

Article

New Insights into Midday Supplemental Lighting in Greenhouse-Grown Sweet Basil (*Ocimum basilicum* L.): Photosynthetic and Sensory Quality Traits

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Abstract

Supplemental light spectrum strongly influences crop physiology, quality, and marketability in controlled-environment horticulture. This study evaluated greenhouse-grown basil (*Ocimum basilicum* L.) under natural daylight supplemented with 250 $\mu\text{mol m}^{-2} \text{s}^{-1}$ of multi-band WHITE or narrow-band RED, GREEN, and BLUE LEDs, compared with non-supplemented controls (CNT). Diurnal gas exchange, cumulative photosynthetic activity, quality, sensory traits, and productive responses were assessed to identify spectrum-specific effects. WHITE supplementation produced the highest net photosynthesis (P_n) throughout the photoperiod, increasing carbon assimilation by up to 90% during active supplementation compared with CNT, while improving stomatal–photosynthetic coordination and titratable acidity. BLUE light promoted the highest stomatal conductance and transpiration, whereas RED induced faster stomatal closure without affecting the plant's final biomass. GREEN supplementation showed intermediate physiological responses while enhancing fresh biomass, leaf brightness, and greenness. Spectral treatments significantly affected chlorophyll content, colorimetric parameters, sensory descriptors, aroma typicality, and texture, although antioxidant activity and overall consumer acceptability remained largely stable. WHITE and CNT samples achieved the highest sensory appreciation, while BLUE supplementation increased bitterness and reduced aromatic typicality. Overall, no single spectrum optimized all production objectives. WHITE provided the most balanced strategy for maximizing photosynthetic efficiency and premium-quality traits, whereas RED, GREEN, and BLUE offered more specialized benefits related to biomass increase, visual quality, or pigmentation. These findings highlight precision spectral management as an effective tool for tailoring basil production to specific agronomic and commercial targets in protected cultivation systems.

Keywords: hedonic evaluation; light modulation; light spectra; narrow band light; precision horticulture



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1. Introduction

Sweet basil (*Ocimum basilicum* L.) is a prominent aromatic crop valued globally for its culinary versatility and rich profile of health-promoting secondary metabolites. In

modern greenhouse horticulture, there is a growing demand for year-round high-quality production, which has led to the adoption of advanced cultivation strategies to optimize growth and nutraceutical value [1]. Among the various environmental factors, light is the primary driver of plant performance, serving both as an energy source for photosynthesis and a regulatory signal for photomorphogenesis [2,3].

Although artificial lighting represents one of the major energy and operating costs in greenhouses, it remains a crucial cultivation strategy for ensuring stable and high yields, accounting for 10–30% of total expenditures and up to 30% of production costs in crops such as lettuce [4]. Research increasingly focuses on narrow-band and monochromatic Light-Emitting Diodes (LEDs), including white, red, blue, and green spectra, as well as adaptive control strategies, to reduce costs and carbon emissions while maintaining or improving productivity [5–7]. Energy-efficient lighting is recognized as a key lever for sustainable greenhouse production, particularly when strategically applied at specific times to achieve targeted goals [8]. In this context, narrow-band red and blue LEDs have demonstrated superior photon efficacy (i.e., approximately $2.3 \mu\text{mol J}^{-1}$ for red light and $1.8\text{--}2.0 \mu\text{mol J}^{-1}$ for blue light) along with enhanced biomass production and nutritional quality [6,9]. In addition, positive results have been observed in the case of midday supplemental narrow-band light, with the aim of “photomodulating” the production of targeted metabolites [10,11]. Combining targeted monochromatic supplementation with a full-spectrum solar baseline is consistently shown to outperform single-wavelength approaches in both yield and light-use efficiency [5,9]. Ultimately, the most viable sustainable strategy is to integrate red and blue LEDs with natural solar radiation under intelligent control systems, though economic feasibility remains dependent on fixture costs and local energy tariffs [8,10].

Beyond their impact on energy consumption, LEDs play a crucial role in enhancing plant performance by providing narrow-band monochromatic light, which allows precise tailoring of specific wavelengths to modulate physiological and biochemical responses [6]. Some authors have shown that blue, red, and green light wavebands elicit distinct responses in leafy vegetables. For instance, blue light is recognized for its role in inducing stomatal opening and chloroplast relocation, thereby enhancing gas exchange and stomatal conductance, when applied as a supplement to solar radiation in greenhouse conditions [11,12]. Red light, while highly efficient for driving photosynthesis and biomass accumulation, often works best when combined with blue light to maintain optimal photosynthetic capacity [13]. Green light, traditionally considered less efficient, is now understood to penetrate deeper into the canopy, significantly contributing to photosynthesis in lower leaf layers and influencing secondary metabolism [14,15].

A critical challenge in greenhouse production is the optimization of supplemental lighting during periods of fluctuating natural light. While many studies focus on end-of-day or morning supplementation [12,16], providing monochromatic LED light during the central hours of the day, when solar radiation is at its peak, remains relatively unexplored, particularly in terms of maximizing photosynthetic efficiency across the diurnal cycle. Recent findings in basil and other species, such as strawberry plants, suggest that specific wavebands can modulate the photosynthetic apparatus without necessarily inducing oxidative stress, as indicated by stable chlorophyll-*a* fluorescence [11,17].

Beyond biomass, the market value of basil is heavily dependent on its organoleptic and nutraceutical quality. Leaf color, a key visual indicator, is determined by the accumulation of pigments such as chlorophylls, carotenoids, and anthocyanins, which are highly sensitive to the light spectrum [18]. Furthermore, the biosynthesis of bioactive compounds, including polyphenols and volatile organic compounds, can be “photomodulated” through specific LED treatments [10]. For example, blue light supplementation has been shown to increase total polyphenol content, while various LED wavebands can alter nutraceutical quality,

potentially reducing undesirable compounds like eugenol and improving the overall sensory profile of the herb [14,19].

Furthermore, the commercial quality of basil among horticultural products is strictly linked to its sensory profile. Light quality plays a pivotal role in modulating the sensory attributes of the plant; for instance, supplemental LED lighting has been shown to alter the concentrations of key aromatic compounds such as linalool and eugenol [14], likely affecting the sensory attributes of light-supplemented basil. Indeed, these biochemical changes directly impact the organoleptic properties, such as aroma, flavor, and taste of the fresh product. Recent studies have emphasized that tailoring the light spectrum can enhance the consumer's sensory experience by promoting a more balanced aromatic profile or reducing the bitterness associated with certain polyphenols, thus bridging the gap between high-yield production and premium culinary quality [14,19].

Despite these advancements, the interaction between narrow-band (along with multi-band light supplementation) and the diurnal rhythm of gas exchange in greenhouse-grown basil requires further investigation to optimize production schedules. Therefore, the aim of this study was to evaluate the effects of polychromatic and monochromatic LED supplementation (white, red, blue, and green lights), applied during the central hours of the day, on diurnal photosynthetic performance, biomass accumulation, nutraceutical and organoleptic quality of sweet basil.

2. Materials and Methods

2.1. Growth Environment and Plant Materials

This study was conducted in a greenhouse located in the Department of Agriculture, Food and Environment of the University of Pisa (43.704700° N, 10.427269° E) from 20 June to 16 July 2025. *O. basilicum* cv. Mia Prospera® was used as the plant material. Around 4-week-old basil plantlets were transplanted into 1-L pots filled with commercial substrate (Dorater, Vigor plant Italia SRL, Fombio, Italy). They were grown for 26 days with daily irrigation using the following nutrient solution: 10.00 mM N-NO₃⁻, 0.51 mM N-NH₄⁺, 1.50 mM P-PO₄³⁻, 9.00 mM K⁺, 4.50 mM Ca²⁺, 2.00 mM Mg²⁺, 0.78 mM Na⁺, 5.37 mM S-SO₄²⁻, 0.68 mM Cl⁻, 40.00 µM Fe²⁺, 40.00 µM BO₃⁻, 3.00 µM Cu²⁺, 10.00 µM Zn²⁺, 10.00 µM Mn²⁺, and 1 µM MoO₄²⁻. Electrical conductivity was 2.40 mS cm⁻¹, and pH was adjusted to 5.6 with diluted sulphuric acid. Water and nutrient solution were added at regular intervals during the growth period to reach an electrical conductivity of 1.2 dS·m⁻¹ at the end of the growth period. The pH was maintained at 6.5. The average air temperature was 21 °C, and the minimum and maximum temperatures recorded during the experiment were 14 and 33 °C, respectively.

2.2. Supplemental LED Lighting Treatments

The light supplementation system consisted of LED light treatments applied under greenhouse conditions. A total of 50 plants (10 replicates per treatment) were exposed to the following supplemental light treatments provided by LED lamps (1200 × 68 × 36 mm; Ambra Elettronica s.r.l., Bolzano Vicentino, Italy): red light (peak at 660 nm; RED), blue (peak at 450 nm; BLUE), green (peak at 520 nm; GREEN), and white light composed of red, green, and blue light in a 1:1:1 ratio (WHITE).

The experiment included five treatment blocks: four supplemental-light treatments and one control (CNT). Each supplemental-light treatment was provided by a single lamp, whereas the control consisted of a shading panel positioned above the plants to mimic the physical shading effect of the lamps without providing supplemental light. Ten plants (n = 10) were assigned to each block, for a total of 50 plants (n = 50).

Within each block, plants were arranged beneath the lamp (or control panel) in two rows of five plants each ($n = 5$; Figure S1). Plant positions were randomized every two days using the open-source software Randomizer (<https://www.randomizer.org/>; accessed on 9 July 2026). Pots were spaced sufficiently to prevent canopy overlap during cultivation. Adjacent treatment blocks were separated by approximately 2 m to minimize light contamination among treatments.

The lamp-to-canopy distance was adjusted to provide a supplemental PPFD of $250 \mu\text{mol m}^{-2} \text{s}^{-1}$ at canopy level and was maintained throughout the experimental period.

Measurements were collected from each individual plant. For statistical analyses, plants grown under the same lamp were considered biological replicates within the corresponding treatment.

