14.49 **	2.52 *	11.69 **
C.V. (%)	6.39	12.09	15.24	22.05	5.21	4.52	14.32	5.19	24.13	5.63

HLC = *Heliconia bihai* cv. Lobster Claw Two; HR = *Heliconia rostrata*; HRO = *Heliconia psittacorum* cv. Red Opal; HGT = *Heliconia psittacorum* × *Heliconia spathocircinata* cv. Golden Torch. Values are expressed as means. Within each factor, means followed by different letters in the same column differ according to the Scott-Knott test ($p \leq 0.05$). ns = not significant; * and ** indicate significance at the 5 and 1% probability levels, respectively; C.V. = coefficient of variation.

When the chlorophyll fluorescence parameters were considered together, the responses indicated distinct adjustments of PSII according to species and foliar treatment. In *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, 100 and 300 mg L⁻¹ SA were simultaneously associated with lower Fv/Fm and higher ABS/RC and Dio/RC, indicating a less favorable photochemical condition characterized by greater excitation pressure per active reaction center and increased energy dissipation. This response was also evident in the comparisons among species, particularly at 100 mg L⁻¹ SA, when Golden Torch showed lower Fv/Fm and higher ABS/RC and Dio/RC than the other species. At 300 mg L⁻¹ SA, Golden Torch also showed lower Fv/Fm, higher ABS/RC, and the highest Dio/RC among the species. In contrast, in *H. rostrata*, kaolin and 100 and 200 mg L⁻¹ SA resulted in higher Fv/Fm and lower Dio/RC than the water control and 300 mg L⁻¹ SA. Such changes in chlorophyll fluorescence parameters reflect adjustments in PSII photochemical efficiency, excitation energy distribution, and energy dissipation and have been widely used as indicators of plant responses to environmental stress (Swoczyna et al., 2022).

The higher mean ETo/RC observed in *H. rostrata* further indicates greater electron transport per active reaction center in this species during the reproductive phase. However, because the species × foliar treatment interaction was not significant for ETo/RC, the effects of foliar treatments on this parameter cannot be specifically attributed to *H. rostrata*.

For membrane integrity (MI), foliar treatments did not differ within *H. bihai* cv. Lobster Claw Two, *H. rostrata*, or *H. psittacorum* cv. Red

Opal during the reproductive phase (Fig. 2D). In *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, kaolin resulted in lower MI than the water control and 100, 200, and 300 mg L⁻¹ SA, which did not differ from each other. Comparisons among species within each foliar treatment (Fig. 2D) showed no differences under the water control or 200 mg L⁻¹ SA. Under kaolin, Golden Torch showed the highest MI, followed by Lobster Claw Two, whereas *H. rostrata* and Red Opal showed the lowest values. At 100 mg L⁻¹ SA, Lobster Claw Two and Red Opal showed higher MI than *H. rostrata* and Golden Torch. At 300 mg L⁻¹ SA, Lobster Claw Two showed higher MI than the other species.

Membrane stability is closely associated with the maintenance of cellular integrity under environmental stress, and increased electrolyte leakage is commonly interpreted as an indication of greater membrane injury (Pettenuzzo et al., 2022). The lower MI observed with kaolin in Golden Torch indicates greater electrolyte leakage and, consequently, lower membrane stability in this species. In contrast, the absence of differences among foliar treatments in the other species indicates that neither SA nor kaolin significantly altered membrane integrity under the conditions evaluated.

During the reproductive phase, the significant species × foliar treatment interaction observed for Chl *a*, Chl *b*, Total Chl, Chl *a/b* ratio, and carotenoid content indicated that pigment responses to SA and kaolin depended on species (Table 2; Fig. 3A-3E).

