Ornamental Horticulture
ISSN 2447-536X | WWW.ORNAMENTALHORTICULTURE.COM.BR
SBFPO Sociedade Brasileira de Floricultura e Plantas Ornamentais

ARTICLE

Morpho-agronomic and physiological evaluation of *Heliconia* (Heliconiaceae) genotypes in simulated rain gardens under flooding and water deficit cycles

Avaliação morfoagronômica e fisiológica de genótipos de *Heliconia* (Heliconiaceae) em jardins de chuva simulados sob ciclos de inundação e déficit hídrico

Jurandir de Almeida Pereira Junior[1,*], Vivian Loges[1], Simone Santos Lira Silva[1], Fábio Valério Conceição Lopes[1], Lucas Yago de Carvalho Leal[1], Edivan Rodrigues de Souza[1], Edson Ferreira da Silva[1], and Maria Fernanda dos Santos Silva[1]

[1]Universidade Federal Rural de Pernambuco (UFRPE), Recife-PE, Brasil.

Abstract
Urban expansion is characterized by the replacement of vegetation and natural soils with impervious surfaces, intensifying flooding and pollution in cities. Rain gardens offer sustainable alternatives to mitigate these impacts through bioretention processes. However, studies on the tolerance of tropical ornamental plants to the water-stress cycles characteristic of these systems remain scarce. This study aimed to evaluate *Heliconia* genotypes under simulated rain garden conditions. The experiment was conducted in a greenhouse using mesocosms simulating rain gardens, alternating 24-h flooding periods with water deficits until reaching 40% of pot water-holding capacity, compared with a control treatment under daily irrigation. The evaluated genotypes were *H. bihai* (L.) L., *H. stricta* Huber, *H. episcopalis* Vell, *H. latispatha* Benth, *H. rostrata* Ruiz & Pav., *H. psittacorum* L.f., *H. richardiana* Miq., cv. 'Nickeriensis' (*H. psittacorum* L.f. × *H. marginata* (Griggs) Pittier), cv. 'Golden Torch' (*H. psittacorum* L.f. × *H. spathocircinata* Aristeg.) and cv.'Sassy' (*H. psittacorum* L.f.), considering vegetative traits of the clumps, floral stem development and morphology, and photosynthetic efficiency (Fv/Fm). The genotypes cv. Nickeriensis, *H. psittacorum*, and cv. Sassy showed the best performance, with rapid establishment, vigorous growth, low stress symptom severity, early flowering, and good inflorescence durability. Although Fv/Fm values remained below the reference range for physiological stress, this did not compromise genotype performance. These results indicate that these genotypes are promising for use in rain gardens in tropical regions, combining tolerance to fluctuations in water availability with high ornamental value.
Keywords: Constructed wetlands, *Heliconia* spp., ornamental plants, photosynthetic efficiency, water-stress.

Resumo
A expansão urbana caracteriza-se pela substituição da vegetação e dos solos naturais por superfícies impermeáveis, o que intensifica inundações e a poluição nas cidades. Os jardins de chuva oferecem alternativas sustentáveis para mitigar esses impactos por meio de processos de biorretenção. Contudo, são escassos os estudos sobre a tolerância de plantas ornamentais tropicais aos ciclos de estresse hídrico característicos desses sistemas. O objetivo deste trabalho foi avaliar genótipos de *Heliconia* sob condições simuladas de jardins de chuva. O experimento foi conduzido em casa de vegetação, utilizando mesocosmos que simularam jardins de chuva, alternando períodos de 24 horas de inundação e de déficit hídrico até 40% da capacidade de pote, comparados com controle sob irrigação diária. Foram avaliados os genótipos *H. bihai* (L.) L., *H. stricta* Huber, *H. episcopalis* Vell, *H. latispatha* Benth, *H. rostrata* Ruiz & Pav., *H. psittacorum* L.f., *H. richardiana* Miq., cv. 'Nickeriensis' (*H. psittacorum* L.f. × *H. marginata* (Griggs) Pittier), cv. 'Golden Torch' (*H. psittacorum* L.f. × *H. spathocircinata* Aristeg.) e cv. 'Sassy' (*H. psittacorum* L.f.), quanto às características vegetativas das touceiras, ao desenvolvimento e à morfologia das hastes florais, além da eficiência fotossintética (Fv/Fm). Os genótipos cv. Nickeriensis, *H. psittacorum* e cv. Sassy apresentaram melhor desempenho, com rápido estabelecimento, crescimento vigoroso, baixa severidade de sintomas de estresse, precocidade na floração e boa durabilidade das inflorescências. Embora os valores de Fv/Fm tenham permanecido abaixo da faixa de referência para estresse fisiológico, isso não comprometeu o desempenho dos genótipos. Conclui-se que esses genótipos são promissores para aplicação em jardins de chuva em regiões tropicais, ao combinarem tolerância a flutuações hídricas e potencial ornamental.
Palavras-chave: Áreas úmidas construídas, *Heliconia* spp., plantas ornamentais, eficiência fotossintética, estresse hídrico.

Introduction

The current model of urban development is characterized by the replacement of natural soil and vegetation with impervious surfaces, thereby altering the hydrological cycle within urban watersheds (Cabral and Braga, 2024; Ferreira et al., 2025). This alteration intensifies surface runoff, promoting flooding, soil erosion, riverbed siltation, and reduced groundwater recharge (Kasprzyk et al., 2022; Cabral and Braga, 2024).

Since the 1990s, sustainable water management initiatives were proposed to minimize the impacts of urban expansion (Alencar et al., 2025). This movement has spurred the development of techniques that mimic the hydrological functions of natural environments, known as Nature-Based Solutions (NBS), aimed at increasing infiltration, reducing surface runoff, and improving urban drainage (Kasprzyk et al., 2022; Cabral and Braga, 2024). Among these techniques, rain gardens (bioretention systems) stand out for their ability to reduce stormwater runoff and non-point source pollution in urban areas (Ribeiro et al., 2025).

Rain gardens consist of depressed planting beds in which the soil is excavated and replaced with layers of highly permeable granular material and organic matter to increase infiltration rates and temporarily retain surface runoff from impervious areas (Yuan and Dunnett, 2018; Kravchenko et al., 2024). In these systems, plants play fundamental roles by removing excess of soil water through evapotranspiration, creating preferential infiltration pathways through their root systems, and contributing to pollutant removal through phytoremediation (Kasprzyk et al., 2022). The continuity of these functions depends on the establishment and persistence of plants that can tolerate contrasting moisture conditions.

Therefore, the selection of suitable plants is crucial for the proper functioning of rain gardens. Following rainfall events, periods of temporary inundation may occur, followed by rapid drainage and potential dry spells between rains. Consequently, priority should be given to species capable of tolerating alternating cycles of inundation and water deficit (Yuan and Dunnett, 2018; Kasprzyk et al., 2022; Chen et al., 2025). The use of a diverse range of native plants adapted to the region's soil and climatic conditions is also recommended to preserve local biodiversity and reduce the likelihood of simultaneous pest and disease outbreaks (Kasprzyk et al., 2022; Chen et al., 2025).

