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Influence of the Spectral Composition of Illuminating Light Sources on Biometric and Phytochemical Characteristics of *Ocimum basilicum* L.

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Abstract: Precise adaptation of the greenhouse lighting spectrum to basic photophysiological processes can effectively and directionally stimulate plant growth and development. The optimal spectrum depends on the plant species and the stage of development and could be assessed empirically. The aim of this study is to determine the LED illumination spectrum that provides a significant improvement in the growth rate and accumulation of biologically active compounds for basil plants (*Ocimum basilicum* L.) under hydroponic cultivation compared to more traditional lighting sources. The following light sources with various emission spectra were used: an LED lamp within a spectral range of 400–800 nm (B:G:R 15%:5%:80%); a high-pressure sodium lamp (HPS) (B:G:R 5%:45%:50%); a compact fluorescent lamp (B:G:R 20%:40%:40%); a grow LED strip (B:G:R 15%:40%:45%); a white LED lamp (B:G:R 30%:45%:25%); a customized LED lighting setup in color ratios 100%B, 75%B + 25%R, 50%B + 50%R, 25%B + 75%R, 100%R, and natural lighting. A photosynthetic photon flux density (PPFD) of 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ was provided with all the sources. It was demonstrated reliably that employing the LED strip as an illumination device gives a 112% increase in basil plant yield compared to the HPS; the transpiration coefficient for the LED strip is six times lower than for the HPS. The content of flavonoids in the basil aerial parts on the 30th, 50th, and 70th days of development is 3.2 times higher than for the HPS; the metabolite composition is also more uniform for LED strip lighting.

Keywords: greenhouse lighting; basil plant; light-emitting diode; high-pressure sodium lamp; fluorescent lamp; flavonoids; HPLC

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1. Introduction

Currently, the world population is growing quite rapidly, and, according to forecasts by the Food and Agriculture Organization of the United Nations for 2050, the population will increase to 9 billion people [1]. In addition to this, the degree of urbanization will reach about 75% by 2050 [2]. The pressure on agriculture, as the central link in the human food chain, is becoming enormous. Outdoor cultivation is still widely used worldwide, despite thousands of hectares rendered unsuitable for farming due to climate change, water shortages, and soil contamination from synthetic pesticides and fertilizers [3]. In densely populated areas with limited available space, where conventional farming is not possible, crop production is being transformed into urban agriculture. The vision behind urban

agriculture implies social and environmental benefits for cities, including increased food security and minimal environmental impact [4].

Vertical farms and plant production systems provide the highest possible level of control over the cultivation process. The growing area is completely isolated from the external environment, and artificial lighting replaces solar illumination. Despite high energy consumption, vertical cultivation has a number of environmental advantages over conventional greenhouse production: the efficiency of water and nutrient use is significantly increased, and the use of pesticides and herbicides can be significantly reduced or eliminated entirely. Urban agriculture is a young but rapidly growing sector, demonstrating a wide range of applications and production models [5]. Alongside monitoring and temperature control, air humidity, water supply, and fertilizer concentration, providing the optimal intensity and spectrum of artificial lighting is a crucial element for horticulture and agricultural mass production. In vertical city farms with modern multispectral LED lamps, it is possible to precisely control a full range of environmental parameters and cultivate numerous nutritional, aromatic, and medicinal crops, e.g., basil, while minimizing interaction with external climatic conditions [6].

The growth and development of various plant species strongly depends on the spectral composition of artificial illumination. When cultivating plants in protected soil or in greenhouse complexes with little or no natural light, the key factors are the correctly adjusted spectrum, intensity, and duration of artificial lighting. Therefore, the emergence and wider implementation of farming in a controlled environment have always been heavily dependent on the development of specialized light sources (grow or phytolamps), which are simultaneously precisely adapted to the basic photophysiological processes in plants and energy efficient.

For a long time, conventional artificial light sources such as fluorescent lamps and high-pressure sodium lamps have been used in plant growth chambers or greenhouses [7]. Such light sources have low efficiency for the growth of highly productive plants. In addition, high-pressure sodium lamps cause light stress in plants, which makes them ineffective for optimal lighting [8]. Research conducted in recent years indicates that more advanced quasi-monochromatic light-emitting diodes (LED), generating light only in the blue and red regions of the spectrum, also do not fully reveal the inherent genetic potential of plants [9]. Despite the obvious progress in the applications of LED technology in agriculture, undoubtedly relevant issues related to the optimization of the spectrum and intensity of artificial sources of photosynthetically active radiation (PAR) at the different stages of plant development and using artificial illumination for the targeted stimulation of biosynthesis of valuable biologically active compounds in medicinal and aromatic plants still remain poorly studied [10].

In the last few decades, the consumption of herbal products in the daily diet has increased, which helps prevent some types of cancer, and cardiovascular and other chronic diseases due to high concentrations of phytonutrients such as essential oils and phenolic compounds. Light is one of the most important environmental factors affecting the quality of medicinal and aromatic plants: it regulates phytonutrient content and has multiple effects on growth, development, and the accumulation of secondary metabolites [11].

One study revealed that the use of LED lighting allows manufacturers to induce the desired response in aromatic and medicinal plants [12]. Previous research [13] demonstrates that the essential oil content (α-pinene, β-pinene, myrcene, limonene, 1,8-cineol, γ-terpinene, linalool) of sweet basil leaves grown under blue light is 1.2–4.4 times higher than that of plants grown under white light. Adaptation of the light spectral composition when using LED light sources makes it possible to optimize the production process and specifically influences the biosynthesis of target functional compounds in plant biomass [14]. Another study [15] reports that the use of UV radiation (except UV-C) in conjunction with fluorescent lamps can stimulate the active growth of basil and the accumulation of essential oils. Supplemental lighting affects the accumulation of essential oils and phenols, but reaction to this factor varies among certain plant species, e.g., the introduction of additional

LED lighting resulted in a twofold increase in orientin content in basil. The use of blue-light-dominant monochromatic LED sources may slightly reduce final height and yield compared to HPS lighting [16]. Because the spectral ranges of red (R) and blue (B) light are maximally absorbed by plant light-harvesting chlorophylls, most LED-related research continues to focus on different R:B ratios to optimize plant growth, morphology, and physiological responses. However, the addition of other wavelengths to the spectrum shows the potential to further improve important plant properties [17].

The aim of this study is to determine the LED illumination spectrum that provides a significant improvement in the growth rate and accumulation of biologically active compounds for basil plants (*Ocimum basilicum* L.) under hydroponic cultivation compared to light sources of the previous generation.

Ocimum basilicum L., commonly known as basil, is an annual flowing plant from the *Lamiaceae* family. Due to the widespread cultivation and use of basil in culinary and traditional medicinal practice, as well as its fast growth cycle, *O. basilicum* is a great model plant for researching the effect of different physical parameters on plant metabolism and growth. For example, the effects of mid-intensity ultraviolet-A radiation [18], ultraviolet-B radiation [19], gamma radiation [20], pulsed electric fields [21], and radiation intensity along with CO_2 concentration levels [22] on *O. basilicum* metabolism have been studied. Overall, by varying the parameters of different spectral characteristics of the illumination used for the cultivation of *O. basilicum*, an optimal yield in metabolite content can be reached. Secondary metabolites are the compounds mainly responsible for different non-nutritional health benefits associated with plant use and consumption. Therefore, the analysis of their content is an important task. The main classes of secondary metabolites contained in *O. basilicum* are terpenoids along with other essential oil components [23] and polyphenols, including flavonoids, tannins, and phenolic acids [24]. Basil is a valuable green spice crop, universally grown in intensive cultivation systems under light culture conditions. Basil of the "Basilisk" variety has the highest percentage of essential oil (0.287%), which gives it a peppery clove scent according to [25].

2. Materials and Methods

Basil of the "Basilisk" variety (agricultural company Gavrish, Moscow, Russia) was chosen due to early ripening (60–70 days from germination to flowering) and a relatively compact bush (20–25 cm high) with a large number of small leaves. The seeds were planted in hydroponic rock wool, which is an inorganic solid growing medium. It is made up of 60% diabase, 20% limestone, and 20% coke. Hydroponic rockwool was placed in mesh pots, which were inserted into hydroponic trays in the laboratory city farm.