Each supplemental light treatment provided a photosynthetic photon flux density (PPFD) of $250 \mu\text{mol m}^{-2} \text{s}^{-1}$ for five hours per day, from 11:30 a.m. to 4:30 p.m., local time. Corresponding to 6 h after sunrise and 5 h before sunset. The spectral distribution of each lamp is shown in Figure 1. Since plants were managed under the greenhouse, information on natural lighting within the greenhouse was reported in Table 1.

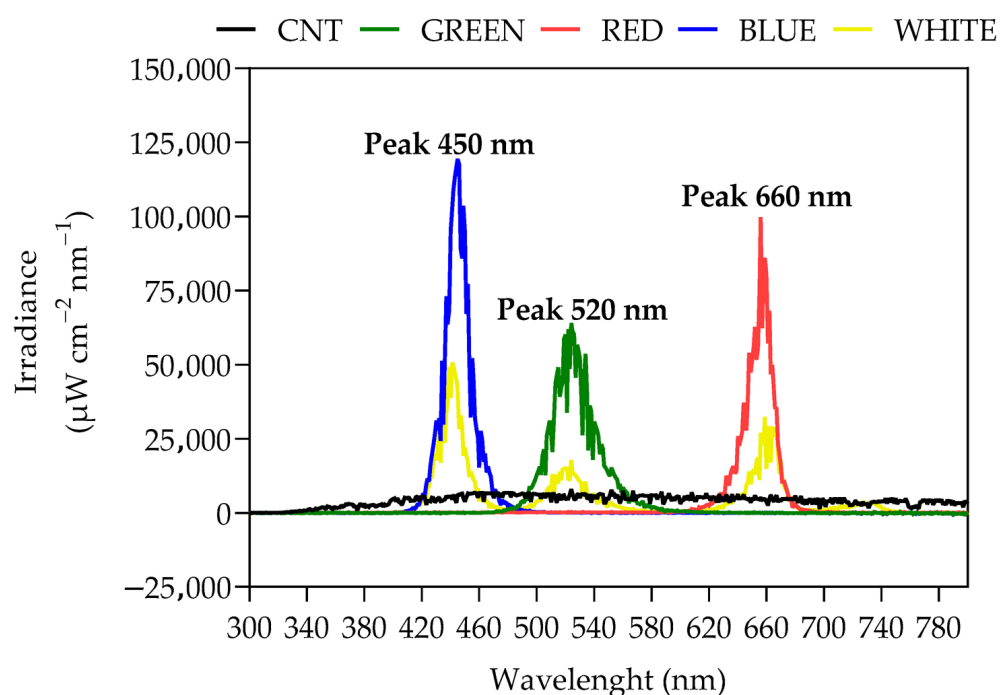


Figure 1. Spectral irradiance distribution of the LED light treatments applied to basil plants under greenhouse conditions, measured at the canopy level. Narrow-band LED treatments included BLUE (peak at 450 nm), GREEN (peak at 520 nm), and RED (peak at 660 nm), along with multi-band LED treatment (WHITE; R:G:B, 1:1:1). The control (CNT) represents ambient greenhouse light without supplemental illumination.

2.3. Gas Exchange Measurements

Photosynthetic performance was assessed on fully expanded leaves after 24 days of treatment. Measurements ($n = 15$) were carried out using a portable infrared gas analyzer (LI-6400, Li-Cor Inc., Lincoln, NE, USA) equipped with a transparent chamber to allow measurements under natural light conditions. Fully expanded leaves were randomly selected for each treatment.

Gas exchange measurements were performed at seven time points throughout the day to capture diurnal variations in photosynthetic activity in relation to both natural light and supplemental LED illumination (Figure 2).

Table 1. Averaged Natural Photosynthetic Photon Flux Density (PPFD) from sunrise to sunset (5:30 a.m. to 9:30 p.m.), natural DLI (Daily Light Integral), total DLI [natural + supplemented narrow-band LED treatments—i.e., BLUE (peak at 450 nm), GREEN (peak at 520 nm), and RED (peak at 660 nm), along with multi-band LED treatment WHITE (R:G:B, 1:1:1)]. Cumulative radiation during the experimental period of basil plants under greenhouse conditions in control (ambient greenhouse light without supplemental illumination; CNT) and LED-treated (T) plants.

	Averaged Natural PPFD ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	Natural DLI ($\text{mol m}^{-2} \text{d}^{-1}$)	Total DLI ($\text{mol m}^{-2} \text{d}^{-1}$)	Cumulative Radiation During the Experimental Period (mol m^{-2})
Greenhouse lighting during the experiment	377	32 ± 3.4	36.4 ± 3.4	831.6 (CNT)/953.1 (T)

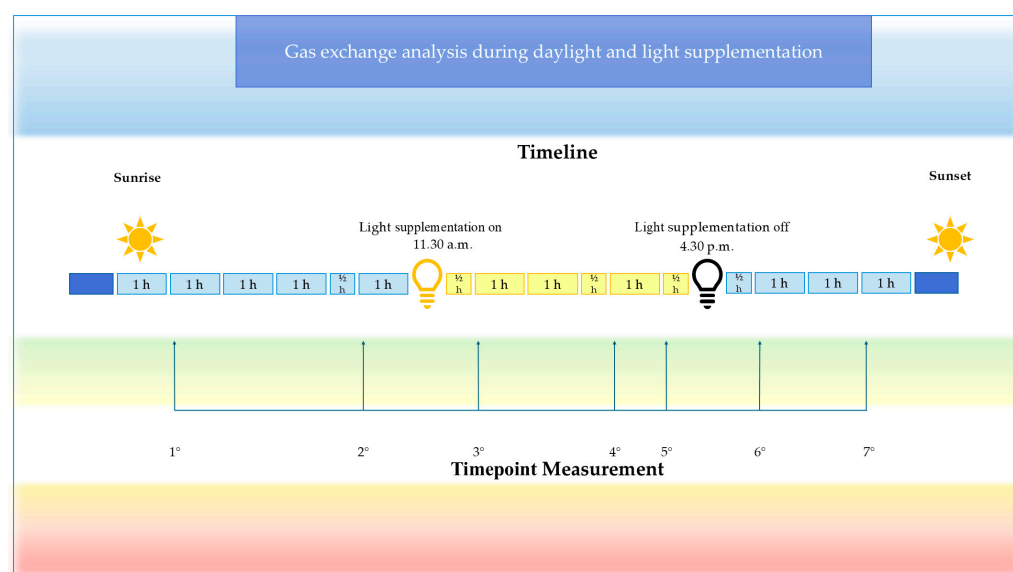


Figure 2. Diurnal monitoring scheme of gas exchange measurements in basil plants under natural daylight and supplemental LED lighting. Measurements were performed at seven time points (1–7°) in relation to the timing of light supplementation.

Specifically, measurements were conducted 1 h after the sunrise (#1), 1 h before the light treatment was switched on (#2), 30 min after the starting of the light treatment (#3), 1 h and 30 min before the light treatment was switched off (#4), 30 min before the light treatment was switched off (#5), 30 min after the light treatment was switched off (#6), and 1 h before the sunset (#7).

Supplemental LED lighting was applied from 11:30 a.m. to 4:30 p.m.; therefore, the 3°, the 4°, and the 5° measurements were performed under combined natural and artificial light conditions, whereas the 1° and the 2° measurements corresponded to natural light only, and the 6° and the 7° measurements to post-supplementation conditions.

The CO_2 concentration inside the leaf chamber was maintained at $400 \mu\text{mol mol}^{-1}$ using the CO_2 mixer, and the flow rate was set at $500 \mu\text{mol s}^{-1}$. Once steady-state conditions were achieved, the following parameters were recorded: net photosynthetic rate (P_n), stomatal conductance (g_s), intercellular CO_2 concentration (C_i), and transpiration rate (T_r).

2.4. Leaf Sampling and Biomass Determination

Biometric measurements and leaf sampling for quality trait analysis were performed 26 days after the starting of LED light supplementation. Leaf samples were immediately frozen in liquid nitrogen and stored at -80°C .

At the end of the experimental period (26 days after the starting of LED light supplementation), plant growth and biomass parameters were evaluated. For each treatment, plants ($n = 5$) were harvested and separated into leaves and stems. Total fresh biomass, as well as leaf fresh weight and stem fresh weight, was recorded. Samples were then oven-dried at 105 °C (to ensure complete removal of water from plant tissue) until they had a constant weight to determine dry biomass. Leaf dry weight and stem dry weight were measured.

2.5. Nutraceutical Quality of Basil Leaves

Leaf quality parameters were evaluated at the end of the experimental period (26 days after the starting of LED light supplementation) using fresh leaf samples. All analyses were performed on randomly selected leaves from each treatment.

2.5.1. Colorimetric Analysis

Colorimetric analysis ($n = 6$) was performed on fresh basil leaves. Color parameters were determined in the CIELab color space using a portable spectrophotometer (CM-1006d, Konica Minolta Holdings, Inc., Osaka, Japan). Before analysis, the instrument was calibrated using a white reference standard with an 8 mm diameter measurement head. Lightness (L^*), red-green coordinate (a^*), and yellow-blue coordinate (b^*) were recorded.