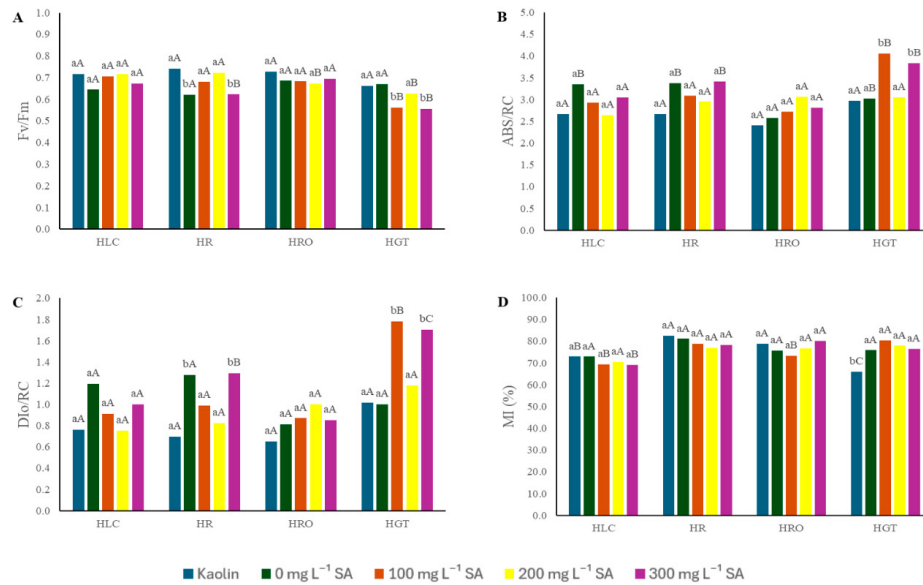


Fig. 2. Maximum quantum efficiency of photosystem II (Fv/Fm) (A), absorbed photon flux per reaction center (ABS/RC) (B), energy dissipation per reaction center (Dlo/RC) (C), and membrane integrity (MI) (D) of *Heliconia* species subjected to foliar treatments with salicylic acid (SA) and kaolin during the reproductive phase (190 DAP). Means followed by the same lowercase letter within each species and the same uppercase letter within each foliar treatment do not differ according to the Scott-Knott test ($p \leq 0.05$). HLC = *Heliconia bihai* cv. Lobster Claw Two; HR = *Heliconia rostrata*; HRO = *Heliconia psittacorum* cv. Red Opal; HGT = *Heliconia psittacorum* × *Heliconia spathocircinata* cv. Golden Torch.

