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RESEARCH ARTICLE

Assessing the planting material size and light intensity levels for maximization of quality flower production in *Heliconia* cv. Golden Torch

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Abstract

The cut-flower industry is witnessing rapid growth, with tropical ornamentals such as *Heliconia* commanding premium value for their vivid inflorescences and long vase life. Among production factors, light environment and propagule size critically influence growth and floral quality, yet their interactive effects remain poorly understood under Indian conditions. This two-year pot experiment (2022-2024) was conducted on the terrace garden of the Department of Floriculture and Landscaping, Faculty of Agricultural Sciences, Siksha 'O' Anusandhan University, Bhubaneswar, to evaluate the response of *Heliconia psittacorum* 'Golden Torch' to two light intensities (open sun, 100 %; 50 % shade net) and three rhizome sizes (single-, double- and triple-node cuttings) in a factorial completely randomised design with four replications. Results revealed that full sun accelerated sprouting (17.15 days vs 19.47 days), enhanced vegetative-to-flowering shoot conversion (136.8 % vs 105.1 %) and produced more spikes per clump (3.68 vs 3.30) as compared to 50 % shade net. In contrast, 50 % shade significantly improved floral quality, with longer inflorescences (24.23 vs 19.03 inch), longer stalks (18.30 vs 14.94 inch), higher chlorophyll content (6.82 vs 5.09 mg cm^{-2}) and prolonged spike longevity (16.2 vs 10.3 days) than open sun (100 %). Propagule size strongly influenced performance: triple-node rhizomes (P_3) produced the tallest plants, the largest leaf area (1009 cm^2), the maximum spikes (4.66 $clump^{-1}$) and superior physiological efficiency. Notably, the P_3 rhizome under protected conditions yielded the highest-quality spikes, while double-node rhizome under open conditions promoted earliness and higher spike numbers. The study concluded that growers targeting export markets should adopt 50 % shade with P_3 rhizomes for premium floral quality, whereas full-sun culture with double-node cuttings is better suited for rapid turnover in domestic markets. These findings provide the first evidence-based recommendations for optimizing *Heliconia* production under coastal Odisha conditions and can guide future commercial scale-up.

Keywords: cut-flower quality; *Heliconia psittacorum*; physiological traits; rhizome size; shade net

Introduction

The global cut-flower industry is expanding rapidly, with the market valued at USD 31.1 billion in 2024 and projected to more than double by 2034 as consumers seek novel, high-impact blooms for decor, gifting and events (1). Within this space, tropical ornamentals occupy a lucrative niche because their vivid colours, bold architectures and long vase life command premium prices in temperate markets. *Heliconia*-a monotypic genus in the family *Heliconia*ceae-has emerged as a flagship of this segment. Plants are herbaceous, rhizomatous and range from 0.5 m to nearly 4.5 m in height, traits that lend themselves equally to landscape use and cut-flower production. Although *Heliconia* is native to the Neotropics, its adaptability to warm, humid conditions and tolerance of partial shade have facilitated successful cultivation across the tropics and subtropics. In India, the hot-humid littoral belt of Odisha offers congenial agro-climatic conditions; growers already intercrop *Heliconia* in orchard systems where dappled light and organic matter are abundant (2). Among commercial cultivars, *H. psittacorum* 'Golden Torch' is favoured for its compact habit, persistent yellow bracts and steady year-round demand. Light environment is a primary driver of growth and floral quality in *Heliconia*. Early work in Florida demonstrated that *H. psittacorum* produced more stems under full sunlight than under 63 % shade (3, 4), whereas subsequent photoperiod studies in Hawaii showed that short-day induction synchronised bud initiation in *H. stricta* 'Dwarf Jamaican', provided plants had accumulated at least four expanded leaves beforehand (5). Recent physiological analyses confirm that excessive irradiance can induce photoinhibition and anatomical adjustments-thicker cuticles, higher stomatal density-across genotypes, underscoring the need to fine-tune shade levels for each production system. Conversely, 50 % shade has been shown to enhance leaf area, chlorophyll content and inflorescence length in several genotypes without significantly depressing yield (5). Equally critical, yet less studied, is the size of the vegetative propagule. Commercial propagation relies almost exclusively on rhizome division because seed progeny are highly variable. Larger rhizome segments possess greater carbohydrate and mineral reserves, accelerating sprouting and supporting early shoot vigour (4). However, the optimum node number is likely to interact with the light regime: under restricted irradiance, the assimilate buffer provided by a larger propagule may become indispensable, whereas in high light the same reserves could hasten, but not necessarily improve, floral differentiation. Despite the volume of *Heliconia* research-more than 74 % of the papers surveyed (250+) worldwide focus on production aspects-the interactive effects of light intensity and rhizome-segment size have seldom been quantified under Indian conditions (7). This knowledge gap hampers growers who must balance earliness (favoured by full sun and smaller propagules) against stem length, bract number and other quality parameters that attract export premiums. Therefore, the present study aimed to elucidate how two contrasting light environments (full sun versus 50 % shade) interact with three propagule sizes (single-, double- and triple-node rhizome cuttings) to influence growth dynamics, physiology and cut-flower quality of *H. psittacorum* 'Golden Torch' under the coastal conditions of Bhubaneswar, Odisha. Understanding these interactions will enable evidence-based recommendations that maximise both yield and market value while supporting year-round production of this high-value tropical flower.