* **Corresponding author:** jurandir.pereirajunior@ufrpe.br | https://doi.org/10.1590/2447-536X.v32.e323055 | Editor: Carmen Silvia Zickel, Universidade Federal Rural de Pernambuco, Brasil | Received: Sep 12, 2025 | Accepted: Aug 31, 2026 | Available online: Nov 16, 2026 | Licensed by CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/)

In this context, *Heliconia* species stand out as ornamental plants with potential for incorporation into rain gardens in tropical regions. They belong to the order Zingiberales, family Heliconiaceae, and are Neotropical in origin, widely distributed across Central and South America (Kress et al., 2025). Brazil is a major center of diversity, hosting approximately 37 native species (Braga, 2025). Beyond their well-known ornamental value, particularly in cut-flower production and landscaping (Linares-Gabriel et al., 2023; Safeena et al., 2023), heliconias can adapt to adverse conditions in environments with seasonal moisture regimes. Their rhizomes can facilitate regrowth following unfavorable water conditions (Andersson, 1989). These characteristics reinforce their potential for use in rain gardens.

Despite these promising characteristics, information on the integrated responses of *Heliconia* genotypes to successive cycles of flooding and water deficit remains scarce. Literature on rain gardens has focused primarily on plant survival and visual appearance, as well as on system hydrology and pollutant removal efficiency, while integrated plant responses to fluctuations in water availability remain poorly understood (Yuan and Dunnett, 2018; Chen et al., 2025). Therefore, it is essential to jointly evaluate traits related to vegetative growth, flowering, physiological stability, and the maintenance of ornamental attributes in these plants under the water regimes characteristic of rain gardens.

Among the tools used to assess the physiological responses of plants subjected to water- stress, leaf chlorophyll fluorescence measured using modulated fluorometers stands out (Yuan and Dunnett, 2018; Lotfi, 2024). This precise, non-destructive, rapid, and easy-to-perform method provides important information regarding electron transport within the photosynthetic apparatus (Maxwell and Johnson, 2000). The maximum quantum efficiency of photosystem II (Fv/Fm) is one of the most widely used parameters for estimating photochemical performance, with values below 0.75 associated with the onset of physiological stress (Peripolli et al., 2021).

Thus, the objective of this study was to evaluate the morpho-agronomic traits and physiological responses of *Heliconia* genotypes subjected to controlled cycles of flooding and water deficit, aiming to identify genotypes with greater tolerance and potential for use in rain gardens. The genotypes were selected based on their adaptation to local soil and climatic conditions and ornamental potential, with priority given to native species. We hypothesized that these genotypes exhibit distinct responses to alternating cycles of flooding and water deficit, and that the most tolerant ones maintain better vegetative performance, flowering capacity, and physiological stability under these conditions.

Materials and Methods

Experimental Area and Mesocosms Characterization

The experiment was conducted in a greenhouse between September 2023 and May 2024, in the experimental area of the Department of Phytotechnics at the Universidade Federal Rural de Pernambuco, in Recife-PE (8°01′01.58″ S; 34°56′41.33″ W; 4 m above sea level). The structure had an arch-shaped cover, with 150 µm diffusing plastic and sides coated with 50% shade cloth.

The minimum and maximum temperatures were 23 and 31 °C, respectively, and the mean relative humidity was 79%, as measured at a weather station near the experimental area. Global external radiation (Fig. 1), estimated according to Villalobos et al. (2024), ranged from 31.9 to 39.0 $MJ.m^{-2}$ day^{-1} throughout the experimental period, with lower values recorded between April and May.

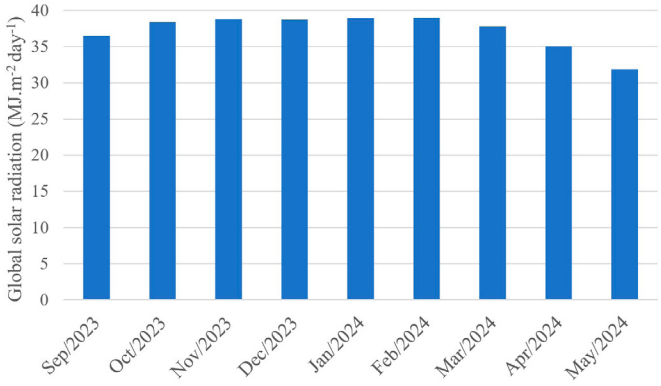


Fig. 1. Mean values of global external radiation during the experimental period.

For the experiment, 80 mesocosms were constructed to simulate rain gardens. Each mesocosm consisted of three 20-L buckets, stacked on top of each other and sealed with acetic silicone and PU silicone adhesives (Fig. 2A). To replicate the same layers of a bioretention system, the mesocosms initially received a 15-cm-thick layer of number 2 gravel (19 mm) used in construction, followed by a geotextile blanket. A 15 cm layer of coarse sand was added over the geotextile, followed by a 30 cm layer of planting substrate. A tap was installed at the bottom of each mesocosm to control drainage (Fig. 2B).

The substrate was composed of a mixture of topsoil, coarse sand, and coconut fiber (2:1:1), classified as sandy-clay loam (74.9% sand, 5.0% silt, and 20.0% clay), exhibiting a total porosity of 54%, a bulk density of 1.20 $g\ cm^{-3}$, a saturated hydraulic conductivity of 57.8 $cm\ h^{-1}$, and a volumetric moisture content at pot capacity of 0.19 $cm^3\ cm^{-3}$, as determined according to Teixeira et al. (2017).

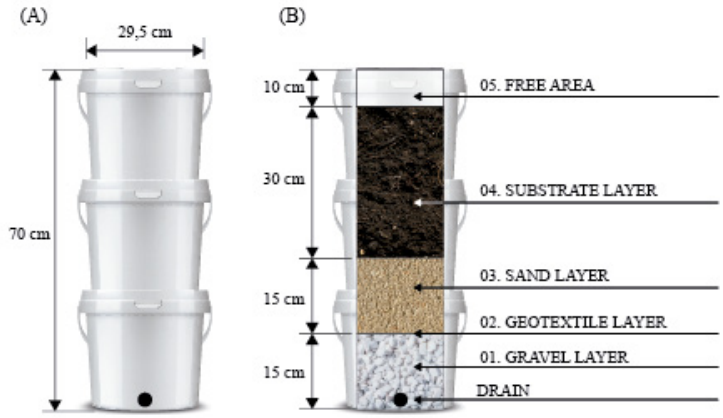


Fig. 2. Mesocosms used to simulate the rain gardens: (A) three 20-L buckets, stacked on top of each other; (B) a layered structure. Source: Elaborated by the author.

Plant material, planting, and management

Ten Heliconia genotypes, representing different species and interspecific hybrids, were evaluated. The genotypes were selected based on their adaptation to local soil and climatic conditions, availability in regional nurseries, and ornamental potential, with priority given to native species: *H. bihai*, *H. stricta*, *H. episcopalis*, *H. latispatha*, *H. rostrata*, *H. psittacorum* L., *H. richardiana,* cv. Nickeriensis *(H. psittacorum* × *H. marginata)*, cv. Golden Torch *(H. psittacorum* × *H. spathocircinata*), and cv. Sassy (*H. psittacorum*).