2.5.2. Total Chlorophyll and Carotenoid Content

Total chlorophyll and carotenoid analysis was performed according to the method described by Porra et al. [20], with minor modifications. Fresh samples (around 0.15 g) were homogenized and extracted in 10 mL of 80% (v/v) acetone. The samples were kept in the extraction solvent under continuous agitation in the dark until complete discoloration of the plant material was achieved. Absorbance of the extracts was measured using a spectrophotometer (Ultrospec 2100 Pro, GE Healthcare Ltd., Little Chalfont, Buckinghamshire, UK) at 663 nm and 648 nm to determine chlorophyll a and chlorophyll b , respectively. Total chlorophyll content was calculated as the sum of chlorophyll a and chlorophyll b . Results ($n = 6$) were expressed as μg of total chlorophylls per gram of fresh weight (FW). Absorbance was measured at 663 nm, 648 nm, and 470 nm for all samples, and only for the acetone 80% blank solution. The absorbance was then converted into chlorophyll content in $\mu\text{g g}^{-1}$ FW using the following calibration curves:

$$\text{Chlorophyll } a = (12.25 \times \text{Abs}_{663}) - (2.55 \times \text{Abs}_{648})$$

$$\text{Chlorophyll } b = (20.31 \times \text{Abs}_{648}) - (4.91 \times \text{Abs}_{663})$$

$$\text{Total carotenoids} = [(1000 \times \text{Abs}_{470}) - 1.82 \times \text{Chlorophyll } a] - (85.02 \times \text{Chlorophyll } b) / 198$$

2.5.3. Antioxidant Activity

Basil leaf samples ($n = 5$; 0.1 g) were extracted with an 80% (v/v) methanolic solution and subjected to ultrasonic treatment (Digital Ultrasonic Cleaner, DU-45, Argo Lab, Modena, Italy) at 4 °C for 30 min. The extracts were centrifuged (MPW 260R, MPW Med. Instruments, Warsaw, Poland) at $10,000 \times g$ for 10 min, and the supernatant was collected for antioxidant activity determination.

The antioxidant activity was assessed using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging, as described by Brand-Williams et al. [21]. An aliquot of 50 μL of the extract was added to 950 μL of a methanolic DPPH solution (3.12×10^{-5} M). The reaction mixture was compared with a blank consisting of 1 mL of DPPH solution. Absorbance was

spectrophotometrically recorded at 515 nm. Antioxidant activity was quantified using a Trolox calibration curve and expressed as mg Trolox equivalents (TE) per g FW.

2.5.4. Titratable Acidity (TA)

Titrateable acidity was determined on fresh leaf extracts. Briefly, 1.5 g of frozen sample was homogenized with 30 mL of distilled water and titrated with 0.1 M NaOH to an endpoint of pH 8.1, using a digital pH meter (XS Instruments, Modena, Italy). Results were expressed as % of citric acid.

2.6. Sensory Evaluation

The sensory analysis of basil leaves was carried out through a Quantitative Descriptive Analysis conducted by a panel of 8 trained assessors (6 females and 2 males, aged 25–63 years). Panelists were recruited from a larger pool of trained assessors who regularly collaborate with the Department of Agriculture, Food and Environment (DAFE) of the University of Pisa. All judges underwent standardized training to enhance their ability to recognize, describe, and quantify tastes, odors, and texture properties in accordance with ISO 8586:2023 standards [22]. As all assessors in the pool had comparable training and experience in sensory evaluation, the final panel composition was determined according to availability.

The sensory profile was assessed using a structured evaluation sheet developed in accordance with previously described methodologies for basil sensory analysis [23]. As shown in Figure 3, 36 descriptors (31 quantitative and 5 hedonic) were utilized, covering attributes related to appearance, olfactory, gustatory-tactile, retronasal, and overall liking. All descriptors were evaluated using a nine-point scale (0–9), applied consistently to both quantitative and hedonic attributes. Panelists were familiarized with the descriptors and evaluation procedure prior to the test. The evaluation sheet was organized into macro-categories, and panelists were allowed to include additional free descriptors within each main category.

The samples consisted of basil leaves grown under greenhouse conditions and exposed to different light treatments (daylight supplemented with three narrow-band LED treatments (RED, GREEN, and BLUE) and one multi-band LED treatment (WHITE), as well as a control (CNT) without supplemental light. Each treatment was represented by three plants; from each plant, five leaves were collected between the fifth and sixth nodes to ensure comparable physiological maturity. Leaves were washed with distilled water and gently dried using thin paper before evaluation. Each assessor evaluated two leaves per sample.

Samples were coded with random identifiers and presented in randomized order in individual containers. In order to assess the panelist performance repeatability [24], a sample was randomly presented twice to the judges. For olfactory assessment, panelists were instructed to tear each leaf along the central vein immediately before smelling, to enhance the release of volatile compounds, following established procedures for basil sensory analysis described by Brindisi et al. [23]. Each sample was assessed orthonasally for a few seconds, with a short break of ten minutes between samples to reduce sensory fatigue. For the tactile evaluation, panelists used their lips.

Unsalted crackers and potable water were provided as palate cleansers. Additionally, to avoid cross-contamination, all samples were removed from the room before the beginning of a new tasting session.

The analysis was conducted at room temperature in a laboratory compliant with ISO 8589 standards [25].



Figure 3. Sensory wheel showing the descriptors used for the sensory analysis of basil leaves.

2.7. Statistical Analysis

Statistical analyses were performed using GraphPad Prism 8 software (GraphPad, La Jolla, CA, USA). Data normality was assessed using the Shapiro–Wilk test at a 95% confidence level.

The best fitting curves for gas exchange parameters (P_n , g_s , C_i , and T_r) were obtained by a third-order polynomial least-squares fit [26,27]. The total curve areas were obtained from 1000 points, then the curve areas were split based on time interval (before light on, BLO; during light on, DLO; after light on, ALO). While this approach summarizes temporal variation into a single biologically meaningful metric, it does not explicitly model the repeated-measures structure of the dataset. Therefore, the results should be interpreted as differences in cumulative daily physiological performance among light treatments.

A one-way analysis of variance (ANOVA) was applied to gas exchange parameters to evaluate the effects of light treatment on each time interval. For total chlorophyll content, titratable acidity, and antioxidant activity, a one-way ANOVA was performed considering the light treatment as the factor of variation. Significant differences among treatments were determined by the LSD Fisher post hoc test ($p \leq 0.05$).

Sensory data were analyzed using CoStat v. 6.451 software (CoHort Software, Birmingham, UK). A two-way analysis of variance (ANOVA) was performed considering sample and panelist as main factors. When significant differences were detected, mean comparisons were carried out using Tukey's HSD post hoc test with a significance level of $p \leq 0.05$.

3. Results

3.1. Daily Photosynthetic Activity from the Activation of Photosynthesis Until Its Inactivation

Figure 4 presents third-order polynomial regression curves depicting the diurnal variation in photosynthetic activity of greenhouse-grown basil under natural daylight supplemented with $250 \mu\text{mol m}^{-2} \text{s}^{-1}$ of three narrow-band LED treatments (RED, GREEN,

and BLUE) and a multi-band LED treatment (WHITE) compared to non-supplemented plants (CNT), measured from sunrise to sunset with LED supplementation active in the middle of the day. Numerically values of the represented curves are reported in Table S1.

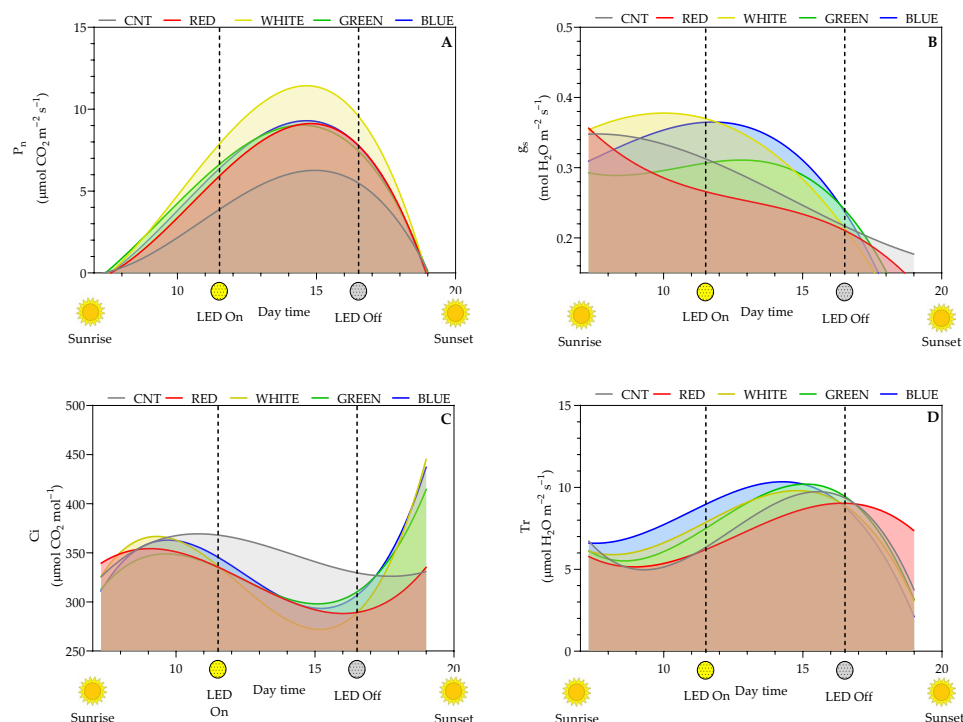


Figure 4. Cubic nonlinear regression of daily photosynthetic activity (P_n , (A)), stomatal conductance (g_s , (B)), intercellular CO_2 concentration (C_i , (C)), and transpiration (T_r , (D)) of basil plants grown in greenhouse daylight supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), multi-band LED treatment (WHITE), and control without supplemental light (CNT).

Accordingly, P_n displayed a unimodal diurnal pattern across all treatments (Figure 4A), peaking between 1 p.m. and 3 p.m. The WHITE treatment yielded the highest photosynthetic rates throughout the measurement period, reaching approximately $12 \mu\text{mol m}^{-2} \text{ s}^{-1}$ at peak, followed by the RED and BLUE treatments. CNT plants consistently showed the lowest P_n during the day (Figure 4A).

The g_s values followed a declining trajectory during the day across all treatments (Figure 4B), with maximum values (~ 0.35 – $0.38 \text{ mol m}^{-2} \text{ s}^{-1}$) recorded in the early morning hours. WHITE-treated plants demonstrated higher values prior to the LED light being switched on. Plants under BLUE supplementation maintained the highest g_s values through midday, whereas plants under GREEN treatment were particularly accelerating g_s during light on. Plants under RED treatment showed a faster decline from early morning to reach lower values when compared with the other treatments. On the other hand, CNT plants' stomatal activity converged toward low g_s values (~ 0.15 – $0.20 \text{ mol m}^{-2} \text{ s}^{-1}$), but these plants were the latest to reach stomatal closure by late afternoon (Figure 4B).

