Trade-off between Biomass and Flavor Compounds in Basil under Red-Blue versus White LED Light

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Abstract

This study investigated the influence of different LED light spectra on yield, efficiency, and flavor-relevant compounds of basil (*Ocimum basilicum* var. Genovese). Red-blue LEDs (ratio 3:1) were compared with white LEDs at identical photosynthetic photon flux density (95 μmol m^{-2} s^{-1}) over 16 weeks. Under red-blue lighting, plant height (+31.1%), fresh weight (+34.2%), and dry weight (+58.4%) were significantly higher. Biomass efficiency reached 38.31 mg/W, representing a 184% increase compared to white lighting (13.5 mg/W). Conversely, GC-MS analysis revealed higher concentrations of flavor-relevant compounds under white light: eucalyptol (+45.5%), linalool (+421%), and bergamotene (+29.8%). The results indicate that red-blue LEDs favor biomass production and energy efficiency, while white light promotes the accumulation of secondary metabolites. Light spectrum selection should therefore be application-specific.

Keywords: LED lighting; basil; secondary metabolites; terpenes; biomass efficiency; controlled environment agriculture

Introduction

In recent decades, artificial plant lighting has gained considerable importance, particularly through the advancing development of LEDs, which are highly efficient, long-lasting, and precisely adjustable with respect to their light spectrum. These properties provide several advantages over older light sources such as high-pressure sodium lamps or fluorescent lamps, especially for plant cultivation in controlled environments. Urban areas benefit particularly, where limited space places higher demands on resource efficiency [1].

LEDs offer the possibility of increasing yield through their high efficiency. Targeted adjustment of the light spectrum can further enhance efficiency and improve plant quality. There are various approaches depending on the objective. For example, a combination of red and blue LEDs can cover exclusively the most effective portion of photosynthetically relevant radiation, resulting in increased efficiency compared to older light sources. Current

studies with basil show notable efficiency gains, which can be further optimized through the correctly adjusted red to blue ratio [2, 3].

In contrast, white LEDs cover a broader spectrum relevant to plants. This reduces photosynthetic efficiency since wavelengths less effective for photosynthesis are also emitted. However, these wavelengths can influence plant development through photoreceptors. The resulting photomorphogenetic effects affect both growth behavior and secondary metabolite production, which constitute the majority of flavor-relevant compounds in many herbs, spices, and vegetables [4–8].

This study investigated how these two approaches affect yield, efficiency, and flavor-relevant compounds in basil. Basil was chosen as a model plant because it is frequently used in scientific studies and comparable results can be expected. Furthermore, it has a high proportion of flavor-relevant compounds in the form of secondary plant substances such as terpenes and related compounds [8].

The hypothesis of this study was that red-blue lighting increases yield and efficiency, since these wavelengths are optimally absorbed by the pigments of photosynthesis. In contrast, an increased concentration of flavor-relevant compounds was expected under white light, since here, in addition to photosynthetically relevant light, wavelengths are also emitted that potentially stimulate photomorphogenetic processes for the formation of secondary metabolites [4, 9].

Materials and Methods

LED module design

The plant lights were based on custom-developed printed circuit boards (PCBs), each equipped with 12 high-power LEDs of the Cree XLamp XP-G3 class. The LEDs were divided into two groups of six LEDs connected in series, with each group having its own connection. The red-blue module was controlled via two separate drivers from MeanWell. The red LEDs used model LPF-16D-12, while the blue LEDs were operated with model LPF-16D-20. This separate control enabled individual adjustment of the light intensity for the red and blue light components to set the red-blue ratio of 3:1. The white LEDs were operated together via a single MeanWell LED driver model NPF-60D-20. Additional series resistors between driver and module were required to ensure uniform distribution of current and brightness between the two LED groups. Heat sinks were attached to the rear of the PCBs to dissipate the heat generated by the LEDs.

