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LED light supplementation in the cultivation of two petunia varieties: physiological and productive aspects

Suplementação luminosa com LED para o cultivo de plantas de duas variedades de petúnia: aspectos fisiológicos e produtivos

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Highlights

Blue and red light maintained pigments and photosynthesis like natural light.
White light increased open flower number in the White petunia variety.
Light supplementation matched natural light in total plant growth response.

Abstract

The objective of this study was to investigate the effects of supplemental lighting (SL) on two varieties of *Petunia × hybrida* (Miliflora – FlashForward White and Pendula – Plush Red) grown under natural light conditions. Light-emitting diodes (LEDs) were used with two blue (B) and red (R) light combinations 15%B + 85%R and 85%B + 15%R as well as white light (W), all at an approximate intensity of 25 µmol m^{-2} s^{-1}. The experiment was conducted in a greenhouse, with daily supplemental lighting following the natural photoperiod of the Pelotas-RS region, Brazil, from sowing to full flowering. Evaluations included photosynthetic pigment indices, gas exchange, and biometric analyses. The two blue and red light combinations did not result in significant differences in pigment indices or net photosynthetic rate compared to natural light. However, the 85%B + 15%R and 100%W treatments promoted greater stem dry weight in the White variety and higher flower and floral bud dry weight in the Red variety. Additionally, white light (100%W) increased the number of open flowers per plant in the White variety. Nevertheless, all three supplemental light treatments performed similarly to natural light in terms of total plant growth (shoot and root biomass).

Key words: *Petunia × hybrida.* Light. Pigments. Photosynthesis. Growth.

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Resumo

O objetivo deste estudo foi investigar os efeitos da suplementação luminosa (SL) sobre plantas de duas variedades de *Petunia × hybrida* (Miliflora – FlashForward - White e Pendula Plush - Red) frente ao cultivo sob luz natural. Foram utilizados diodos emissores de luz (LED) com duas combinações de luz azul (A) e vermelha (V), sendo: 15%A+85%V e 85%A+15%V, e luz branca (B), com intensidade luminosa aproximada de 25 μmol m^{-2} s^{-1}. O experimento foi conduzido em estufa de cultivo e o fornecimento diário da SL acompanhou o fotoperíodo da região de Pelotas-RS, ocorrendo desde a semeadura até a fase de plantas adultas em florescimento pleno. Foram realizadas avaliações do índice de pigmentos fotossintéticos, trocas gasosas e análises biométricas das plantas. As duas combinações de luz azul e vermelha não proporcionaram diferenças significativas nos índices de pigmentos ou na taxa fotossintética líquida em comparação ao cultivo sob luz natural. As fontes de SL 85%A + 15%V e 100%B promoveram maior massa seca de ramificações das plantas da variedade White e massa seca de flores e botões florais das plantas da variedade Red. Por outro lado, a luz branca (100%B) aumentou o número de flores abertas por planta da variedade White. No entanto, as três fontes de suplementação apresentaram desempenho similar ao da luz natural no crescimento da planta inteira (parte aérea e radicular).

Palavras-chave: *Petunia × hybrida.* Luz. Pigmentos. Fotossíntese. Crescimento.

Introduction

One of the main challenges faced by petunia growers, especially in the southern region of Brazil, during both the seedling and adult stages, is maintaining satisfactory production levels during periods of low solar radiation. According to data from Instituto Nacional de Meteorologia [INMET] (2022), the average monthly global solar radiation during winter in the Pelotas-RS region (latitude: -31.776) can be up to 63% lower compared to summer, the period with the highest solar incidence. This situation is further aggravated by the use of plastic film in greenhouses, which can reduce the global transmission of sunlight to the plant canopy by approximately 76% (Beckmann et al., 2006).

The use of artificial lighting in flower production not only compensates for the lack of natural light but also allows fine adjustments in the growing environment to optimize plant growth and improve the quality of the flowers produced (Trivelinni et al., 2023). Studies indicate that manipulating light properties such as intensity, photoperiod, and spectral composition, as discussed by Xu (2019), can be used to induce flowering, control leaf morphology, and modulate overall plant architecture. Within the photosynthetically active radiation (PAR) spectrum, approximately 90% of the energy absorbed by leaves occurs at blue and red wavelengths. Therefore, these regions of the visible spectrum strongly influence plant development and physiology (Terashima et al., 2009).

However, because white light includes not only blue and red wavelengths but also green, it can promote better plant responses compared to the combined use of only blue

and red light. Green light, which has a lower absorption index by pigments, can penetrate deeper into the leaf tissue under high light intensities (Battle et al., 2020). This condition increases the likelihood of light reaching regions with high pigment concentrations in the thylakoids (Terashima et al., 2009). Thus, green light also contributes to the photosynthetic process, although its effects on plant physiology depend on the spectral requirements of each species (Lazzarini et al., 2017).