The C_i parameter displayed a more complex pattern characterized by a clear trough and peak (Figure 4C). Across all treatments, values started at approximately 300 – $350 \mu\text{mol CO}_2 \text{ mol}^{-1}$ at sunrise and declined slightly during the LED-active period. After LED deactivation (4:30 p.m.), C_i increased sharply, with plants under WHITE and BLUE supplementation reaching the highest values near sunset (~ 430 – $450 \mu\text{mol CO}_2 \text{ mol}^{-1}$). In contrast, RED-treated and CNT plants showed similar final values of about $\sim 325 \mu\text{mol CO}_2 \text{ mol}^{-1}$ (Figure 4C).

On the other hand, T_r exhibited a dual pattern, with rates decreasing after sunrise and reaching a trough between approximately 9:00 and 10:00 a.m., followed by a peak during the light supplementation period (Figure 4D). GREEN and BLUE treatments maintained the highest transpiration rates during midday ($\sim 9\text{--}10\text{ }\mu\text{mol H}_2\text{O m}^{-2}\text{ s}^{-1}$), followed by WHITE-supplemented and CNT plants, whereas RED-treated plants consistently showed the lowest rates. Toward sunset, T_r declined across all treatments. Notably, RED-supplemented plants decreased to values comparable to those observed during the early morning ($\sim 6\text{ }\mu\text{mol H}_2\text{O m}^{-2}\text{ s}^{-1}$; Figure 4D).

Inspection of P_n and g_s residual plots (Figure S2, Tables S2 and S4) and coefficients of determination (Table 2) reveals that the majority of residuals cluster near zero across the central diurnal window, combined with high R^2 values, indicating that the cubic polynomial captures the dominant trend adequately during peak metabolic activity. However, divergences were observed mainly in the C_i residual plot combined with lower R^2 , a common phenomenon in plant gas exchange data due to the rapid and nonlinear nature of stomatal opening at dawn and closure at dusk, which a third-degree polynomial may only partially resolve (Figure S2, Tables S2 and S4). In general, most calculated coefficients of determination were higher than 0.5, except for transpiration of plants grown under RED light supplementation and under control conditions (Table 2).

Table 2. Coefficients of determination (R^2) of cubic nonlinear regressions fitted to gas exchange parameters (P_n , g_s , C_i , and T_r) measured in basil plants grown under greenhouse daylight supplemented with RED, GREEN, BLUE, or WHITE LEDs, or under non-supplemented conditions (CNT).

R ² of Cubic Nonlinear Regression					
	CNT	RED	WHITE	GREEN	BLUE
P_n	0.8852	0.8546	0.8690	0.8592	0.8916
g_s	0.6020	0.5398	0.7777	0.6435	0.7788
C_i	0.6346	0.5679	0.8740	0.8158	0.8373
T_r	0.4851	0.2811	0.6013	0.6644	0.8972

3.2. Cumulative Photosynthesis Assimilates and Products of Basil Plants from the Active to Inactive State of Photosynthesis

Table 3 presents the cumulative and individual net CO₂ assimilation of basil plants across the three daily periods under investigation (before light on, BLO; during light on, DLO; and after light on, ALO). Over the full photoperiod, WHITE supplementation yielded the highest cumulative P_n , differing significantly from all the other treatments. GREEN and BLUE-supplemented plants were statistically comparable to each other, while RED supplementation produced intermediate values. CNT plants recorded the lowest cumulative P_n , significantly lower than all the supplemented plants. Period-specific analysis revealed that the most pronounced treatment effects occurred during DLO, consistent with the active supplementation window. During this period, WHITE-supplemented plants assimilated markedly more carbon (+90%) than CNT plants, while BLUE (+54%), GREEN (+52%), and RED (+47%) treatments showed intermediate levels compared to the CNT plants. During BLO, the light treatments also outperformed the control, particularly RED-treated plants, with a +265% increase compared to CNT plants. Whereas after supplemented lights were switched off (ALO), differences were reduced but remained statistically significant, especially for WHITE-treated plants (+70%) when compared with controls (Table 3).

Table 3. Cumulative values and values before light on (BLO), during light on (DLO), and after light on (ALO) of net CO₂ assimilation (P_n) in basil plants grown in greenhouse daylight, once supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), multi-band LED treatment (WHITE), and non-supplemented (CNT).

Treatment	P _n (μmol CO ₂ m ⁻² s ⁻¹)			
	BLO	DLO	ALO	Cumulative
CNT	3.08 ± 0.88 c	28.8 ± 1.48 d	11.09 ± 1.01 d	42.96 ± 2.77 d
RED	11.25 ± 1.14 a	42.31 ± 2.43 c	15.56 ± 1.41 b	62.76 ± 4.34 c
WHITE	6.94 ± 0.92 b	54.83 ± 1.91 a	18.84 ± 1.11 a	81.55 ± 2.49 a
GREEN	6.70 ± 1.65 b	43.82 ± 3.43 bc	14.55 ± 0.57 c	67.54 ± 5.84 b
BLUE	5.57 ± 1.62 b	44.44 ± 2.94 b	14.9 ± 0.72 bc	66.29 ± 3.94 b

Data (means ± standard deviation) were subjected to one-way ANOVA, and means with different letters are significantly different ($p \leq 0.05$) after the LSD Fisher post hoc test with different light treatments as the only source of variability.

Table 4 also affirms the diurnal trajectories depicted in Figure 4B and reports cumulative and individual g_s values across the same three daily periods. No statistical differences were observed in the cumulative daily g_s values among treatments. Period-level data indicate the highest g_s values during the DLO period across all treatments, declining progressively through the ALO period. During DLO, plants under WHITE (+14.3%) and BLUE (+22.4%) treatments maintained comparatively higher g_s values than CNT plants and the other treatments. During RED supplementation, basil plants showed a decrease in g_s of 7% when compared with CNT plants (Table 4). During BLO, WHITE supplementation induced the highest g_s values, whilst RED and GREEN treatments had the lowest values. Conversely, the latter induced the highest g_s values, similar to CNT plants, during the ALO period (Table 4).

Table 4. Cumulative values and values before light on (BLO), during light on (DLO), and after light on (ALO) of stomatal conductance (g_s) in basil plants grown in greenhouse daylight, once supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), multi-band LED treatment (WHITE), and non-supplemented (CNT).

Treatment	g_s (mol H ₂ O m ⁻² s ⁻¹)			
	BLO	DLO	ALO	Cumulative
CNT	1.04 ± 0.07 b	1.61 ± 0.14 c	0.56 ± 0.06 a	3.24 ± 0.22
RED	0.94 ± 0.06 c	1.47 ± 0.16 d	0.55 ± 0.04 a	2.94 ± 0.15
WHITE	1.12 ± 0.07 a	1.89 ± 0.10 a	0.46 ± 0.03 b	3.46 ± 0.17
GREEN	0.88 ± 0.07 d	1.73 ± 0.13 b	0.56 ± 0.08 a	3.13 ± 0.16
BLUE	1.03 ± 0.08 b	1.97 ± 0.06 a	0.48 ± 0.05 b	3.45 ± 0.14

Data (means ± standard deviation) were subjected to one-way ANOVA, and means with different letters are significantly different ($p \leq 0.05$) after LSD Fisher post hoc test with different light treatments as the only source of variability. The lack of letters beyond the averages means no significant differences using the same statistical analysis.

On the other hand, CNT plants exhibited the highest total daily cumulative and individual C_i values, significantly exceeding all supplemented light treatments (Table 5). Comparing supplemented treatments, BLUE light induced (−3.5% compared to CNT plants) the highest C_i values, followed by GREEN (−5.0%), WHITE (−5.8%), and RED lights (−7.2%). Period-specific data revealed a consistent pattern: C_i values were higher during DLO when compared to BLO and ALO across all treatments, reflecting less active carboxylation during the supplementation window. The marked post-supplementation C_i increases during ALO were particularly notable in plants under BLUE light (+6.7%) in comparison with CNT plants and consistent with the sharp rise in C_i values observed after LED deactivation in Figure 4C.

Table 5. Cumulative values and values before light on (BLO), during light on (DLO), and after light on (ALO) of intercellular CO₂ concentration (C_i) in basil plants grown in greenhouse daylight, once supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), multi-band LED treatment (WHITE), and non-supplemented (CNT).

Treatment	C _i (μmol CO ₂ mol ⁻¹)			
	BLO	DLO	ALO	Cumulative
CNT	1063 ± 10.17 ab	2033 ± 16.79 a	979.3 ± 25.6 c	4068 ± 32.66 a
RED	1054 ± 12.05 b	1825 ± 28.73 b	907.1 ± 22.43 d	3775 ± 46.56 e
WHITE	1071 ± 11.69 a	1747 ± 19.40 c	1014 ± 34.10 b	3834 ± 33.17 d
GREEN	1022 ± 9.321 c	1819 ± 31.52 b	1030 ± 24.01 ab	3866 ± 35.67 c
BLUE	1053 ± 18.07 b	1835 ± 17.86 b	1045 ± 14.76 a	3925 ± 35.83 b

Data (means ± standard deviation) were subjected to one-way ANOVA, and means with different letters are significantly different ($p \leq 0.05$) after LSD Fisher post hoc test with different light treatments as the only source of variability.

Table 6 reports cumulative and individual T_r values of treated basil plants across the three daily periods under investigation (Table 6). BLUE supplementation resulted in the highest cumulative T_r values (+13.2% compared to CNT plants), followed by plants under GREEN and WHITE lights. RED-supplemented plants reported T_r values similar to those of CNT plants and lower than those of the other treatments. Before and during light supplementation, BLUE-treated plants maintained the highest T_r values, consistent with the elevated g_s values of these plants in Table 4. In the second place, a significantly higher performance was observed in plants treated with WHITE and GREEN lights before and during light supplementation, compared with the controls (on average +6.7%). Notably, transpiration of CNT and RED-supplemented plants reported the lowest values comparatively before and during light supplementation (Table 5). In contrast, after light supplementation, transpiration values changed in a significant order, with the highest value in RED-treated plants, which outperformed all other treatments.