In the vertical laboratory city farm (Figure 1), a transition has been made to soilless plant cultivation using mineral components. This is due to the potential to increase the quality and quantity of products by controlling external factors such as humidity, temperature, pests, and pathogens through the use of substrates instead of soil. The hydroponic growing method allows plants to obtain all the necessary micro- and macroelements from a nutrient solution. The basis of the hydroponic installation was the NFT method, consisting of 3 levels [26]. This installation was chosen as optimal, taking into account the distances from the radiation sources to the plants, the size of the pallets and the space for equipment under the installation racks. The total height of the installation was 2 m. The rack with dimensions of 100 × 50 × 200 cm was used as a frame for the entire installation. We used a closed hydroponic system with constant water circulation: "reservoir-installation-reservoir". The pressure was adjusted using ball valves on each of the racks. During the experiment, it was necessary to ensure the continuity of the lighting sources, as well as the functioning without interruptions of the hydroponic installation. For this purpose, a fully automated solar power plant with lead–acid battery storage and a backup diesel generator installed on the university roof was used as an emergency power source for the farm (building 5, department of Photonics, Saint Petersburg Electrotechnical University "LETI", Russia). The solar cell array consists of three Hevel HVL310 heterostructure photovoltaic modules and

one Hevel HVL300 (Hevel Energy Group, Novocheboksarsk, Russia). The power output of the panels is 310 and 300 W, respectively, the efficiency is about 19%. The operating temperature range is from −40 to +85 °C.

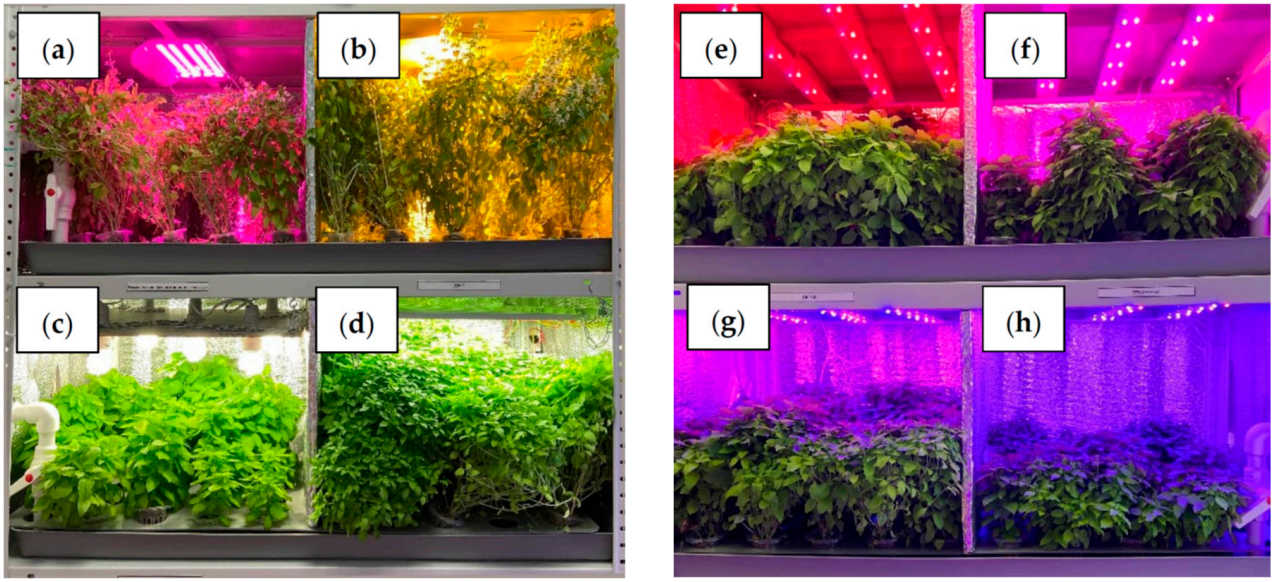

Figure 1. Vertical laboratory city farm. The figure shows the following lighting sources used in this study: (**a**) the LED grow light, (**b**) HPS, (**c**) fluorescent lamp, (**d**) LED strip, (**e**) 100%R, (**f**) 75%R + 25%B, (**g**) 50%R + 50%B, (**h**) 25%R + 75%B. The PPFD level and uniformity were controlled by adjusting the power of individual luminaires.

2.1. Light Sources and City Farm Characteristics

The following radiation sources with a given photosynthetic photon flux density (PPFD) parameter were used for illumination (Table 1): a phytolamp based on phyto-LEDs 400–800 nm (LED grow light) with main peaks at 461 nm and 638 nm [27]; a high-pressure sodium lamp; a compact fluorescent lamp with main peaks at 546 nm and 611 nm; an LED strip; a white LED lamp; LED lighting in color ratios according to GOST R 58461—2019 100% radiation in the "blue" region of PAR; 75%B + 25% radiation in the "red" region of the PAR; 50%B + 50%R; 25%B + 75%R; 100%R; natural light, PPFD—143 μmol·m^{-2}·s^{-1}. The light sources' spectral characteristics used in the experiment are shown in Figure 2.

Table 1. The percentage ratio of the light spectrum in the applied illuminating light sources and PPFD values (B refers to blue 400–500 nm, G refers to green 500–600 nm, R refers to red 600–700 nm).

Lighting Mode (Manufacturer)	Blue	Green	Red	PPFD, μmol·m^{-2}·s^{-1}
LED grow light (GLANZEN, Kolomna, Russia)	15	5	80	151
HPS lamp (LEDVANCE GmbH, Garching, Germany)	5	45	50	155
Fluorescent lamp (Litarc Lighting & Electronic Ltd., Shenzhen, China)	20	40	40	148
LED strip (Arlight, Moscow, Russia)	15	40	45	157
White LED lamp (Fuzhou Linsheng Import&Export Trading Co., Ltd., Lianyungang, China)	30	45	25	152
100%R (Epistar, Hsinchu, Taiwan)	-	-	100	148
75%R + 25%B (Epistar, Hsinchu, Taiwan)	25	-	75	150
50%R + 50%B (Epistar, Hsinchu, Taiwan)	50	-	50	150
25%R + 75%B (Epistar, Hsinchu, Taiwan)	75	-	25	150
100%B (Epistar, Hsinchu, Taiwan)	100	-	-	146