Several traits related to photosynthesis are influenced by light quality, including responses to red and blue light. Blue LEDs are generally associated with chlorophyll synthesis and stomatal opening (Miao et al., 2016; Zheng & Labeke, 2017). It has also been observed that exposure to red and blue light increases the accumulation of phenolic compounds such as flavonoids and anthocyanins in various species, in contrast to white LED light (Wang et al., 2015). However, the effects of these light treatments depend on the species, the bioactive compounds present, and the light quality (Naznin et al., 2019).

In recent years, several researchers have tested different supplemental light (SL) sources to evaluate their effects on petunia growth and development (Gautam et al., 2015; Akbarian et al., 2016; Park & Runkle, 2018). Randall and Lopez (2014) recommended combining red and blue light in an 85%:15% ratio for high-quality petunia seedling production under protected conditions. On the other hand, Phansurin et al. (2017) suggested using white light to achieve high productivity in this species, highlighting the positive role of green light in the spectral composition.

Despite the various studies on artificial lighting in protected cultivation, which have shown mixed results regarding petunia growth and development (Randall & Lopez, 2014; Gautam et al., 2015; Akbarian et al., 2016; Phansurin et al., 2017; Kong et al., 2018b; Park & Runkle, 2018), there are still no reports of such research conducted under the protected cultivation conditions of southern Brazil. Therefore, petunia growers in this region lack guidance on the use of artificial lighting from seedling production to commercialization.

In this context, the aim of this study was to evaluate the effects of three types of supplemental light (SL; two combinations of blue and red light, and white light) by analyzing pigment indices, photosynthetic parameters, and biometric variables in two Petunia × hybrida varieties grown under protected conditions.

Materials and Methods

Location, period, and cultivation structure

The experiment was carried out at the Experimental Teaching Field of the Department of Crop Science, Eliseu Maciel Faculty of Agronomy, Federal University of Pelotas, located in Capão do Leão, RS, Brazil (31°48'S, 52°25'W). The study was conducted from May 27 to October 12, 2021, in a greenhouse with a galvanized iron structure and arched roof, oriented north-south. The central ceiling height was 5 m, and the structure was covered with a 150 µm thick translucent diffusing plastic film. The side curtains were manually operated, being opened during warmer periods to allow

ventilation and closed during cooler periods to retain heat, according to daily weather conditions. The internal area used for the experiment covered 110 m2 (10 m × 11 m). Two wooden benches (1.20 m × 8.00 m), oriented north-south and lined with plastic film, were installed inside the greenhouse. Above the benches, the artificial lighting system was installed. Petunia plants were placed on these benches throughout the plug, seedling, and mature flowering stages.

Plant material, containers, substrates, and nutrient solution

The two selected Petunia × hybrida varieties - Petunia miliflora F1 'FlashForward' (White) and Petunia pendula F1 'Plush' (Red) - are recommended for container cultivation. The cultivation cycle was divided into three stages: plug production, seedling growth, and full flowering of mature plants.

In the plug stage, seeds were sown in Carolina Soil® substrate reference XV (electrical conductivity of 0.11 dS m^{-1}) using polystyrene trays with 288 cells, with half of the cells allocated to each variety. Three seeds were sown per cell, and after 20 days, thinning was performed to leave one plant per cell. Floating trays ("floating pools") were installed on the benches, maintaining a nutrient solution layer approximately 5 cm deep.

At the seedling stage (50 days after sowing), plugs were transplanted individually into black polypropylene pots with a volume of 0.5 L, containing Carolina Soil® reference XVIII (EC of 0.07 dS m^{-1}). Irrigation was carried out via localized drip systems using self-compensating, anti-drainage button emitters (2 L h^{-1}), with two emitters per pot. Watering was automated through a timer, adjusted hourly according to greenhouse temperature and humidity conditions.

Thirty-nine days after transplanting (89 days after sowing), when more than half of the plants had open flowers, seedlings were transplanted individually into 2 L black polypropylene pots ("cuia" type) containing a substrate mix (Carolina Soil® references V and XVIII in a 1.5:2 ratio; EC 0.18 dS m^{-1}). Irrigation followed the same drip system, now with four emitters per pot.

A nutrient solution was supplied daily from the first week after plant emergence, following the formulation of Oh et al. (2010). The solution contained (in mg L^{-1} for plugs/seedlings and mature plants, respectively): calcium nitrate (Calcinit) 295/590, magnesium sulfate 170/340, monopotassium phosphate (MKP) 30/60, potassium nitrate 145/290, iron EDDHA (6%) 4.2/8.4, boron 0.3/0.6, molybdenum 0.15/0.3, manganese 0.8/1.6, zinc 1.1/2.2, and copper 0.9/0.9. Electrical conductivity (EC) ranged from 0.6 to 0.8 dS m^{-1} during the plug stage and from 0.8 to 1.0 dS m^{-1} during the seedling and mature stages.