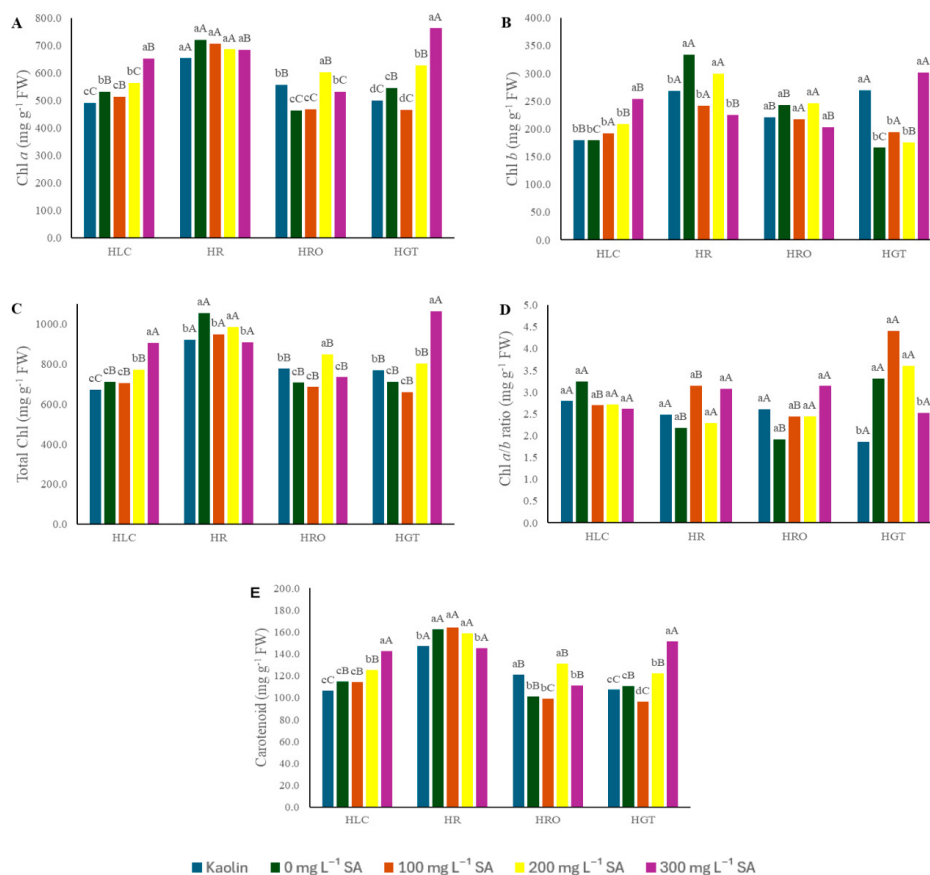


Fig. 3. Chlorophyll a (Chl a) (A), chlorophyll b (Chl b) (B), total chlorophyll (Total Chl) (C), Chl a/b ratio (D), and carotenoid content (E) of *Heliconia* genotypes subjected to foliar treatments with salicylic acid (SA) and kaolin during the reproductive phase (190 DAP). Means followed by the same lowercase letter within each species and the same uppercase letter within each foliar treatment do not differ according to the Scott-Knott test ($p \leq 0.05$). HLC = *Heliconia bihai* cv. Lobster Claw Two; HR = *Heliconia rostrata*; HRO = *Heliconia psittacorum* cv. Red Opal; HGT = *Heliconia psittacorum* × *Heliconia spathocircinata* cv. Golden Torch.

For Chl *a*, foliar treatments did not differ within *H. rostrata* (Fig. 3A). In *H. bihai* cv. Lobster Claw Two, 300 mg L⁻¹ SA resulted in the highest Chl *a* content, followed by the water control and 200 mg L⁻¹ SA, whereas kaolin and 100 mg L⁻¹ SA showed the lowest values. In *H. psittacorum* cv. Red Opal, 200 mg L⁻¹ SA resulted in the highest Chl *a* content; kaolin and 300 mg L⁻¹ SA showed intermediate values, while the water control and 100 mg L⁻¹ SA resulted in the lowest values. In *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, 300 mg L⁻¹ SA resulted in the highest Chl *a* content, followed successively by 200 mg L⁻¹ SA and the water control, whereas kaolin and 100 mg L⁻¹ SA resulted in the lowest values. Comparisons among species within each foliar treatment further evidenced the interaction (Fig. 3A). Under kaolin, Lobster Claw Two showed the highest Chl *a* content, followed by Red Opal and Golden Torch, whereas *H. rostrata* showed the lowest value. Under the water control, Red Opal showed the highest Chl *a* content, Lobster Claw Two and Golden Torch showed intermediate values, and *H. rostrata* showed the lowest value. At 100 mg L⁻¹ SA, Red Opal and Golden Torch showed the highest values, followed by Lobster Claw Two, whereas *H. rostrata* showed the lowest value. At 200 mg L⁻¹ SA, Lobster Claw Two showed the highest Chl *a* content, followed by Red Opal and Golden Torch, whereas *H. rostrata* showed the lowest value. At 300 mg L⁻¹ SA, Red Opal showed the highest value, Lobster Claw Two and *H. rostrata* showed intermediate values, and Golden Torch showed the lowest value.

For Chl *b*, foliar treatments did not differ within *H. psittacorum* cv. Red Opal (Fig. 3B). In *H. bihai* cv. Lobster Claw Two, 300 mg L⁻¹ SA resulted in higher Chl *b* content than all other treatments, which did not differ from each other. In *H. rostrata*, the water control and 200 mg L⁻¹ SA resulted in higher Chl *b* contents than kaolin and 100 and 300 mg L⁻¹ SA. In *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, kaolin and 300 mg L⁻¹ SA did not differ and resulted in higher Chl *b* contents than the water control and 100 and 200 mg L⁻¹ SA. Comparisons among species within each foliar treatment (Fig. 3B) showed that, under kaolin, Lobster Claw Two and Red Opal had higher Chl *b* contents than *H. rostrata* and Golden Torch. Under the water control, Lobster Claw Two showed the highest Chl *b* content, followed by Golden Torch, whereas *H. rostrata* and Red Opal showed the lowest values. No differences among species were observed at 100 mg L⁻¹ SA. At 200 mg L⁻¹ SA, Lobster Claw Two and Golden Torch showed higher Chl *b* contents than *H. rostrata* and Red Opal. At 300 mg L⁻¹ SA, Golden Torch showed lower Chl *b* content than the other species.