The vegetative propagation structures (rhizomes) were obtained from tropical flower producers in the metropolitan region of Recife. The rhizomes were washed in running water, and the roots were then cleaned to reduce the risk of pest and disease contamination. These were standardised, maintaining the pseudostem, which was bevel-cut at 50 cm from the base, serving as a source of reserves for shoot emergence. After preparation, they were kept in moistened newspapers for 48 hours before planting.

One rhizome was planted per mesocosm at a depth of 5-20 cm, depending on its size. Basal fertilization was carried out with 7 g of single superphosphate (18% P_2O_5), 7.5 g of urea (45% N), and 2.0 g of potassium chloride (60% K_2O) per mesocosm, as recommended by Segovia (2020). After planting, the experiment was kept under 50% shade for 90 days, with daily irrigation until plant establishment and the start of treatment application.

Topdressing was applied every 60 days, with 2.5 g of ammonium sulfate (20% N), 1 g of potassium chloride (60% K_2O), and 1 g of magnesium sulfate (9% Mg and 12% S) per plot, according to Segovia (2020). Weed control was carried out manually as needed, weekly.

Experimental design and water regimes

The experimental design was a randomized complete block design (RCBD) in a 10 × 2 factorial scheme with four replications. The factors consisted of ten *Heliconia* genotypes and two water regimes: 1) water-stress cycles – saturation of the substrate with a water layer of 20 mm above the surface for 24-h (flooding stress), followed by suspension of irrigation until the substrate reached 40% of the pot capacity (water-deficit stress); and 2) Control – daily irrigation at pot capacity. The water-stress treatment was applied from 120 to 265 days after planting (DAP), totaling 12 cycles.

Moisture monitoring was performed using the estimated crop evapotranspiration (ETc). Reference evapotranspiration (ET0) was calculated daily using the Hargreaves-Samani equation (Equation 1) (Villalobos et al., 2024).

$$ET_0 = 0.0023\ Ra\ (T_{max}-T_{min})^{0.5}\ (T_{med}+17.8) \quad \text{(Equation 1).}$$

Where: T_{min}: Minimum temperature (°C); T_{max}: Maximum temperature (°C); Tmed: mean temperature (°C); Ra: Extraterrestrial radiation (MJ m^{-2} day^{-1}).

To estimate ETc, the daily ET0 values were multiplied by the crop coefficient (Kc), according to Equation 2. The crop coefficients (Kc) used throughout the experiment were based on studies by Felisberto et al. (2015).

$$ETc = ET_0 * Kc \quad \text{(Equation 2).}$$

Where: ETc: crop evapotranspiration (mm day $^{-1}$).

To verify water content relative to the pot capacity at the end of the water-deficit periods, random substrate samples (0-20 cm) were collected from 10 mesocosms on four occasions. Substrate water content was determined gravimetrically by drying the samples in an oven at 105 °C until a constant mass was reached (Teixeira et al., 2017). The moisture content ranged from 35% to 47% of the pot capacity, confirming the effectiveness of the imposed water deficit.

Biometric and physiological evaluations

Vegetative traits, flowering traits, and floral stalk morphology were evaluated weekly.

Vegetative traits of the clumps: the start of shoot emission (SSE), in days after planting the rhizomes; number of shoots per clump (NSPC); shoot emission rate (SR); final clump height (FCH), measured from the base to the highest fully expanded leaf; number of leaves lost (NLL), recorded when completely dry leaves were removed from the clump.

The SR was calculated using Equation 3:

$$SR = \frac{\sum_{i=1}^{n}(Di-(Di-1)}{n} \quad \text{(Equation 3)}$$

Where: Di = the day on which the i-th shoot was emitted; Di – 1 = the day on which the previous shoot was emitted, and n = the total number of intervals, which corresponds to the total number of shoots.

Flowering traits: beginning of flowering in the clump (BF), counted from planting; days to inflorescence emission (DIE), from shoot emission; days to reach the inflorescence harvest point (IHP), counted from emission when two to three bracts were open; number of inflorescences produced (NI), throughout the experiment; number of leaves (NL); inflorescence durability on the plant (IDP), in days, measured from emergence to senescence; plant cycle (PC), given by the sum of DIE + IDP. Inflorescences were considered senescent when one-third of the bracts were necrotic, and all flowers had fallen. Although IHP was evaluated, the flower stems were kept on the plants throughout the cycle.

Floral stalk morphology: floral stalk length (FSL), measured from the base of the pseudostem to the point of attachment of the first bract; inflorescence length (IL), measured from the point of attachment of the

basal bract to the apex; inflorescence width (IW), measured between the two widest points of the inflorescence; floral peduncle diameter (FPD), measured at the midpoint below the point of attachment of the first bract.

Each shoot was labeled with a number according to its order of emergence. To identify each developmental stage, the floral stalks were marked with ribbons of different colors. Biometric measurements of the inflorescences were performed whenever they reached the IHP stage.

Leaf chlorophyll fluorescence measurements were performed to obtain maximum quantum efficiency of photosystem II (Fv/Fm) and assess stress induced in the plants. Readings were taken on the second fully expanded apical leaf, which was dark-adapted for 30 min using clips, at two points during each water-stress cycle: whenever estimated substrate moisture reached 40% of pot capacity and at the end of the 24-h flooding periods; measurements were simultaneously performed on control plots, totaling 18 evaluations across 9 cycles. All measurements were performed using a FluorPen F100 fluorometer (Photon Systems Instruments, Drasov, Czech Republic) between 150 and 265 days after planting (DAP).

Statistical analysis

The data were subjected to analysis of variance (ANOVA) after verifying the assumptions of normality (using the Lilliefors test) and homogeneity of variances (using Bartlett's test). For all evaluated traits, means were compared using the Scott-Knott clustering test and Tukey's test, at the 5% probability level ($p < 0.05$). Analyses were performed using the GENES software (Cruz, 2013).

Results and Discussion

According to the analysis of variance results, at 265 DAP, there was a significant difference among the genotypes for almost all traits related to clump growth, flowering, and floral stalk morphology, with a significance level of 1% ($p < 0.01$), except for IHP, which was significant at 5% ($p < 0.05$). These results demonstrate the high variability among the genotypes studied.

Regarding water regimes (water-stress cycles and control), significant differences were observed only for NLL and FPD, with significance levels of $p < 0.01$ and $p < 0.05$, respectively. Additionally, there was a significant interaction ($p < 0.05$) between genotypes and water regimes for the NLL variable only, indicating that leaf loss was strongly influenced by moisture conditions, with greater loss during periods of water-stress cycles.

The absence of significant differences between water regimes regarding the other traits indicates that the evaluated *Heliconia* genotypes maintained their growth and development even under water-stress cycles, demonstrating tolerance to the conditions imposed by the simulated rain gardens (Fig. 3).

Evaluations of *H. richardiana* were discontinued because that species did not adapt to cultivation conditions, exhibiting low tillering and reduced growth, with a mean height of only 10 cm (Fig. 3, M and N).