Table 6. Cumulative values and values before light on (BLO), during light on (DLO), and after light on (ALO) of transpiration (T_r) in basil plants grown in a greenhouse, once supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), multi-band LED treatment (WHITE), and non-supplemented (CNT).

Treatment	T _r (mmol H ₂ O m ⁻² s ⁻¹)			
	BLO	DLO	ALO	Cumulative
CNT	16.09 ± 0.95 d	44.97 ± 2.11 c	22.65 ± 2.13 b	84.49 ± 3.73 d
RED	16.13 ± 0.97 cd	44.46 ± 3.10 c	25.72 ± 1.53 a	84.73 ± 3.14 d
WHITE	18.33 ± 0.84 b	50.36 ± 1.34 b	20.83 ± 1.44 cd	90.24 ± 2.88 bc
GREEN	16.94 ± 1.40 c	51.04 ± 2.22 b	21.90 ± 2.19 bc	90.08 ± 2.06 c
BLUE	21.31 ± 0.56 a	54.61 ± 1.56 a	19.55 ± 0.91 d	95.64 ± 1.73 a

Data (means ± standard deviation) were subjected to one-way ANOVA, and means with different letters are significantly different ($p \leq 0.05$) after the LSD Fisher post hoc test with different light treatments as the only source of variability.

3.3. Dry and Fresh Biomass of Basil Plants

Table 7 presents the effects of different light treatments in supplementation under greenhouse conditions on total above-ground dry and fresh biomass (g plant⁻¹). Statistically significant differences were observed for both biomass parameters.

For total dry biomass, the RED and GREEN light treatments yielded the highest values in comparison with the control (+22.25%), followed by the WHITE treatment. The CNT and BLUE treatments produced the lowest dry biomass, with plants grown under BLUE-enriched light significantly inferior to all other treatments. A similar trend was observed for total

fresh biomass, where basil plants grown under GREEN light supplementation produced the highest yield, followed by RED and WHITE (+26.43%, +21%, and +17.15%, all relative to the CNT, respectively). The CNT and BLUE treatments again recorded the lowest fresh biomass values, with no statistically significant difference between them.

Table 7. Above-ground Fresh and Dry biomass of basil plants grown in a greenhouse under daylight, once supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), multi-band LED treatment (WHITE), and non-supplemented (CNT).

	Total Biomass (g plant ⁻¹)				
	CNT	RED	WHITE	GREEN	BLUE
Fresh Biomass	69.4 ± 5.7 b	84.09 ± 12.9 ab	81.3 ± 9.8 ab	87.74 ± 13.8 a	72.02 ± 11.8 b
Dry Biomass	6.74 ± 0.6 bc	8.24 ± 1.3 a	7.27 ± 0.9 ab	8.26 ± 1.3 a	5.8 ± 0.9 c

Data (means ± standard deviation) were subjected to one-way ANOVA, and means with different letters are significantly different ($p \leq 0.05$) after the LSD Fisher post hoc test with different light treatments as the only source of variability.

3.4. Organoleptic and Nutraceutical Quality of Basil Leaves

After basil plants were harvested, quality attributes were assessed (Figure 5). As far as the total chlorophyll content is concerned, plants under RED, BLUE, and GREEN lights reported higher content when compared with plants under WHITE light, even though all treated plants reported total chlorophyll content similar to CNT plants (Figure 5A). Within the same samples analyzed for chlorophylls, the carotenoid content was not significantly different (Figure 5B). Differently, WHITE-supplemented plants reported the highest TA values, and these values were significantly different from TA values of plants under RED and GREEN lights (Figure 5C). No statistically significant differences were detected among any of the five treatments in terms of antioxidant activity, with a mean value of around 3.0 to 3.7 mg TE⁻¹ FW (Figure 5D). CIE L*, a*, and b* values of basil leaves are displayed in Figure 5E–G. RED and GREEN supplementation induced significantly higher L* values (+6.5% and +2.2%, respectively) in comparison to the controls. In contrast, plants under BLUE light yielded the lowest L* values (−4.35% compared to CNT plants), corresponding to the darkest leaves among the rest of the treated plants (Figure 5E). On the other hand, all treatments produced negative a* values, confirming the characteristic green pigmentation of basil foliage across all conditions (Figure 5F). CNT plants exhibited the least negative a* values, indicating the least pronounced green coloration, followed by plants under BLUE light. RED, WHITE, and GREEN treatments produced significantly more negative values (+3.1%, +6.53%, +9.1%, respectively) in greenness compared to CNT (Figure 5F). Differently, GREEN-supplemented plants showed the highest b* values (+20.3% compared to CNT), significantly exceeding all other treatments. Plants under RED and WHITE lights were statistically grouped together (on average, +2.8%), while CNT and BLUE-supplemented plants recorded the lowest b* values (Figure 5G).

3.5. Sensory Analysis Results

The sensory analysis revealed that light treatments significantly modulated most attributes of basil leaves (Figure 6). The radar profiles highlighted a clear differentiation among treatments, particularly in aroma-related, visual, and textural descriptors.

Among visual traits, brightness was significantly affected by light treatments ($p < 0.001$). Leaves from RED-treated plants showed lower brightness scores, indicating a darker appearance compared to the other treatments, whereas WHITE and GREEN samples were generally perceived as brighter. This perception was only partially consistent with instrumental measurements, where higher L* values were observed under RED and GREEN treatments. While L* quantifies surface lightness based on diffuse reflectance, visual percep-

tion is influenced by additional factors such as pigment distribution, tissue microstructure, and light scattering properties [28]. Green color tone was not significantly influenced by light treatments, suggesting that differences in pigment composition, although detected instrumentally, were not clearly perceived by panelists.

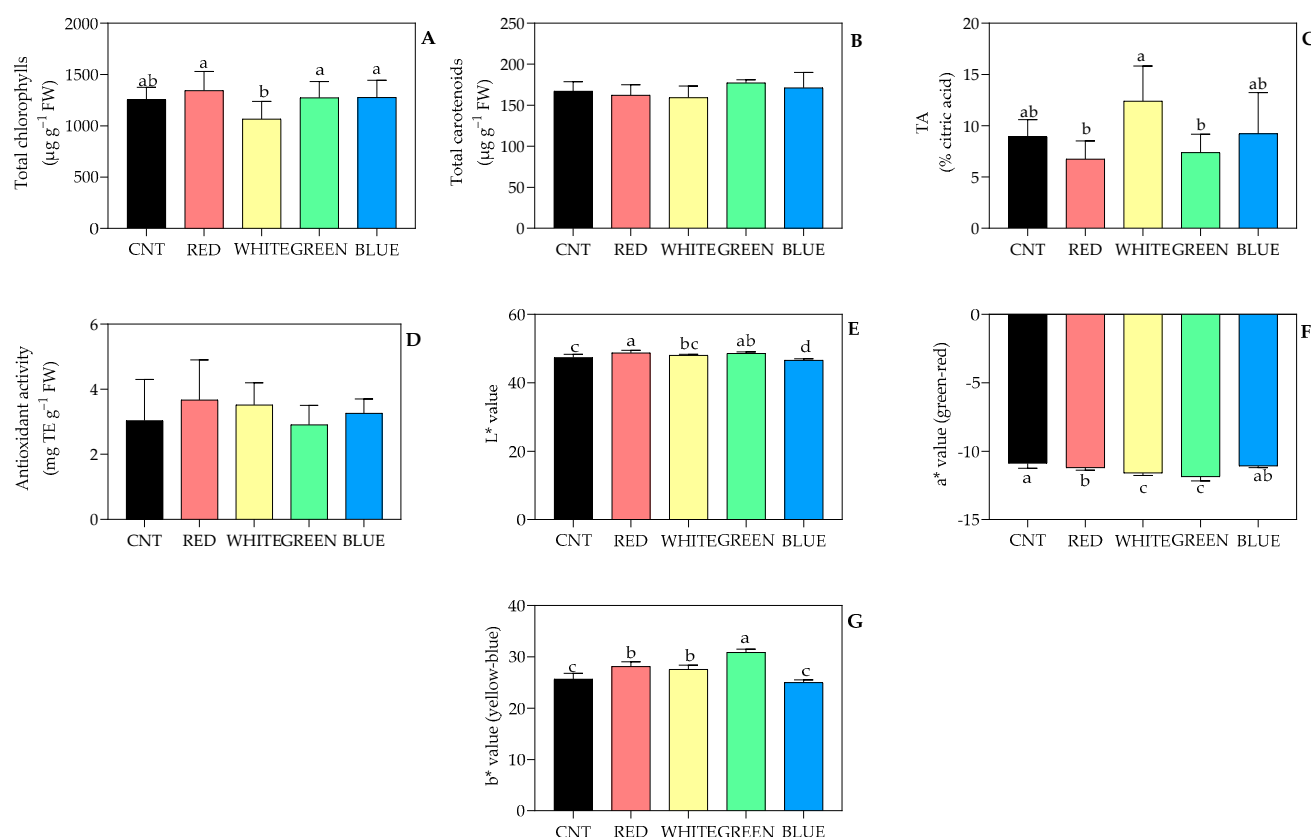


Figure 5. Total chlorophylls (A), total carotenoids (B), titratable acidity (TA) (C), antioxidant activity (D), and colorimetric values—L* value (E); a* value (F); b* value (G)—of basil leaves of plants grown in greenhouse daylight supplemented with narrow-band LED treatments (RED, GREEN, and BLUE) and multi-band LED treatment (WHITE) and control without supplemental light (CNT). Data (means $\pm$ standard deviation) were subjected to one-way ANOVA, and bars with different letters are significantly different at $p \leq 0.05$ after LSD Fisher post hoc test with different light treatments as the only source of variability. The absence of letters indicates no significant differences according to the same statistical analysis.