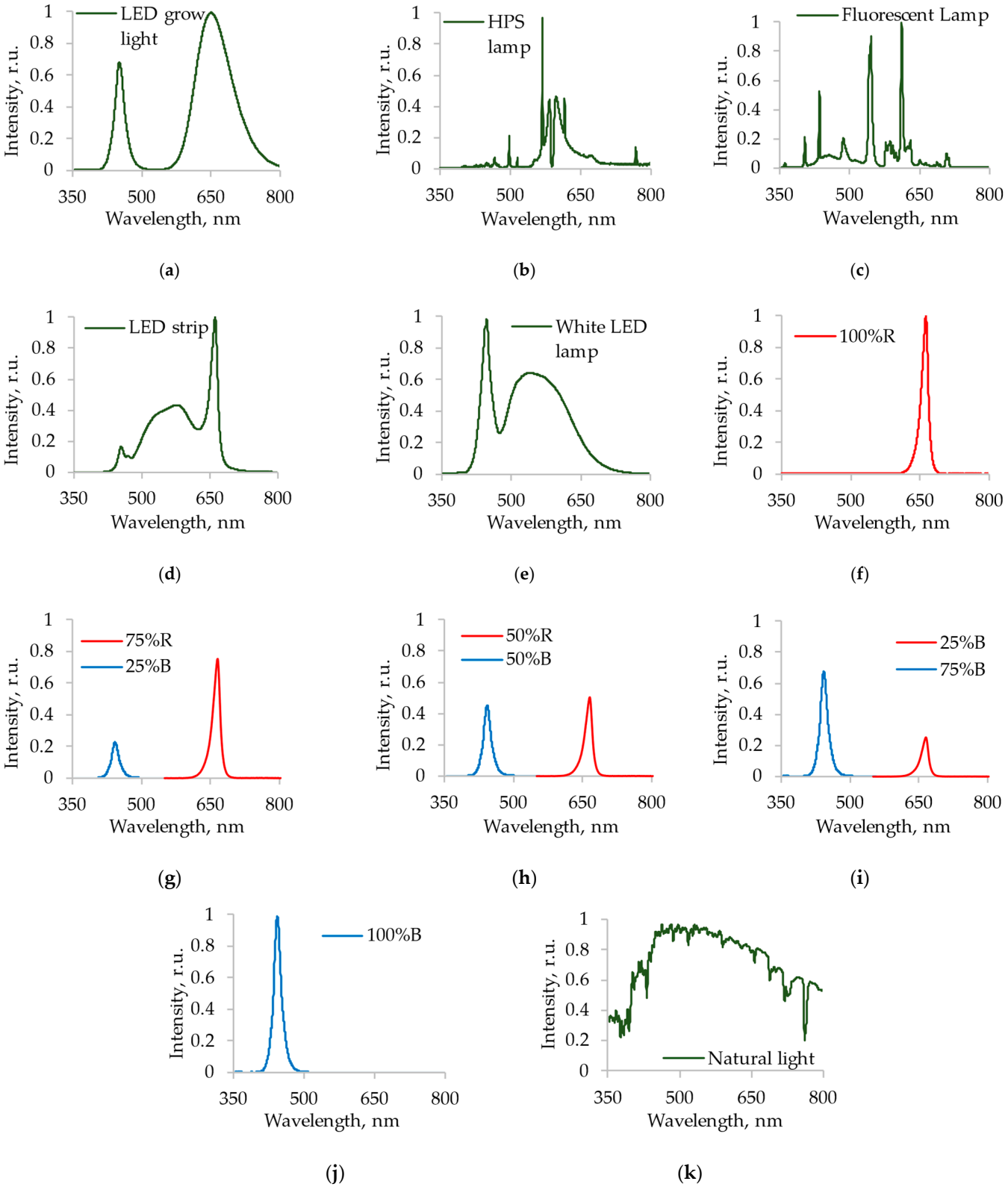

Figure 2. Spectral composition of illuminating light sources used in this study: (**a**) LED grow light, (**b**) HPS, (**c**) fluorescent lamp, (**d**) LED strip, (**e**) white LED lamp, (**f**) 100%R, (**g**) 75%R + 25%B, (**h**) 50%R + 50%B, (**i**) 25%R + 75%B), (**j**) 100%B, (**k**) natural light.

The LED strip consists of red LED structures based on AlGaAs solid solution (665 nm) and white LEDs consisting of a phosphor (575 nm) deposited on a blue crystal made from

InGaN solid solution (455 nm). LEDs from TDS Lighting Co. were used for LED lighting. Red LEDs based on AlGaInP solid solution had a peak at 665 nm, blue LEDs based on InGaN solid solution had a peak at 445 nm [28].

The photosynthetic photon flux density was assessed using the UPRtek PG200N spectrometer (Taiwan). The PPFD measurements were carried out at 30 points under each radiation source in empty growth chambers. The PG200N device measures spectral density in the wavelength range from 350 to 800 nm, plots a spectral curve, and analyzes the data obtained [29].

The hydroponic installation was divided into isolated sections with different types of light sources. All sections contained 30 cells with 3 seeds planted in each cell. Stable microclimate conditions (25 °C and at least 50% humidity) were maintained for 70 days using a heater and humidifier, which were interfaced via a Wi-Fi system with temperature and humidity sensors. The process was automated by installing smart timer sockets with the ability to set the lighting time regime. Using a mechanical timer, this was set as follows: 16 h of lighting from 6 am to 10 pm. Using an electronic timer, the watering time regime was set: every 3 h starting from 00:00 for 2 min. Additionally, the indoor carbon dioxide level, formaldehyde concentration, and volatile organic compound concentration were monitored using the air quality sensor. Throughout the experiment, the parameters were within normal limits. The experiment was conducted from 28 March to 5 June 2023. Daytime length for samples grown in natural light conditions ranged from 13 to 18 h. The samples were placed in an open space (southeast window) in the laboratory, where stable microclimate conditions were also maintained (ambient temperature 25 °C and humidity of at least 50%, the hydroponic solution pH from 5.5 to 6.5, and its electrical conductivity from 1.3 to 1.5 mS/cm).

The mineral solution of two components was used as a nutrient solution for plants. The first component consisted of fruit and berry aquarin (Buyskiye Fertilizers, Buy, Russia), magnesium sulfate 7-aqueous, zinc chelate, and boric acid. The second component consisted of calcium nitrate and iron chelate. The components were dissolved in distilled water and subsequently added to the water until the required electrical conductivity of 1.4 mS/m was achieved. Using a water control sensor, the acidity parameters of the aquatic environment were maintained in the range from 5.5 to 6.5 and electrical conductivity in the range from 1.3 to 1.5 mS/cm. In this solution with the selected parameters, the basil received all the necessary micro- and macroelements, which prevented the occurrence of various diseases, leaf necrosis, and degradation of the root system [30,31].

Measurements of the basil biometric parameters were carried out on the 10th, 15th, 25th, 30th, 50th, and 70th days (control days) of the experimental cultivation under various illumination conditions. The following parameters of basil development were determined:

(1) Average hypocotyl length (plant height) (mm);
(2) Average area of all leaves for each plant (cm^2);
(3) Average number of leaves of a plant (from 30 to 70 days);
(4) Average water use (transpiration coefficient);
(5) Average values of dry, wet mass, and root mass for one plant (on the final 70th day of the experiment);
(6) Wet matter productivity on the final 70th day of the experiment.

2.2. Phytochemical Analysis of Ocimum basilicum L.

For the quantitative and qualitative analysis of *Ocimum basilicum* L. polyphenolic secondary metabolites, differential UV-spectrophotometry and HPLC analysis, respectively, were used. Before analysis, the aerial parts of the cultivated *O. basilicum* were air-dried at 45 degrees to constant mass.

2.2.1. Quantification of Flavonoid Total Content in Terms of Rutin

O. basilicum raw material was crushed and passed through a sieve with 1.0 mm openings. Exactly 1.0 g of the crushed raw material was placed into a 250 mL round-bottom

flask, after which 100 mL of 80% ethyl alcohol was added. The flask was connected to a reflux condenser and heated over a boiling water bath for 90 min with occasional stirring. The flask was further cooled for 20 min to room temperature and the extract was filtered through a paper filter. Then, 1.0 mL of the resulting extract was transferred into a 25 mL volumetric flask. Next, 4.0 mL of a 2% aluminum chloride solution in 95% ethyl alcohol was added to the flask, after which the solution was acidified with 1 drop of dilute acetic acid and adjusted with 80% ethyl alcohol to 25 mL (solution A). After 35 min, the optical density of solution A was measured and further compared to the optical density of the rutin reference solution on a spectrophotometer at a wavelength of λ = 409 nm in a quartz cuvette with a path length of 10 mm [32].

Preparation of rutin reference solution. Exactly 0.013 g of a standard sample of rutin, previously dried to a constant weight at a temperature of 100–105 °C, was transferred to a 25 mL volumetric flask along with a small volume of 80% ethyl alcohol and heated over a hot water bath until full dissolution, after which the volume of the solution was adjusted to 25 mL with 80% ethyl alcohol. Then, 1.0 mL of the resulting solution was transferred to a 25 mL volumetric flask, after which 2.0 mL of a 2% aluminum chloride solution in 95% ethyl alcohol was added and further acidified with 1 drop of diluted acetic acid and adjusted with 80% ethyl alcohol to 25 mL. After 35 min, the optical density of the resulting reference solution could be measured on a spectrophotometer at a wavelength of λ = 409 nm in a cuvette with a path length of 10 mm.

Preparation of a 2% solution of aluminum chloride. A total of 2.0 g of aluminum chloride was dissolved in 95% ethyl alcohol and adjusted to 100 mL in a volumetric flask.