For Total Chl, 300 mg L⁻¹ SA resulted in the highest content in *H. bihai* cv. Lobster Claw Two, followed by 200 mg L⁻¹ SA, whereas kaolin, the water control, and 100 mg L⁻¹ SA did not differ and showed the lowest values (Fig. 3C). In *H. rostrata*, the water control and 200 mg L⁻¹ SA resulted in higher Total Chl contents than kaolin and 100 and 300 mg L⁻¹ SA. In *H. psittacorum* cv. Red Opal, 200 mg L⁻¹ SA resulted in the highest Total Chl content, followed by kaolin, whereas the water control and 100 and 300 mg L⁻¹ SA showed the lowest values. In *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, 300 mg L⁻¹ SA resulted in the highest Total Chl content, followed by kaolin and 200 mg L⁻¹ SA, while the water control and 100 mg L⁻¹ SA resulted in the lowest values. Comparisons among species within each foliar treatment (Fig. 3C) showed that, under kaolin, Lobster Claw Two had the highest Total Chl content, followed by Red Opal and Golden Torch, whereas *H. rostrata* showed the lowest value. Under the water control and at 100 and 200 mg L⁻¹ SA, *H. rostrata* showed lower Total Chl than the other species, which did not differ from each other. At 300 mg L⁻¹ SA, Red Opal showed higher Total Chl than the other species.

For the Chl *a/b* ratio, foliar treatments did not differ within *H. bihai* cv. Lobster Claw Two, *H. rostrata*, or *H. psittacorum* cv. Red Opal (Fig. 3D). In *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, kaolin and 300 mg L⁻¹ SA did not differ and resulted in lower Chl *a/b* ratios than the water control and 100 and 200 mg L⁻¹ SA. Comparisons among species within each foliar treatment (Fig. 3D) showed no differences under kaolin or at 200 and 300 mg L⁻¹ SA. Under the water control, *H. rostrata* and Red Opal showed higher Chl *a/b* ratios than Lobster Claw Two and Golden

Torch. At 100 mg L⁻¹ SA, Golden Torch showed a lower Chl *a/b* ratio than the other species.

Carotenoid content also showed contrasting responses among species (Fig. 3E). In *H. bihai* cv. Lobster Claw Two, 300 mg L⁻¹ SA resulted in the highest carotenoid content, followed by 200 mg L⁻¹ SA, whereas kaolin, the water control, and 100 mg L⁻¹ SA did not differ. In *H. rostrata*, the water control and 100 and 200 mg L⁻¹ SA resulted in higher carotenoid contents than kaolin and 300 mg L⁻¹ SA. In *H. psittacorum* cv. Red Opal, kaolin and 200 mg L⁻¹ SA resulted in higher carotenoid contents than the water control and 100 and 300 mg L⁻¹ SA. In *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, 300 mg L⁻¹ SA resulted in the highest carotenoid content, followed by 200 mg L⁻¹ SA; kaolin and the water control showed intermediate values, while 100 mg L⁻¹ SA resulted in the lowest value. Comparisons among species within each foliar treatment (Fig. 3E) showed that, under kaolin, Lobster Claw Two had the highest carotenoid content, followed by Red Opal and Golden Torch, whereas *H. rostrata* showed the lowest value. Under the water control and at 200 mg L⁻¹ SA, *H. rostrata* showed lower carotenoid contents than the other species, which did not differ from each other. At 100 mg L⁻¹ SA, Red Opal and Golden Torch showed the highest carotenoid contents, followed by Lobster Claw Two, whereas *H. rostrata* showed the lowest value. At 300 mg L⁻¹ SA, Red Opal showed higher carotenoid content than the other species.