Materials and Methods

Experimental site and climate

The work was conducted as a two-year pot experiment (2022-23 and 2023-24) on the south-facing terrace garden of the Department of Floriculture and Landscaping, Institute of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University) (SOADU), Bhubaneswar, India (20°15′ N, 85°50′ E; 25.5 m a.s.l.). The site lies ~ 63 km inland from the Bay of Bengal and enjoys a warm subtropical climate with a mean annual rainfall of 1522 mm, 85 % of which is received between July and September. Average daily maxima reach 35-40 °C in May-June, while minima drop to 13-15 °C in December-January; relative humidity varies between 40 % (pre-monsoon) and 90 % (monsoon).

Plant material and preparation

Rhizomes of *Heliconia* (*H. psittacorum* L.f. × *H. spathocircinata*) 'Golden Torch' were obtained from the Government Nursery, Unit-2, Bhubaneswar. Propagules were prepared by rhizome division following Criley's protocol. Segments with 6-12 cm of attached pseudostem were trimmed, dusted with a benzimidazole fungicide and cured for 48 hr under shade until root initials emerged. Three planting material sizes viz., single-node (P_1), double-node (P_2) and triple-node (P_3) cuttings, were used for planting.

Experimental design and treatments

The factorial experiment consisted of two factors, viz., two light intensity levels and three planting material sizes and was laid out in a Completely Randomised Design with four replications. Each treatment per replication comprised five 12–L UV-stabilised polyethylene bags. The treatment details are presented in Table 1.

Execution of the experiment

Prior to commencement of the experiment, a portion of the terrace garden of the Department of Floriculture and Landscaping was earmarked and cleaned properly. To create the two environmental conditions i.e., light intensity levels as per the requirement, a part of the demarcated area was kept open, allowing 100 % sunlight and the other portion was used to create shade by fixing a UV-stabilized agro shade net allowing 50 % light at a height of 3.90 m from the ground /floor level.

Substrate characterisation

The clay soil used in the substrate contained 16.2 % sand, 27.3 % silt and 50.5 % clay with pH 5.6, EC 0.31 dS m^{-1} and available N 265 kg ha^{-1}, P 55 kg ha^{-1} and K 122 kg ha^{-1} (8). Other components were well-decomposed, air-dried farmyard manure (FYM) and cocopeat, which had an EC ≤ 0.4 dS m^{-1} after leaching. The substrate consisted of soil, FYM and cocopeat in a 2:1:1 ratio on a volume basis.

Pot preparation and planting

Polybags were perforated laterally and at the base to ensure drainage, filled with the designated medium to within 2 cm of the rim and planted on 22 March 2022 with one rhizome segment per bag at a depth of 7.5 cm. All bags were drenched with 0.15 % carbendazim and lightly watered to initiate sprouting.

Crop management

Bags were watered at 2-3-day intervals during establishment and thereafter at 3-5-day intervals under both light intensities depending on the moisture status (with drainage ensured during the rainy season). A 2 % water-soluble fertiliser (19:19:19 NPK) was drenched at three-month intervals. Hand weeding was done as required. Cutworm and spider mite infestations under shade conditions were controlled with 0.05 % chlorpyriphos applied at 10 -15-day intervals.

Environmental monitoring

Photosynthetically active irradiance was estimated twice weekly at 11:00 and 15:00 hr using a digital lux meter (Model 5200). Mean midday irradiance under the 50 % shade net was 45–55 klx, roughly half that of open sun (90–105 klx). Air temperature and relative humidity were recorded concurrently using a max–min thermometer and a digital hygrometer.

Data collection

All five tagged plants under each treatment and replication were used for recording observations on various vegetative, reproductive, physiological and biochemical traits, as well as flower yield, as follows:

Table 1. The different factors used in the experiment

Factor	Levels	Code	Description
Growing environment (E)	2	E_1	Open, full sun
		E_2	50 % shade, green UV-stabilised agro-net (3.9 m ridge height)
Rhizome size (P)	3	P_1	Single node
		P_2	Double nodes
		P_3	Triple nodes

i. Vegetative traits - days to 80 % sprouting, number of sprouts bag^{-1}, plant height (monthly), days to leaf unfurling, number of leaves clump^{-1}, leaf area (length × breadth × empirical factor determined using a Leaf Area Meter - SYSTRONICS-211), number of suckers bag^{-1} and percentage of vegetative shoots converting to flowering shoots.

ii. Reproductive traits - days to first visible bud, days to full spike opening, spike length, stalk length (from junction of pedicel to first bract), number of bracts spike^{-1}, flowering duration of the spike and number of spikes clump^{-1}.

iii. Physiological and biochemical traits - net photosynthetic rate (measured using a portable IRGA), transpiration rate (TR) (Ganong potometer), chlorophyll content (SPAD-502; converted using Y = 0.178x - 3.531) and carotenoids in petals (acetone extract, measured with a UV-Vis spectrophotometer at 450, 470 and 480 nm; expressed as mg g^{-1} fresh weight).

iv. Flower yield - harvestable flowers were cut when the lowermost bract opened and data from all flushes were pooled to compute the annual yield.

