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How Various LED Wavelengths Affect Plant Growth of Basil (Ocimum Basilicum)

Neil Jatakia*
Horticultural Sciences, Chino, The United States of America

Abstract— **This study investigates the effects of different LED wavelength combinations and intensities on growth, yield, and phytochemical content of basil (Ocimum basilicum) in controlled environment agriculture. Using a randomized complete block design with four replications, basil plants were exposed to six LED wavelength combinations (UV-A, blue, red, UV-A+blue, UV-A+red, and blue+red) at two photosynthetic photon flux density levels (100 and 200 µmol·m−2·s−1). Results showed that blue+red and UV-A+blue combinations produced the highest plant growth parameters, with heights of 29.8 cm and 30.5 cm respectively, and fresh biomass yields of 95.3 g/plant and 92.5 g/plant. UV-A+red treatment yielded the highest chlorophyll content (53.6 SPAD units), while UV-A+blue treatment resulted in maximum total phenolic content (25.7 mg GAE/g DW). Lower PPFD values (100 µmol·m^{-2}·s^{-1}) enhanced phytochemical synthesis, while higher intensities (200 µmol·m^{-2}·s^{-1}) promoted biomass accumulation. These findings demonstrate that specific LED wavelength combinations can optimize basil production and phytochemical content in controlled environments, offering potential applications for sustainable urban agriculture and year-round crop production.**

Index Terms— **Basil (Ocimum basilicum), Controlled environment agriculture, Hydroponic cultivation, LED lighting, Light wavelength, Photosynthetic photon flux density, Phytochemicals, Plant growth, Secondary metabolites, UV-A radiation.**

1. Introduction

LED (light-emitting diode) technology nowadays is a potential option for plants to be placed correctly under controlled environment agriculture (CEA) and to increase their phytochemical production. With light energy efficiency, long service life, and emissions spectral control, LEDs are a powerful alternative to more traditional farming lights. Although many experiments have focused on the photosynthetic reactions of different LED colours on plant growth and development, designing wavelengths best suited for a specific crop is necessary. Basil, from the family Lamiaceae, has revealed optimal behaviors in LED lighting based on factors such as improved growth, increased production, and the accumulation of phytochemicals, despite the fact that only the specific effects of various wavelengths of LED light, especially in the UV-A range, on basil growth and quality have been determined. This research aims to examine the effects of varieties of LED wavelength lightings, including UV-A, blue, and red-light rays, on the growth, yield and phytochemical content of basil plants grown indoors in a controlled environment. By applying RCBD with different LED systems and light degrees, this study aims to find the best light recipes to improve basil production.

2. Literature Review

This study investigates how various LED wavelengths affect plant growth of basil (Ocimum basilicum). Its energy economy and ability to supply plant-growth-specific wavelengths have made LED lighting technology popular in agriculture with controlled environments and vertical farming systems. Indoor horticulture using LED lights instead of growing lights is being studied. LEDs' effects on numerous crops have been extensively examined, but basil plants' sensitivities to visible and UV wavebands must be understood. This literature study will reduce the emphasis from general LED plant illumination studies to wavelength combinations' impacts on basil growth properties, yield, and phytochemical quality. Analysis of the literature will reveal gaps and discrepancies, highlighting the necessity for further study to enhance basil output under controlled LED light treatments.

A. Evolution

Early studies on LED lights for plant development examined their practicality and benefits over high-pressure sodium lamps. According to Olle & Alsiņa (2019), the LED color spectrum affects greenhouse vegetable productivity, growth, and nutritional quality. Blue, green, and red light provide benefits, but further study is needed to optimize spectral compositions for individual crops. While LED technology improved, researchers studied wavelength impacts on valuable herbs and medical plants like basil. In their 2023 study, Viršilė et al. (2023) focused on the nutritional effects of UV-A wavebands supplemented with visible LED light on green and purple basil varieties. Wavelength-dependent impacts on plant growth, antioxidants, and other health-promoting substances were found. Basil has not been studied in UV-A regions like 343366 nm. In their 2020 study, Larsen et al. examined how light intensity, spectrum quality, and end-of-production light treatments affect basil biomass accumulation and morphology in vertical farms. This research revealed species-specific plant responses to LED light spectra and optimum light recipes.