Supplemental light treatments

Supplemental lighting (SL) was applied for 138 days, covering the period from plug production to full flowering, when plants were ready for sale as mature specimens. Tubular LED (light-emitting diode) lamps were positioned approximately 30 cm above the plant canopy. Two combinations of blue LEDs (451-469 nm, B) and red LEDs (621-650 nm, R) were used in the following

proportions: 85%B + 15%R and 15%B + 85%R. Additionally, 100% white light (W) with a color temperature of 4500 K (broad spectrum) was applied, along with a control treatment under natural light conditions (no artificial lighting). For each supplemental lighting treatment, two 120 cm lamps were arranged in a continuous line along the center of the benches.

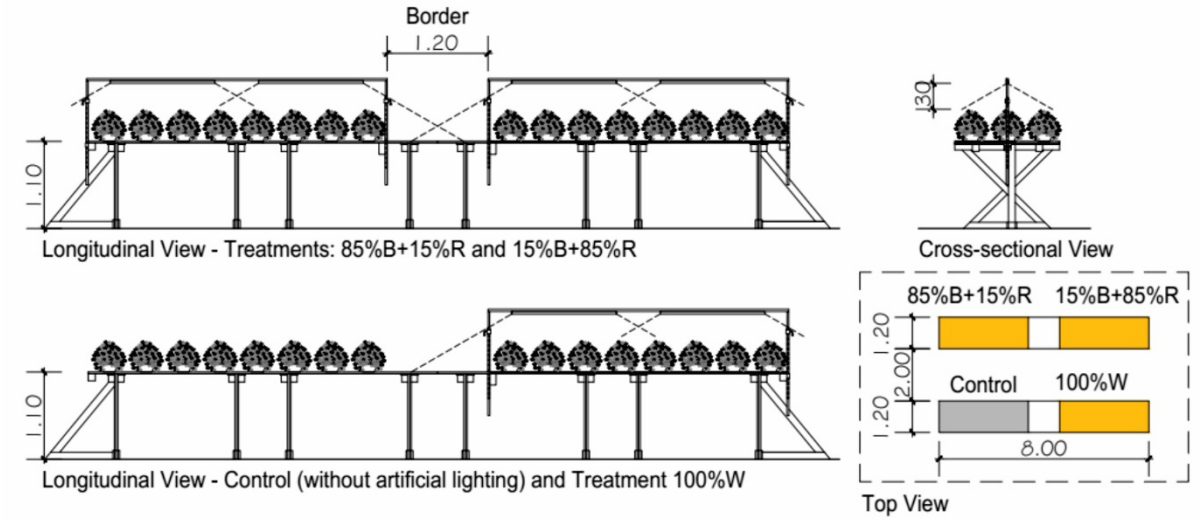
The artificial lighting system was designed to allow height adjustment of the lamps according to plant growth. Activation followed the natural photoperiod of the Pelotas-RS region, with the shortest and longest durations being 9.9 h (June) and 12.6 h (October), respectively. To ensure this, the system was coupled to a photoelectric relay with a photocell, which activated the lamps only during daylight hours.

The photosynthetic photon flux density (PPFD) of the three SL treatments was 25 (±5) μmol m^{-2} s^{-1}. Values were measured using a LI-COR® quantum sensor (model Li-185B), recorded with a LI-COR® datalogger (model CR 1000), and calculated from the average of three measurements taken at equidistant points along the bench [directly below the lamp (reference point) and at distances of 30 cm and 45 cm from this point]. At each position, two measurements were recorded with a 10-min interval. Measurements were taken over the benches in the absence of plants, during the night period between 19:00 h and 22:00 h, ensuring no interference from natural light.

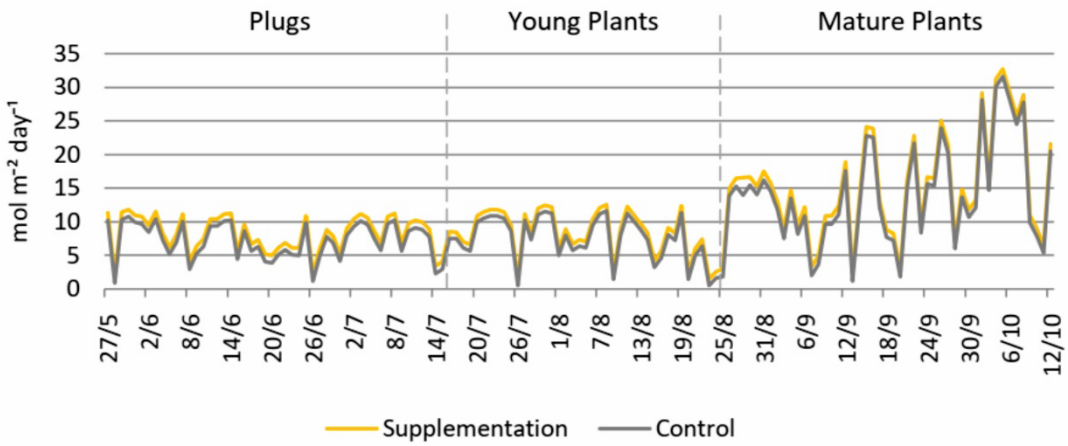
Environmental monitoring

The daily light integral (DLI) incident on the plants was calculated based on the daily average PPFD, measured in μmol m^{-2} s^{-1} using a LI-COR® quantum sensor. Data were recorded every 10 min with a LI-COR® datalogger (model CR 1000). These values were then multiplied by the photoperiod, determined using the free software Daylight Hours Explorer (version LNX 32.0.0.0), according to the latitude of the Pelotas-RS region. Units were properly converted to obtain values expressed in mol m^{-2} day^{-1} (Figure 1).