Aroma-related descriptors were among the most responsive to light treatments. Typical aroma and olfactory persistence were significantly higher in CNT samples ($p < 0.001$), indicating a more characteristic basil aromatic profile under natural light conditions. In contrast, LED-treated samples showed reduced aromatic typicality and persistence, suggesting a modulation of volatile composition under monochromatic light conditions [14]. Floral, balsamic, and spicy notes were also significantly affected ($p < 0.01$ – 0.001), supporting the hypothesis that light quality modifies the balance among aroma-active compounds rather than overall aroma intensity, which remained unchanged.

Regarding taste perception, basic taste attributes (sweetness, acidity, saltiness, and umami) were not significantly influenced by light treatments, in agreement with the limited variation observed in titratable acidity and antioxidant activity. However, typical taste and bitterness were significantly affected ($p < 0.01$), with CNT samples showing higher typicality and BLUE samples higher bitterness.

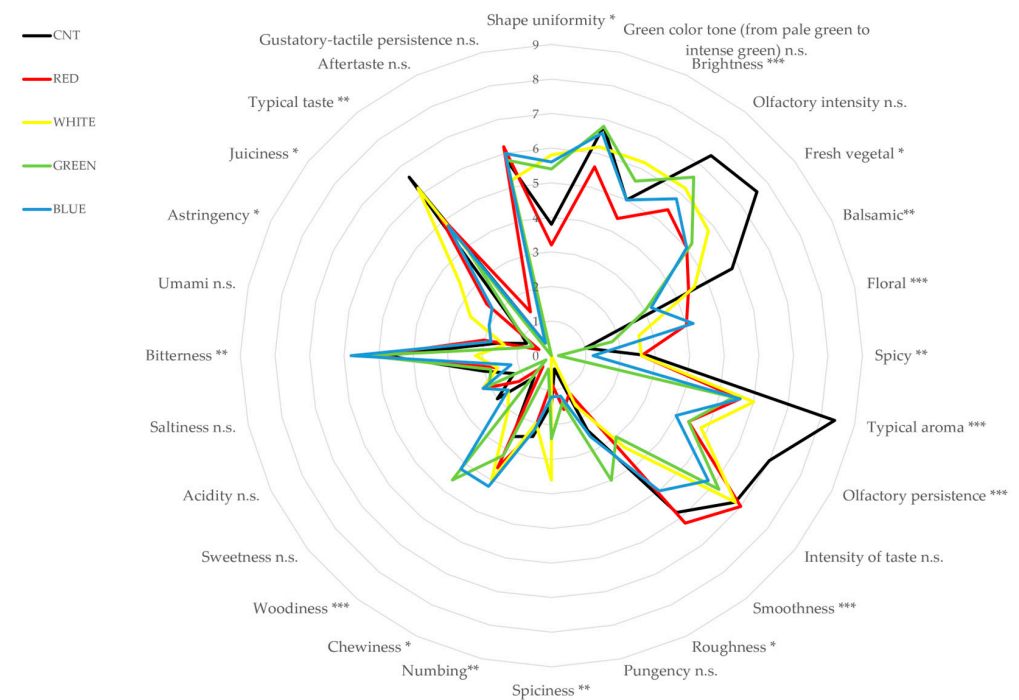


Figure 6. Radar plot of quantitative sensory attributes of basil leaves under different light treatments (CNT, RED, BLUE, GREEN, WHITE). Asterisks indicate significant differences among treatments (*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns not significant).

Textural and tactile attributes showed a clear response to light treatments. Smoothness was higher in CNT and RED samples ($p < 0.001$), whereas roughness and astringency differed among treatments ($p < 0.05$), with GREEN samples showing the highest roughness and WHITE samples the highest astringency. Juiciness and chewiness were also influenced ($p < 0.05$), with WHITE samples generally showing improved mouthfeel. These differences may be related to variations in tissue hydration and cell turgor, which are known to influence the mechanical properties of plant tissues and the perception of juiciness and chewiness [29]. Spiciness and numbing sensations were significantly affected ($p < 0.01$), indicating that light treatments also modulated chemesthetic perception.

In addition to the quantitative sensory profile, panelists reported free descriptors within each macro-category, providing further qualitative insights into basil sensory perception under different light conditions. These descriptors confirmed and refined the trends observed in the quantitative analysis (Figure 7A–E).

In particular, CNT samples were predominantly associated with typical basil descriptors, including “fresh basil”, “tomato leaf”, and “balsamic-anise”, together with peppery notes, confirming a well-balanced and recognizable aromatic profile. In contrast, RED-treated samples showed a shift toward pungent and mentholated notes (e.g., pepper, eucalyptus), while BLUE samples were characterized by less typical and more complex descriptors (e.g., clove, lavender, aloe-like), consistent with the increased bitterness observed. GREEN samples were mainly described by fresh vegetal and balsamic notes, whereas WHITE samples exhibited the widest descriptor diversity, combining fresh, floral, spicy, and balsamic notes, indicating a more heterogeneous aromatic profile.

Overall, qualitative descriptors indicate that light treatments primarily affected the composition and complexity of aroma-related compounds rather than their overall intensity, leading to changes in aroma typicity. This is consistent with the quantitative results, where intensity scores remained relatively stable while specific descriptors varied among treatments.

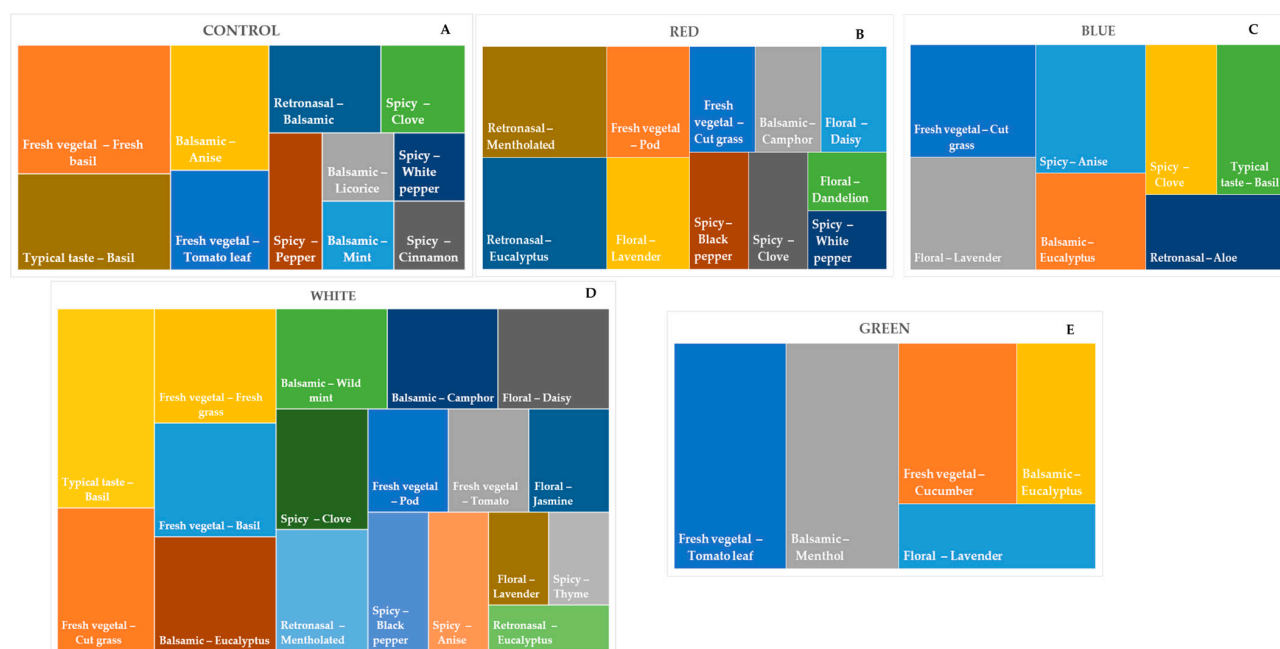


Figure 7. Free sensory descriptors reported by panelists for basil leaves under different light treatments—(A) CNT; (B) RED; (C) BLUE; (D) WHITE; (E) GREEN. Descriptor relevance was calculated by combining the frequency of citation and perceived intensity.

Hedonic attributes were also significantly influenced by light treatments (Figure 8). CNT and WHITE samples showed the highest scores, whereas BLUE samples showed the lowest, particularly for taste and retronasal perception.

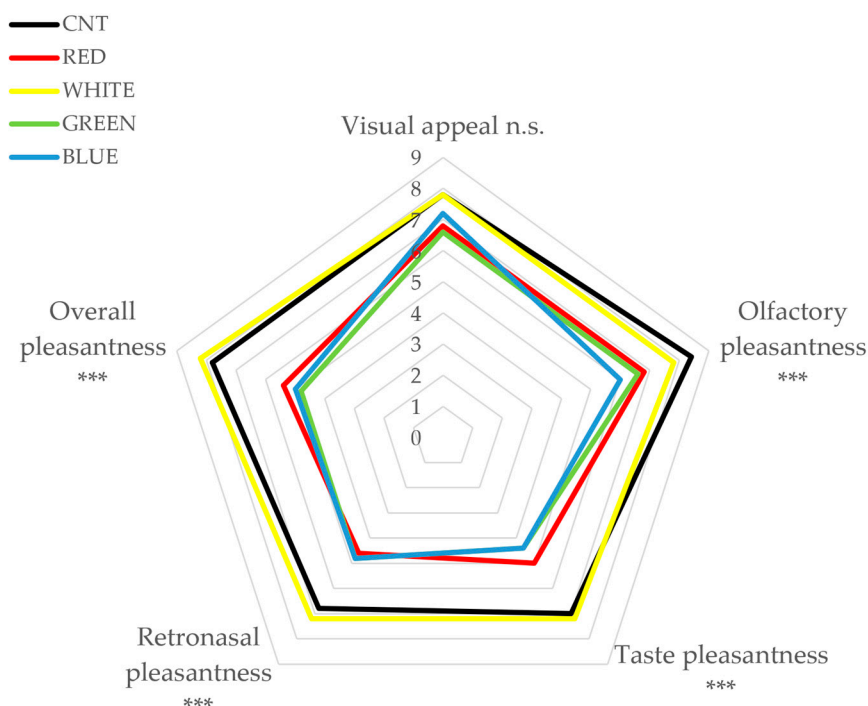


Figure 8. Hedonic evaluation of basil leaves under different light treatments (CNT, RED, BLUE, GREEN, WHITE). Asterisks indicate significant differences among treatments (***) $p < 0.001$; ns: not significant).