2.2.2. HPLC analysis of *O. basilicum* Extracts

For the analysis of the component composition of *O. basilicum* extracts by HPLC, we used extracts obtained with 96% ethyl alcohol by maceration overnight at a raw material–extract ratio of 0.5 g to 10 mL. The analytical chromatography system consisted of a Shimadzu prominence LC-20AD liquid chromatograph (Shimadzu, Kyoto, Japan), equipped with a Shimadzu prominence SIL-20A autosampler (Shimadzu, Kyoto, Japan), a Supelcosil LC-18 column 25 cm × 4.6 mm, 5 µm (USA), a CTO-20AC thermostat (Shimadzu, Kyoto, Japan), and a Shimadzu prominence diode array detector SPD-M20A (Shimadzu, Kyoto, Japan).

The mobile phase system consisted of eluent A—ultrapure water with the addition of 0.1% trifluoroacetic acid (TFA) (*v*/*v*) (PanReac AppliChem, Darmstadt, Germany) and eluent B—acetonitrile HPLC Far UV/Gradient Grade (J.T. Baker, Phillipsburg, NJ, USA) with the addition of 0.1% TFA.

Elution profile: 0.01–5.0 min 5% B (isocratic mode), 5.0–45.75 min 5–100% B (linear gradient), 45.75–50.0 min 100% B (isocratic mode), 50.0–60.0 min 100–5% B (linear gradient), 60.0–65.0 min 5% B (isocratic mode, bringing the column to equilibrium). The sample to be analyzed was introduced in a volume of 10 µL, the column temperature during the analysis was 40 °C, and the flow rate used was 1.0 mL/min. UV spectrum registration was performed in the range from 190 nm to 800 nm, chromatograms were registered at the following analytical wavelengths—235, 254, 280, and 340 nm. Peak identification was performed in comparison to an internal library of secondary metabolites.

2.3. Statistical Analysis

This research was conducted as a one-factorial experiment as an independent design. The illumination parameters were analyzed separately for eleven light sources in empty growth chambers. The PPFD mean values represent the average value of photosynthetic photon flux density measured at thirty points of the installation. For the experiment, 990 plants were selected, of which 11 groups of 90 plants were formed and placed in different lighting conditions. The results are presented as the average ± standard deviation of 90 plants, $n = 90$ per light condition. Developmental parameters were analyzed separately for each plant. Jamovi statistical software V2.3.28.0 was used for all statistical analyses at

the confidence level $p = 0.05$. The data were evaluated in terms of their normality using the Shapiro–Wilk test [33] and subsequently subjected to the Kruskal–Wallis test [34] to evaluate the differences among illumination modes. The Kruskal–Wallis test was used to compare median values among the eleven groups, followed by post hoc testing using unpaired Mann–Whitney U tests. The Kruskal–Wallis least significant difference test was performed at a significance level of 5%. In figures, asterisks denote statistical significance test as compared to the controls indicated in the figure legends.

3. Results

3.1. Biometric Measurements

The average plant height was monitored from the 10th to 70th days. Throughout almost the entire experiment, samples under the HPS lighting conditions had the greatest height. On average, compared to the HPS, the results were 27% lower for samples under the LED grow lighting conditions and 35% lower for samples under the LED strip lighting conditions. Excessive elongation of the basil observed under the HPS lighting is an adaptive growth strategy that occurs under low light conditions, particularly low blue light. Etiolation is the result of changes in plant physiology and morphology that occur in response to a lack of blue light. The presented results could be explained by the program of scotomorphogenesis, in which an increased ratio of the proportion of "far red" light in the spectrum leads to elongation of the petioles and internodes of adult plants [35]. Far-red light emission is absorbed by the protein receptor phytochrome, which is responsible for analyzing light conditions. There are two forms of this pigment: Fr—660 nm (inactive form) and Pfr—730 nm (active form), and they have the ability to transform from one form to another when irradiated with the appropriate wavelengths. Plant leaves primarily selectively absorb light at a wavelength of 655–665 nm, while transmitting light at a wavelength of 725–735 nm, which is perceived in plants in the shade. In response to a shift in the spectrum towards far-red light, a program of scotomorphogenesis is activated, during which the distribution of resources in the seedling is aimed at elongating the hypocotyl rather than developing the root system. In this way, by correctly varying the red/far red ratio of light, it is possible to regulate a wide range of biochemical processes in the plant [36]. The spectrum of LED grow, natural, and white light includes a significant proportion of "far-red" radiation compared to other emitters, whose spectra are characterized by the presence of clear luminescence maxima and a small spectral linewidth (Figure 2k). It is quite common to add far-red LEDs to growth light now.

The average plant leaf area shown in Figure 3 was measured using a method based on multiplying the length and width of the leaf (simply assuming that the leaf has a rectangular shape). However, since leaves are elliptical in shape, it is necessary to use a shape factor to account for uncertainty in this approximation. The shape factor was determined experimentally by measuring the length and width of a certain number of leaves, as well as calculating their area when transferring their shape onto graph paper. As a result, the leaf shape coefficient was calculated as 0.82. The measurements were carried out using a caliper. The average plant leaf area shown in Figure 3 was measured on the control days, starting from the 10th day of the experiment. Before the 50th day, samples under the HPS lighting had the greatest height and the largest leaf area. At this stage, good results were also observed for samples illuminated with the LED grow light, the LED strip, and the 100%R LED lighting, which were inferior to the HPS samples by 41%, 32%, and 28%, respectively. On the 70th day of research, a decrease in leaf area was observed in samples grown under the LED grow light and the HPS lighting conditions, which is associated with their early flowering, which is due to the high relative intensity of radiation in the yellow and red parts of the visible spectrum. At this stage, the samples under the LED strip had a 51% larger leaf area than the samples under the HPS lighting, and three times larger area than under natural lighting. The 100%R and the 75%R + 25%B radiation at this stage also showed better results by 16% and 11% compared to the HPS lighting. According to Table 1, lighting modes in which plants had the largest leaf area (HPS, LED grow light, LED strip,

75%R + 25%B, and 100%R) are characterized by the lowest percentage of the blue part of the spectrum (5, 15, 15, 25, and 0%, respectively). Consequently, a high proportion of blue light in the emission spectrum of the lamp causes inhibition of the growth of vegetative organs of plants, while the predominance of red light in the spectrum promotes more intense vegetative growth, as evidenced, in particular, by a significant increase in leaf area. This effect may be due to the fact that, in addition to direct participation in photosynthesis, blue light entering the plant triggers a number of genetic programs: it enhances the synthesis of growth inhibitors, such as abscisic and hydroxycinnamic acids, and, accordingly, leads to a decrease in leaf area [37]. Similar patterns can be traced in terms of the mass of leaves and their number. Moreover, the leaf area of plants grown under irradiation with the 100% blue light was greater than the average leaf area of plants in the control group (natural light). Moreover, the leaf area of plants grown under irradiation with the 100% blue light was greater than the average leaf area of plants in the control group (natural light). This may be due to the fact that blue light stimulates stem and root growth, while red light promotes leaf and fruit development. As a result, when plants are exposed to predominantly blue light, leaves may shrink in size to provide more energy for the development of other parts of the plant [38].

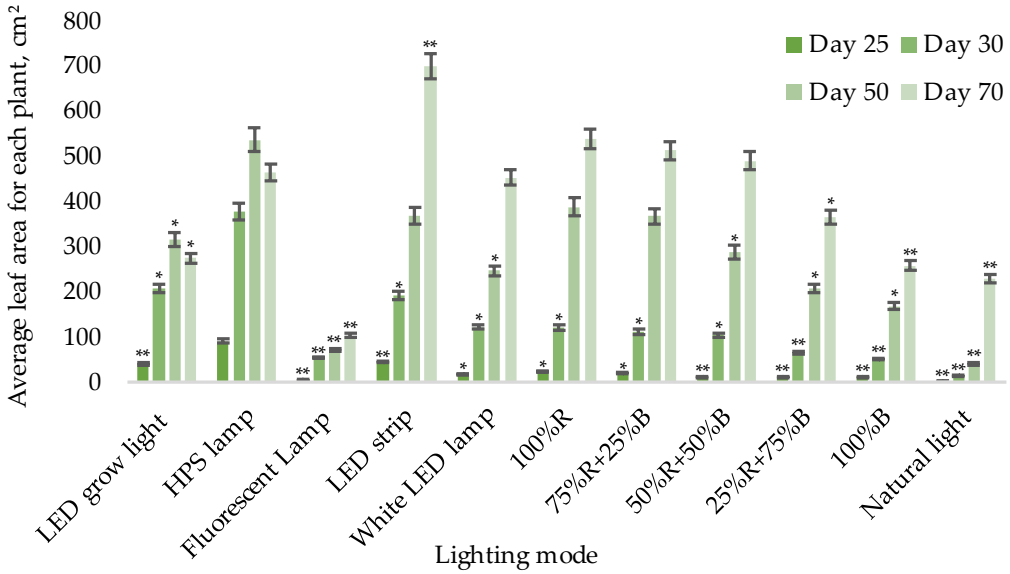

Figure 3. Average leaf area for each plant on the 25th, 30th, 50th, and the final 70th days of the experiment. Data in the columns are statistically different for different light sources and different culture days ($p < 0.05$). Asterisks indicate the significance level of the differences in average leaf area for different light sources and HPS lamp (Kruskal–Wallis test with Mann–Whitney U post hoc test; * $p < 0.03$; ** $p < 0.001$). The mean values represent an average of ninety plants per experiment. Standard deviations are marked for each group.