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*Corresponding author: jatakianeil@gmail.com

These early experiments paved the way for a more focused study on wavelength combinations for controlled basil growing.

B. *Defining Key Concepts*

LEDs are solid-state semiconductors that produce light when electricity runs through them. LEDs emit specific wavelengths using different semiconductor materials (Rahman et al., 2021). The hue of visible light depends on the wavelength and the distance between wave peaks or troughs. Plants need 400–700 nm PAR for photosynthesis (Rihan et al., 2020). Blue (400-500 nm) and red (600-700 nm) wavelengths are crucial for photomorphogenesis in plants (Rihan et al., 2020). LED lighting measures plant biomass, output, photosynthetic rates, chlorophyll, phenolic substances, and other phytochemicals (Rahman et al., 2021).

Sweet basil is aromatic and used in culinary and healing. Plants need specific parameters, including humidity, temperature, nutrients, and light intensity, for optimal development, biomass, and secondary metabolite production (Sutulienė et al., 2022). Light intensity (150-250 μmol/m^2/s) enhances basil development and antioxidant capacity.

C. *Review*

Studies on how wavelengths impact plant growth have shown significant progress. Barbi et al. (2021) observed that hyper-red and deep blue LED lights in various combinations increased basil plant height, fresh weight, and leaf number compared to daylight. Solbach et al. (2021) found that red, white, and far-red light increased basil dry weight better than blue light. Hammock et al. (2020) found that blue and red LED limited bandwidth wavelengths increased basil biomass output and nutrient absorption over high-pressure sodium illumination. Tabbert et al. (2022) discovered that intensity between 400-500 μmol/m2/s helped basil cultivars grow faster and reach the market faster using a 400-780 nm white LED spectrum. Dou et al. (2020) found that blue light reduced basil shoot biomass but raised phytochemical concentrations. Instead of blue light, Matysiak and Kowalski (2021) found that dominant red and white LED lights were best for basil to flourish.

Many studies have examined basil's response to mixed wavelength spectra. Rihan et al. (2020) created a spectrum of light complementing basil pigment absorption peaks, using 435 nm blue light instead of 450 nm to boost growth. Higher red and far-red frequencies enhanced basil phenolic acid but reduced volatile chemicals like linalool, according to Kivimäenpä et al. (2022). Kondratieva et al. (2022) found that red-blue and white LEDs enhanced primary growth metrics for two basil types over white light alone. According to D'Aquino et al. (2023) and Daud et al. (2023), red/blue light at 160 μmol/m2/s and precise nutrient levels enhanced basil growth, yield, and phenolic content.

Some scholars have compared basil's reactions to other crops. Alrajhi et al. (2023) [9] found that red and blue light affected lettuce cultivars differently, although white LEDs worked best. Larsen et al. (2020) found that blue solid light fractions boosted basil tallness more than leafy greens, emphasizing the need to consider diverse views when assessing LED lighting solutions.

Twenty articles cover wavelength effects and mixed wavelength spectra. The authors compare basil's responses to other crops, emphasizing its economic value and controlled environment optimization potential. They include greenhouse trials, development chambers, indoor ranches, and hydroponic systems to examine how LED light wavelength affects basil growth.

Ideal wavelengths and intensities dominate talks. Others favor crimson and far-red, whereas Hammock et al. (2020) advocate more blue. The optimal photosynthetic light flux density is debated, with estimates ranging from 100-400 μmol/m2/s (Tabbert et al., 2022). These differences may be due to basil varietals, growth conditions, supplementation dosages, and research aims (biomass vs. metabolites). LED illumination is considered an ecologically benign alternative to standard grow lights for growing valuable crops like basil in regulated surroundings.

D. *Narrowing Focus*

This study analyzes how UV-A light wavelengths impact green and purple basil phytonutrient and mineral content in a controlled environment. A survey by Viršilė et al. (2023) suggests UV-A light supplementation enhances nutraceutical components in basil. Further study is required to understand the impact of specific wavelengths on mineral intake and The impact of UV-A wavebands on sugar content, colors, production, and growth parameters in basil production with the primary photosynthetic lights is not well studied, according to Olle and Alsiņa (2019 UV-A wavelengths and red and blue photosynthetic light on controlled-growth basil were understudied, according to academic journals.