Statistical analysis

Data from both years were pooled after homogeneity of variance was confirmed. Percentages were arcsine-transformed wherever necessary. A three-way ANOVA, appropriate for the factorial CRD, was performed and treatment means were separated using the critical difference (CD) at $P \leq 0.05$. All analyses were carried out in R 4.3.1 (R Core Team, 2024).

Results

Sprouting and early vegetative growth

Sprouting behaviour and early vegetative responses were significantly influenced by both the light environment and rhizome size (Table 2). On average, plants in open sun (E_1) reached 80 % sprouting in 17.15 days, significantly earlier than those in 50 % shade (E_2), which took 19.47 days. Rhizome size also affected sprouting: P_3 sprouted earliest (16.80 days), while P_1 were slowest (19.50 days). The leaf unfurling period was markedly extended under shade. Plants under E_2, i.e., 50 % shade, took 9.75 days to unfurl leaves, compared to 6.07 days in full sun. Rhizome size showed a mild influence, with P_2 taking the longest (8.33 days) and P_3 being statistically at par. Plant height during flowering was significantly higher in E_2 (4.4 ft) compared to E_1 (2.6 ft) and was greatest in P_3 (3.9 ft), suggesting a positive effect of shade and larger propagules on vertical growth. The number of functional leaves per plant also increased with rhizome size: P_3 produced the most (7.45), while P_1 produced the least (5.79). A highly significant interaction was observed for plant height during flowering: all three propagules were significantly taller in E_2 (differences of 1.20-2.12 ft) than in E_1, well above the CD_5% (0.415). The leaf unfurling period rose by 3.40 – 4.05 days in E_2, significantly exceeding the CD_5% of 0.820, indicating a strong interaction between propagule and environment. The number of leaves, on the other hand, demonstrated a comparatively weak connection between environment and propagules. P_1 and P_3 showed modest, non-significant variations, while only P_2 showed a drop (-1.138 leaves), somewhat above the CD_5% (1.084). Overall, our findings showed that whereas leaf number is rather constant across environments for the majority of propagules, propagule performance (P) is significantly impacted by environment (E) for sprouting, height and unfurling duration.

Leaf area, shoot dynamics and flowering initiation

Significant differences in canopy traits were observed (Table 3). Leaf area per shoot was notably higher under shade (1112.9 cm^2) than in full sun (775.9 cm^2), representing a 43 % increase. Among rhizome sizes, P_3 plants recorded the maximum leaf area (1009.2 cm^2) and the $E_2 \times P_3$ combination yielded the highest individual value (1230.9 cm^2). Conversion, i.e., vegetative shoots to flowering shoots (% V-F transition), was also environment-dependent. Plants in full sun showed a significantly higher conversion rate (136.78 %) compared to those in shade (105.14 %). Similarly, among the rhizome sizes, P_3 exhibited the lowest conversion (87.78 %) irrespective of light treatment. With respect to the interaction effect, the highest conversion was observed in $P_2 \times E_1$ (162.57 %), while $P_3 \times E_2$ recorded the lowest flowering conversion (80.86 %). The initiation of flowering was delayed under shade. Days to flowering were significantly longer in E_2 (189.7 days) than in E_1 (165.4 days). While rhizome size had only marginal effects, P_3 showed the earliest flowering overall (176.8 days) irrespective of light treatment. Sprout number during flowering was highest in full sun, i.e., E_1 (4.62 clump^{-1}). On the other hand, P_3 again outperformed other sizes under E_1, i.e., $P_3 \times E_1$ which recorded 4.93 sprouts.

Table 2. Assessment of growing condition and planting material size on vegetative growth of *Heliconia* cv. 'Golden Torch'

	Days to 80 % sprouting			Plant height during flowering (ft)			Leaf unfurling period (days)			Number of leaves		
	E_1	E_2	Mean	E_1	E_2	Mean	E_1	E_2	Mean	E_1	E_2	Mean
P_1	18.02	20.96	19.49	2.52	3.72	3.12	5.59	9.16	7.38	6.02	5.55	5.79
P_2	16.58	20.68	18.63	2.48	4.52	3.50	6.62	10.02	8.32	7.25	6.11	6.68
P_3	16.85	16.75	16.80	2.85	4.96	3.90	6.00	10.04	8.02	7.94	6.95	7.44
Mean	17.15	19.46		2.62	4.40		6.07	9.74		7.07	6.20	
Sem	P – 0.18, E – 0.14, P×E – 0.25			P – 0.09, E – 0.08, P×E – 0.14			P – 0.19, E – 0.15, PxE – 0.27			P – 0.25, E – 0.21, P×E – 0.36		
CD_5%	P – 0.54, E – 0.44, P×E – 0.76			P – 0.29, E – 0.24, P×E – 0.41			P – 0.59, E – 0.47, PxE – 0.82			P – 0.76, E – 0.62, P×E – 1.08		

Table 3. Assessment of growing condition and planting material size on vegetative growth and flowering dynamics of *Heliconia* cv. 'Golden Torch'