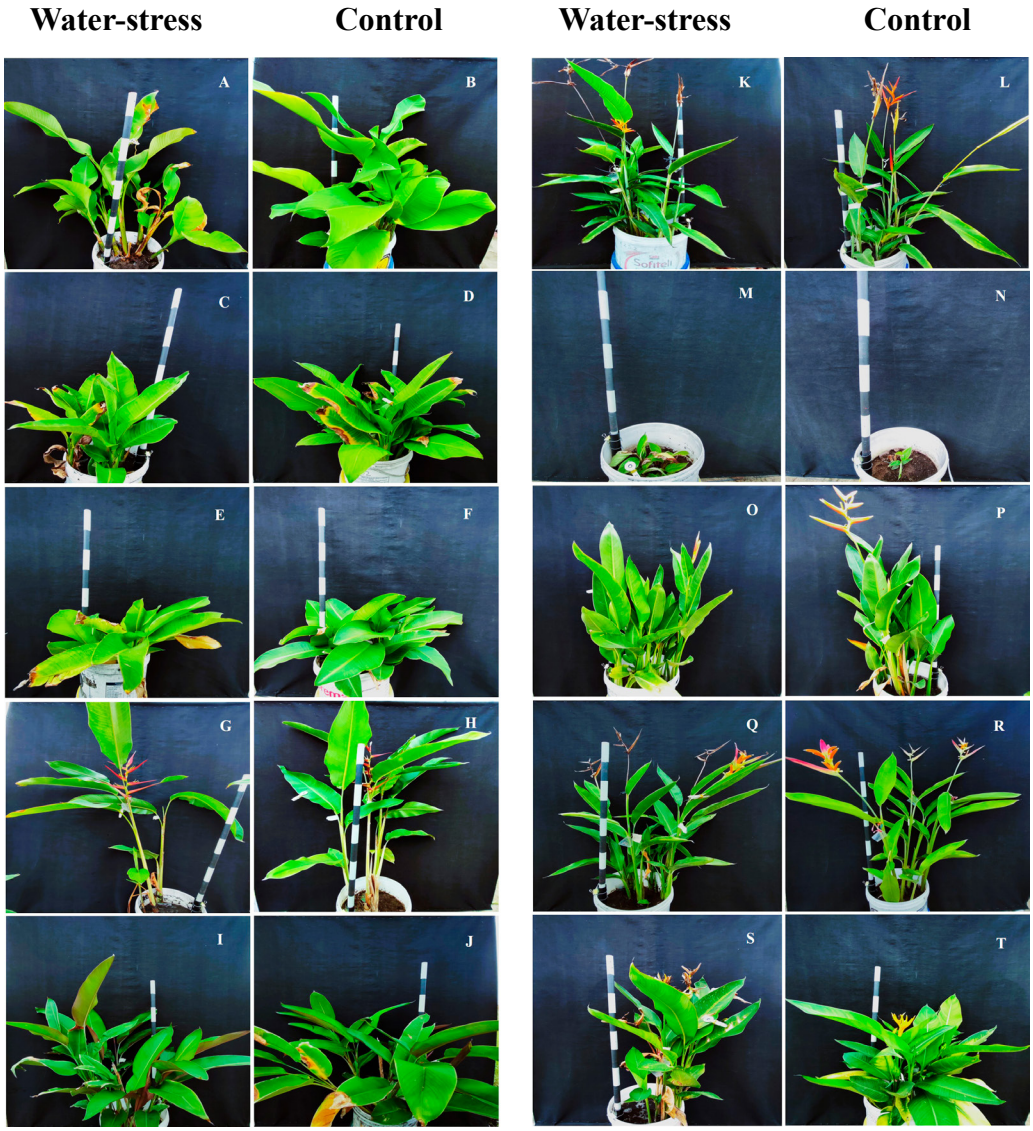


Fig. 3. Images of *Heliconia* genotypes cultivated in simulated rain gardens (mesocosms) in a greenhouse and subjected to water-stress cycles (flooding and water deficit) and control conditions, at 265 days after planting (DAP). Letters correspond to: A, B - *H. bihai*; C, D - *H. stricta*; E, F - *H. episcopalis*; G, H - *H. latispatha*; I, J -*H. rostrata*; K, L - *H. psittacorum*; M, N - *H. richardiana*; O, P – cv. Nickeriensis; Q, R – cv. Sassy; S, T - cv. Golden Torch.

Clump traits

Water-stress cycles (flooding and water deficit) significantly influenced only NLL and had no effect on clump characteristics such as NSPC, SR, and FCH, a result consistent with the phenotypic plasticity commonly reported in *Heliconia* species naturally exposed to seasonal variations in water availability in their native habitats (Andersson, 1989). However, significant differences were observed among genotypes for all evaluated variables, highlighting the substantial variability.

Regarding the start of shoot emission (SSE), the genotypes were classified into two distinct groups using the Scott-Knott test ($p < 0.05$). The earliest group consisted of *H. bihai* (22.75 DAP), *H. psittacorum* (25.75 DAP), cv. Sassy (25.75 DAP), cv. Nickeriensis (30.88 DAP), *H. stricta* (33.88 DAP), and cv. Golden Torch (35.50 DAP), suggesting a greater initial capacity to mobilize rhizome reserves for the production of aboveground biomass. The genotypes *H. rostrata* (39.50 DAP), *H. episcopalis* (45.38 DAP), and *H. latispatha* (47.25 DAP) were grouped into a second group, with later shoot emission (Table 1).

It should be noted that these results were obtained prior to subjecting the genotypes to water-stress cycles, which began only at 120 days after planting (DAP). Thus, grouping genotypes into distinct classes based on SSE may reflect differences in genetic makeup, thereby influencing the efficiency of rhizome reserve mobilization and characteristics such as initial rhizome vigor and the number of lateral buds. Rhizomes serve as storage organs for water, nutrients, and photoassimilates, which are essential for plant growth (Oliveira et al., 2024).

Early shoot emergence may be advantageous for the initial establishment of plants in rain gardens, as it reduces the time required for plant adaptation and establishment, may enhance the plants' ability to withstand the moisture fluctuations typical of these systems during the initial growth phase, and narrows the post-planting window of vulnerability.

Regarding NSPC, there was significant variation among genotypes at 265 DAP, with the Scott-Knott test identifying three distinct groups ($p < 0.05$). The first group included the genotypes *H. stricta*, cv. Golden Torch, cv. Sassy, and *H. psittacorum*, which presented the highest NSPC values, ranging from 10.75 to 11.63. In the second group, *H. rostrata*, *H. episcopalis*, *H. bihai*, and cv. Nickeriensis presented intermediate values, ranging from 8.63 to 9.25. Finally, *H. latispatha* had the lowest number of shoots (4.63) and remained isolated in the third group (Table 1).

Regarding shoot emission rate (SR), *H. latispatha* exhibited the lowest rate, with a mean interval of 51.37 days for the emergence of a new shoot; this differed statistically from the other genotypes, whose values ranged from 21.45 to 29.36 days (Table 1), indicating a lower capacity for vegetative renewal. The association between a lower SR and a higher NSPC observed in the other genotypes highlights greater vegetative vigor throughout the cycle.

Table 1. Characteristics of clumps of *Heliconia* genotypes grown in simulated rain gardens (mesocosms), in a greenhouse, and under cycles of water-stress (flooding and water deficit) and control, at 265 days after planting (DAP).