The average number of leaves was measured during the transition of plants to the senile stage of growth. Samples under the LED strip lighting had 56% more leaves than samples grown under the HPS. The decrease in the number of leaves in the samples when illuminated with the HPS and the LED grow light is also due to a large amount of the yellow-red part of the spectrum, which led to premature aging of plants and the falling of some leaves.

The largest number of fully expanded leaves at the final stage of growth was observed for samples which were exposed to the lighting modes containing a significant share of the green part of the spectrum, i.e., samples grown under the white LED lamp had a large number of leaves with relatively small area. It should be noted that the white LED lamp had the highest G/B light ratio (Table 1). Despite the fact that an excess of the blue part of the spectrum causes a decrease in leaf area, a significant amount of green light successfully

penetrated deep into the dense leaf cover of the upper layers of plants and reached the lower tiers, which contributed to the increase in their overall illumination, in contrast to the modes in which the proportion of green light was minimal or totally absent (LED grow light, 100%R, 75%R + 25%B, 50%R + 50%B, 25%R + 75%B, and 100%B). Green light stimulates and regulates photosynthesis deep in the leaf or canopy profile, helping to increase carbon production and subsequent yield [39]. This occurs because chlorophyll a and b are more likely to absorb blue and red light on the leaf surface as opposed to green light: most of it penetrates deeper inside and is absorbed by chlorophyll and other pigments located in the inner parts of the leaf. Therefore, photosynthesis occurs more efficiently than in the absence of the green component.

Despite the numerical advantages of the green spectrum at this stage, a large proportion of such light in the spectrum can have an inhibitory effect on the growth and development of plants. A possible reason is that excess green light, especially with a peak of 550 nm, disrupts cell division processes [40]. As a result, thin and small leaves are formed, which is also confirmed in this study.

The highest fresh weight of plants on the final 70th day of research, shown in Figure 4, was observed in the box with the LED strip. Compared to natural light, the average weight of plants in the box with the LED strip showed a fivefold advantage. In addition, the average fresh weight of basil when germinated under the white LED lamp was 3.75 times higher than samples with natural lighting, 3 times higher than samples with the 100%R LED lighting, and 2.4 times higher than samples with the HPS lighting. The root system was also most developed in samples under the LED strip lighting conditions. It was 7.7 times more than the root system of samples in natural light, which allows more essential micro- and macroelements to be supplied.

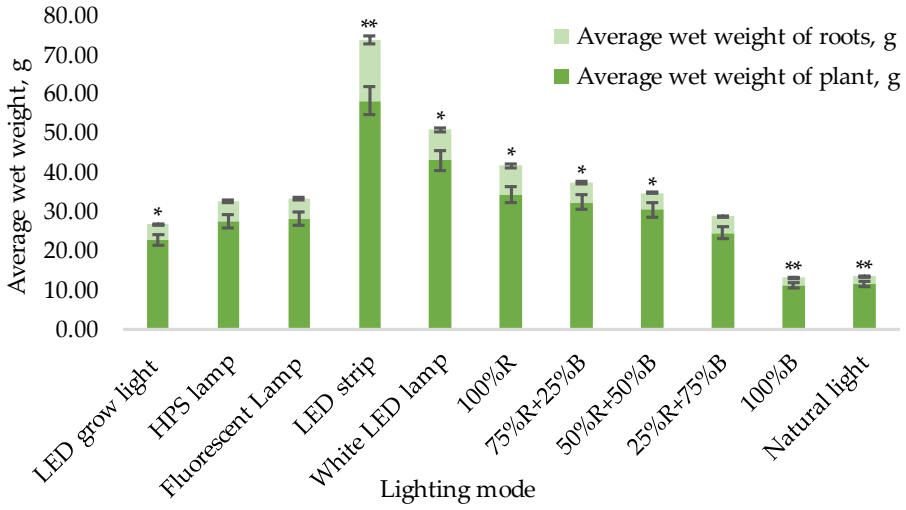

Figure 4. Average wet weight on the final 70th day of the experiment. Data in the columns are statistically different for different light sources ($p < 0.05$). Asterisks indicate the significance level of the differences in average wet weight for different light sources and HPS lamp (Kruskal–Wallis test with Mann–Whitney U post hoc test; * $p < 0.03$; ** $p < 0.001$). The mean values represent an average of thirty plants per experiment (the remaining plants were used for phytochemical analysis and seed planting material preparation). Standard deviations are marked for each group.

Figure 5 shows the wet matter productivity of basil plants for each light source studied. The highest productivity values were obtained in boxes with the LED strip (9.81 kg/m^2 ($\pm$0.44 SD)), the white LED lamp (7.25 kg/m^2 ($\pm$0.34 SD)), and the red spectral light-emitting diodes (6.28 kg/m^2 ($\pm$0.30 SD)). The results in boxes with the LED grow light and the HPS on the 70th day are below the limit for the entire growth cycle, which is again due to the large amount of radiation in the yellow region of the spectrum. The worst yield indicator for samples was under natural light (1.93 kg/m^2 ($\pm$0.09 SD)) and under LEDs in the blue spectrum (1.86 kg/m^2 ($\pm$0.08 SD)).

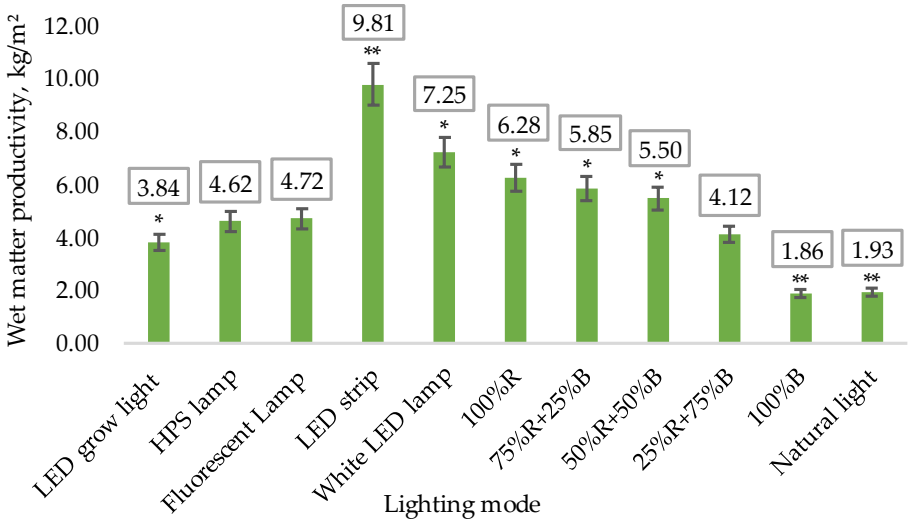

Figure 5. Wet matter productivity on the final 70th day of the experiment. Data in the columns are statistically different for different light sources ($p < 0.05$). Asterisks indicate the significance level of the differences in wet matter productivity for different light sources and HPS lamp (Kruskal–Wallis test with Mann–Whitney U post hoc test; * $p < 0.03$; ** $p < 0.001$). The mean values represent an average of thirty plants per experiment (the remaining plants were used for phytochemical analysis and seed planting material preparation). Standard deviations are marked for each group.