Air temperature and relative humidity were monitored in each supplemental lighting treatment and in the control (one sensor per treatment) using digital thermo-hygrometers placed on the cultivation benches, positioned below the lamps at a height of 1.10 m from the floor (Figure 2).



I) Representation of the longitudinal, cross-sectional, and top views of the cultivation benches.



II) Graph of the Daily Light Integral (DLI).

Figure 1. I) Representation, in the adult plant stage, of the longitudinal, cross-sectional, and top views of the benches with the light supplementation treatments (SL: 85%B+15%R, 15%B+85%R, 100%W) and the control.
II) Daily Light Integral (DLI) inside the greenhouse throughout the plug, seedling, and adult stages of production of petunia plants under light supplementation treatments and the control. Light supplementation (%) – B: blue light, R: red light, and W: white light.

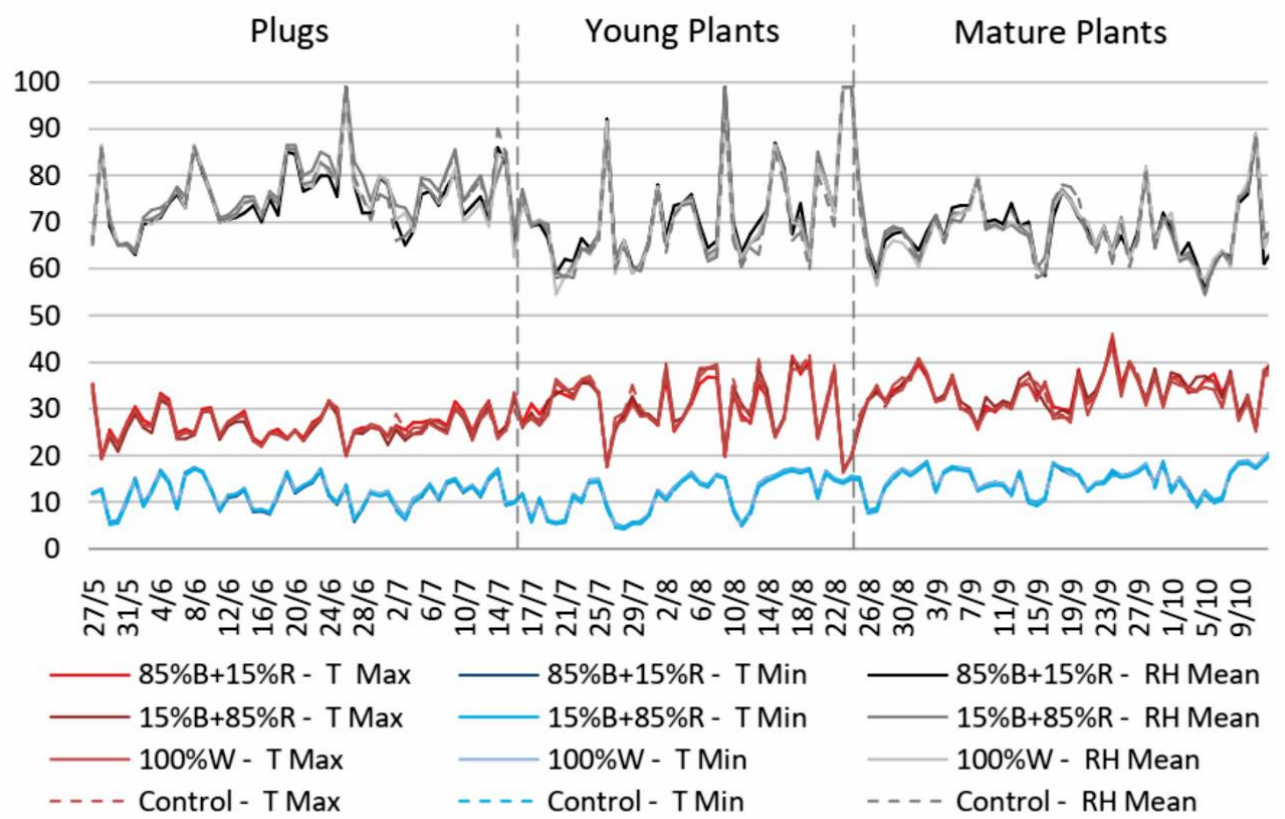


Figure 2. Daily variation in maximum and minimum temperatures (T; °C) and mean relative air humidity (RH; %) over the petunia cultivation benches throughout the plug, seedling, and adult plant stages under light supplementation treatments (85%B+15%R, 15%B+85%R, 100%W) and control (no artificial lighting). Light supplementation (%) – B: blue light, R: red light, and W: white light.