	Leaf area (cm^2)			Vegetative to flowering shoot (%)			Days to flowering			No. of sprouts during flowering		
	E_1	E_2	Mean	E_1	E_2	Mean	E_1	E_2	Mean	E_1	E_2	Mean
P_1	767.31	1003.58	885.44	153.05	125.52	139.28	162.83	194.41	178.62	4.27	3.40	3.84
P_2	772.84	1104.22	938.53	162.56	109.05	135.80	167.08	187.36	177.22	4.66	3.25	3.95
P_3	787.45	1230.88	1009.16	94.71	80.85	87.78	166.30	187.31	176.80	4.92	3.24	4.08
Mean	775.86	1112.89		136.77	105.14		165.40	189.70		4.62	3.30	
Sem	P – 9.53, E – 7.78, P×E – 13.44			P – 3.57, E – 2.91, P×E – 5.04			P – 0.42, E – 0.34, P×E – 0.60			P – 0.06, E – 0.05, P×E – 0.08		
CD_5 %	P – 28.33, E – 23.13, P×E – 40.07			P – 10.60, E – 8.66, P×E – 14.9			P – 1.26, E – 1.03, P×E – 1.79			P – 0.18, E – 0.14, P×E – 0.25		

Cut-flower yield and floral quality traits

Floral output and quality traits were significantly influenced by both environmental and propagule treatments (Table 4). Plants in open sun produced more flowers (3.68 spikes clump^{-1}) than those in shade (3.30 spikes), but floral quality traits such as inflorescence length and stalk length, were significantly better in shaded plants. Inflorescence length increased from 19.03 inch in E_1 to 24.23 inch in E_2, a 27 % improvement, while stalk length increased from 14.94 inch to 18.30 inch. Bract count, although slightly higher in full sun, showed only marginal differences (4.42 in E_1 vs 3.88 in E_2). Among rhizome sizes, P_3 again yielded the best performance, producing 4.66 flowers clump^{-1}, the longest inflorescences (23.52 inch) and the longest stalks (17.27 inch). These results indicate that larger propagules are crucial for maximising visual and marketable floral traits, especially under shade. The number of flowers per clump, inflorescence length, stalk length and number of bracts all showed a significant P × E interaction. There was a significant interaction (CD_5% = 0.204), with strong environmental responsiveness demonstrated by propagule P_3, which showed the largest environment-wise change. Smaller, non-significant changes were seen in P_1 and P_2. With CD_5% = 2.184, the interaction was highly significant. In E_2, all propagules produced noticeably taller inflorescences, indicating a favourable environmental influence; P_2 showed the largest increase, followed by P_1 and P_3. There was a highly significant P × E impact (CD_5% = 0.816). Under E_2, P_1 and P_3 demonstrated significant decreases in bract number, although P_2 remained mostly constant across all conditions.

Blooming behaviour and physiological traits

Environmental conditions had a strong impact on flowering duration and physiological efficiency (Table 5). The blooming period per spike was significantly prolonged in shade, averaging 16.20 days in E_2 vs 10.30 days in E_1. The total flowering duration per clump was also higher in E_2 (62.1 days) than E_1 (51.2 days). Gas exchange parameters revealed that shade-grown plants had higher net photosynthesis (21.24 µmol CO_2 m^{-2} s^{-1}) than sun-grown ones (13.11 µmol) and a lower TR (3.24 mmol H_2O m^{-2} s^{-1} vs 5.54 mmol H_2O m^{-2} s^{-1}), suggesting improved water-use efficiency (WUE) and reduced stress under protected environments.

P_3 exhibited the highest values for both traits. The blooming period (BP) (CD_5% = 0.866) and duration of flowering (CD_5% = 2.633) showed a significant P × E interaction. When cultivated under E_2, all propagules showed a noticeable increase in blooming length. These variations exceeded the critical difference, indicating that Heliconia's blooming length is extremely sensitive to environmental factors, particularly light and humidity. This also indicates that all propagules had significantly longer flower lifespans in E_2, with P_1 exhibiting the largest extension. Transpiration (CD_5% = 0.221) and photosynthetic rate (CD_5% = 0.938) showed a strong P × E interaction. Transpiration was significantly reduced in all propagules from E_1 to E_2. These decreases were greater than the CD, suggesting a steady environmental impact.

Photosynthetic pigments

As shown in Fig. 3, pigment content was significantly enhanced under shade. Chlorophyll content increased from 5.09 mg cm^{-2} in E_1 to 6.82 mg cm^{-2} in E_2, a 34 % rise (CD_5 % = 0.27). Similarly, carotenoid concentration rose from 2.53 mg g^{1} fresh weight (E_1) to 3.07 mg g^{-1} (E_2) (CD_5 % = 0.10). Although rhizome size did not significantly affect pigment concentration, P_3 plants maintained numerically higher values, indicating that larger propagules supported greater photosynthetic capacity, which in turn may have contributed to better floral development and bract coloration.

Correlation

Correlation among phenological and floral traits

A Pearson correlation analysis was conducted to explore interrelationships among key phenological and floral yield traits of *Heliconia* under two environments (E_1: open sun and E_2: 50 % shade) (Fig. 1). The results indicated distinct correlation patterns between the environments. In E_1, a significant negative correlation was observed between leaf unfurling period (LUP) and number of leaves (NoL) (r = -0.76), suggesting that faster leaf development is associated with increased leaf production. Vegetative-to-flowering shoot conversion (VtF) showed a strong positive correlation with NoL (r = 0.84) and flowers per clump (FpC) (r = 0.79), indicating that leaf density positively impacts reproductive efficiency and yield. Days to flowering (DtF) was negatively correlated with FpC (r = -0.68), implying that earlier flowering contributes to higher floral output.