Light calibration

For calibration of the LED modules, the PPFD measuring device “Parwise” from manufacturer ITC was used and positioned at 20 cm height in the cultivation box. Per color, 5 to 7 data points were recorded, on the basis of which calibration curves were created. According to the maximum values of all LEDs, a total PPFD of 95 μmol m^{-2} s^{-1} was selected. Due

to limitations from maximum LED output, a ratio of 2.8:1 was chosen for the red-blue combination, which approximately corresponds to the target value of 3:1. The spectral distributions of both LED modules are shown in Figure 1. Operating parameters were: RB total = 12.92 W (red: 13.0 V × 0.60 A = 7.80 W; blue: 16.5 V × 0.31 A = 5.12 W); white = 23.12 W (17.0 V × 1.36 A). Voltage and current were monitored throughout the experiment using inline volt- and ammeters (DSN-VC288).

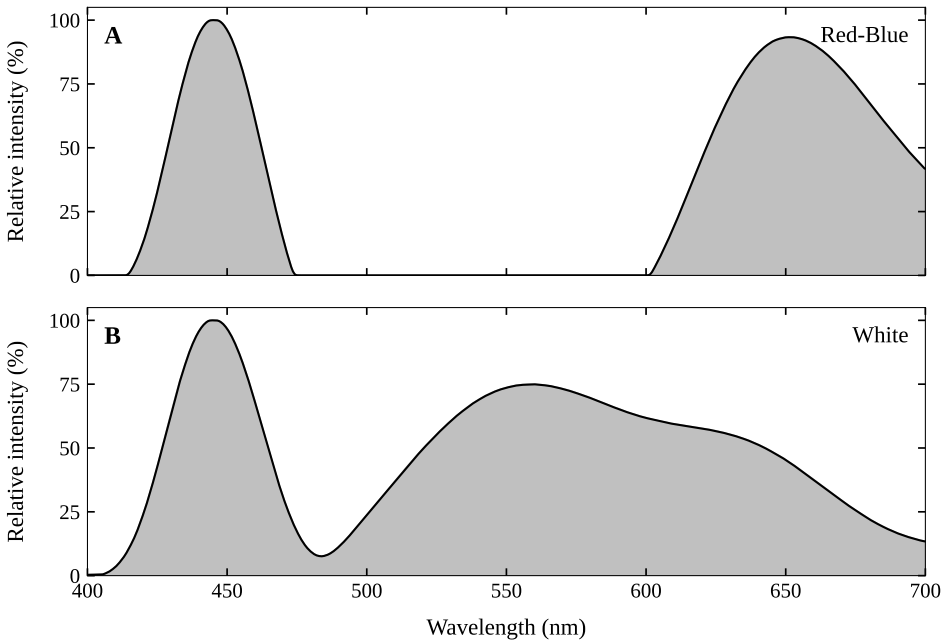


Figure 1. Spectral distribution of the LED modules used in this study. A: Red-blue LED module showing distinct emission peaks in the blue (∼450 nm) and red (∼660 nm) regions with minimal emission in the green-yellow range. B: White LED module (phosphor-converted) showing a blue peak (∼450 nm) from the LED chip and broad phosphor emission spanning the green to red region (500–700 nm). Spectra were recorded using a PARwise quantum sensor (ITC).

Cultivation setup

Two identically sized boxes were constructed from MDF panels and squared timber for reinforcement. The dimensions were 600 × 600 × 750 mm (W × D × H). The inner surfaces were covered with glossy white furniture film. The front of the boxes was initially left open and later covered with a matching white PVC tarpaulin. Two plant trays, each containing eight pots, were prepared and filled with commercially available herb potting soil. Seeds of *Ocimum basilicum* var. Genovese were sown. Germination rate was not quantitatively recorded. These trays were positioned centrally in the boxes. The LED modules were suspended approximately 10 cm below the ceiling. From the start of sowing, both cultivation groups were watered at the same time and with the same amount of water. Both cultivation boxes were located in the same non-climatized room. Although temperature and humidity conditions varied over time, they remained equal between the boxes. The photoperiod was 16 h light / 8 h dark.