Evaluation parameters

The effect of light supplementation on photosynthetic pigments was assessed through instantaneous measurements of chlorophyll, flavonoid, anthocyanin indices, and nitrogen balance using a portable chlorophyll meter (DUALEX®, model FORCE-A, Orsay, France) at 44 days after transplanting (DAT). Additionally, photosynthetic parameters were evaluated at 44 DAT using a gas exchange analyzer (IRGA, LI-COR®, model 6400 XT) under a photosynthetic active photon flux density of 1,200 µmol photons. The parameters included net photosynthetic rate, stomatal conductance, intercellular carbon concentration, and transpiration rate. The quantum efficiency of photosystem II was also measured at 45 DAT using a portable fluorometer (model OS30p, Opti-Sciences, USA). All assessments were performed in the cultivation environment on sunny days between 09:00 h and 11:00 h, selecting leaves of appropriate size for each device from the median portion of the plant shoots.

Chlorophyll a, chlorophyll b, and carotenoid contents were determined only from leaves collected at 49 DAT using a fluorescence spectrophotometer (SpectraMax®, model M3), according to the dimethyl sulfoxide (DMSO) method neutralized with calcium carbonate (CaCO3), as described by Hiscox and Israelstam (1979), and quantified by the equations proposed by Wellburn (1994).

The following biometric parameters were determined 49 days after transplanting (138 days after sowing) the seedlings into bowl-type pots: shoot height (SH), number of floral buds (NFB), number of open flowers (NOF), leaf area (LA), leaf dry weight (LDW), stem dry weight (SDW), root dry weight (RDW), flower and floral bud dry weight (FBDW), and total plant dry weight (TPDW = LDW + SDW + RDW + FBDW). Dry weight was measured using a precision balance after drying the plant material in a forced-air circulation oven at 65 °C until constant weight. Leaf area was measured using a LI-COR® leaf area meter (model LI-300C).

Data analysis

A completely randomized experimental design was adopted, in a factorial arrangement (2 × 4) resulting from the combination of two petunia varieties (White and Red) and four supplemental lighting (SL) treatments (85%B + 15%R; 15%B + 85%R; 100%W; and control/no supplemental lighting). For the measurement of photosynthetic parameters, six plants of each variety were used at each SL level. For biometric data analysis, evaluations were performed with three replicates, each corresponding to the average of two plants per SL treatment. Data normality was verified using the Shapiro-Wilk test, and homogeneity of variances was assessed by Bartlett's test. Subsequently, the data were subjected to analysis of variance (ANOVA), followed by Tukey's multiple comparison test at a 5% significance level. All analyses were performed using RStudio software, version 2023.03.0+386.

Results and Discussion

Homogeneity of variances was assessed using Bartlett's test, which did not indicate a violation of the homoscedasticity assumption ($p > 0.05$) for most of the variables analyzed. The only exception was the number of floral buds for the 'variety' factor alone ($p = 0.0128$); however, since the analysis considered the interaction between factors, the ANOVA was retained.

The results for the flavonoid index, nitrogen balance, chlorophyll index, and anthocyanin index (Table 1) showed no significant interaction between supplemental lighting (SL) and variety, nor a significant isolated effect of SL. However, significant differences were observed between varieties for the chlorophyll and anthocyanin indices. The Red variety exhibited chlorophyll levels 22% higher than White, while the White variety showed an anthocyanin index 4.3% higher than Red, reinforcing the role of genetic diversity in physiological responses, as highlighted by Silvestri et al. (2019).

Results for net photosynthetic rate, stomatal conductance, intercellular CO_2 concentration, and transpiration rate indicate that supplemental lighting (SL) significantly influenced parameters related

to stomatal function, although it did not lead to statistically significant changes in net carbon assimilation (Table 1). These findings suggest that the light spectrum directly affects stomatal opening and, consequently, transpiration dynamics, indirectly influencing photosynthetic efficiency. The white light treatment (100%W), which includes the green spectrum, resulted in the highest values of stomatal conductance and transpiration rate, without a corresponding increase in CO_2 assimilation. These results partially corroborate the findings of Chen et al. (2024), who reported increased water use efficiency and reduced stomatal conductance under green light. Therefore, water use efficiency may vary depending on species, light intensity, and genotypic interactions.

