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Evaluation of the Effectiveness of Different LED Irradiators When Growing Red Mustard (*Brassica juncea* L.) in Indoor Farming

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Abstract: Investigation is devoted to the optimization of light spectrum and intensity used for red mustard growing. Notably, most of the studies devoted to red mustard growing were conducted on micro-greens, which is not enough for the development of methods and recommendations for making the right choices about the irradiation parameters for full-cycle cultivation. In this study, we tested four models of LED with different ratios of blue, green red and far red radiation intensity: 12:20:63:5; 15:30:49:6; 30:1:68:1, in two values of photon flux density (PFD)—120 and 180 µmol m^{-2} s^{-1}—to determine the most effective combination for red mustard growing. The study was conducted in a container-type climate chamber, where the red leaf mustard was cultivated in hydroponics. On the 30th day of cultivation, the plant's morphological, biochemical and chlorophyll fluorescence parameters, and reflection coefficients were recorded. The results indicated that the PFD 120 µmol m^{-2} s^{-1} had a worse effect on both mustard leaf biomass accumulation and nitrate concentration (13–30% higher) in the plants. The best lighting option for growing red mustard was the blue–red spectrum, as the most efficient in terms of converting electricity into biomass (77 Wth/g). This light spectrum contributes to plant development with a larger leaf area (60%) and a fresh mass (54%) compared with the control, which has a maximum similarity in spectrum percentage to the sunlight spectrum. The presence of green and far red radiation with the blue–red light spectrum in various proportions at the same level of PFD had a negative effect on plant fresh mass, leaf surface area and photosynthetic activity. The obtained results could be useful for lighting parameters' optimization when growing red mustard in urban farms.

Keywords: red leaf mustard; light-emitting diode; spectral composition of light; productivity; photosynthesis

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1. Introduction

The leaf mustard (Korean red mustard) is an annual cruciferous plant (Brassicaceae Burnett), which is a valuable food and officinal crop due to its unique composition and low maintenance for cultivation [1,2]. It is a very popular leafy green in Russia, China and India. Due to its beneficial properties, the leaf mustard is recommended for use for the prevention of chronic cardiovascular system diseases, oncology, diabetes and obesity [3–5].

The leaf mustard can be grown both outdoors and indoors under artificial illumination, which expands the geography of this crop cultivation. Lighting is one of the most significant environmental factors affecting the plant's growth and morphology [6]. Among the other cost elements of vegetable production in greenhouses, the cost of lighting can make up 40–80% of the total [7]. Currently, for plant cultivation in urban farms, in lighting systems, the LEDs of various spectral ranges are used due to their high efficiency, and low heat emission in comparison to the gas-discharge lamps. LEDs allow the spectral composition of light to be easily and quickly changed, causing specified reactions of the plants [8–11]. For crop production, some lighting equipment manufacturers produce a special series of LEDs with increased radiation efficiency in the PAR spectrum [12]. In most of the current studies, the red–blue (RB) LEDs are used. The effect of the red/blue light ratio at various emission intensities on the growth of leafy greens is being studied. It is important that the emission spectra of RB LEDs are in good coincident with the absorption spectra of the plant photosynthetic pigments. Additionally, RB LEDs are considered the most energy-efficient LEDs [13,14]. However, studies show that green light (G) is also necessary for plants as it prevents the inhibition of plant generative development [15,16]. In addition, some researchers note that additional illumination of plants with green (G) and far red (FR) lights can increase the fresh mass of the leafy greens [17]. The green light increases the leaf surface area and reduces the specific leaf mass [18–21]. The addition of G to the BR spectrum results in improvement of the plant's nutritional value as the G spectrum maintains a high net photosynthesis rate and photochemical efficiency [22,23]. However, those light sources with G photons making up more than a 50% share of the total photosynthetic photon flux (PPF) cause plant growth inhibition [24]. It was established that additional G irradiation with a 505 nm peak wavelength (cyan) has a significant positive effect on the photosynthetic pigment content [25]. In addition, the positive role of the G light was proven in the balance maintenance between the biomass production and the synthesis of the secondary metabolites involved in plant defensive reactions [26]. It also affects the activity of nitrate assimilation enzymes [27].