Genotypes	Means					
	SSE (days)	NSPC	SR (days)	FCH (cm)	NLL	
					Water-stress cycles	Control
H. bihai	22.75 B	9.13 B	27.94 B	97.75 B	10.00 B a	6.25 B a
H. stricta	33.88 B	11.63 A	21.45 B	68.75 D	19.25 A a	10.50 A b
H. episcopalis	45.38 A	9.13 B	28.46 B	52.63 E	13.50 B a	11.50 A a
H. latispatha	47.25 A	4.63 C	51.37 A	132.00 A	11.50 B a	4.25 B b
H. rostrata	39.50 A	8.63 B	29.36 B	97.75 B	3.50 C a	2.50 B a
H. psittacorum	25.75 B	10.75 A	24.09 B	88.88 C	4.00 C a	1.50 B a
cv. Nickeriensis	30.88 B	9.25 B	27.31 B	106.75 B	5.25 C a	3.25 B a
cv. Sassy	25.75 B	11.13 A	22.37 B	87.75 C	5.25 C a	3.50 B a
cv. Golden Torch	35.50 B	11.38 A	23.38 B	86.50 C	14.25 B a	4.00 B b

SSE - Start of shoot emission; NSPC - Number of shoots per clump; SR – Shoot rate; FCH - Final clump height; NLL - Number of leaves lost (water-stress cycles and control). Means with the same uppercase letters in the columns do not differ according to the Scott-Knott test at a 5% significance level. Means followed by the same lowercase letters in the rows do not differ according to Tukey's test at the 5% significance level. Note: For NLL, means are presented separately for each water regime because this was the only variable showing a significant genotype × water-regime interaction.

Regarding plant maintenance, low tillering, combined with a longer interval between new shoots, can reduce the need for pruning in purely ornamental beds. However, in rain gardens, these characteristics may compromise the vegetation's functions regarding water interception, evapotranspiration, and water retention and purification.

Shoot production in *Heliconia* does not depend solely on genetic variability; it is strongly influenced by environmental factors such as nutrient availability, substrate type, and light intensity (Dräger et al., 2023; Oliveira et al., 2024; Silva Souza et al., 2024). Furthermore, the volume of soil available for the growth of rhizomes and the root system can be a determining factor for the increase in NSPC. In this context, Costa et al. (2006) observed substantially higher NSPC values (18.3 to 57.0) in the field at 316 DAP than those recorded in the present study (4.63 to 11.63).

The study by Fernández-Echeverría et al. (2022), which evaluated *H. latispatha* in constructed wetlands (1.60 x 0.40 x 0.60 m) supplied with swine and domestic effluents for 210 days, corroborates this statement. Although the authors observed slow initial development, which they attributed to adaptation after transplantation, they recorded a significant increase in shoot formation from 90 DAP (days after planting), reaching a mean emission rate of 2.5 shoots month^{-1} and a final mean of 18 shoots per clump. These results suggest that, under field conditions, shoot production tends to be significantly higher, indicating that the spatial restriction imposed by mesocosms simulating rain gardens may have limited rhizome growth and, consequently, shoot production.

When considering the SSE, SR, and NSPC variables together, the genotypes *H. stricta*, cv. Sassy, *H. psittacorum*, and cv. Golden Torch showed the best performance regarding clump growth under simulated rain garden conditions. On the other hand, although *H. bihai* was the first genotype to initiate shoot emergence, it showed intermediate values for SR and NSPC. The worst performance was observed in *H. latispatha*, which presented the highest SSE (47.25 DAP), the lowest SR (51.37 days), and the lowest NSPC (4.63), resulting in a lower capacity for establishment (Table 1). This behavior suggests a growth strategy that prioritizes expanding the aerial parts at the expense of producing new shoots.

Regarding clump height (FCH), the genotypes were separated into five groups using the Scott-Knott test ($p < 0.05$). The first group was represented exclusively by *H. latispatha*, which had the greatest height (132.00 cm). The genotypes cv. Nickeriensis (106.75 cm), *H. bihai,* and *H. rostrata* (97.75 cm) constituted the second group. The third group included *H. psittacorum* (88.88 cm), cv. Sassy (87.75 cm) and cv. Golden Torch (86.50 cm). The two groups with the lowest FCH were formed by *H. stricta* (68.75 cm) and *H. episcopalis* (52.63 cm) (Table 1).

Under partial shade field conditions, Costa et al. (2006) classified *H. bihai* and *H. stricta* as tall (FCH > 2.51 m) and *H. latispatha*, *H. rostrata*, and *H. episcopalis* as medium-sized (1.51–2.50 m). In the present study, these genotypes were less than 1.50 m tall, indicating a significant reduction in growth compared to field conditions. This difference may be

related to unshaded growing conditions and space limitations imposed by the experimental mesocosms, which may have restricted rhizome and root system development, although these factors were not directly evaluated.

Additionally, light conditions may be one of the factors explaining this response, given that Silva Souza et al. (2024) observed that high-irradiance conditions significantly reduced the height of medium- and large-sized genotypes, such as *H. rostrata*, *H. bihai*, and *H. rauliniana*, whereas small-sized genotypes, such as 'Golden Torch' and *H. psittacorum* cv. Red Opal, showed less sensitivity to variations in light levels. These results suggest that height in *Heliconia* genotypes is strongly influenced by the environment, especially in medium- and tall-stature materials.

Regarding NLL under water-stress cycles, *H. stricta* (19.25) showed the highest NLL value, placing it in group A, while cv. Golden Torch, with the second-highest value (14.25), was in group B. On the other hand, *H. psittacorum*, cv. Nickeriensis, cv. Sassy, and *H. rostrata* showed the lowest values (3.50 to 5.25), evidencing greater resistance to leaf loss. In the control treatment, *H. stricta* and *H. episcopalis* maintained the highest NLL means (10.50 and 11.50, respectively). The same genotypes with the best performance under stress (*H. psittacorum*, cv. Nickeriensis, cv. Sassy, and *H. rostrata*) continued to show the lowest values (1.50 to 3.50).

Senescence followed by leaf abscission is a common stress response that reduces the plant's transpirational demand (Taiz and Zeiger, 2021). This mechanism may explain the greater leaf loss observed in cv. Golden Torch, *H. latispatha*, and *H. stricta* under water-stress cycles. Conversely, adaptive mechanisms, such as aerenchyma formation in rhizomes and roots (facilitating oxygen diffusion during flooding) and the mobilization of water and carbohydrate reserves from rhizomes during periods of water deficit (helping to maintain leaf integrity) (Méndez-Mendoza et al., 2015). These factors may have contributed to the lower leaf loss observed in *H. psittacorum*, cv. Nickeriensis, cv. Sassy, and *H. rostrata*, suggesting greater tolerance to alternating conditions of flooding and water deficit (Table 1).

Flowering characteristics

The genotypes *H. latispatha*, *H. psittacorum*, cv. Sassy, cv. Golden Torch, cv. Nickeriensis, and *H. bihai* flowered within 265 DAP. In contrast, *H. stricta*, H. *rostrata*, and *H. episcopalis* did not flower during this period, characterizing them as later-flowering genotypes, a finding that corroborates the observations of Costa et al. (2009).