The average dry weight of plants, shown in Figure 6, is one of the most important indicators for assessing the effectiveness of a light source used for growing basil. The highest indicator was determined for samples illuminated with the LED strip (3.9 g (±0.17 SD)), the HPS (2.97 g (±0.13 SD)), the white LED lamp (2.95 g (±0.13 SD)), and red spectral LEDs (2.73 g (±0.12 SD)). The worst indicator was found for samples in natural lighting conditions (0.81 g (±0.03 SD)) and blue-light-emitting diodes (0.61 g (±0.02 SD)).

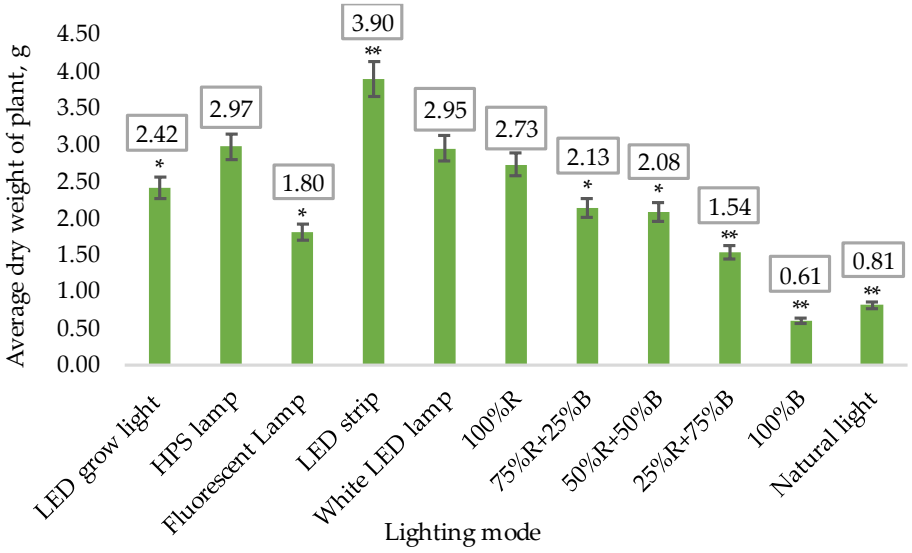

Figure 6. Average dry weight on the final 70th day of the experiment. Data in the columns are statistically different for different lights ($p < 0.05$). Asterisks indicate the significance level of the differences in average dry weight for different light sources and HPS lamp (Kruskal–Wallis test with Mann–Whitney U post hoc test; * $p < 0.03$; ** $p < 0.001$). The mean values represent an average of thirty plants per experiment (the remaining plants were used for phytochemical analysis and seed planting material preparation). Standard deviations are marked for each group.

The transpiration coefficient (TC) is the amount of water consumed to produce 1 g of plant dry matter. The transpiration coefficient for different crops varies from 200 to 1000 or more. This parameter decreases with improved nutritional conditions, hydration, and light. The lower the transpiration coefficient (shown in Figure 7) is, the better. The lowest TC value was observed in a box with the LED strip, as well as under LED lighting. Compared to natural lighting, the transpiration coefficient for the LED strip was 11.7 times lower, 3.4 times lower for the HPS lamp, and 7.2 times lower (on average) for LEDs with a predominance of red radiation.

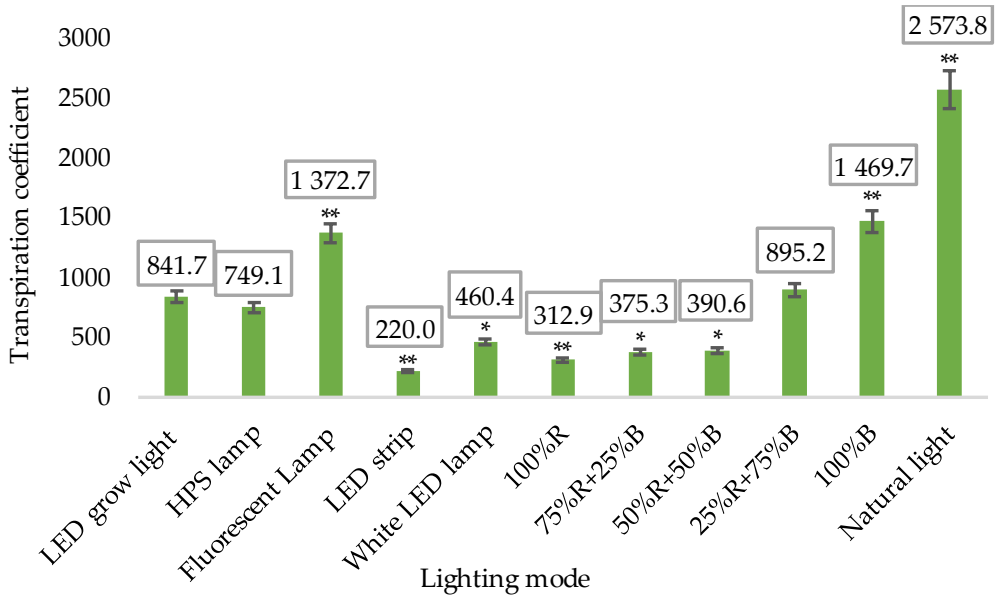

Figure 7. Transpiration coefficient on the final 70th day of the experiment. Data in the columns are statistically different for different light sources ($p < 0.05$). Asterisks indicate the significance level of the differences in transpiration coefficient for different light sources and HPS lamp (Kruskal–Wallis test with Mann–Whitney U post hoc test; * $p < 0.03$; ** $p < 0.001$). The mean values represent an average of thirty plants per experiment (the remaining plants were used for phytochemical analysis and seed planting material preparation). Standard deviations are marked for each group.

The highest transpiration coefficients were observed for the following lighting modes: natural light (2573.8), 100%B (1469.7), fluorescent lamp (1372.7), and 25%R + 75%B (895.2). The same lighting modes correspond to the lowest plant dry mass yield. Thus, illuminating samples with these emitters is not economically profitable: the highest consumption of water resources with the lowest dry mass yield. TC decreases with improved nutritional conditions, humidity, lighting, and reduced plant stress.

Visual representations of the development of individual basil samples under various light sources are presented in Figure 8.