When studying 8, 12, 16, 20, and 24 h photoperiods under blue, red, and far red LED illumination modules at a PFD of 300 μmol m^{-2} s^{-1}, it was found that the 8 h photoperiod resulted in the elongation of hypocotyls and an increase in the leaf area and fresh mass of mustard, red pak choi and tatsoi microgreens. The elongation of plants decreased due to the lengthening of the day from 12:00 to 20:00, and the 24 h photoperiod most suppressed the growth process [28].

Several research groups studied the effect of blue and red light combination treatments on microgreens at different values of the photosynthetic photon flux density (PPFD). Jones-Baumgardt and co-authors [29] studied the impact of PPFD values on microgreens of cabbage, arugula and mustard. For all types of microgreens, it was found that anthocyanin concentration was proportional to the PPFD value. In the other research by the same authors, the effect of LED irradiation on the growth indicators and yield of sunflower, cabbage, arugula and mustard microgreens grown in a greenhouse was studied. During the experiment, various PPFD levels were tested in the range from 17 to 304 μmol m^{-2} s^{-1} with a 16 h-long photoperiod. An increase in PPFD value was accompanied by growth of the dry mass, the stability index and the relative chlorophyll content, and by the formation of leaves of a smaller area in cabbage, arugula and mustard [30]. A decrease in PPFD led to an increase in total nitrogen content and a decrease in the total acidity [31,32].

There are studies devoted to the effect of different proportions of red and blue lights (B) at the same level of PPFD on plant development. Ying and co-authors did not find any differences in the content of chlorophyll, carotenoids and nitrates in the microgreens of mustard, arugula and red cabbage at different proportions of B (from 5% to 30%) and R light (from 70% to 95%) [33]. With all types of microgreens, the change in the share of B light did not affect the total content of the extracted chlorophyll, carotenoids or nitrates [33]. Light intensity, in contrast to light quality, affects the total amount of carotenoids in the microgreens and significantly decreased with increased light intensity [34]. It was noted that the accumulation of phenolic compounds in the cabbage and the mustard was more effective at 30% of blue light in the total illumination; at the same time, the concentration of anthocyanins in arugula and red cabbage correlated well with B light proportion [33]. Mustard microgreen cotyledons darkened under a high proportion of blue light [35]. Note that a high proportion of the blue radiation (from 20% to 50%) can lead to inhibition of the leaf plate growth [36,37] and has a positive effect on the accumulation of macro-and microelements [38,39]. It was found that R light and magenta (450 + 650 nm) light compared to white light promoted the accumulation of both total and individual anthocyanins, while B light was found to be the predominant factor in the a non-anthocyanin phenolic accumulation in mustard microgreens [40].

Recent studies have been focused on plant lighting modes optimization including by the addition of different proportions of G and far-red (FR) to the RB at the same PPFD value [17,39,41,42]. The FR addition treatment can inhibit seed germination; so, it is reasonable to use FR treatment after the germination period [43,44]. The addition of G or FR (plus 50 μmol m^{-2} s^{-1}) to the RB light (4:1) increase both the fresh lettuce shoots mass by 20.5% (in the case of G light) and 40.4% (in the case of FR light) and the dry shoot mass by 24.2% and 45.2%, for green and FR light, respectively [45]. The addition of the FR light of high-intensity to the RB light increased the plant height and the cotyledon area of mustard microgreens and did not affect either fresh or dry biomass, while the addition of G light did not have a significant effect [41].

Most recent studies of red mustard cultivation were carried out on microgreens, which is not enough for developing methods and recommendations for leaf maturity growing and choosing the most effective irradiation parameters. The species-specific reaction of plants to the spectral composition of the light, including the plant growth parameters and their biochemical composition, has been mentioned [46–48]. In order to test the hypothesis about the different responses of plants to the spectral composition of irradiation at different levels of PPFD, it is necessary to comprehensively study the effect of the spectral composition of optical radiation on the productivity of mustard leaf with an emphasis on morpho-biochemical parameters and indicators of plant photosynthesis. The study of the irradiation intensity and the spectral composition of light for red mustard growing will allow us to select the optimal lighting modes to obtain maximum yield with minimal energy consumption. The development of technology elements for growing red mustard can be useful for the introduction and dissemination of this rare crop in city farming.

The purpose of this work is to select the optimal lighting option to reduce energy costs when growing red mustard in indoor farming.