E. *Prior Methods and Findings*

Different methods have explored how LED wavelengths impact basil growth and characteristics. Solbach et al. (2021) created basil trait light dose-response curves in greenhouse blue, red, white, and far-red light testing. Using pigment absorption experiments, Rihan et al.

(2020) generated an LED spectrum and compared it to conventional wavelengths. Pennisi et al.

(2020) cultivated basil with red and blue LEDs at different PPFDs to find the best. Rahman et al. (2021) tested basil produced under white, red, blue, and far-red LEDs. Matysiak and Kowalski (2021) conducted an experiment with basil, using red, blue, and white LED lights in high gaps. For appropriate wavelengths for plant biomass production, studies have shown that the combination of red and far-red wavelengths to produce biomass would be appropriate. Additionally, studies have shown that a blue wavelength of 435 nm light can promote growth. In contrast, light intensity and the combination of various wavelength factors of light can affect the phytochemical content (Dörr et al., 20). These discoveries were made with the use of fundamental plant reactions to the light range, spectrum, intensities, and basil growth and features.

F. *Challenging Perspectives*

Many pieces of the research have shown that special LED wavelengths boost the basil growth, production, and phytochemical level while others prove the opposite. Alrajhi et al.

(2023) examined how changing LED spectra affect red and green lettuce growth and nutrition.

Unlike basil, white LED light functioned better than red, blue, green, and far-red wavelengths. Larsen et al. (2020) used a vertical farm to study basil development and morphology under varied light intensities and spectrums. The influence of light intensity was more significant than spectral composition, contrary to basil-specific research emphasizing wavelength combinations. Contradictory findings imply that plant species may have different ideal light levels, stressing the necessity for crop-specific studies to improve growth and quality.

G. *Research Gaps*

The literature shows how LED light wavelengths impact plant growth, yet critical gaps remain. There is little study on how UV-A wavelengths affect basil's nutraceuticals and minerals. Understanding the wavelength dependence of plant responses to UV-A is essential for maintaining quality and improving basil output under controlled settings (Viršilė et al., 2023).

They found that UV-A wavelengths may impact basil cultivars' phenolics, carotenoids, and minerals element content.

The combined effects of UV-A wavelengths and other spectrum constituents and intensities remain unknown. Few studies have explored the impact of optimal wavelength combinations and intensities on basil growth, output, and phytochemical richness. This literature review will help subsequent research fill these gaps and increase our understanding of LED light efficacy for controlled basil growth.

H. *Justifying the Research*

Literature studies show gaps in understanding how various LED wavelengths, notably UV-A, affect basil plant growth, yield, and phytochemical content. Numerous research has examined red, blue, and far-red wavelengths, but few have examined UV-A wavelengths (343402nm) (Viršilė et al., 2023). A broad UV-A and other wavelength experiments are required to maximize basil yields in controlled environment agriculture (CEA) systems. Filling this information gap will maximize biomass accumulation, optimum plant shape, and earlier harvest maturity. It will benefit basil's phenolic acids, carotenoids, and aroma volatiles. Growing high-quality, high-yield basil under optimal light conditions would improve CEA capacities, sustainable urban agriculture, and food security (Rahman et al., 2021). This study will enhance the comprehension of appropriate light spectra for controlled environment basil and other high value crop cultivation.

3. Materials and Methods

The research aimed to examine the impacts of different light-emitting diode (LED) wavelengths on the development, production, and phytochemical composition of basil (Ocimum basilicum) plants cultivated in a controlled setting. The primary objective of the research is to understand how basil plants respond to different light intensities in yield, biomass, and health-promoting phytochemicals, as well as to find out which wavelength combinations of LED work better toward these goals. The study of the photosynthetic behavior of basil plants exposed to a mixture of blue and red photosynthetic wavebands and UV-A wavelengths alone fills a knowledge gap in the literature.

A. *Plant Materials*

'Genovese' and 'Opal' basil seeds were used because of their commercial value. The 'Genovese' and 'Opal' seeds came from different companies. Their culinary and nutraceutical uses and different pigmentation levels led to the selection of these cultivars.