Table 4. Assessment of growing condition and planting material size on reproductive growth of *Heliconia* cv. 'Golden Torch'

	No. of flowers per clump			Inflorescence length (inch)			Length of stalk (inch)			Number of bracts		
	E_1	E_2	Mean	E_1	E_2	Mean	E_1	E_2	Mean	E_1	E_2	Mean
P_1	2.89	2.78	2.83	17.41	22.91	20.16	14.17	17.68	15.93	4.45	3.75	4.10
P_2	2.88	3.06	2.97	17.55	24.86	21.20	15.01	18.28	16.64	4.33	4.09	4.21
P_3	5.25	4.07	4.66	22.12	24.91	23.52	15.61	18.93	17.27	4.45	3.78	4.12
Mean	3.67	3.30		19.03	24.23		14.93	18.30		4.41	3.87	
Sem	P – 0.04, E – 0.04, P×E – 0.06			P – 0.52, E – 0.42, P×E – 0.73			P – 0.19, E – 0.15, P×E – 0.27			P – 0.12, E – 0.10, P×E – 0.17		
CD_5%	P – 0.14, E – 0.11, P×E – 0.20			P – 1.54, E – 1.26, P×E – 2.18			P – 0.57, E – 0.47, P×E – 0.81			P – 0.37, E – 0.30, P×E – 0.53		

Table 5. Assessment of growing condition and planting material size on flowering and physiological parameters of *Heliconia* cv. 'Golden Torch'

	Blooming period			Duration of flowering			Transpiration rate (µmol H_2O m^{-2} s^{-1})			Rate of photosynthesis (µmol CO_2 m^{-2} s^{-1})		
	E_1	E_2	Mean	E_1	E_2	Mean	E_1	E_2	Mean	E_1	E_2	Mean
P_1	9.57	15.89	12.73	49.61	62.13	55.87	5.39	3.08	4.24	11.40	19.96	15.68
P_2	10.18	16.45	13.31	50.33	62.44	56.39	5.67	3.29	4.48	12.97	21.28	17.12
P_3	11.15	16.26	13.70	53.58	61.65	57.61	5.55	3.34	4.44	14.94	22.46	18.70
Mean	10.30	16.20		51.17	62.07		5.54	3.24		13.10	21.23	
Sem	P – 0.20, E – 0.16, P×E – 0.29			P – 0.62, E – 0.51, P×E – 0.88			P – 0.05, E – 0.04, P×E – 0.07			P – 0.22, E – 0.18, P×E – 0.31		
CD_5 %	P – 0.61, E – 0.50, P×E – 0.86			P – 1.86, E – 1.52, P×E – 2.63			P – 0.15, E – 0.12, P×E – 0.22			P – 0.66, E – 0.54, P×E – 0.93		

	LUP (E1)	LUP (E2)	NoL (E1)	NoL (E2)	BP (E1)	BP (E2)	VtF (E1)	VtF (E2)	DtF (E1)	DtF (E2)	FpC (E1)	FpC (E2)
LUP (E1)	1											
LUP (E2)	0.7847	1										
NoL (E1)	0.5286	0.941	1									
NoL (E2)	0.279	0.8142	0.9627	1								
BP (E1)	0.2634	0.8046	0.9581	0.9999	1							
BP (E2)	0.9494	0.9397	0.7685	0.5665	0.5531	1						
VtF (E1)	0.2512	-0.403	-0.689	-0.859	-0.868	-0.066	1					
VtF (E2)	-0.247	-0.794	-0.953	-0.999	-1	-0.538	0.8761	1				
DtF (E1)	0.8899	0.9811	0.8576	0.6864	0.6745	0.9881	-0.218	-0.662	1			
DtF (E2)	-0.794	-1	-0.936	-0.806	-0.796	-0.945	0.3893	0.7851	-0.984	1		
FpC (E1)	-0.127	0.5148	0.7746	0.9169	0.9233	0.1906	-0.992	-0.93	0.3391	-0.502	1	
FpC (E2)	0.0818	0.6819	0.8893	0.9799	0.983	0.3907	-0.944	-0.986	0.5274	-0.671	0.9781	1

Fig. 1. Correlation matrix between leaf unfurling period (days), number of leaves, blooming period, vegetative to flowering shoot (%), days to flowering and flowers per clump.

*LUP (E_1): Leaf unfurling period (days) of E_1; LUP (E_2): Leaf unfurling period (days) of E_1; NoL (E_1): Number of leaves of E_1; NoL (E_2): Number of leaves of E_2; BP (E_1): Blooming period of E_1; BP (E_2): Blooming period of E_2; VtF (E_1): Vegetative to flowering shoot (%) of E_1; VtF (E_2): Vegetative to flowering shoot (%) of E_2; DtF (E_1): Days to flowering of E_1; DtF (E_2): Days to flowering of E_2; FpC (E_1): Flowers per Clump of E_1; FpC (E_2): Flowers per Clump of E_2

In E_2, the correlation between LUP and NoL was weaker (r = -0.49), but FpC still showed a significant positive relationship with VtF (r = 0.81) and NoL (r = 0.76). Blooming period (BP) displayed a moderate positive correlation with DtF (r = 0.61), suggesting that prolonged vegetative growth may extend the blooming duration.