2. Materials and Methods

2.1. Red Musturd Variety

The experiments were carried out on the red leaf mustard of the variety "Red Hill" ('Gavrish', Moscow, Russia). This is a cold-resistant and early-ripening variety (the period of leaf ripening is 25–30 days). It is grown both outdoors and in indoor farming. The leaf rosettes can reach 25–35 cm in length and 50–60 g in mass when grown outdoors.

2.2. Cultivation Conditions

The experiment was conducted in three replications from September 2021 to November 2021 in container-type climate chambers for green crops cultivation. The plants were grown in plastic trays on racks equipped with circulated hydroponics (Figure 1). The seeds were sown into pots with a mineral wool substrate. In order to avoid the FR negative effect, the seeds were germinated in the dark. After the cotyledons appeared, the lighting was turned on. When the first leaves appeared, three plants were left in every pot. Eight light-insulated racks were used for the mustard plant cultivation. The cultivation area for each light treatment was equal to 0.68 m^2. The planting density was 50 plants per 1 m^2. The microclimate in the chamber was maintained by an automatic system. The day/night air temperature was 25/22 °C at a relative humidity of 75%. The carbon dioxide concentration was maintained by the ventilation system and corresponded to atmospheric values of 400–450 ppm. No additional CO_2 was used. For nutrient solutions preparation, the Flora Series® (GHE, Fleurance, France) complex of fertilizers for hydroponics was used. The components of the FloraGro, FloraMicro SW, and FloraBloom kits were used in the following ratio: 2.5:2.0:2.5. The electrical conductivity of the nutrient solution was maintained within 1500–1600 µS/cm.

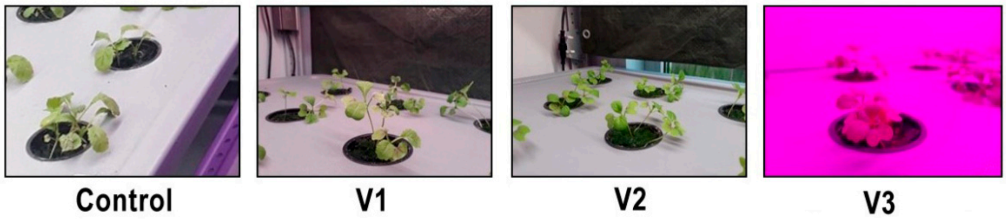


Figure 1. The appearance of mustard plants of 'Red Hill' variety in the phase of first true leaf development under 4 types of lighting with the following spectral composition (B:G:R:FR): Control (15:32:42:11), V1 (12:20:63:5), V2 (15:30:49:6), V3 (30:1:68:1).

2.3. Irradiation Conditions

In the phytochamber, irradiation was provided by combined irradiators based on LEDs of various spectral compositions. As a control, full-spectrum LED luminaires based on Refond RF-W40QI35DS-DF-J-Y LEDs with a 4000 K color temperature and a color rendering index of Ra95 manufactured by Shenzhen Refond Optoelectronics Co., Ltd. (Shenzhen, China) were used. The emission spectrum is as close as possible to the sunlight spectrum. The rest of the irradiators of our own production consisted of combinations of the latest generation LEDs of TM LUXEON 2835 for plant growing: there were blue LEDs (445 nm), red ones (630 nm and 660 nm), far-red ones (730 nm) and white ones with a color temperature of 3000 K. In V1 and V2 modes, 20% and 30% of green light was respectively chosen, since it is known that the addition of G light to B and R can increase shoot mass [15,43]. In the V 3 mode, only red and blue LEDs were used; their percentage was chosen based on the known data, in which anthocyanins and phenolic compound concentrations were at a maximum [33,35]. The LEDs were manufactured by Lumileds Holding B.V. (San Jose, CA, USA). The light period was 16 h. The irradiation parameters are presented in Table 1. Two variants of PFD were used—120 and 180 µmol m^{-2} s^{-1}.The measurements of the photon flux density and the spectral composition of the irradiation were carried out using the MK350D Compact Spectrometer (UPRtek Corp. Miaoli County, Taiwan). For the irradiation variants with 120 µmol m^{-2} s^{-1} PFD, the specific power consumption amounted to 105 ± 1.5 W m^{-2}. For the lighting system with 180 µmol m^{-2} s^{-1} PFD, the specific power consumption was 140 ± 2.1 W m^{-2}. The measurements were carried out using a CVM-MINI CIRCUTOR electric power parameter meter (Barcelona, Spain).