Harvest and biomass measurements

After 16 weeks, the differences between both groups were clearly visible, whereupon the experiment was terminated and data collection began. To obtain comparable data, 5 randomly selected plants were first removed from each pot and cut at substrate level. Plant height was measured using a 3M measuring tape (accuracy class II). Fresh weight was recorded using a G&G TSWB balance (300 g / 0.01 g). The plants were then dried in an oven at 50 °C for 6 hours. After successful drying, dry weight was measured. The measurement was not performed for each individual plant, but per pot, since the weights of individual dried plants were too close to the accuracy limit of the balance.

GC-MS analysis

The GC-MS analyses of the plant samples were performed with the support of Prof. Dr. Mathias Schäfer and Ms. G. Gömec at the Department of Mass Spectrometry, Institute of Organic Chemistry, University of Cologne. For the analysis, 20 grams of randomly collected leaf material were packed in sealable plastic bags and handed over to the Mass Spectrometry Department. The measurements were conducted on a Thermo Fisher Scientific TRACE 1310 GC coupled to an Exactive GC Orbitrap mass spectrometer. Extraction solvent was ethanol (EtOH), solvent was methanol (MeOH), sample volume in measurement vial was 1 mL at approximately 80 mg/mL concentration (1:2.5 dilution). Injection volume was 1 μL. Carrier gas was helium at 1.2 mL/min flow rate. Temperature program: 50 °C (2 min hold) $\rightarrow$ 15 °C/min $\rightarrow$ 150 °C $\rightarrow$ 10 °C/min $\rightarrow$ 280 °C. Separation column: TG-5SilMS (30 m $\times$ 0.25 mm $\times$ 0.25 μm). Electron ionization (70 eV) was used with a mass range of 50–750 m/z at 60,000 resolution.

Eucalyptol and linalool were selected because they are among the most frequently reported volatile constituents of *Ocimum basilicum* and are recognized markers of basil aroma [10]. Bergamotene was additionally included because it appeared as a prominent peak in the chromatograms of both treatments and, as a sesquiterpene, represents a further class of secondary metabolites in basil essential oil. The selected compounds therefore combine literature relevance with their prominence in the present dataset. Signal intensity (counts per second, CPS) was used for relative quantification; absolute concentrations were not determined.

Statistical analysis

Height and fresh weight data (n = 40 per treatment) were analyzed by two-tailed independent-samples t-tests. Dry weight data (n = 8 pot-level measurements per treatment) were similarly analyzed. Significance levels were set at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). In this study, yield refers to dry biomass per plant. Biomass efficiency was calculated as total dry weight divided by electrical power consumption of the LED module (mg/W). Because both treatments were operated under identical photoperiod and duration, this metric reflects the relative efficiency of the two modules at equal cumulative energy input. GC-MS data are reported as mean $\pm$ standard deviation of triplicate injections of a pooled sample per treatment and therefore represent technical, not biological, replication.

Results

Plant growth and biomass

As expected, significantly larger plants developed under red-blue lighting. The average height was 125.75 mm with a standard deviation of 23.36, while under white lighting it was 95.95 mm with a deviation of 16.37. Plant height in group RB was highly significantly greater than under white lighting ($t(78) = 6.60$, $p < 0.001$), corresponding to an increase of 31.1%.

A clear difference was also evident for weight, with red-blue showing higher values as expected. Plants in group RB showed an average fresh weight of 511.8 mg with a standard deviation of 175.3. In group W, the weight was 381.5 mg with a deviation of 178.7. Fresh weight of plants in group RB was significantly higher than those from group W ($t(78) = 3.30$, $p = 0.0015$), an increase of 34.2%.

For dry weight, a similar pattern emerged. Group RB showed dry weight of 99 mg with a standard deviation of 28.3, while group W showed 62.5 mg with a deviation of 25.7. Dry weight of group RB was significantly higher ($t(14) = 2.50$, $p = 0.025$), an increase of 58.4% compared to white light. This increase exceeds the 34.2% observed for fresh weight, indicating that plants from group W contained proportionally more water and volatile substances. Dry matter content was 19.3% for red-blue light and 16.4% for white light (Table 1).

Table 1. Growth parameters of basil under red-blue (RB) and white (W) LED illumination after 16 weeks.