Correlation among physiological and yield traits

In Fig. 2, the correlation matrix explored the physiological drivers of floral yield. In E_1, FpC exhibited a strong positive correlation with rate of photosynthesis (RPs) (r = 0.87) and chlorophyll content (ChlC) (r = 0.84). Conversely, TR was negatively correlated with FpC (r = -0.65), suggesting that higher water loss may reduce floral productivity. In E_2, the correlation between FpC and ChlC was even stronger (r = 0.91), emphasizing the role of pigment enhancement under shade in yield augmentation. Similarly, RPs was positively linked to FpC (r = 0.88), while TR maintained a negative but moderate correlation (r = -0.53). These patterns highlight the advantage of physiological efficiency under shaded environments.

Discussion

Sprouting and early vegetative growth

The sprouting response of *H. psittacorum* L.f. × *H. spathocircinata* 'Golden Torch' was significantly influenced by both light environment and rhizome size. Plants exposed to full sun (E_1) reached 80 % sprouting notably faster than those grown under 50 % shade (E_2), indicating that higher irradiance accelerated the initiation of active growth (Table 2). This finding aligns with previous studies on tropical monocots, where early development is promoted under high light intensities due to greater thermal accumulation and hormonal stimulation (3–5). Among the planting materials, P_3 exhibited the fastest and most uniform sprouting (16.80 days), likely due to greater carbohydrate and nutrient reserves per segment, which support meristem activation and early growth, as also observed in rhizomatous ornamentals such as *Curcuma* and *Zingiber* (9). For the same reason, the interaction $E_2 \times P_1$ (single-node cuttings under 50 % shade) showed the maximum delay in sprouting (20.96 days). Additionally, taller plants and a greater number of leaves were recorded in P_3 treatments, reinforcing that propagule size directly affects early vigour and leaf production, both of which are foundational to future spike quality (5). Interestingly, the leaf unfurling period was considerably delayed under shade (9.75 vs 6.07 days in full sun), suggesting that although shade favoured overall plant stature and chlorophyll concentration (discussed below), it might have slowed initial leaf expansion, potentially due to lower photosynthetic photon flux density (PPFD). Despite this, the increased height and leaf number in P_3 plants highlight the compensatory effects of stored reserves and suggest that the use of larger rhizomes may partially buffer shade-induced delays.

	FpC (E1)	FpC (E2)	TR (E1)	TR (E2)	RPs (E1)	RPs (E2)	ChlC (E1)	ChlC (E2)
FpC (E1)	1							
FpC (E2)	0.9781	1						
TR (E1)	0.0458	0.2526	1					
TR (E2)	0.6387	0.7848	0.7979	1				
RPs (E1)	0.8954	0.9684	0.4858	0.9145	1			
RPs (E2)	0.8472	0.9392	0.5694	0.9499	0.9951	1		
ChlC (E1)	0.6384	0.7846	0.7981	1	0.9144	0.9498	1	
ChlC (E2)	0.3397	0.5279	0.9551	0.9406	0.7229	0.7874	0.9408	1

Fig. 2. Correlation matrix between flowers per clump, transpiration rate, rate of photosynthesis and chlorophyll content.

*FpC (E_1): Flowers per clump of E_1; FpC (E_2): Flowers per clump of E_2; TR (E1): Transpiration rate of E_1; TR (E_2): Transpiration rate of E_2; RPs (E_1): Rate of photosynthesis of E_1; RPs (E_2); Rate of photosynthesis of E_2; ChlC (E_1): Chlorophyll content of E_1; ChlC (E_2): Chlorophyll content of E_2

Leaf area, shoot dynamics and flowering initiation

The significant increase in leaf area under shade (1112.9 cm^2 vs 775.9 cm^2 in full sun) aligns with known shade-adaptive strategies in tropical plants, which typically develop larger leaves to maximise light capture under low irradiance (10, 11, 13). This trait was most pronounced in P_3 plants under E_2 (1230.9 cm^2), confirming the combined role of environmental and endogenous resource availability in promoting canopy expansion. Although shoot conversion to reproductive structures (% V-F) was higher in full sun (136.78 %), shaded plants still maintained adequate flowering potential (~ 105 %), particularly in P_2 and P_3 propagules (Table 3).

The lower flowering conversion in $E_2 \times P_3$ (80.86 %) may be attributed to shade-induced delays in sink establishment or assimilate partitioning. Nonetheless, DtF were significantly extended under shade (~ 190 vs 165 days in full sun), which is consistent with light-mediated regulation of floral induction reported in other *Heliconia* species (5). Sprout number during flowering was also highest in $E_1 \times P_3$, suggesting that full light exposure combined with larger propagules supports higher tillering and greater sink strength. While this favours spike quantity, shaded conditions may offer advantages in quality attributes (as discussed below), allowing growers to tailor production objectives through specific environment-propagule combinations.