Table 1
Chlorophyll index (Chl), anthocyanin index (ANTH), flavonoid index (FLAV), nitrogen balance index (NBI), net photosynthetic rate (Pn), stomatal conductance (Gs), intercellular CO2 concentration (Ci), and transpiration rate (E) of two petunia varieties subjected to light supplementation at 44 days after transplanting (133 days after sowing)

Study factor	CHL	ANTH	FLAV	NBI
Light supplementation				
85%B+15%R	25.85 a	0.352 a	1.52 a	17.84 a
15%B+85%R	26.24 a	0.355 a	1.50 a	17.45 a
100%W	24.28 a	0.357 a	1.55 a	17.36 a
Control	24.40 a	0.357 a	1.54 a	16.59 a
Variety				
White	22.71 b	0.363 a	1.36 a	18.17 a
Red	27.67 a	0.348 b	1.70 a	16.45 a
Light supplementation × Variety	ns	ns	ns	ns
CV (%)	9.13	2.80	8.32	13.74
Study factor	**Pn µmol CO_2 m^{-2} s^{-1}**	**Gs mol H_2O m^{-2} s^{-1}**	**Ci µmol CO_2 m^{-2}**	**E mmol H_2O m^{-2} s^{-1}**
Light supplementation				
85%B+15%R	16.37 a	0.264 a	241.10 b	4.20 b
15%B+85%R	16.84 a	0.236 a	255.18 a	4.96 ab
100%W	18.15 a	0.258 a	249.16 ab	5.23 a
Control	16.77 a	0.176 b	203.08 b	3.15 c
Variety				
White	16.67 a	0.227 a	235.64 a	4.05 a
Red	17.67 a	0.240 a	238.62 a	4.72 a
Light supplementation × Variety	ns	ns	ns	ns
CV (%)	12.40	16.70	13.96	13.30

Means followed by the same letters do not differ significantly according to Tukey's test at the 5% probability level. ns = not significant interaction according to the F-test at 5%. Light supplementation (%) – B: blue light, R: red light, and W: white light.

The maximum quantum efficiency of photosystem II (Fv/Fm), an indicator of the functional integrity of the photosynthetic apparatus (Baker, 2008), ranged from 0.757 to 0.799. Only the treatments with supplemental lighting maintained values within the recommended optimal range (0.78-0.83), as shown in Table 2, indicating the absence of photoinhibitory stress under these conditions. The initial (F0) and maximum (Fm) chlorophyll fluorescence parameters remained stable across treatments with and without supplemental lighting, suggesting balanced PSII functionality. The Red variety exhibited an Fm approximately 13% higher than the White variety, while Fo showed no significant differences between genotypes, possibly reflecting genetic variation in photosynthetic capacity. These results partially corroborate the findings of Frąszczak et al. (2023), highlighting the influence of genotype and environmental conditions on the photosynthetic response to light spectrum.

Table 2
Photochemical quantum efficiency of photosystem II (Fv/Fm), initial fluorescence (F_0), and maximum fluorescence (Fm) of plants from two petunia varieties subjected to light supplementation at 45 days after transplanting (134 days after sowing)

Study factor	Fv/Fm	F0	Fm
Light supplementation			
85%B+15%R	0.791 a	157 a	717 a
15%B+85%R	0.799 a	159 a	714 a
100%W	0.778 ab	160 a	705 a
Control	0.757 b	164 a	699 a
Variety			
White	0.786 a	158 a	670 b
Red	0.776 a	162 a	747 a
Light supplementation × Variety	ns	ns	ns
CV (%)	2.42	5.38	3.11

Means followed by the same letters do not differ significantly according to Tukey's test at the 5% probability level. ns = not significant interaction according to the F-test at 5%. Light supplementation (%) – B: blue light, R: red light, and W: white light.

The highest levels of chlorophyll a, chlorophyll b, and total chlorophyll were observed in plants subjected to light supplementation (SL) with 85%B + 15%R and 15%B + 85%R, although no statistically significant differences were found among the different lighting conditions (Table 3). These results align with theoretical expectations, considering the high absorption of blue and red light by photosynthetic pigments, as described by Taiz et al. (2017).

Table 3
Chlorophyll contents (Chlor. a and Chlor. b), carotenoids (Carot), total chlorophyll (a+b) in mg g^{-1} of dry weight, chlorophyll a/b ratio, and total chlorophyll/carotenoid ratio in plants of two petunia varieties subjected to light supplementation at 49 days after transplanting (138 days after sowing)

Study factor	Chlor. a	Chlor. b	Carot.	Total chlor. (a+b)	Chlor. (a/b) ratio	Total chlor./ carot. ratio
Light supplementation						
85%B+15%R	3.54 a	1.52 a	0.500 a	5.00 a	2.77 a	9.35 a
15%B+85%R	3.54 a	1.64 a	0.477 a	5.28 a	2.87 a	10.03 a
100%W	3.31 a	1.15 a	0.426 a	4.41 a	2.23 a	9.90 a
Controle	3.39 a	1.37 a	0.481 a	4.64 a	2.88 a	8.51 a
Variety						
White	3.27 b	1.35 a	0.452 a	4.61 a	3.15 a	9.67 a
Red	3.62 a	1.49 a	0.491 a	5.06 a	2.73 a	9.62 a
Light supplementation × Variety	ns	ns	ns	ns	ns	ns
CV (%)	13.62	28.82	13.38	15.4	28.09	10.59

Means followed by the same letters do not differ significantly according to Tukey's test at the 5% probability level. ns = not significant interaction according to the F-test at 5%. Light supplementation (%) – B: blue light, R: red light, and W: white light.