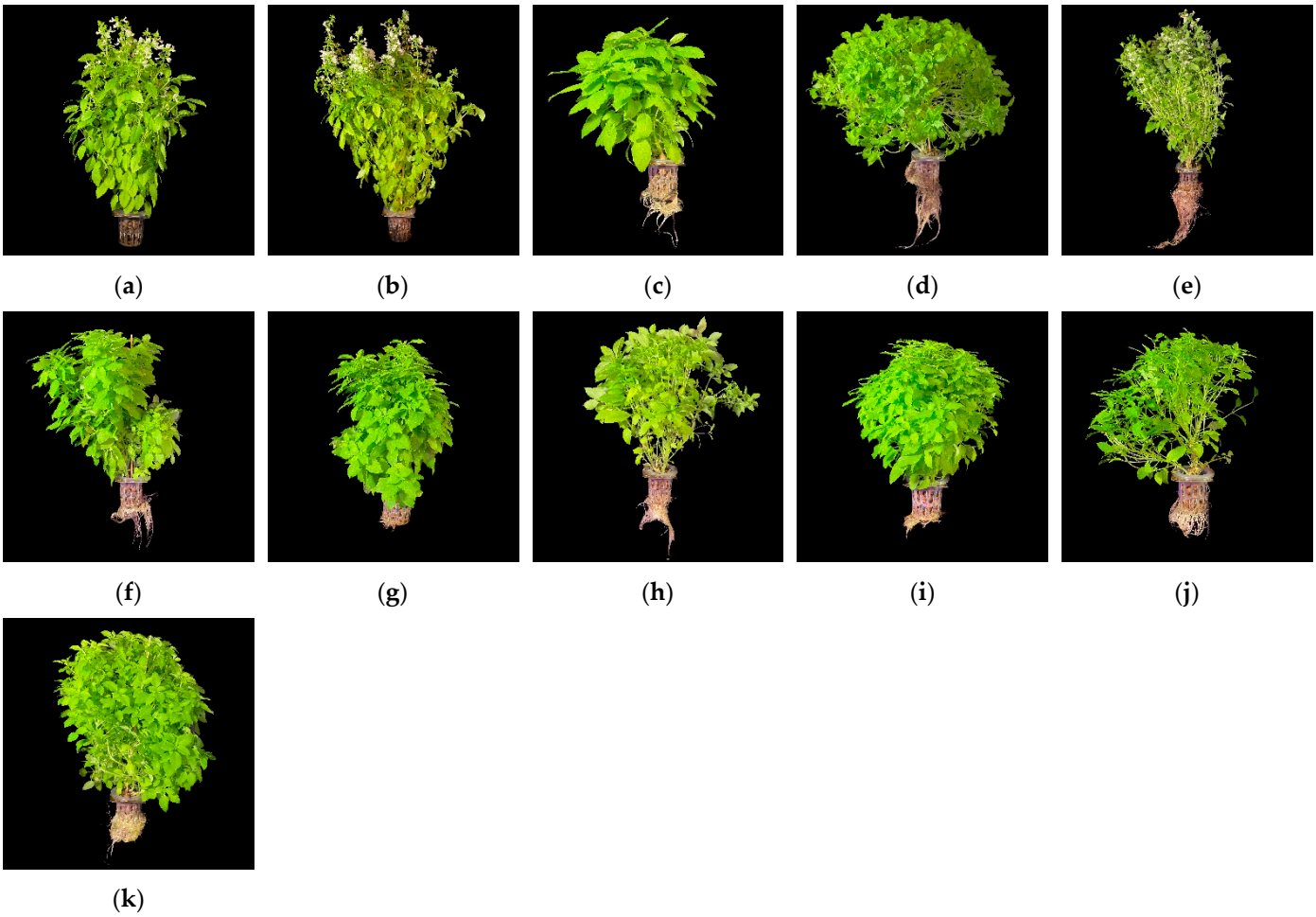

Figure 8. Development of individual basil samples on the 70th growth day under (**a**) LED grow light, (**b**) HPS, (**c**) fluorescent lamp, (**d**) LED strip, (**e**) white LED lamp, (**f**) 100%R, (**g**) 75%R + 25%B, (**h**) 50%R + 50%B, (**i**) 25%R + 75%B), (**j**) 100%B, (**k**) natural light.

3.2. Phytochemical Analysis

Since flavonoids are a major group of plant secondary metabolites that play an essential role in plant metabolism and are the active components of medicinal herbs [41], we measured the total flavonoid content in *O. basilicum* samples grown under different illumination sources on the 30th, 50th, and 70th days of growth (Figure 9). The greatest flavonoid content was found in the *O. basilicum* samples grown under the LED strip, while plants grown under the LED grow light, the HPS lamp, and the 100%R showed generally similar values for day 30 and 70, while day 50 values had greater variation. It is worth noting that all four samples showed similar dynamics of flavonoid accumulation: day 30 highest flavonoid content, day 50 lowest flavonoid content, and day 70 medium flavonoid content (in some cases similar to day 50 flavonoid content). The dynamic of flavonoid accumulation by plants differs significantly and depends on a multitude of factors including plant species, genetics, growth cycle, temperature, soil composition, and illumination. Based on our data, it can be concluded that *O. basilicum* grown under the LED strip illumination showed the greatest total content of flavonoids in terms of rutin.

To compare secondary metabolite production and accumulation by *O. basilicum* samples grown under different lighting modes, we analyzed and compared the HPLC fingerprints of total 96% ethanol extracts collected on days 30, 50, and 70 of growth under the LED grow light, the HPS lamp, the LED strip, and the 100%R. HPLC chromatograms obtained from samples collected on day 70 showed the greatest quantitative and qualitative

content of metabolites (Figure 10). Peak identification was performed in comparison to an internal library of secondary metabolites.

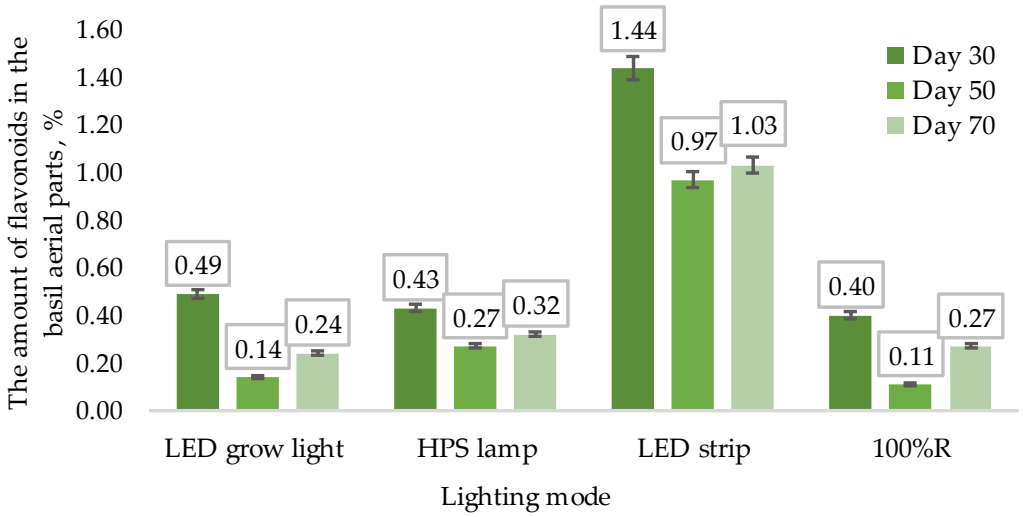

Figure 9. The content of flavonoids (% of dry weight) in *O. basilicum* aerial parts. All experiments were performed in triplicate, and data are expressed as the mean of three samples with standard deviation; $p < 0.05$ was considered statistically significant. Standard deviations are marked for each group.