Cut-flower yield and floral quality traits

While the number of FpC was higher in full sun (3.68) than in shade (3.30), key floral quality parameters such as inflorescence length and stalk length were significantly enhanced in shaded conditions (Table 4). Inflorescences in shade reached 24.23 cm, a 27 % increase over full sun, while stalks extended from 14.94 cm to 18.30 cm. These quality enhancements are commercially important, particularly in export markets that demand long, thick and visually uniform spikes (6). P_3 plants consistently outperformed other propagule sizes, producing 4.66 FpC with the longest inflorescences (23.52 cm) and stalks (17.27 cm). These findings support earlier reports in which larger propagules resulted in superior flowering performance, attributed to better resource buffering and stable carbon allocation (12). Although bract number was only marginally influenced by light or rhizome size, the improvement in inflorescence and stalk length under shade may enhance visual symmetry and structural robustness-traits highly valued in florist markets. Therefore, while full sun cultivation maximises spike number, moderate shade combined with P_3 propagules provides a more desirable spike architecture for premium-quality cut-flower production (14–16).

Blooming behaviour and physiological traits

The BP and overall flowering duration per clump were significantly extended under shade (16.2 and 62.1 days respectively), likely due to improved hydration and reduced oxidative stress under lower vapour pressure deficit (VPD) conditions (Table 5). These extended durations provide growers with a wider harvest window, potentially stabilising market supply and enhancing returns. The photosynthetic rate was significantly higher under shade (21.24 µmol CO_2 m^{-2} s^{-1}) compared to full sun (13.11 µmol), a finding that contradicts the traditional expectation that higher irradiance equates to higher photosynthetic activity. This can be explained by the lower photoinhibition and optimised stomatal behaviour under diffuse light conditions, as previously observed in ornamentals such as Anthurium and Strelitzia (10, 11, 13). Transpiration was lower in shaded plants (3.24 mmol H_2O m^{-2} s^{-1}), indicating higher water-use efficiency and reduced evaporative stress. Among rhizome sizes, P_3 again exhibited superior physiological performance, reinforcing its suitability for both open and protected systems. Reduced VPD, lower leaf temperature, diffused light and increased humidity are all suggested by lower transpiration rates under E_2. Every propagule showed a significant increase in E_2. This suggests that a better photosynthetic environment was given by E_2 (14-16). *Heliconia* is a tropical plant that thrives in shade. Photosynthetic rates frequently rise under moderate shade because photoinhibition is avoided, leaf chlorophyll stability is enhanced, stomatal conductance is optimal and heat stress is decreased (17, 18). This physiological resilience supports longer-lasting spikes and improved pigment retention, both of which are crucial for post-harvest performance.

Photosynthetic pigments

Total chlorophyll content increased by 34 % under shade, rising from 5.09 to 6.82 mg cm^{-2} (Fig. 3). Carotenoids followed a similar trend, with shaded plants recording 3.07 mg g^{1} fresh weight compared to 2.53 mg g^{-1} in full sun. These increases indicate shade-induced acclimation mechanisms that boost pigment synthesis to compensate for lower light availability (10, 11, 13). Although rhizome size had no statistically significant effect on pigment content, P_3 segments consistently exhibited the highest values, suggesting that larger propagules may enhance the development of photosynthetic machinery, likely due to better nutrient and water uptake from stronger root systems. The enhanced pigment profile under shade also explains the observed improvement in bract colour intensity, which is a key visual quality criterion in flower crops.

Correlation

Phenological traits and flowering performance

The correlation analysis revealed strong interdependencies among the vegetative and reproductive phases of *Heliconia*. Under full sun (E_1), the negative correlation between LUP and NoL implies that accelerated shoot development contributes to vegetative vigour. Moreover, the robust association of vegetative -to-flowering shoot conversion with both leaf number and number of FpC reinforces that early and robust vegetative growth directly contributes to yield. These findings align with previous studies indicating that faster canopy expansion enhances assimilate supply to developing inflorescences (19, 20). Under shaded conditions (E_2), the correlation strength between traits was slightly attenuated but still pointed towards the positive influence of vegetative robustness on floral output. Interestingly, DtF was moderately correlated with BP, suggesting that longer vegetative duration under shade translates into prolonged flowering windows, a desirable trait in ornamental crops for extended marketability.

Physiological traits and floral yield

The positive correlation between photosynthetic rate and FpC across both environments underscores the central role of carbon assimilation in floral productivity. Under full sun, higher photosynthetic rates were strongly associated with flower yield, reflecting the importance of source activity under high light intensity. The stronger correlation under shade between ChlC and FpC highlights the compensatory role of pigment