The genotypes cv. Nickeriensis and *H. bihai* initiated flowering at 233 and 236 DAP, respectively. However, the number of observations was insufficient to perform statistical analyses of the floral stalk characteristics of these genotypes.

Flowering traits in the *H. latispatha*, *H. psittacorum*, cv. Sassy and cv. Golden Torch genotypes were not significantly influenced by water regimes, indicating that reproductive processes remained stable even under alternating cycles of flooding and water deficit in simulated rain garden conditions. However, significant differences among genotypes were observed for all variables evaluated for flowering characteristics (Table 2), demonstrating distinct genotypic responses.

Table 2 - Flowering characteristics of *Heliconia* genotypes under cultivation in mesocosms simulating rain gardens, under conditions of water-stress cycles (flooding and water deficit) and control, in a greenhouse, at 265 days after planting (DAP).

Genotypes	Means						
	BF (DAP)	DIE	IHP (days)	IDP (days)	NI	NL	PC (DAP)
H. latispatha	206.25 a	159.17 a	13.63 a	-	1.25 b	7.13 ab	-
H. psittacorum	129.75 c	84.14 d	15.50 a	48.98 b	3.34 a	5.89 b	132.44 b
cv. Sassy	161.88 b	107.34 c	13.80 a	64.43 a	3.25 a	7.54 a	172.23 a
cv. Golden Torch	173.13 b	124.29 b	17.75 a	58.06 ab	3.00 a	6.56 ab	183.31 a

BF - Beginning of flowering; DIE - Days to inflorescence emission; IHP - Inflorescence harvest point; IDP - Inflorescence durability on the plant; NI - Number of inflorescences; NL - Number of leaves; PC - Plant cycle. Means followed by the same lowercase letters in the columns do not differ according to Tukey's test at the 5% significance level.

Among the genotypes evaluated, *H. psittacorum* exhibited the greatest earliness, initiating flowering (BF) at 129.75 days after rhizome planting and completing the plant cycle (PC) at 132.44 DAP. Considering the interval from shoot emergence (DIE), flowering occurred after 84.14 days, with an IHP of 15.50 days and an IDP of 48.98 days (Table 2).

Earlier flowering and a shorter plant cycle can be advantageous in rain gardens, as they provide an earlier ornamental effect and accelerate vegetation establishment in these systems. From the perspective of commercial flower stem production, genotypes with shorter cycles are also preferable, as they are exposed to adverse biotic and abiotic factors for a shorter period, thereby facilitating a greater year-round supply of flower stems (Costa et al., 2006).

The cv. Sassy and cv. Golden Torch genotypes presented mean BF values of 161.88 and 173.13 DAP, respectively. The cv. Sassy exhibited a mean DIE of 107.34 days and a mean PC of 172.23 days, while the cv. Golden Torch required 124.29 days and completed PC in 183.31 days. The IHP ranged from 13.63 to 17.75 days, with no significant differences between the genotypes. Furthermore, the cv. Sassy stood out for having the longest IDP (64.43 days), which did not differ statistically from the cv. Golden Torch (58.06 days) (Table 2).

The observed values for IDP agree with those reported by Safeena et al. (2023), who, when evaluating 41 *Heliconia* genotypes, identified that cv. Golden Torch and cv. Sassy were among those with the most prolonged inflorescence persistence on the plant. In rain gardens, genotypes with higher IDP are desirable, as they help maintain the ornamental value and visual appeal of landscape.

The *H. latispatha* genotype showed later flowering, with a BF of 206.25 DAP, the longest DIE interval (159.17 days), resulting in the lowest number of inflorescences produced (NI = 1.25). In contrast, cv. Golden Torch, cv. Sassy, and *H. psittacorum* showed NI values ranging from 3.00 to 3.34 at 265 DAP (Table 2), with no statistically significant differences among them. These results corroborate those of Kannan et al. (2019) and Safeena et al. (2023), who reported greater earliness and flowering potential in hybrids and cultivars of *H. psittacorum* than in *H. latispatha* cultivars. Furthermore, the IHP values observed in this study are close to those reported by these authors, with means values of 15.43 days for cv. Golden Torch, 13.84 for cv. Sassy and 15.59 days for *H. latispatha* Bentham cv. Red-Yellow.

Regarding the number of leaves (NL), cv. Sassy showed the highest mean (7.54), differing statistically from *H. psittacorum*, which had the lowest mean (5.89). However, cv. Sassy did not differ from cv. Golden Torch (6.56) and *H. latispatha* (7.13), which in turn did not differ statistically from *H. psittacorum* (Table 2). These results agree with those of Kannan et al. (2019). A greater number of leaves increases the plant's photosynthetically active area, favoring the supply of photoassimilates for reproductive development. In rain gardens, this characteristic can improve the system's efficiency in removing excess soil water through evapotranspiration.

Morphological traits of floral stems

The only morphological trait of the floral stems that differed significantly between water regimes was FPD. In some genotypes, FPD increased under water-stress cycles, although no significant interaction between genotypes and water regimes was observed. However, significant differences among genotypes were observed for all evaluated morphological traits of the floral stems, reflecting genetic variability among the genotypes (Table 3).

Table 3. Morphological characteristics of floral stems of *Heliconia* genotypes cultivated in mesocosms simulating rain gardens, under water-stress cycles (flooding and water deficit) and control conditions, in a greenhouse, at 265 days after planting (DAP).

Genotypes	Means					
	FSL (cm)	IL (cm)	IW (cm)	BN	FPD (cm)	
					Water-stress cycles	Control
H. latispatha	81.38 A	27.56 A	39.56 A	10.38 A	0.98 A a	0.83 A b
H. psittacorum	90.53 A	17.76 B	18.62 B	4.74 B	0.48 C a	0.46 B a
cv. Sassy	88.05 A	15.63 B	16.19 B	4.54 B	0.61 B a	0.52 B a
cv. Golden Torch	52.30 B	14.43 B	18.10 B	4.50 B	0.66 B a	0.55 B b

FSL - Floral stem length; IL - Inflorescence length; IW - Inflorescence width; BN – Bract number; FPD - Floral peduncle diameter (water-stress cycles and control). Means followed by the same uppercase letters in the columns and lowercase letters in the rows do not differ according to Tukey's test at the 5% significance level. Note: For FPD, means are presented separately for each water regime because this was the only variable significantly affected by the two water conditions.

Floral stem length (FSL) differed significantly among the genotypes. *Heliconia psittacorum* (90.53 cm), cv. Sassy (88.05 cm), and *H. latispatha* (81.38 cm) stood out for having the greatest floral stem lengths. In contrast, cv. Golden Torch exhibited the shortest FSL (52.30 cm), which differed significantly from those of the other genotypes (Table 3). The FSL is one of the main commercial quality criteria. Stems shorter than 80 cm limit their use in arrangements, whereas stems longer than 1.51 m make handling and transport difficult (Gonçalves et al., 2021; Linares-Gabriel et al., 2023; Safeena et al., 2023). The cv. Golden Torch was the only genotype that did not meet the recommended FSL standard.