During the reproductive phase, photosynthetic pigments and chlorophyll fluorescence parameters showed distinct responses depending on species and foliar treatment. Increases in pigment content under some treatments were not consistently accompanied by responses indicative of improved PSII photochemical performance. For example, in *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, 300 mg L⁻¹ SA resulted in the highest Chl *a*, Total Chl, and carotenoid contents, while the same treatment resulted in lower Fv/Fm and higher ABS/RC and Df/RC. These contrasting responses indicate that increases in pigment content alone should not be interpreted as evidence of improved photochemical performance. Changes in chlorophyll content and the Chl *a/b* ratio may reflect adjustments in the organization of the photosynthetic apparatus, while chlorophyll fluorescence parameters provide complementary information on PSII photochemical functioning and energy dissipation (Swaczyna et al., 2022; Gjindali and Johnson, 2023). Overall, the contrasting responses both among treatments within species and among species within treatments demonstrate that the effects of SA and kaolin on the photosynthetic apparatus were species- and concentration-dependent during the reproductive phase.

Relative growth increment expresses the percentage change in morphological traits over time to be assessed, reducing the influence of differences in initial plant size and facilitating comparisons of vegetative performance among species and foliar treatments. In the present study, relative growth increment was calculated from 98 to 190 DAP. This approach has been widely used in plant growth studies to compare individuals or treatments with different initial values (Lamont et al., 2023; Pommerening et al., 2023). Significant species effects were observed for plant height (PH), number of tillers (NT), total leaf area per clump (TLA) and clump area (CA). Foliar treatments significantly affected only PH and CA, whereas no significant species × foliar treatment interaction was detected for any of the evaluated traits (Table 3).

Relative growth responses differed among species depending on the evaluated trait (Table 3). For plant height, *H. psittacorum* cv. Red Opal showed a lower relative increment than *H. bihai* cv. Lobster Claw Two and *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, but did not differ from *H. rostrata*. For tiller number, *H. psittacorum* × *H. spathocircinata* cv. Golden Torch showed a greater relative increment than *H. rostrata* and *H. psittacorum* cv. Red Opal, whereas *H. bihai* cv. Lobster Claw Two showed an intermediate response and did not differ from the other genotypes. For total leaf area per clump, *H. bihai* cv. Lobster Claw Two showed a greater relative increment than the other genotypes, while for clump area, *H. psittacorum* cv. Red Opal showed a lower relative increment than the other species.

Table 3. Relative increment in plant height (PH), number of tillers (NT), total leaf area per clump (TLA) and clump area (CA) from 98 to 190 DAP in *Heliconia* species subjected to foliar treatments with salicylic acid (SA) and kaolin.

Source of variation	PH	NT	TLA	CA
	-----%-----			
Species (A) ("F")	5.04 **	6.17 **	10.33 **	10.97 **
HLC	99.8 a	164.1 ab	10.8 a	387.4 a
HR	63.76 ab	83.9 b	3.3 b	560.1 a
HRO	30.0 b	118.4 b	2.8 b	60.3 b
HGT	122.1 a	303.8 a	4.0 b	516.8 a
Foliar treatments (B) ("F")	4.12 **	0.93 ns	1.38 ns	5.59 **
Kaolin	132.75 a	217.0	7.9	827.5 a
0 mg L ⁻¹ SA	93.8 ab	217.7	5.1	332.0 ab
100 mg L ⁻¹ SA	68.2 b	133.8	4.3	378.1 ab
200 mg L ⁻¹ SA	43.9 b	132.3	4.5	253.4 b
300 mg L ⁻¹ SA	55.9 b	136.9	4.4	114.8 b
Species x Foliar treatments (A x B) ("F")	0.83 ns	1.54 ns	1.38 ns	1.16 ns

HLC = *Heliconia bihai* cv. Lobster Claw Two; HR = *Heliconia rostrata*; HRO = *Heliconia psittacorum* cv. Red Opal; HGT = *Heliconia psittacorum* × *Heliconia spathocircinata* cv. Golden Torch. Within each factor, means followed by different letters in the same column differ according to pairwise comparisons with Tukey adjustment ($p \leq 0.05$) following Aligned Rank Transform (ART) analysis. ns = not significant; * and ** indicate significance at the 5 and 1% probability levels, respectively.

When average across species, foliar treatments significantly affected only plant height and clump area; however, none differed significantly from the water control for either trait. Although kaolin resulted in the highest numerical means for both variables, it did not significantly increase their relative increments compared with water control. No significant effect of foliar treatments was observed for number of tillers or total leaf area per clump. These responses indicate that vegetative growth during the evaluated period was strongly species-dependent, consistent with the contrasting growth patterns previously reported for these *Heliconia* species by Souza et al. (2023) and Souza et al. (2024).