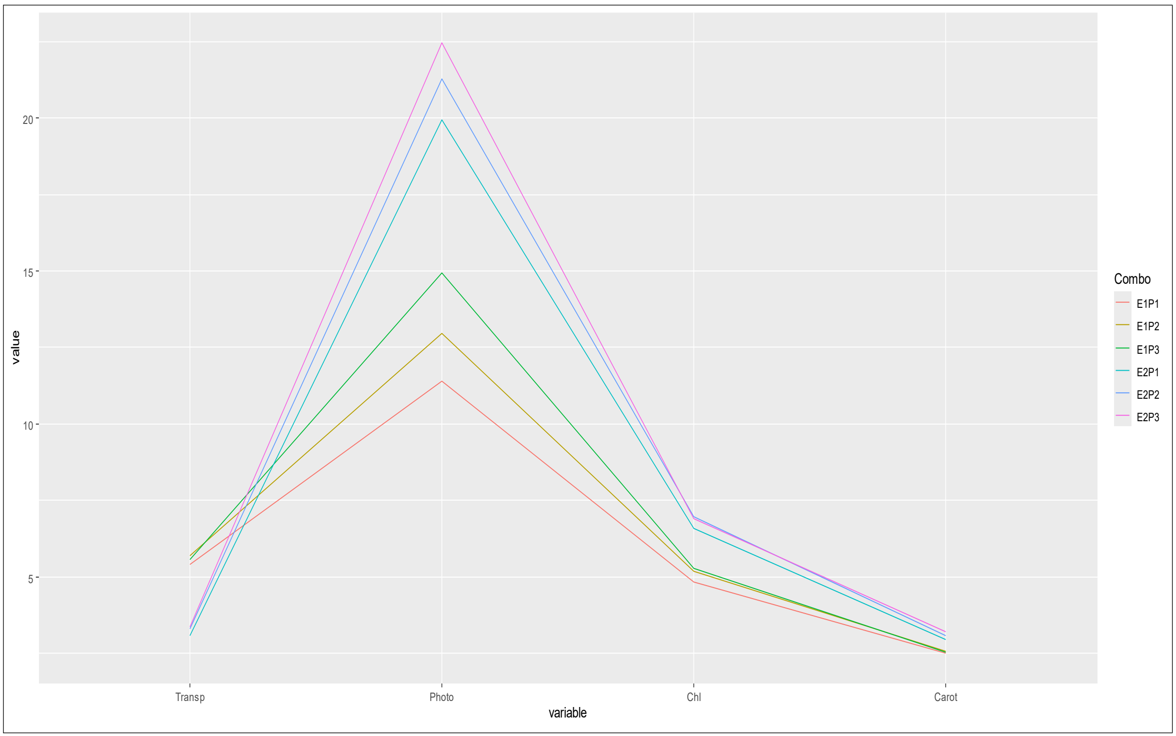

Fig. 3. Combination graph between transpiration rate, rate of photosynthesis, carotenoid content and chlorophyll content of *Heliconia.*

*E_1P_1: Full sun, Single node rhizome, E_1P_2: Full sun, Double node rhizome, E_1P_3: Full sun, Triple node rhizome, E_2P_1: 50 % shade, Single node Rhizome, E_2P_2: 50 % shade, Double node Rhizome, E_2P_3: 50 % shade, Triple node Rhizome

enhancement in suboptimal light environments (21, 22). Negative correlations of TR with FpC in both environments suggest that WUE may also play a role in supporting reproductive development. This observation mirrors findings in other tropical ornamentals, where moderated transpiration supports turgor maintenance during spike elongation (23).

Combination graph

The parallel coordinate plot provides a holistic view of the multi-trait performance of the different treatment combinations (E_1P_1-E_2P_3) (Fig. 3). A consistent trend was observed wherein all E_2 combinations exhibited higher values for photosynthetic rate, ChlC and carotene content compared to their respective E_1 treatments, indicating the superiority of environment E_2. Photosynthetic rate showed the widest separation among treatments, with E_2P_3 recording the highest value (~ 22.5 µmol CO_2 m^{-2} s^{-1}), while E_1P_1 recorded the lowest (~ 11.4 µmol CO_2 m^{-2} s^{-1}). ChlC followed a similar pattern, with E_2P_2 and E_2P_3 outperforming the E_1 counterparts. Carotene content, although showing narrower variation, was consistently greater under E_2. In contrast, transpiration rate showed a reverse trend, with higher values in E_1 treatments (5.4-5.7 µmol H_2O m^{-2} s^{-1}) than in E_2 (3.0-3.3 µmol H_2O m^{-2} s^{-1}), suggesting a more efficient water-use pattern under E_2. Overall, the plot demonstrates clear interaction effects between environment and propagule size, with E_2P_3 emerging as the most favourable combination-balancing high photosynthetic efficiency, chlorophyll and carotene accumulation, while maintaining lower transpiration losses. This multidimensional representation underscores the complementary nature of the traits and helps visualize the integrated advantage of specific treatment combinations.

Conclusion

The findings of this study clearly demonstrate that both the light environment and rhizome segment size significantly influence the growth dynamics, physiological performance and flower quality of *H. psittacorum* L.f. × *H. spathocircinata* 'Golden Torch'. Full sunlight promoted earlier sprouting, faster flowering and a higher spike numbers per clump, making it suitable for rapid crop turnover. In contrast, cultivation under 50 % shade markedly improved inflorescence length, stalk diameter, spike longevity and pigment concentration-traits essential for premium-grade cut-flower markets. Among the planting materials, P_3 rhizomes consistently outperformed P_1 and P_2 segments in terms of vegetative vigour, flowering efficiency, physiological parameters and flower aesthetics. Notably, the combination of $E_2 \times P_3$ resulted in the highest-quality floral stems with extended blooming duration and superior post-harvest traits. For growers targeting export-oriented floriculture, adopting protected cultivation using triple-node propagules offers a strategic advantage. Conversely, when early flowering and higher spike quantity are desired for local markets, full-sun (E_1) cultivation with P_2 may be preferable. Future studies should explore the use of coloured or spectrally selective shade nets, cost–benefit analysis of propagule grading and post-harvest handling practices to further optimise quality and profitability in *Heliconia* production systems.

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Authors' contributions

SM recorded the data and drafted the manuscript. CRM provided technical support and assisted in the writing process. SJ performed the statistical analysis. SR contributed technical help during manuscript preparation. VLPK assisted in revising the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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