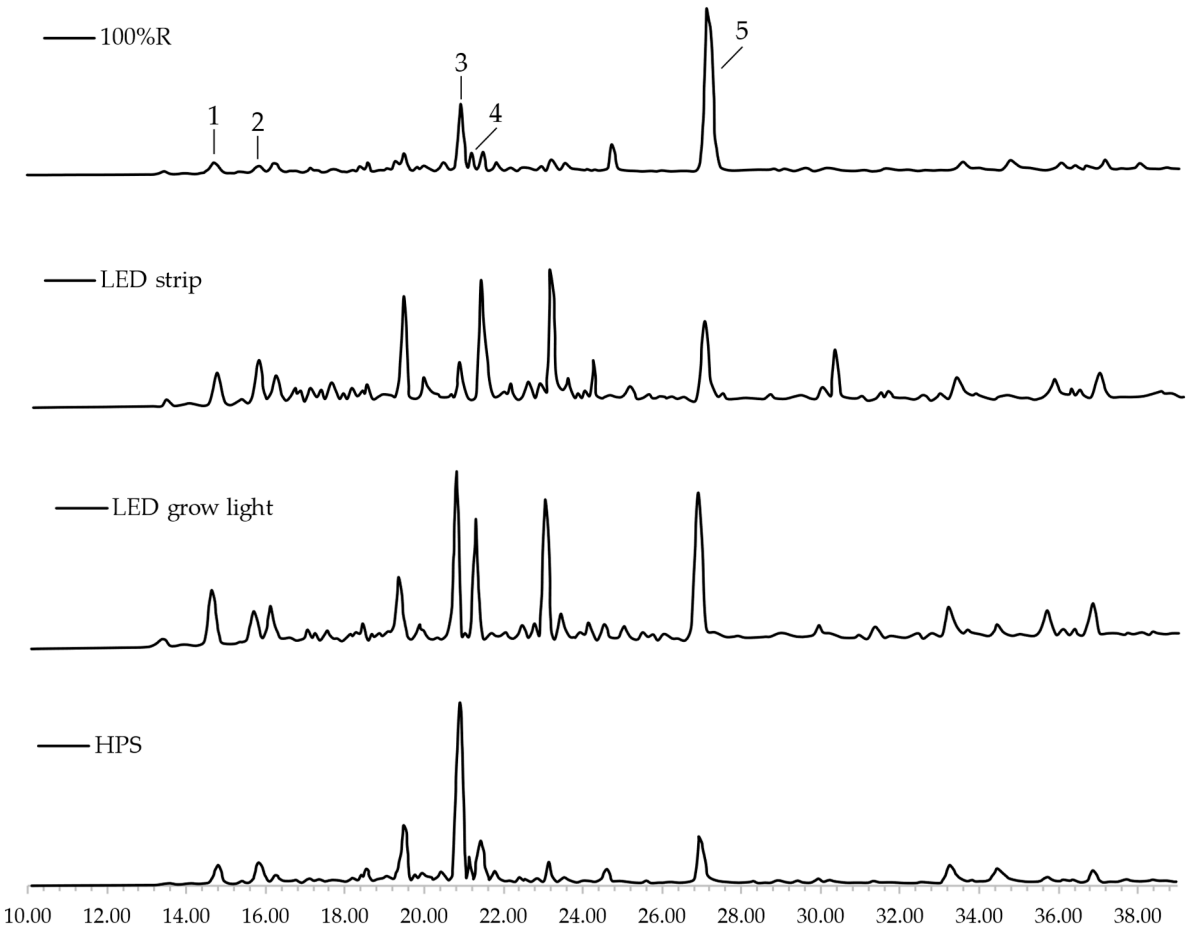

Figure 10. Magnified HPLC fingerprint comparison of samples (day 70). 1—Caffeic acid, 2—(−)-epicatechin, 3—rosmarinic acid, 4—astragalin, 5—eugenol.

Analysis of the obtained HPLC fingerprint data indicated that differences in lighting modes did not significantly affect the qualitative composition of secondary metabolites in *O. basilicum* samples. Most of the same major metabolite peaks were present in all HPLC chromatograms. The main difference between the HPLC fingerprints obtained from different lighting modes was the secondary metabolites' quantitative composition. *O. basilicum* samples grown under the 100%R and the HPS lamp lighting modes led to the greater biosynthesis and accumulation of certain polyphenolic metabolites over others, while samples grown under the LED grow light and the LED strip showed a more uniform metabolite profile.

4. Discussion

The influence of a set of artificial light sources with various spectra on the development and yield of basil in a hydroponic system was comprehensively evaluated. Despite the positive effects of the HPS lighting, there is a significant risk of shadow avoidance syndrome and physiological decline. This is revealed in the death of the lower leaves due to lack of light and possible damage to the photosynthetic system of the plants. At the juvenile stage of growth, the greatest contribution was made by optical radiation in the blue part of the visible spectrum, which was manifested in earlier activation of seeds, faster germination, and accelerated growth. As the basil developed, the influence of blue light decreased. By the 20th day of the experiment, radiation from the red part of the spectrum was more important for the development of basil than blue light. In boxes with a higher ratio of red light, earlier appearance of the first and subsequent leaves, faster plant growth, and higher yields were observed at the end of the experiment. Red light is an important factor in the activation of phytochromes, pigments that play an important role in regulating plant growth. These pigments respond to light signals and control many biological processes in the plant, including the formation of shoots, leaves, and flowering.

Based on the yield indicators, transpiration coefficient, the most optimal lighting conditions for the Basilisk variety basil were 100%R, 75%R + 25%B, and 50%R + 50%B radiation under hydroponic cultivation. Boxes with lighting of 25%R + 75%B and 100%B showed good growth at the juvenile stage of development; subsequently, the growth dynamics were lower than in boxes with a predominance of red radiation. A possible reason for this is the fact that the emission spectrum of the LED strip is better adapted to the absorption spectra of the main photosynthetic pigments of plants. In addition to better matching of light emission and absorption spectra of photosynthetic pigments, the LED light source has greater efficiency in converting electrical energy into useful light energy in the PAR region. It has been determined that the less blue light in the spectral composition of illuminating light sources, the larger the leaf area. This is proven by the largest average leaf area for LED strip, 100%R, 75%R + 25%B, and 50%R + 50%B. Blue light also reduced the biomass of basil shoots, as evidenced by the results of measuring the average dry weight of plants. These results are consistent with the conclusions of an article [42] which studied the morphological and physiological reactions in basil based on the proportions of red, blue, and green wavelengths. The advantage of the LED strip can also be explained by the spectral composition of the radiation: blue light with a wavelength of 450 nm can promote the opening of stomata, which increases the transpiration rate [43]; red light with a wavelength of 660 nm corresponds to the maximum absorption of chlorophyll and has the greatest effect on the process of photosynthesis, stimulating the formation of carbohydrates; radiation in the range from 500 to 600 nm, which is included in the spectral composition of the LED strip, also takes part in photosynthesis (plants absorb up to 70% of "green" light), and also play a role in phototropism and photomorphological processes in basil. Basil plants grown under lighting mode that included a significant proportion of green light in the spectrum had the greatest number of formed leaves on the final day of the experiment. Irradiation with such sources (LED strip, white LED lamp, HPS lamp) made it possible to increase the average dry weight of basil due to the penetrating action of green light, which is likely capable of increasing photosynthesis of plants on the lower tiers and promotes

increasing productivity. The emission of fluorescent lamps has a limited spectrum with a prominent red component at a wavelength of 610 nm, which enhances vegetative growth and photosynthesis, but has less influence than the red light at 660 nm. Fluorescent lighting supports plant vegetative growth, color, appearance, and product quality, similar to solar radiation. However, a decrease in growth rate and biomass accumulation was observed [44]. The combined effect of blue (450 nm) and red (610 nm) light contributed to the formation of a large number of relatively small leaves in basil. In addition, the LED strip radiation had a beneficial effect on the chemical composition of the plants: the plants in the box under this light source had a pronounced clove–pepper aroma, while basil under other light sources had virtually no aroma. The described features and advantages of LED lighting made it possible to achieve high basil yields. *O. basilicum* samples grown under the 100%R and the HPS lamp lighting modes led to the greater biosynthesis and accumulation of certain polyphenolic metabolites—eugenol and rosmarinic acid, respectively—over others, while samples grown under LED grow light and the LED strip showed a more uniform metabolite profile. It was demonstrated that, due to the best matching of the light source emission spectrum to the absorption spectra of basil leaves and the highest efficiency as an emitter of photosynthetically active radiation, the LED strip is the preferred choice for creating artificial lighting for basil. This not only results in increased biomass growth but can also boost the content of the aromatic and essential oil, which helps to enhance the plant's antimicrobial, anti-inflammatory, and antioxidant properties.

5. Conclusions

Increasing the basil yield and flavonoid content, as well as enhancing the uniformity of the metabolite profile, which was achieved by the application of LED lighting with the optimized spectrum, allows for the production of a large amount of high-quality product in a limited space. This may benefit both commercial crop production, where high productivity and efficient use of resources are key factors, and the production of medicinal raw materials, where the phytochemical composition of plants is most important. The highest flavonoid content was found in the *O. basilicum* samples grown under the LED strip, while plants grown under the LED grow light, the HPS lamp, and the 100%R showed significantly lower values. The use of the artificial LED lighting 15%B + 40%G + 45%R (PPFD 157 $\mu mol \cdot m^{-2} \cdot s^{-1}$) increased the basil yield by 112% compared to the high-pressure sodium lamp, increased the flavonoid content in the aerial parts by 3.2 times, and provided a more uniform profile of metabolites.

Further implementation of adaptive LED light sources with an adjustable spectrum will potentially enable controlled modification of the morphological, anatomical, and physiological characteristics of plants. Adaptation of the artificial illumination spectrum for various plant species at different stages of their development could increase crop yields, product quality, and nutritional value. This approach will help avoid generation of excess non-optimized optical radiation, which is not properly absorbed by the plants and does not produce any positive effect while increasing energy consumption and inducing unnecessary heat damage. In addition, artificial illumination strongly influences the biosynthesis and accumulation of various plant secondary metabolites, which are critical to crop quality, especially for medicinal plants. Modification of the spectral composition of the light sources appears to be a viable practical approach to producing crops with better nutritional values in hydroponic and indoor cultivation.

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D.M.: conceptualization, resources. All authors have read and agreed to the published version of the manuscript.

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