Although SA and kaolin induced changes in some physiological and biochemical traits, these responses were not accompanied by consistent increases in vegetative growth. Foliar treatments did not affect tiller

number or total leaf area, and none differed from the water control for plant height or clump area. Thus, the physiological adjustments observed under full-sun conditions were not necessarily translated into greater vegetative growth during the evaluated period, with growth responses remaining predominantly species-dependent.

Floral stem quality differed among species, with significant species effects observed for floral stem length (FSL), stem diameter (SD), inflorescence length (IL), inflorescence width (IW), and relative water content (RWC) (Table 4). In contrast, foliar treatments did not significantly affect any of these traits, and no significant species × foliar treatment interaction was detected. These results indicate that, under the conditions of this study, differences in floral stem quality were predominantly associated with intrinsic differences among species rather than with foliar treatments.

Table 4. Floral stem length (FSL), stem diameter (SD), inflorescence length (IL), inflorescence width (IW), and relative water content (RWC) of *Heliconia* species subjected to foliar treatments with salicylic acid (SA) and kaolin.

Source of variation	FSL (cm)	SD (mm)	IL (cm)	IW (cm)	RWC (%)
Species (A) ("F")	20.72 **	67.69 **	81.33 **	74.01 **	22.34 **
HLC	63.18 b	11.33 a	29.44 a	22.5 a	89.20 a
HR	77.06 a	6.80 b	26.02 b	15.25 c	80.97 c
HRO	63.47 b	6.16 c	17.65 c	14.68 c	88.08 a
HGT	80.45 a	7.31 b	17.43 c	18.41 b	84.82 b
Foliar treatments (B) ("F")	0.48 ns	0.61 ns	0.85 ns	0.69 ns	1.23 ns
Kaolin	71.57	7.87	22.12	17.9	85.88
0 mg L ⁻¹ SA	69.70	7.96	22.18	17.65	86.82
100 mg L ⁻¹ SA	72.78	7.52	22.44	17.29	84.53
200 mg L ⁻¹ SA	69.17	8.22	22.61	18.2	86.57
300 mg L ⁻¹ SA	71.99	7.93	23.83	17.43	85.05
Species x Foliar treatments (A x B) ("F")	1.37 ns	1.46 ns	0.64 ns	1.20 ns	1.36 ns
C. V. (%)	12.45	16.05	13.24	10.49	4.08

HLC = *Heliconia bihai* cv. Lobster Claw Two; HR = *Heliconia rostrata*; HRO = *Heliconia psittacorum* cv. Red Opal; HGT = *Heliconia psittacorum* × *Heliconia spathocircinata* cv. Golden Torch. Values are expressed as means. Within each factor, means followed by different letters in the same column differ according to the Scott–Knott test ($p \leq 0.05$). ns = not significant; * and ** indicate significance at the 5 and 1% probability levels, respectively; CV = coefficient of variation.

Floral stem length is an important quality criterion for the commercialization of *Heliconia* species because stem size influences handling and suitability for floral arrangements. Loges et al. (2005) reported approximately 80 cm as a desirable minimum stem length for commercialization. In the present study, *H. psittacorum* × *H. spathocircinata* cv. Golden Torch and *H. rostrata* showed the greatest FSL, with 80.45 and 77.06 cm, respectively, and did not differ statistically (Table 4). In contrast, *H. bihai* cv. Lobster Claw Two and *H. psittacorum* cv. Red Opal showed shorter stems, averaging 63.18 and 63.47 cm, respectively. Thus, Golden Torch reached the reference value reported by Loges et al. (2005), whereas *H. rostrata* approached this value and the other species produced comparatively shorter floral stems.