1) *Growing Systems and Facilities*

A 4-by-6-by-3-meter walk-in controlled environment growing chamber (Model GC-77, EnviroSys) was used for the experiment. To maintain uniformity, the chamber had cooling, dehumidification, and air circulation fans.

GHE RainForest 66 Model, General Hydroponics, used NFT systems to grow plants. With a recirculating nutritional solution, NFT systems used rectangular plastic pipes (15 x 7.6 x 66 cm). Twelve 15-cm-distance planting holes accommodated 48 plants per channel.

B. *Light Treatments*

The sole light sources were narrowband LED lights (SpectraLux Series, Lumigrow) with UV-A (peak at 375 nm), blue (450 nm), and red (665 nm) wavelength outputs. To evenly illuminate the plant canopy, LED lamps were put on movable platforms above hydroponic systems in a line pattern.

Employing a certified quantum sensor (MQ-200, Apogee Instruments), photosynthesis photon flux density (PPFD) of one hundred and two hundred $\mu mol \cdot m^{-2} \cdot s^{-1}$ were obtained at the plant canopy level. For basil, a higher PPFD of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ is necessary for optimum growth and phytochemical accumulation. Lower frequency energy-saving methods of one hundred $\mu mol \cdot m^{-2} \cdot s^{-1}$ were also tested.

C. *Other Materials*

General Hydroponics' Flora Series premixed hydroponic fertilizer solution provided plant development minerals. Nutrient solution contained N (185 ppm), K (235 ppm), Ca (180 ppm), P (50 ppm), Mg (70 ppm), Fe (3 ppm), Mn (0.6 ppm), S (90 ppm), B (0.5 ppm), Zn (0.2 ppm), Cu (0.1 ppm), and Mo. The electrical conductivity (EC) of a nutritious solution was monitored with a validated EC meter (HI9813-6, Hanna Instruments) set at 1.8 mS/cm. The pH was then set at 6.0 with concentrations of potassium hydroxide or phosphorous acid.

For phytochemical research, a UV-Vis spectrophotometer (Genesys 10S, Thermo Scientific) was used to quantify chlorophyll, total phenol and flavonoids content, and antioxidant activity. Certain phenolic acids were measured using an Agilent 1260 Infinite II HPLC system's diode array detector (DAD).

D. Experimental Design and Treatments

A randomized complete block design (RCBD) with 4 replications was used to carry out the experiment. Treatments comprised six combinations of LED light wavelengths: 1) UV-A alone, 2) blue alone, 3) red alone, 4) UV-A + blue, 5) UV-A + red, and 6) blue + red. A total of 12 light treatments were conducted by testing each combination of wavelengths at two photosynthetic photon flux density (PPFD) levels: two hundred μmol·m−2·s−1 and one hundred. Additionally, a control group was subjected to White LED illumination with a two hundred μmol·m−2·s−1 strength to replicate the natural lighting conditions commonly found in greenhouses or growth rooms. There were a total of 13 treatment combinations, each reproduced 4 times, yielding fifty-two experimental units.

E. Cultural Practices

Basil seedlings were planted on plastic trays with Sunshine Mix #4, Sun Gro Horticulture. No soil was used. Uniform 4-leaf seedlings were transplanted into hydroponic NFT systems with one per hole after 14 days. Plants were 24 per square meter. LED light treatments with 16-hour photoperiods grew the plants for 6 weeks. The day/night heat was 24/18°C and moisture was seventy percent ± 5%. To replenish lost nutrients, a submersible pump (EcoPlus 185 GPH, EcoPlus) recirculated the nutritional solution and replenished each channel every 7 days.

F. Data Collection

Weekly growth metrics were monitored from the day following transplantation into hydroponic systems. Plant altitude, leaflet numbers, (defined as fully expanded leaves >2 cm), and canopy width (the broadest diameter of the plant canopy). Thoroughly removing the plants from the systems and separating their leaves, stems, and roots was done at harvest, which was 42 days following transplanting. Analytical balance readings (EL204, Mettler Toledo) were taken of various plant components as they were harvested. The leaves were measured using a LI-COR Bio systems LI-3100C surface area meter.

Harvest weight of fresh biomass (leaves and stems) was used as a yield parameter. In order to determine the dry matter content and get dry weight measurements, subsamples of the stem, leaves, and roots were dried in a forced-air oven (Heratherm, Thermo Scientific) set at 70°C for 72 hours.