Parameter	**RB**	**W**	**Δ (%)**	***p*-value**
Height (mm)	125.75 ± 23.36	95.95 ± 16.37	+31.1	<0.001***
Fresh weight (mg)	511.8 ± 175.3	381.5 ± 178.7	+34.2	0.0015**
Dry weight (mg)	99.0 ± 28.3	62.5 ± 25.7	+58.4	0.025*
Dry matter content (%)	19.3	16.4	—	—

Values are mean ± SD. Height and fresh weight: n = 40. Dry weight: n = 8 (5 plants pooled per pot).

Biomass efficiency

A clear result was evident here. The power consumption of the red-blue combination was lower, while the yield was higher. Biomass efficiency, calculated as dry weight divided by power, was 13.5 mg/W for plants under white light and 38.31 mg/W for red-blue—an efficiency increase of 184%. This can be attributed to two factors: first, the higher electrical efficiency of the uncoated red and blue LEDs, and second, the higher photosynthetic efficiency since the emitted wavelengths are close to the absorption peaks of the action spectrum (Table 2).

Table 2. Power consumption and biomass efficiency.

Treatment	Power (W)	Dry weight (mg)	Efficiency (mg/W)
Red-Blue	12.92	495.0	38.31
White	23.12	312.5	13.5

Dry weight = total from eight pots (40 plants).

Secondary metabolite concentrations

In contrast to biomass production, the results for secondary metabolites showed the opposite pattern. Group W showed higher concentrations of all measured compounds.

The measured CPS value (counts per second, signal intensity) from the GC-MS analysis served as a measure of concentration. Although no absolute concentration could be derived, the values allowed relative comparison. Since measurements were performed under identical conditions, a linear correlation between CPS value and concentration could be assumed.

For eucalyptol, group RB showed 8.80×10^7 CPS with a deviation of 1.63×10^7, while group W showed 12.8×10^7 CPS with a deviation of 4.48×10^7. Eucalyptol concentration tended toward higher values under white light, an increase of 45.5%.

Linalool showed the strongest effect. Group RB showed 5.14×10^7 CPS with a deviation of 0.53×10^7, while group W reached 26.8×10^7 CPS with a deviation of 7.90×10^7—an increase of 421%.

For bergamotene, the value for group RB was 53.1×10^7 CPS with a deviation of 6.92×10^7. For group W, it was 68.9×10^7 CPS with a deviation of 12.9×10^7. From the values, a percentage increase of 29.8% under white light compared to red-blue light resulted.

These differences between groups RB and W regarding secondary metabolites became even more pronounced when the concentration or intensity per gram dry weight was considered: linalool increased by 726%, eucalyptol by 130%, and bergamotene by 106% under white light relative to red-blue (Table 3).

Table 3. GC-MS signal intensities (CPS $\times 10^7$) for volatile compounds.

Compound	RB	W	Δ absolute (%)	Δ per g DW (%)
Eucalyptol	8.80 ± 1.63	12.8 ± 4.48	+45.5	+130
Linalool	5.14 ± 0.53	26.8 ± 7.90	+421	+726
Bergamotene	53.1 ± 6.92	68.9 ± 12.9	+29.8	+106

Values are mean ± SD of triplicate GC-MS injections from pooled samples, representing technical, not biological, replication. CPS = counts per second. DW = dry weight.

Discussion

In accordance with the hypothesis, higher yield values were recorded under red-blue light, while white light produced higher concentrations of flavor-relevant compounds. The difference in dry weight (+58.4% under red-blue) was more pronounced than for fresh weight

(+34.2%). One possible explanation is that plants in group W contained proportionally more water and volatile substances, although this was not directly quantified in the present study. Dry matter content was 19.3% for red-blue light and 16.4% for white light.

The efficiency increase from white light to red-blue light at 184% was substantial. Similar applied to secondary metabolites in the opposite direction, although increases varied by compound: from 45.5% for eucalyptol to 421% for linalool to 29.8% for bergamotene. Additionally, white light produced higher standard deviations than red-blue light, both for growth parameters and CPS values.