To provide an integrated measure of sensory acceptance, a global hedonic index was also calculated (Figure 9). Differences among treatments were limited, with all samples achieving values above 6 on a 10-point scale, indicating a generally good level of acceptability.

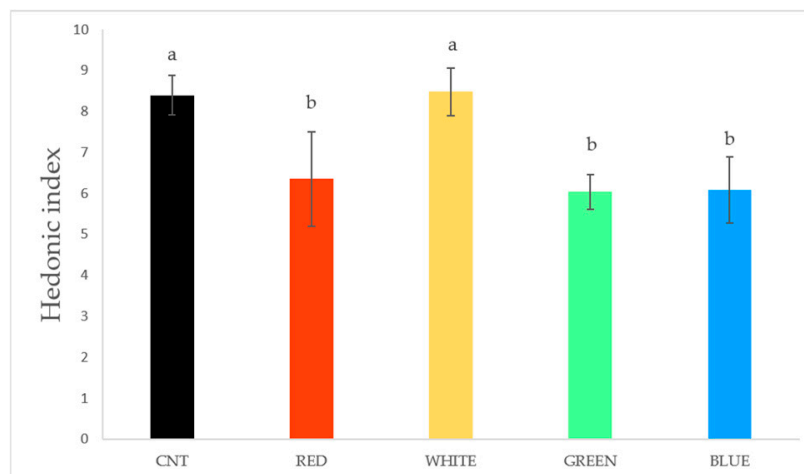


Figure 9. Global hedonic index of basil leaves under different light treatments, calculated as the average of hedonic attributes. Data (means $\pm$ standard deviation) were subjected to two-way ANOVA, considering sample and panelist as main factors. Bars with different letters are significantly different at $p \leq 0.05$ after the LSD Fisher post hoc test.

Taken together, these findings indicate that light treatments significantly modulated several specific sensory attributes while having only a limited impact on overall acceptability. Multi-band WHITE supplementation emerged as the most effective LED treatment, providing a balanced sensory profile and achieving hedonic scores comparable to those of the control.

4. Discussion

4.1. Photosynthetic Traits Under Different Light Spectra

The diurnal gas-exchange dynamics observed in basil under supplemental LED lighting demonstrate that spectral quality not only modulates instantaneous photosynthetic performance during the active light period but also influences stomatal regulation and carbon assimilation before and after supplementation. Recent controlled-environment studies increasingly emphasize that the light spectrum functions as a regulatory signal shaping both photosynthetic biochemistry and stomatal behavior, rather than merely an energy source [2,30]. Overall, the present results indicate that multi-band WHITE light provided the most physiologically advantageous environment for maximizing daily carbon gain, while narrow-band spectra elicited distinct trade-offs between photosynthesis, stomatal conductance, internal CO₂ dynamics, and transpiration.

In general, P_n and g_s nonlinear regression plots have been demonstrated to be models that successfully capture the biologically meaningful response shape without systematic over- or underestimation across the photoperiod [31].

Across treatments, P_n followed the expected unimodal diurnal pattern, peaking during the early afternoon when solar irradiance and supplemental lighting jointly enhanced photosynthetic photon flux. Such midday maxima are consistent with previous reports in basil and other *Lamiaceae* species, where supplemental lighting amplifies photosynthetic capacity during periods of highest natural irradiance [32,33]. However, the superior and sustained P_n under WHITE supplementation suggests that a spectral distribution more effectively supported photosynthetic metabolism than monochromatic or narrow-band

spectra. This likely reflects the ability of white light to simultaneously stimulate chlorophyll absorption, accessory pigments, and multiple photoreceptors, thereby improving excitation balance between photosystems I and II and enhancing dynamic photosynthetic efficiency, already highlighted by other authors [34,35]. The nearly 90% increase in DLO carbon assimilation relative to CNT plants underscores that spectral completeness, rather than photon quantity alone, is critical for maximizing basil performance in greenhouse systems. Moreover, the persistence of elevated P_n during ALO suggests that WHITE supplementation may suggest a possible residual “photosynthetic priming” effect through prolonged Rubisco activation or delayed photosynthetic downregulation, phenomena also noted under multi-band spectrum LEDs in herbs [36].

Although RED light is strongly absorbed by chlorophyll and is generally associated with high quantum efficiency, its comparatively moderate cumulative P_n and rapid stomatal decline suggest that carbon assimilation under RED was constrained primarily by stomatal limitations rather than photochemical inefficiency. This observation aligns with the evidence found in the scientific literature suggesting that red light alone can inadequately stimulate blue-light-mediated guard cell signaling, often resulting in reduced stomatal aperture despite sufficient photosynthetic photon absorption [37]. The sharp reduction in g_s under RED, culminating in near-complete midday stomatal closure, indicates that stomatal limitation likely restricted CO_2 influx and prevented RED from fully translating photon capture into carbon gain. While RED-treated plants exhibited elevated BLO assimilation, possibly reflecting altered circadian or preconditioning effects, this advantage was not maintained during DLO, reinforcing the importance of balanced spectral composition for sustained productivity.

BLUE supplementation, in contrast, promoted the highest midday g_s and cumulative transpiration, consistent with the established role of blue wavelengths in activating phototropins and plasma membrane H^+ -ATPases in guard cells [38,39]. Elevated stomatal conductance under BLUE likely facilitated greater CO_2 diffusion and supported improved P_n relative to CNT plants. However, BLUE did not surpass WHITE in cumulative carbon assimilation, suggesting that enhanced stomatal opening alone was insufficient when spectral diversity was limited. This supports previous findings that blue light is particularly effective in stomatal regulation and leaf anatomy modulation, but should require integration with red or broad-spectrum wavelengths for maximal plant performance [40,41]. The elevated transpiration rates under BLUE further imply greater water expenditure, potentially reducing intrinsic water-use efficiency despite enhanced gas exchange [42].

GREEN supplementation produced an intermediate physiological profile, with relatively high midday transpiration and improved g_s responsiveness, yet without the photosynthetic superiority of WHITE. Although historically underestimated, green wavelengths are, nowadays, recognized for their capacity to penetrate deeper leaf tissues and dense canopies, contributing to whole-canopy photosynthesis and stomatal modulation [43]. In basil, GREEN may therefore enhance internal light distribution and maintain gas exchange without maximizing top-leaf chloroplast excitation, which may explain its comparable cumulative P_n to BLUE but lower performance than WHITE. These findings support the emerging perspective that green light can play a complementary, rather than primary, role in optimized spectral strategies [15].

The C_i dynamics provide further insights into treatment-specific responses. CNT plants consistently exhibited the highest cumulative C_i despite the lowest P_n , indicating that the stomatal closure was not a limitation under non-supplemented conditions. Conversely, lower C_i under supplemental treatments—especially RED and WHITE—suggests stronger photosynthetic CO_2 fixation during active periods. The pronounced post-supplementation rise in C_i under BLUE and WHITE likely reflects a lag between declining photosynthetic

CO₂ fixation and continued stomatal openness, temporarily increasing internal CO₂ accumulation after LED deactivation. Similar post-illumination C_i rebounds have been associated with delayed stomatal kinetics under dynamic light transitions [44].

The absence of significant differences in total daily cumulative g_s despite substantial diurnal variation among treatments highlights that stomatal timing, rather than absolute conductance, was a key determinant of plant performance. Dynamic synchronization between stomatal aperture and irradiance availability is increasingly recognized as a major driver of photosynthetic efficiency under fluctuating greenhouse environments [45,46]. WHITE treatment appeared to optimize this synchronization most effectively, balancing carbon gain with moderated transpiration, whereas BLUE prioritized stomatal openness and RED induced conservative closure. This latter may also explain the sudden increase in T_r observed after light supplementation was switched off. RED-treated plants have directly activated stomatal opening, leading to increased transpiration [15].

4.2. Organoleptic and Nutraceutical Traits

After harvest, quality assessments revealed that supplemental light spectrum significantly influenced basil leaf pigmentation and visual quality traits, while exerting comparatively limited effects on antioxidant activity. These findings reinforce the concept that light spectral composition can selectively modulate primary and secondary metabolic pathways associated with pigment biosynthesis, leaf optical properties, and marketability, even when physiological growth responses are similar [2].

No clear differences were noted in terms of carotenoids in basil leaves. However, total chlorophyll content was generally enhanced under narrow-band RED, BLUE, and GREEN supplementation relative to WHITE, although values remained statistically comparable to those of CNT plants. This suggests that monochromatic or narrow-band supplementation may stimulate chlorophyll biosynthesis or delay chlorophyll degradation more effectively than multi-band-spectrum white light, possibly through spectrally specific regulation of chlorophyll-associated genes, such as CHLH and PORA [47]. Blue wavelengths, in particular, are frequently associated with increased chloroplast development and chlorophyll accumulation through cryptochrome-mediated pathways, while red light can enhance chlorophyll synthesis via phytochrome activation [48]. The relatively lower chlorophyll concentration under WHITE supplementation may reflect a dilution effect associated with greater photosynthetic productivity and leaf expansion, where biomass accumulation outpaces pigment concentration per unit tissue rather than indicating reduced photosynthetic competence. This phenomenon has also been reported in basil and lettuce grown under multi-band-spectrum LEDs [36].