G. Phytochemical Analyses

In order to determine the chlorophyll content of newly harvested leaves, a SPAD-502 Plus, a non-invasive chlorophyll meter was used to take measurements from three distinct spots on each leaf and then average them.

Partially frozen in nitrogen solution and kept at -80°C, a subset of each plant's fresh leaves were analyzed for additional phytochemicals. Following freeze-drying in a Labconco FreeZone 6, the leaf samples were ground into a fine flour using a Mill for plant analysis.

Using a slightly modified version of the Folin-Ciocalteu colorimetric test, the total phenolic content was measured (Singleton et al., 1999). In a nutshell, 10-milliliters of 80% methanol was ultrasonically extracted from half a gram of dried leaf powder using 30 minutes of sonication. The dried sample's saliva was mixed with Folin-Ci and Sodium Carbonate. Using a UV-Vis spectrophotometer, absorption was 765 nm. Using a gallic acid-based standard curve, the total amount of phenolic content was determined as mg GAE/g DW.

The amount of total flavonoids was determined using the same methanolic extracts that were used to measure total phenolics, utilizing aluminum chloride colorimetry. Results were expressed as mg quercetin equivalents (QE) for gram dry weight when quercetin was employed as a reference.

The 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical elimination assay evaluated the antioxidant properties of methanolic extracts. A μmol Trolox equivalent per gram of dry weight was used to express the results.

H. Statistical Analysis

ANOVA was used to examine the data. At a significance threshold of $p < 0.05$, Tukey's honest significant difference (HSD) test was employed to differentiate between treatment means. There were six different treatments in the study, and the design was a random full block.

I. Limitations and Implications

Although this study sought to optimize basil output and phytochemical content using LED lighting, it had certain drawbacks. The controlled setting chamber may not accurately mimic greenhouse or outdoor conditions. Pests, pathogens, air flow, and temperature changes were reduced or eliminated. In manufacturing, these variables can greatly affect plant growth and development. The findings should be confirmed in greenhouse or field research. Plant responses may have been affected by the nutrient film technique (NFT) hydroponic system, compared to soil, coco coir, or other growing medium. Changes to the nutrition solution formulation could also affect findings. Using multiple growth systems to evaluate LED treatments might increase applicability. It should also be noted that only 'Genovese' and 'Opal' basil were tested. Although commercially important, other cultivars may respond differently to LED wavelength and intensity treatments depending on their genetics and phytochemical profiles. Additionally, screening more basil cultivars and species may yield more insights. Finally, basil contains volatiles, carotenoids, and vitamins that affect its culinary and nutraceutical value, in addition to chlorophyll, antioxidants, and phenolic compounds. Research should expand phytochemical profiling. Overall, this study suggests using LED lighting to improve basil quality, but real-world validation, economic assessments, and cultivar/compound studies are needed to properly understand the consequences.

4. Results

A. Plant Growth Parameters

The study was designed to investigate the outcomes of diverse LED treatments on the basil plant parameters that comprise the plant height, leaf count, biomass production and an area of total canopy. Significant differences between treatments were found by statistical analysis ($p < 0.05$). Blue +

Red and UV-A + Blue LEDs demonstrated the highest influences on plant height (29.8 cm and 30.5 cm correspondingly) and leaf number (54 and 57 correspondingly) compared to other treatments. This is the same as the study by Rihan et al. (2020) and Solbach et al. (2021); they all focused on the stimulation of stem extension and morphogenesis through the use of blue and red wave spectrum regions. When it comes to fresh and dry weight biomass yield, both Blue + Red and UV-A + Blue treatments were responsible for the highest (95.3 g/plant and 92.5 g/plant, for fresh and 16.8 g/plant and 15.5 g/plant, respectively for dry). Conversely, the UV-A treatment plants were the shortest (22.4 cm), and their leaves were also the least (35) in number. The wet biomass yield was also at 53.1 g/plant, and the dry biomass yield was the lowest (8.3 g/plant). These findings are consistent with Chandraosi et al.'s (2020) and Kondratieva's (2022) observations regarding the importance of green and red light in plant development.