IL in *H. latispatha* (27.56 cm) was significantly greater than in the other genotypes, which did not differ from one another: *H. psittacorum* (17.76 cm), cv. Sassy (15.63 cm), and cv. Golden Torch (14.43 cm). A similar pattern was observed for IW and BN, with *H. latispatha* exhibiting higher values (39.56 cm and 10.38, respectively) than the other genotypes (*H. psittacorum*: 18.62 cm and 4.74; cv. Sassy: 16.19 cm and 4.54; cv. Golden Torch: 18.10 cm and 4.50) (Table 3). The development of more robust inflorescences *in H. latispatha* may be related to the larger size of this species; however, this morphological performance was not accompanied by vegetative vigor or reproductive potential, as observed in the growth and flowering evaluations.

Regarding FPD*, H. latispatha* and cv. Golden Torch exhibited an increase in floral peduncle diameter under water-stress cycles (0.98 cm and 0.66 cm, respectively) compared to the control (0.83 cm and 0.55 cm, respectively). This increase may be associated with an adaptive response to stress, conferring greater mechanical resistance to the floral stems and reducing the risk of lodging. In contrast*, H. psittacorum* and cv. Sassy showed no differences in floral peduncle diameter between water regimes, maintaining similar values under water- stress cycles and control conditions (0.48 cm and 0.46 cm for *H. psittacorum*, and 0.61 cm and 0.52 cm for cv. Sassy).

The selection of *Heliconia* species for rain gardens should consider relevant ornamental characteristics, given that these gardens are part of the urban landscape. According to Vivian Loges[1] (personal communication), attributes such as clump size, growth habit, and the position, visibility, and durability of the inflorescence should guide the selection of species for landscaping. In addition to aesthetic quality, management-related factors, such as the need to remove dry leaves and the risk of lodging, should be considered. Based on these criteria, the genotypes *H. psittacorum*, cv. Nickeriensis, and cv. Sassy can be recommended, as they showed good growth, flowering capacity, and low leaf loss in rain gardens, maintained satisfactory growth and performance under water-stress cycles, and fulfilled their ornamental function.

Chlorophyll Fluorescence

The photochemical efficiency of photosystem II (Fv/Fm) was analyzed separately during the water deficit and flooding periods, with each condition compared to its respective control plots. Under water deficit, the analysis of variance indicated a significant difference among genotypes ($p < 0.01$). However, no significant effects were observed for the water deficit itself or for the interaction between genotype and water condition, indicating that reduced water availability did not alter mean Fv/Fm values and that this response was similar across genotypes.

During the flooding period, in addition to the significant effect of genotypes ($p < 0.01$), an effect of water condition was observed ($p < 0.05$), indicating that flooding altered mean Fv/Fm values compared to the control. However, no significant interaction between genotypes and water condition was detected. Therefore, although the genotypes exhibited different Fv/Fm levels, the effect of flooding was similar across them. These results suggest that Fv/Fm was more sensitive to flooding than to water deficit under the conditions evaluated in this study.

The absence of a significant difference between the water deficit and control treatments suggests that the genotypes maintained relative photochemical stability of photosystem II under water restriction. This response may be associated with photoprotective mechanisms, such as osmotic and stomatal adjustments, osmolyte accumulation, and morphological adaptations that minimize water loss, including reduced leaf area and leaf rolling (Taiz and Zeiger, 2021).

Under water deficit, the genotypes formed three groups according to the Scott-Knott test ($p < 0.05$) (Table 4). cv. Nickeriensis comprised the first group and showed the highest mean Fv/Fm value (0.7324). This result was accompanied by high vegetative vigor and low leaf loss, highlighting the correspondence between photochemical stability and the vegetative performance of this genotype. The second group, with intermediate means values (ranging from 0.6777 to 0.7124), included *H. episcopalis*, *H. latispatha*, *H. psittacorum*, *H. rostrata*, *H. stricta*, and cv. Golden Torch. The third group, with the lowest means, comprised *H. bihai* (0.6660) and cv. Sassy (0.6499).

[1] Loges, Vivian (Federal Rural University of Pernambuco, UFRPE – Recife campus). Personal communication, 2024.

Table 4. Mean Fv/Fm values in *Heliconia* genotypes grown in mesocosms simulating rain gardens under water-stress cycles (water deficit and flooding) and control conditions in a greenhouse between 150 and 265 DAP.

Genotypes	Means	
	Fv/Fm (water deficit)	Fv/Fm (flooding)
H. bihai	0.6660 C	0.6946 C
H. stricta	0.6777 B	0.7055 B
H. episcopalis	0.7124 B	0.7061 B
H. latispatha	0.7077 B	0.7051 B
H. rostrata	0.6932 B	0.7146 B
H. psittacorum	0.6984 B	0.6959 B
cv. Nickeriensis	0.7324 A	0.7393 A
cv. Sassy	0.6499 C	0.6582 D
cv. Golden Torch	0.7015 B	0.6695 C

Means followed by the same uppercase letters within a column do not differ according to the Scott-Knott test at the 5% significance level.

Under flooded conditions, four groups were formed. cv. Nickeriensis stood out again, remaining isolated in the first group and exhibiting the highest mean Fv/Fm value (0.7393). *H. rostrata*, *H. stricta*, *H. latispatha*, *H. episcopalis*, and *H.psittacorum* formed the second group, with means ranging from 0.6959 to 0.7146. *H. bihai* and cv. Golden Torch constituted the third group, with means of 0.6946 and 0.6695, respectively. Cv. Sassy recorded the lowest mean Fv/Fm value (0.6582) among all genotypes, forming the fourth group (Table 4). Despite the lower Fv/Fm, cv. Sassy showed satisfactory vegetative and reproductive performance.

All genotypes exhibited Fv/Fm values below 0.75 under the evaluated conditions. According to Maxwell and Johnson (2000), the Fv/Fm ratio generally ranges from 0.75 to 0.85 in plants under optimal environmental conditions, with lower values indicating the onset of physiological stress (Peripolli et al., 2021).

One possible explanation for the reduced Fv/Fm values is the level of solar radiation during the experimental period, with estimated global irradiance ranging from 31.9 to 39.0 MJ·m^{-2}·day^{-1} (Fig. 1). Although light is a crucial factor for plant development, under certain conditions, the absorbed light energy can exceed the plant's photochemical utilization capacity, resulting in photoinhibition (Zuo, 2025). Thus, although the irradiance directly incident on the leaves was not measured, it is likely that the high light intensity inside the greenhouse contributed to the reduction in photochemical efficiency. Supporting this hypothesis, Nihad et al. (2019), while evaluating *H. stricta* under different light intensities, observed a significant increase in Fv/Fm under conditions of lower irradiance.

Fig. 4 shows the temporal variation of Fv/Fm across the chlorophyll fluorescence assessments for each water condition. The cv. Nickeriensis stood out by exhibiting the highest mean Fv/Fm values and high photochemical stability under all evaluated conditions, reinforcing the genotype's physiological stability throughout the moisture cycles. In contrast, the cv. Sassy showed slight variations in Fv/Fm in response to changes in water conditions over time, yet it recorded the lowest mean values compared to the other genotypes.