Stem diameter is also an important quality attribute because it contributes to stem support and mechanical resistance during harvesting, handling, and commercialization. *H. bihai* cv. Lobster Claw Two showed the greatest SD (11.33 mm), followed by *H. rostrata* and *H. psittacorum* × *H. spathocircinata* cv. Golden Torch, which did not differ from each other, whereas *H. psittacorum* cv. Red Opal showed the smallest diameter (6.16 mm) (Table 4). All species, however, showed mean SD values below the 20-mm reference cited for *Heliconia* floral stems (Castro et al., 2011; Gonçalves et al., 2021). The marked differences among species reinforce the strong influence of intrinsic characteristics on floral stem morphology.

Inflorescence dimensions also differed among species (Table 4). *H. bihai* cv. Lobster Claw Two showed the greatest IL (29.44 cm), followed by *H. rostrata* (26.02 cm), whereas *H. psittacorum* cv. Red Opal and *H. psittacorum* × *H. spathocircinata* cv. Golden Torch showed shorter inflorescences and did not differ from each other. For IW, Lobster Claw Two also showed the greatest value (22.50 cm), followed by Golden Torch (18.41 cm), whereas *H. rostrata* and Red Opal showed the lowest values and did not differ statistically. These differences reflect the contrasting inflorescence morphology of the evaluated species, an important component of the ornamental characteristics of *Heliconia* floral stems (Loges et al., 2005; Castro et al., 2011; Safeena et al., 2023). According to the classification proposed by Costa (2007), all evaluated species produced medium-sized inflorescences (10.0-30.0 cm in length), with IL values ranging from 17.43 to 29.44 cm.

Relative water content also differed statistically among species (Table 4). *H. bihai* cv. Lobster Claw Two and *H. psittacorum* cv. Red Opal showed the highest RWC values (89.20 and 88.08%, respectively), followed by *H. psittacorum* × *H. spathocircinata* cv. Golden Torch (84.82%), whereas *H. rostrata* showed the lowest value (80.97%). RWC is an important indicator of tissue hydration and turgidity in cut flowers, and the maintenance of an adequate water balance is relevant to postharvest quality because water deficit may lead to loss of turgor and wilting (Fanourakis et al., 2022). Therefore, the higher RWC observed in Lobster Claw Two and Red Opal indicates that their floral stem tissues were relatively more hydrated at harvest than those of Golden Torch and *H. rostrata*.

Overall, floral stem quality was strongly species-dependent, whereas SA and kaolin did not significantly modify the morphological attributes or water status of the harvested stems. The contrasting combinations of stem length, stem diameter, inflorescence dimensions, and RWC therefore reflect intrinsic differences among the evaluated *Heliconia* species under the cultivation conditions of this study.

Conclusions

Foliar applications of salicylic acid and kaolin modulated physiological and biochemical responses of *Heliconia* grown under full-sun conditions in a semi-arid environment, with effects depending on species, foliar treatment, and phenological phase. Changes in photosynthetic pigments, membrane integrity, and PSII photochemistry indicated physiological adjustments to the foliar treatments; however, these responses were not consistently translated into improved vegetative growth or floral stem quality compared with the water control. Among the evaluated species, *H. rostrata* showed the most consistent favorable physiological responses, particularly to kaolin and SA at 100 and 200 mg L⁻¹ during the reproductive phase. Growth and floral stem quality were predominantly species-dependent. Therefore, the use of SA and kaolin as photoprotective strategies for *Heliconia* under full-sun semi-arid conditions should consider species-specific responses, as no generalized beneficial effect was observed across the evaluated species. For the other species, further

studies are needed to refine SA concentrations and application strategies and to determine whether the observed physiological adjustments can translate into agronomic benefits.

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Author Contribution

HFF: Writing – Original Draft, Validation, Visualization, Investigation, Methodology, Data Curation, Formal Analysis, Supervision, Conceptualization. **VBR:** Investigation, Methodology, Data Curation. **EAFF:** Investigation, Methodology. **JVMB:** Investigation, Methodology. **TCLA:** Writing – Review & Editing, Investigation. **MCRZ:** Data Curation, Methodology, Visualization. **RRS:** Writing – Review & Editing, Visualization, Methodology, Conceptualization, Supervision. **MZBC:** Visualization, Methodology, Conceptualization, Supervision, Project Administration, Writing – Review & Editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All the research data is contained in the manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT (OpenAI) to assist with English language and improvement of text clarity and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and took(s) full responsibility for the content of the publication.

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