Overall, in addition to our results, we also suggest that RED and GREEN light spectra promote greater biomass accumulation compared to the control condition, highlighting the importance of light quality in modulating plant growth responses. In contrast, WHITE-supplemented plants exhibited the highest TA, significantly exceeding RED and GREEN treatments. Organic acid accumulation is a key determinant of flavor intensity and, after harvesting, sensory quality in herbs, often linked to carbon partitioning and respiratory metabolism [49]. The elevated TA under WHITE light may therefore reflect enhanced synthesis or retention of organic acids due to greater overall carbon assimilation and broader metabolic activation. Because multi-band-spectrum light supports balanced photoreceptor stimulation, it may better coordinate carbohydrate metabolism with downstream acid biosynthesis pathways, improving sensory complexity, as evidenced also by the sensory analysis results. These results are particularly relevant for culinary basil, where acidity contributes to flavor balance and perceived freshness.

Despite spectral effects on pigment and acidity traits, antioxidant activity remained statistically unchanged across treatments. This suggests that under the tested supplementation intensity and duration, light quality did not substantially alter total antioxidant capacity, even though pigment composition and visual appearance were modified. Similar outcomes have been reported where moderate spectral adjustments affected morphology and chlorophyll content more readily than phenolic or radical scavenging pathways [50]. Antioxidant metabolism in basil is highly genotype- and stress-dependent, often responding more strongly to high-intensity blue, UV-A, or combined abiotic stressors than to moderate visible-light spectral shifts alone [51]. Thus, while supplemental LEDs modified appearance-related quality parameters, they may not have imposed sufficient oxidative or metabolic stimulus to significantly alter antioxidant compound accumulation.

Leaf colorimetric responses further demonstrate the substantial role of spectral composition in determining the commercial visual quality of basil. RED and GREEN supplementation increased L^* values, producing brighter leaves, whereas BLUE supplementation generated the darkest foliage. Lower L^* values under BLUE are commonly associated with denser chlorophyll packing, thicker palisade tissues, or increased anthocyanin-related optical absorption, all of which reduce reflectance and deepen leaf coloration [52]. In leafy herbs, darker green coloration is often perceived positively by consumers as an indicator of freshness and nutrient density, suggesting that BLUE supplementation may improve visual market appeal despite lower brightness.

The universally negative a^* values across treatments confirm that basil maintained its characteristic green phenotype regardless of spectral regime; however, more negative a^* values under RED, WHITE, and especially GREEN treatments indicate intensified green saturation compared with CNT plants. This enhanced greenness likely corresponds with improved chlorophyll visibility and altered chlorophyll-to-carotenoid balance, which may be influenced by spectral regulation of pigment biosynthetic pathways [53]. GREEN-treated plants, despite not having the highest chlorophyll concentration, displayed the strongest green chromaticity, suggesting that perceived greenness is influenced not only by chlorophyll abundance but also by leaf anatomical structure, pigment distribution, and optical reflectance properties. This distinction is important because consumer preference is often driven more by visual saturation than by biochemical pigment concentration alone.

The markedly elevated b^* values under GREEN supplementation indicate increased yellow-green tonality, potentially reflecting enhanced carotenoid visibility or altered accessory pigment balance. Green wavelengths have been shown to penetrate deeper into mesophyll tissues and may influence carotenoid-associated photoprotection differently than red or blue light [40,41]. Although no effect has been registered of light regimes on carotenoids leaf content, increased b^* values may therefore indicate shifts toward warmer leaf hues, which could influence perceived freshness depending on market expectations. By contrast, BLUE and CNT plants exhibited the lowest b^* values, corresponding to cooler, darker foliage tones.

Taken together, these quality outcomes highlight that supplemental light spectra can differentially shape basil biochemical and aesthetic attributes beyond growth performance alone. Although sensory data should be regarded as supplementary to the physiological and quality measurements, they provide important complementary evidence on how light treatments may influence the perceived organoleptic quality and market relevance of fresh basil. WHITE light appears most advantageous for enhancing acidity and potentially flavor-related quality, while BLUE may improve darker coloration and chlorophyll density, and GREEN may intensify visual greenness and brightness. RED supplementation, although beneficial for chlorophyll accumulation and brightness, appears less distinctive in sensory-related parameters.

Light-dependent changes in basil sensory perception are likely related to the ability of different wavelengths to modulate secondary metabolism and volatile compound biosynthesis. Previous studies have shown that LED lighting can alter key aroma compounds such as linalool, eugenol, and methyl chavicol, which are directly involved in basil sensory perception [14,23].

More generally, the relationship between environmental stimuli and sensory quality has been demonstrated through combined metabolomic-sensory approaches, where variations in secondary metabolism are directly associated with perceptual changes [54].

In the present study, these effects were not expressed as changes in overall aroma intensity, but rather as shifts in descriptor composition and dominance, indicating a modification in the relative abundance of aroma-active compounds. This interpretation is supported by both the quantitative analysis and the evaluation of free descriptors, which accounted for frequency and perceived intensity. These results suggest that light treatments primarily influence the balance among volatile compounds, rather than their total amount, as also reported in previous sensory-metabolomic studies [55]. Nevertheless, because volatile organic compounds were not measured in the present study, further analyses would be required to confirm this interpretation. Importantly, these modifications did not result in a proportional decrease in overall liking, as indicated by the relatively stable global hedonic index. This suggests that basil's sensory quality is not strictly dependent on a single "typical" profile but can tolerate shifts in aroma composition while maintaining a good level of acceptability. This highlights the potential of light management as a practical tool to modulate basil sensory characteristics according to specific production goals or market preferences.

5. Conclusions

This study confirms that supplemental LED spectral quality is a major determinant of basil physiological performance, biomass production and quality, demonstrating that greenhouse lighting strategies should move beyond light intensity alone toward integrated spectral management. No single spectrum optimized all production objectives; instead, each light treatment produced distinct advantages depending on whether the target was photosynthetic efficiency, biomass, or crop quality. Multi-band WHITE supplementation provided the most balanced physiological performance, whereas the control treatment maintained the highest aromatic typicity. These results indicate a trade-off between physiological enhancement and aroma preservation, highlighting that the optimal lighting strategy depends on the targeted quality attributes. In contrast, narrow-band spectra produced more specialized outcomes. BLUE light promoted stomatal conductance, transpiration, and darker leaf coloration. GREEN supplementation enhanced fresh biomass, visual greenness, and brightness, offering a strong compromise between yield and marketable appearance. Overall, future studies might consider additional measurement points during gas exchange analysis to reduce the over- or underestimation of the physiological transpiration pattern before, during, and after light supplementation. Quality analyses further showed that spectral manipulation significantly influenced chlorophyll concentration, pigmentation, acidity, and leaf color without substantially altering antioxidant activity. These findings indicate that supplemental lighting can selectively improve sensory and commercial traits while maintaining nutraceutical stability. Thus, spectral design can be tailored not only to maximize productivity but also to target specific market demands such as premium flavor, visual quality, or production efficiency. Overall, this work demonstrates that precision spectral management is essential for optimizing basil cultivation in protected systems. Multi-band WHITE showed the best overall balance among the analyzed physiological and qualitative traits, while RED, GREEN, and BLUE provided targeted functional benefits.

Future advances should focus on dynamic multispectral lighting strategies that combine spectral strengths across crop developmental stages to maximize sustainability, profitability, and product quality in high-value aromatic herb production. A limitation of the present study is that the spectral treatments were restricted to monochromatic lights and a single white-light spectrum with a fixed R:G:B ratio. Therefore, the observed responses should be interpreted within the context of these specific lighting conditions and cannot be directly extrapolated to more complex spectral environments. Recent evidence suggests that multi-band light spectra may provide synergistic effects by simultaneously regulating plant growth, physiology, and secondary metabolism. Future studies should therefore investigate different combinations and proportions of multiple wavelengths to identify lighting strategies capable of optimizing multiple production traits simultaneously.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/horticulturae12070856/s1>. Table S1: Total curve area of cubic nonlinear regression (see Figure 4 in the manuscript) of daily net photosynthesis (P_n), daily stomatal conductance (g_s), daily intercellular CO_2 concentration (C_i) and daily transpiration (T_r) of basil plants grown in greenhouse, once supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), multi-band LED treatment (WHITE) and non-supplemented (CNT). Data (means $\pm$ standard deviation) were subjected to one-way ANOVA, and means with different letters are significantly different at $p \leq 0.05$ after Tukey's HSD post hoc test with different light treatments as the only source of variability. Table S2: Sum of squares of cubic nonlinear regression (see Figure 4 in the manuscript) of daily net photosynthesis (P_n), daily stomatal conductance (g_s), daily intercellular CO_2 concentration (C_i) and daily transpiration (T_r) of basil plants grown in greenhouse, once supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), broadband LED treatment (WHITE) and non-supplemented (CNT). Table S3: Standard error of the estimate (SEE) associated with the cubic polynomial models used to describe the daily trends (see Figure 4 in the manuscript) of daily net photosynthesis (P_n), daily stomatal conductance (g_s), daily intercellular CO_2 concentration (C_i) and daily transpiration (T_r) of basil plants grown in greenhouse, once supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), broadband LED treatment (WHITE) and non-supplemented (CNT). Figure S1: Basil plants grown under different light spectral conditions. From top to bottom: control plants (CNT) and plants supplemented with white light (WHITE), red light (RED), green light (GREEN), and blue light (BLUE). Figure S2: Residual plots versus predicted y axis of cubic nonlinear regression (see Figure 4 in the manuscript) of daily net photosynthesis (A), daily stomatal conductance (B), daily intercellular CO_2 concentration (C) and daily transpiration (D) of basil plants grown in greenhouse, once supplemented with narrow-band LED treatments (RED, GREEN, and BLUE), broadband LED treatment (WHITE) and non-supplemented (CNT).

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Abbreviations

The following abbreviations are used in this manuscript:

ALO	After Light On
BLO	Before Light On
C _i	Intercellular CO ₂ Concentration
CNT	Control Plants
DLO	During Light On
DPPH	2,2-diphenyl-1-picrylhydrazyl
FW	Fresh Weight
g _s	Stomatal Conductance
LED	Light-Emitting Diode
P _n	Net Photosynthetic Rate
PPFD	Photosynthetic Photon Flux Density
TA	Titrateable Acidity
T _r	Transpiration Rate

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