Similarly, carotenoid content, as well as the chlorophyll a/b and total chlorophyll/carotenoid ratios, did not show significant variation among the SL treatments (Table 3). These data suggest that, under the experimental conditions used, light supplementation had a limited effect on pigment composition, possibly due to the intensity or duration of exposure. This behavior is consistent with the findings of García-Caparrós et al. (2020) and Matysiak (2021), who emphasized that more pronounced physiological responses occur under light intensities above 100 µmol m^{-2} s^{-1}.

Still in Table 3, regarding the variety factor, a statistically significant difference was observed only for chlorophyll a, with the Red variety showing levels 11% higher than White. Although not statistically significant, Red also showed higher mean values for chlorophyll b (10%), carotenoids (9%), and total chlorophyll (10%), which may indicate a greater capacity for light capture and utilization. No significant interaction between supplemental lighting and variety was observed.

The biometric data presented in Table 4 show that the two supplemental lighting (SL) sources combining blue and red light did not influence the reduction of shoot height in plants of the two evaluated varieties. This result contrasts with previous studies reporting the inhibitory effect of blue light on stem elongation in petunias when combined

with red light (Randall & Lopez, 2014; Akbarian et al., 2016). On the other hand, the fact that the three SL sources did not affect shoot height (Table 4) confirms the findings of Kong and Zheng (2024) on the versatility of blue light when combined with other spectral ranges in controlling stem elongation in various species. Runkle (2016) also described the attenuating effect of natural light on the spectral quality of supplemental lighting in inhibiting stem extension in plants.

However, the two combinations of blue and red light caused a reduction in leaf area in plants of the White variety, but only under SL 15%B + 85%R was leaf dry weight lower than in control plants. Furthermore, under SL with red and blue light, the leaf area (Table 4) of plants of the Red variety reached values similar to those of White plants. These results are supported by Wollaeger and Runkle (2013), who also observed reduced biomass accumulation and leaf expansion in impatiens, petunias, and salvias when exposed to combinations of blue and red LEDs.

In contrast, in plants of the White variety, SL 85%B + 15%R resulted in greater root dry weight accumulation compared to plants without supplemental lighting, unlike the Red variety, which showed similar responses under the four growing conditions (Table 4). However, when subjected to the three types of supplemental lighting, root dry weight production (Table 4) in White plants reached values similar to those of Red plants, while control White plants had lower values. Similar results regarding the positive effect of SL sources with a higher proportion of blue light combined with red light were observed for Gaura, in this case under 50%B + 50%R (Owen & Lopez, 2019). However, the results obtained in this experiment for both species did not align with those reported by Randall and Lopez (2015), who conducted experiments with ornamental plants such as vinca, impatiens, and geraniums under variable proportions of red and blue light, resulting in decreased root dry weight.

Moreover, in the White variety, plants grown under 100% white light (100%W) supplemental lighting provided stem dry weight production similar to those under SL 85%B + 15%R, with values higher than those of control plants. Additionally, stem dry weight was the parameter that contributed most (about 44%) to increasing total plant dry weight in this variety (Table 4), which, regardless of SL treatment, was greater in White plants compared to Red plants, being 23% higher (Table 4). Craver et al. (2019) reported similar effects between broad-spectrum light sources and combinations of blue and red light in ornamental plants grown in protected environments. Park and Runkle (2018) also affirmed that white LEDs and mixtures of white and red light can produce plant dry weight as efficiently as combinations of blue and red light.

Table 4
Shoot height (SH), leaf area (LA), leaf dry weight (LDW), stem dry weight (SDW), root dry weight (RDW), flower and bud dry weight (FBDW), total plant dry weight (TPDW), number of floral buds (NFB), and number of open flowers (NOF) of two petunia varieties subjected to light supplementation at 49 days after transplanting (138 days after sowing)