The light treatment involving the combination of blue + red and UV-A + blue lights activates a synergistic effect on biochemical processes related to photosynthesis, photo morphogenesis, and resource allocation, which, in turn, impact plant growth and biomass production. This different outcome for wavelengths' responses may be caused by photosynthetic pigment, enzymes, and metabolic paths imitating the assimilation of carbon metabolism and partitioning.

B. *Yield Parameters*

LED treatments showed great impact on yield parameters, and Blue + Red and UV-A + Blue treatments turned out to yield the highest fresh and dry biomass ($p < 0.05$). Concretely, Blue + Red and UV-A + Blue treatments yielded 95.3 g/plant and 92.5 g/plant, respectively, while dry biomass yields were 16.8 g/plant and 15.5 g/plant, respectively. This observation corresponds to the studies conducted by d'Aquino et al (2023) which revealed that the same thing happens to the biomass as well as to the amount of phenolic compounds in basil. The further review of the response lead to perception of complex association of LED treatments with the amount of biomass allocation. The striking result of the Blue + Red procedure where fresh biomass was also balanced with dry biomass. The highest biomass yield was exhibited in this treatment. On the contrary, the UV-A treatment, with a lower final total biomass, still resulted in a higher ratio of fresh to dry biomass showing the potential presence of different water content in the organisms or metabolic processes linked to the UV-A wavelength.

C. *Phytochemical Content*

LED treatment significantly affected the basil leaves ($p < 0.05$). The highest chlorophyll content (SPAD values of 53.6 and 51.9 units, respectively) was produced by the UV-A + Red and Red treatments, which can suggest the role of red light in chlorophyll synthesis and photosynthetic efficiency. However, the highest total phenolic content obtained after the treatments with a combination of blue light and either red or UV-A wavelengths, such as Blue + Red and UV-A + Blue, was 24.6 mg GAO/g DWE and 25.7 mg GAO/g DWE, respectively. These treatments also showed the highest antioxidant activity. Uncovering the diversity of phenolic acids, flavonoids, and other phytochemicals helped provide more subtle outcomes for LED treatments. Culinary Blue + Red treatment, for instance, not only augmented total phenolic content but also induced the concentration of some phenolic acids like rosmarinic acid, caffeic acid, and caftaric acid, which can scavenge free radicals. Furthermore, UV-A + Blue treatment observed heavenly amounts of flavonoids that were able to enhance the leaf's total antioxidant capacities.

Table 1
Effects of LED wavelengths on basil plant growth and nutrition

Treatment	Fresh Biomass Yield	Dry Biomass Yield	Chlorophyll Content	Total Phenolics	Total Flavonoids	Antioxidant Activity
Blue + Red LEDs	Very High	Very High	Moderate	Moderate	Moderate	Moderate
UV-A + Blue LEDs	Very High	Very High	High	Very High	Very High	Very High
UV-A LEDs	Moderate	Moderate	Very High	Very High	Very High	Very High
UV-A + Red LEDs	Moderate	Moderate	Very High	High	High	High
Blue LEDs	Moderate	Moderate	Low	Low	Low	Low
Red LEDs	Moderate	Moderate	Moderate	Low	Low	Low
White LEDs (Control)	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate

'Very High', 'Moderate', and 'Low' are relative qualitative ratings compared across treatments. Blue + Red and UV-A + Blue LED treatments had the highest fresh and dry biomass yields.

5. Discussion, Analysis, and Evaluation

A. *Significance of the Findings*

The outcomes of the study have shown that the selective LED wavelength combinations have a remarkable influence on the growth, yield, and airborne phytonutrient composition of the mentioned basil species. The beverage garnered its quality and quantity either from the incision of blue and red lights or from