The comparison of CPS values per gram dry weight suggests that metabolite production is influenced by different spectral components than photosynthesis. When signal intensities are normalized to dry weight, values remain higher under white light despite the lower biomass of this group, indicating that the effect is not merely a dilution artifact from increased biomass under red-blue light. This interpretation should be regarded as indicative rather than definitive, since the GC-MS analysis was based on pooled samples and relative signal intensities rather than absolute quantification at the individual-plant level.

It is noteworthy that secondary metabolites increased under white light although the UVR8 receptor, which is considered an important regulator of secondary metabolite biosynthesis [4, 9], was not activated. Since neither LED spectrum emits UV light, activation of the UVR8 signaling pathway was not expected. The observed differences in secondary metabolite concentration must be attributable to other photoreceptors in the visible spectrum. Examining the light spectra of both LED modules, the only substantial difference is green to yellow light. Some studies report positive effects of this spectral range on photosynthesis, but information on its influence on secondary metabolites remains scarce [11].

Neither lighting method can be described as universally better. Red-blue light is better suited for high yields and efficiency, while white light produces higher concentrations of flavor compounds. The choice should be application-specific.

The interpretation of the results must take into account several methodological limitations. The most important limitation concerns the experimental design with only one cultivation box per lighting scenario. As a result, possible differences between the boxes cannot be separated from the effects of the lighting, and the study lacks biological replication at the treatment level. Differences in temperature or air circulation within the boxes could have influenced the results. In the GC-MS analysis, the leaf samples of all plants from one group were mixed and this mixed sample was measured three times. This made statistical evaluation at the biological level impossible, and the differences found in the compounds can therefore only be interpreted descriptively. The analysis was based on relative signal intensities rather than absolute concentrations, and total essential oil content—a standard parameter in basil research—was not determined, which limits direct comparability with the existing literature. Morphological characterization was restricted to height, fresh weight, and dry weight; additional parameters such as leaf number, plant width, or flowering status were not recorded. The target PPFD of 95 μmol m^{-2} s^{-1} was below the optimal range for basil (approximately 200–250 μmol m^{-2} s^{-1} [3]) due to limitations in LED output after calibration. While both treatments received identical PPFD, effects may differ at higher

light intensities. Additionally, temperature and humidity were not continuously measured during the experiment. Since both factors can influence both growth and the production of secondary metabolites, this makes the clear assessment of the results more difficult.

Conclusion

This study describes a trade-off between biomass efficiency and flavor compound accumulation in basil grown under red-blue versus white LED illumination. Red-blue light produced 58% more dry weight with 184% higher energy efficiency, while white light increased linalool signal intensity by 421%, eucalyptol by 46%, and bergamotene by 30%.

Spectrum selection should be guided by production objectives: red-blue for maximum yield and efficiency, white light for enhanced secondary metabolite concentration. Future research could test whether combinations of red-blue with green light can increase secondary metabolite production without reducing biomass efficiency. More detailed investigations on the controlled addition of UV light to a red-blue base for activation of the UVR8 receptor would be equally conceivable.

Declarations

Funding: The author received no specific funding for this work.

Competing interests: The author declares no competing interests.

Ethics approval: Not applicable. This study did not involve human participants, animals, or protected species.

Data availability: All relevant data underlying the findings are provided in the supplementary information file (S1_Data.xlsx).

Author contributions: J.P. conceived and designed the study, conducted the experiments, performed data analysis, and wrote the manuscript.

Use of AI assistance: The author acknowledges the use of an AI assistant (Claude, Anthropic) for language editing, structural refinement, and formatting of the manuscript. All scientific content, experimental design, data collection, analysis, and interpretation were carried out by the author, who takes full responsibility for the final content.

Acknowledgments

The author thanks Prof. Dr. Michael Schäfer (University of Applied Sciences Ruhr West) for supervision of this research project. The author also gratefully acknowledges Prof. Dr. Mathias Schäfer and the Department of Mass Spectrometry (Institute of Organic Chemistry, University of Cologne) for performing the GC-MS analyses.

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