Study factor	SH (cm)		LA (cm² plant⁻¹)		LDW (g plant⁻¹)	
	Variety					
Light supplementation	White	Red	White	Red	White	Red
85%B+15%R	18.00 aB	27.16 aA	1535.87 bA	1555.76 aA	5.68 abB	6.37 aA
15%B+85%R	18.50 aB	26.83 aA	1466.23 bA	1454.04 bA	5.38 bB	5.8 bA
100%W	18.66 aB	26.16 aA	1674.97 aA	1505.47 abB	5.63 abB	5.92 bA
Control	18.83 aB	26.00 aA	1634.68 aA	1475.93 abB	5.81 aB	6.58 aA
CV (%)	2.56		2.44		2.35	
Study factor	**SDW (g plant⁻¹)**		**RDW (g plant⁻¹)**		**FBDW (g plant⁻¹)**	
Light supplementation	*White*	*Red*	*White*	*Red*	*White*	*Red*
85%B+15%R	14.58 aA	10.25 aB	2.13 aA	1.93 aA	10.60 aA	8.21 abB
15%B+85%R	13.13 bA	9.37 bB	1.96 abA	2.05 aA	9.80 aA	7.19 cB
100%W	14.91 aA	9.39 bB	1.76 bA	1.83 aA	9.79 aA	8.57 aB
Control	13.23 bA	9.07 bB	1.73 bB	2.06 aA	10.07 aA	7.45 bcB
CV (%)	2.46		6.09		4.74	
Study factor	**NFB plant⁻¹**		**NOF plant⁻¹**			
	Variety					
Light supplementation	*White*	*Red*	*White*	*Red*		
85%B+15%R	91.00 cA	37.83 aB	188.33 dA	120.16 abB		
15%B+85%R	109.00 aA	34.16 abB	222.00 cA	111.50 bB		
100%W	102.33 bA	30.66 bB	287.00 aA	126.00 aB		
Control	103.66 abA	31.5 bB	263.83 bA	114.66 abB		
CV (%)	3.84		2.85			

Study factor	TPDW (g plant⁻¹)
Light supplementation	
85%B+15%R	29.35 a
15%B+85%R	27.75 b
100%W	28.43 ab
Control	28.40 ab
Variety	
White	31.44 a
Red	25.53 b
Light supplementation × Variety	ns
CV (%)	2.78

Means followed by the same letters, lowercase in columns and uppercase in rows, do not differ significantly according to Tukey's test at the 5% probability level. ns = not significant interaction according to the F-test at 5%. Light supplementation (%) – B: blue light, R: red light, and W: white light.

Regarding flower production in the Red variety, the dry flower weight of plants grown under SL 100%B was comparable to that of plants under SL 85%B + 15%R. For the White variety, values were consistent across the four cultivation conditions evaluated (Table 4). The role of blue light in promoting flowering in petunia was confirmed by Gautam (2020) and Kong et al. (2018a). Considering the number of open flowers per plant in the White variety, a 52% increase was observed in plants under white light (100%W) compared to those under SL 85%B + 15%R (Table 4). It is likely that the presence of green light in SL 100%W contributed to this positive flowering response. This assumption is supported by the findings of Meng and Runkle (2019), who highlighted the effectiveness of supplemental green light in promoting petunia flowering in greenhouse cultivation. Conversely, in the Red variety, the three SL sources resulted in responses similar to those of the control group. As for the number of floral buds per plant in the White variety, the control plants showed superior performance compared to those under SL 85%B + 15%R, while performing similarly to those under SL 15%B + 85%R and 100%W (Table 4). In the Red variety, once again, all SL sources produced effects equivalent to those observed in the control plants (Table 4).

Overall, the results of biometric and photosynthetic parameters indicated that plant responses to different supplemental lighting sources are highly dependent on the studied variety. Variability in light quality responses between the two petunia genotypes may be associated with leaf morphology and mesophyll anatomy specific to each variety (Zheng & Labeke, 2017). This reinforces the importance of considering plant genetic diversity when using different supplemental lighting sources (Kobori et al., 2022; Huché-Thélier et al., 2016; Lazzarini et al., 2017), as evidenced in this study.

However, this research identified the potential of using the three LED sources, which are more energy-efficient compared to other lamp technologies. Among the various options available, the white LED lamp with a color temperature around 4500K emerges as an especially promising alternative for petunia producers. In addition to offering a more accessible initial cost, this technology is widely available on the market, making it an economical and practical choice for large-scale plant production. At the same time, it improves human vision and the perception of visible alterations in plant form or anatomy (Park & Runkle, 2018) compared to different combinations of red and blue LEDs.

Nevertheless, the three supplemental lighting sources showed only limited effects on growth and flower production in the two varieties compared to the absence of supplemental lighting. Therefore, further studies are recommended to test different supplemental lighting sources at higher intensities to determine whether such conditions might lead to greater productivity and also improve plant quality standards.

Conclusions

Petunia × hybrida plants of the Miliflora - White and Pendula - Red varieties exhibit distinct responses to the three supplemental light sources.

Treatments with supplemental lighting improved stomatal conductance compared to natural light, indicating greater efficiency in gas exchange. However, no significant differences were observed in net photosynthetic rate or pigment content, suggesting that the light intensity used was insufficient to affect plant growth.

The treatments with 85% blue light and 15% red light, as well as 100% white light, promoted greater dry biomass accumulation in the stems of the White variety and in the flowers and floral buds of the Red variety, compared to the absence of supplemental lighting. White light (100%W) also resulted in the highest number of open flowers per plant in the White variety.

Nevertheless, when considering overall plant growth, including both shoot and root systems, the three supplemental light sources performed similarly to natural light, regardless of variety.

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