Table 2
Treatment result table

Treatment	Plant Height (cm)	Number of leaves per plant	Fresh Biomass Yield (g/plant)	Dry Biomass (g/plant)	Chlorophy ll Content (SPAD Units)	Total Phenolics (mg GAE/g DW)
Blue + Red	29.8	54	95.3	16.8	47.2	24.6
UV-A + Blue	30.5	57	92.5	15.5	40.8	25.7
UV-A	22.4	35	53.1	8.3	51.9	19.5
UV-A + Red	22.5	43	68.4	10.7	53.6	18.2
Blue	23.7	38	59.3	9.5	41.3	13.6
Red	26.2	46	72.8	11.6	43.7	14.8
White (control)	24.1	41	62.7	10.2	38.5	12

the UV-A and blue lights, which turned out to be the most effective for the plant to thrive with the maximum biomass yield. Thus, these results reflect that a thoughtful decision of how the wavelengths are going to be selected and used is a key element in the control-environment agriculture (CEA) system, and it is a factor to be taken into account in the process. The metabolic effects of the joint action of the blue and the red wavelengths on photosynthesis and vegetative development can demonstrate the efficiency of these two spectral lights; the red one is irreplaceable in photosynthesis, while blue light affects the various developmental stages of shoots, for instance, the development of leaves (Rihan et al., 2020).

The advantage of the UV-A / blue treatment on plant growth can be pointed out as its ability to strengthen protein synthesis and the role of UV-A radiation in secondary metabolite synthesis (Viršilė et al., 2023). The synergy between the two functions can express itself in both directions – growth promotion and biosynthesis of compounds that are beneficial to the plants, thus ensuring the ideal rate of development. For example, using the best wavelength combinations, crop yield can be enhanced significantly and the crop cycle time, as well as basil harvest time, can be minimized. Blue + red, UV-A, and blue radiations were similarly successful in the stimulation of the plant growth and the plant growth was found to be a lot faster. With different wavelengths incorporated in the CEA systems, the number of harvests to be increased or production cycles shortened, which, in turn, would lead to higher production and, thus, profitability and profit maximization.

The secondary finding is that the extreme boldness of UV-A irradiation favours the concentration of phytochemicals in the leaves of basil. According to the outcome of UV-A and UV-A + blue treatments, the highest equal amounts of phenolic compounds, flavonoids, antioxidants, and phenolic acids, known as being involved with health and antioxidant properties, were obtained. Through the application of UV-A within the LED range used in CEA systems, UV-A may be released within the product form; thereby, its antioxidant and phenolic features would be enhanced, allowing basil to be sold as a premium functional food with higher benefits and price for consumers.

B. Support for Initial Hypotheses

The results that were obtained in the context of this research served as proof for the writing of the initial hypotheses that it is red and blue wavelengths that stimulate plant growth and biomass accumulation. The red and blue, as well as UV-A and blue light combinations, were found to produce the best results on growth and biomass parameters, which suggests that specific wavelengths might give the best possible environment for growth and development (Kondratieva et al., 2022). The evidence obtained by this survey also shows the claim that the light wavelength of UV-A is responsible for the phytochemical properties of basil. During the treatments with UV-A the phenolic and flavonoid compounds were increased quite significantly, and the antioxidant activity rose as well. This is most probably because UV light stimulates the secondary metabolite production that is the plant's "defence response". This is a similar way as the plant responds to the external factors such as UV light.

The research hypothesis that there is a direct correlation between higher PPF (photosynthetic photon flux) and increased plant tissue is proven by the fact that the photo combinations that were used here, such as blue+red and UV-A + blue, have resulted in plant tissue that weighed more at a PPFD of 200 μmol.m^{-2}.s^{-1}. While low PPFD gives high PH accumulation (100 μmol·m^{-2}·s^{-1}) can be gathered, phytochemicals may also be increased because low light intensity is a mild stressor and a trigger of protective mechanism for the plants.

C. The Research Process was Discussed and Evaluated

The study has the strength of the complete test occurrences and statistical test validation. The study adopts its experimental design as a randomized complete block design with four replications with each treatment. Statistical tools, including the ANOVA and Tukey's HSD test, are also employed to ascertain the reliability of the differences between treatments.

On the downside, the research has some disadvantages. The study looked only at the performance of two economical basil cultivars, Genovese and Opal. LED lighting's mechanism of action involves genetic factors (pigments and pathways). This, in turn, will result in the basil cultivars having different responses to the type and intensity of light (Alrajhi, 2023). Broadening the number of varieties grown for experiments could lead to more enlightening results on the impact of LED in stimulating basil growth and phytochemical aggregation.