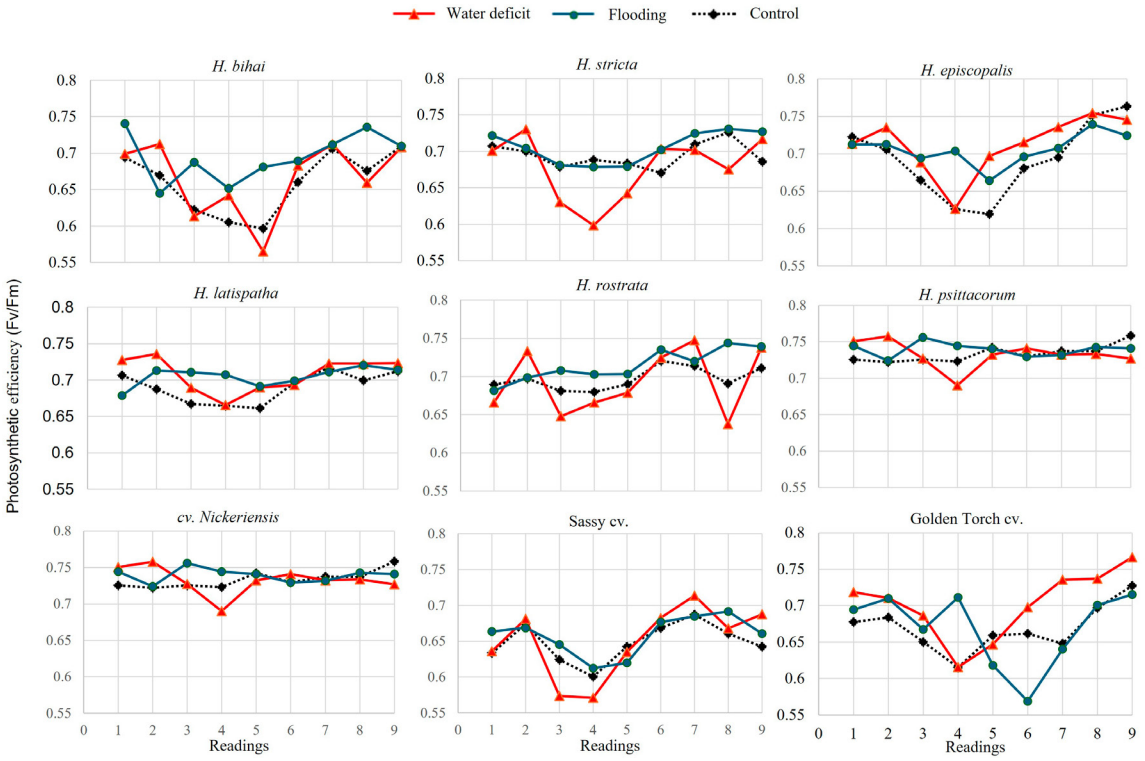


Fig. 4. Photosynthetic efficiency (Fv/Fm) of *Heliconia* genotypes grown in mesocosms simulating rain gardens under water-stress cycles (water deficit and flooding) and control conditions, in a greenhouse, between 150 and 265 DAP.

Some genotypes, such as *H. bihai*, *H. stricta*, and *H. rostrata*, exhibited higher mean Fv/Fm values after flooding compared to those recorded during water deficit (Fig. 4). This variation may indicate a trend toward the recovery of photochemical efficiency upon plant rehydration, even under waterlogged conditions. In contrast, genotypes such as cv. Golden Torch and *H. episcopalis* showed a further decline in photosynthetic efficiency after flooding, exacerbating the effects of the water deficit. This response was accompanied by symptoms of necrosis and significant leaf loss, indicating correspondence between the reduction in Fv/Fm and visible signs of stress.

Although mean Fv/Fm values generally remained below the optimal range, some genotypes maintained satisfactory growth and development. cv. Sassy and *H. psittacorum*, for example, exhibited low Fv/Fm values yet maintained a good establishment capacity, characterized by rapid shoot emergence and satisfactory shoot production, in addition to developing floral stems with desirable traits for landscaping. These results demonstrate that moderate reductions in Fv/Fm did not limit the establishment, shoot production, or flowering performance of these genotypes.

On the other hand, *H. stricta*, *H. bihai*, *H. rostrata*, *H. episcopalis*, and *H. latispatha* exhibited significant limitations regarding various growth and development characteristics. With the exception of *H. rostrata*, these genotypes showed considerable leaf loss, as well as symptoms of necrosis and leaf-margin scorching, particularly in *H. stricta* and *H. episcopalis*, indicating greater sensitivity to water-stress cycles. *H. latispatha* showed the lowest establishment performance, with the lowest number of shoots and substantial leaf loss and scorching. However, because these genotypes exhibited intermediate Fv/Fm values, the results suggest that this parameter alone was insufficient to explain the observed differences in vegetative performance.

Conclusions

This study presents an innovative approach to evaluating plants for use in rain gardens, using experimental mesocosms subjected to alternating cycles of water deficit and flooding under controlled conditions.

Among the genotypes evaluated, cv. Nickeriensis, *H. psittacorum*, and cv. Sassy stood out as the most promising, exhibiting relatively rapid establishment, high vegetative vigor, and a low incidence of stress symptoms. *H. psittacorum* and cv. Sassy also displayed desirable ornamental traits, such as early flowering, production of high-quality inflorescences, and long inflorescence durability on the plant, whereas cv. Nickeriensis stood out for its greater photochemical stability and superior vegetative performance.

Although photosynthetic efficiency (Fv/Fm) remained below the reference range considered ideal in the genotypes with the best vegetative and reproductive performance, this response was not accompanied by a reduction in establishment, growth, or flowering. These results indicate that photochemical efficiency alone was insufficient to explain the satisfactory morpho-agronomic performance of these genotypes.

These results demonstrate the potential of the selected genotypes for use in rain gardens in tropical regions subject to extreme fluctuations in water availability, particularly because they maintained vegetative, reproductive, and ornamental performance under the evaluated conditions. These genotypes can expand the range of plants available for use in green infrastructure while adding aesthetic value to the urban landscape. However, further long-term studies conducted under actual urban conditions are needed to confirm these results and investigate the contribution of these genotypes to functional processes such as evapotranspiration, water retention, infiltration, and phytoremediation.

Acknowledgments

The authors are thankful to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, DS-88887.802416/2023-00) for granting the scholarship.

Author Contribution

JAPJ: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Writing – Original Draft. **MFSS:** Data Curation, Formal Analysis, Methodology, Supervision. **SSLS:** Data Curation, Formal Analysis, Methodology, Supervision. **FVCL:** Data Curation, Formal Analysis, Methodology, Supervision. **LYCL:** Methodology, Resources, Software. **ERS:** Methodology, Resources, Software. **EFS:** Conceptualization, Methodology, Project Administration, Writing – Review & Editing. **VL:** Conceptualization, Investigation, Methodology, 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 influenced the work reported in this paper.

Data Availability Statement

Data will be made available upon request to the authors.

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

The authors declare that AI and AI-assisted technologies were not used in the writing process.

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