Research findings could be further expanded in multiple directions as future studies. List of key points to restore society when a world war takes place: Clearly define goals and objectives. Discuss the long-term impact on social structures and institutions. One future move is to evaluate the effect of different species of basil plants by using LED lighting and phytochemical analysis (Kondratieva et al., 2022). Running the experiments under greenhouse conditions will improve the way we understand the effect of LED light treatments in somewhat more production-minded settings (Solbach et al., 2021). To measure the feasibility and scalability of the LED tools, economic feasibility studies need to be conducted which should include factors such as energy consumption, yield improvements, phytochemical value and overall networking cost (Rahman et al., 2021).

Higher photon flux intensities (e.g., 200 μmol·m^{-2}·s^{-1}) can encourage biomass accumulation and plant development. Lower PPFD values (100 μmol·m^{-2}·s^{-1}) can boost phytochemical synthesis by activating defense systems as a moderate stressor. This study's optimized LED recipes are valuable for controlled environment agricultural systems. Growers can increase yields, biomass, phytochemical content, and year-round production without seasonal or geographical constraints. This promotes food security, supply, sustainable urban agriculture, and local food production. Optimized LED lighting solutions support sustainable and resource-efficient farming. The energy efficiency, extended lifetime, and precise spectrum control of LEDs reduce energy and resource needs compared to standard grow lights (Rahman et al., 2021).

Increased yields and phytochemical content might boost profitability and production per unit area, increasing resource efficiency.

This research illuminates how LED wavelength combinations and intensities affect basil growth, production, and phytochemical content. The finding of ideal LED recipes boosts tightly controlled basil production, addressing the rising need for high-quality, nutritionally packed crops in a sustainable way. However, further study, including greenhouse experiments, cultivar testing, and economic feasibility evaluations, is needed to refine and scale these procedures for commercial usage.

D. Conclusion and Future Directions

The findings from this research represent significant contributions to understanding how most LED spectrum mixtures and light intensity influence the growth, harvest, and phytochemical content of basil plants grown in controlled environments. This proves that the calibration of LED provides basil production and produces the best plant nutrient value in CEA systems. The analysis of our tests shows that some LED wavelength combinations, for instance, blue + red and UV-A + blue, were more effective in promoting better growth and productivity of our plants than other treatments. The interaction of two light wavelengths, Blue and Red, with the processes of photosynthesis, photo morphogenesis and resource allocation, likely trigger the growth enhancement of crop yield observed under such treatments.

This study results in information gathering and has diverse implications since the improved LED recipes identified here open a new vista for basil planting in the CEA systems potentially transforming the whole industry. This will support the provision of realistic light schemes to greenhouse producers, enabling them to develop more and more manageable, sustainable, and profitable growing systems. Advancements in LED lighting systems, resulting in higher yields, reduced production timelines and intensified phytochemical content, can be leveraged to meet the soaring demand for excellent food products for the nourishment of the people but also to minimize the ecological impacts of agricultural production.

Nevertheless, it should be underlined that the revealed limitations are another reason for the need for this research to be addressed deeply and improved in future research. Future studies should consider the following directions: Future studies should consider the following directions:

1) Economic Feasibility Analysis

Conduct a global-scale LED technology-based basil production systems' complete economic analysis that considers the energy inefficiency, systemic costs, yields, and the market price of the increased phytochemical content.

2) Phytochemical Profiling

Extending examination to other phytochemicals would be helpful to determine the interest points, such as essential oils, carotenoids, and vitamins, beside those discussed before. This will help explore the comprehensive profile of LED-grown basil for nutritional and medicinal value.

3) Mechanistic Studies

Scrutinizing the plant physiological and molecular mechanisms of how spectral-led radiation range leads to selective plant growth development and a concentration of valuable plant compounds through photosynthesis for basil and other high-value crop species.

4) Integration with Other CEA Technologies

To ask whether the optimized LED light has a positive impact on indoor basil production with other advanced CEA technologies, such as precision feeding and environmental control systems, the synergy effect between these technologies will be even more significant.

The research gaps can be closed, and the scope of the case study can be expanded in future research utilising the system incorporating LEDs for basil cultivation in CEA systems by bridging the previous survey. The implications of these efforts go beyond basil and improve our ability to create, maintain, and enhance the entire local food chain and, hence, global food security. This study highlights crucial advancement in how red light mixing with given amounts of blue light may affect the growth, yield and composition of phytochemicals in hydroponics.

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