Table 1. Average density of photon flux coming from LEDs in each of spectrum zones: Blue (B), Green (G), Red (R) and Far-Red (FR) for s cultivation of "Red Hill" variety red leaf mustard (*Brassica juncea* L.) in the climatic chamber. Average values obtained in five measurement sessions are presented here.

Irradiation Variant	Photon Flux, µmol Photons m^{-2} s^{-1}						Percentage Composition of Light (B:G:R:FR)
	PFD (400 nm–800 nm)	Blue (400 nm–500 nm)	Green (500 nm–600 nm)	Red (600 nm–700 nm)	Far Red (700 nm–800 nm)	PPFD (400 nm–700 nm)	
Control	120 ± 2.8	17.5 ± 0.3	38.5 ± 1.2	51.0 ± 1.5	13.0 ± 0.2	107.0 ± 2.7	15:32:42:11
	180 ± 3.3	26.4 ± 0.6	58.0 ± 1.5	76.0 ± 1.9	19.6 ± 0.4	160.4 ± 3.2	
V1	120 ± 2.3	14.2 ± 0.2	26.2 ± 1.1	73.2 ± 1.6	6.4 ± 0.1	113.6 ± 2.2	12:20:63:5
	180 ± 3.1	21.4 ± 0.5	36.7 ± 1.3	112.9 ± 1.5	9.0 ± 0.3	171.0 ± 3.0	
V2	120 ± 3.0	18.0 ± 0.2	36.0 ± 0.9	58.8 ± 0.9	7.2 ± 0.1	112.8 ± 2.8	15:30:49:6
	180 ± 3.3	26.2 ± 0.7	53.9 ± 1.6	88.8 ± 1.1	11.3 ± 0.5	168.9 ± 3.1	
V3	120 ± 1.5	36.5 ± 0.3	1.5 ± 0.1	81.0 ± 1.0	1.0 ± 0.1	119.0 ± 1.5	30:1:68:1
	180 ± 3.8	54.5 ± 0.7	2.0 ± 0.2	122.0 ± 2.3	1.5 ± 0.1	178.5 ± 3.8	

2.4. Evaluation of Biometric Indicators

The sampling of the mustard plants was carried out according to the principle of representativeness, i.e., in such a way that the characteristics of the selected plants corresponded to that of the entire set of plants of the certain experiment variant. For analyzing the fresh and dry leaf mass indicators and the leaf surface area, we selected 10 plants from each tested variant. The measurements were made on the 30th day after germination.

When determining the fresh mass, the plants were weighed on the laboratory scale GF-3000 (A&D Company, Japan). For the measurement of the leaf surface area, the photo-planimeter LI-COR—LI-3100 AREA METER (LI-COR, Inc. Lincoln, NE, USA) was used. In order to determine dry mass, the samples were crushed to a particle size of no more than 1 cm, dried in an oven at a temperature of 60–70 °C for 3 h until a constant mass was obtained, weighed on the Sartorius LA230S analytical scales (Laboratory Scale, Göttingen, Germany).

2.5. Pigment Content

To determine the content of pigments, the third leaves from the top (fully illuminated) were used. The samples of the fresh materials were crushed in porcelain mortars with the addition of quartz sand. All procedures were repeated three times.

In order to determine the chlorophyll and carotenoid content, we selected samples with 0.1 g mass, and ground them in the mortar with the addition of 2–3 mL of 100% acetone to obtain an extract. Then, the extract was moved to a funnel with a glass filter (No.3) inserted into the Bunsen flask and connected to a vacuum pump. The mortar and the filter were washed repeatedly with 100% acetone until the pigments were completely extracted. Then, the filtrate was transferred to a measuring bottle and the acetone was added up to 25 mL. The contents of the measuring bottles were thoroughly mixed and used for the evaluation of the pigment contents by the spectrometric method on the SPECS SSP-705 spectrophotometer (Russia). The optical density of the pigment solution was determined at wavelengths of 662 nm (for the chlorophyll a), 644 nm (for the chlorophyll b) and 440.5 nm (for the carotenoids). The thickness of the cuvette absorbing layer was 10 mm. The pigment concentration was calculated using the Holm–Wettstein method for 100% acetone [43].

2.6. Nitrates Content

For the nitrate content determination in the leaf mustard samples, we selected three plants in each variant of the experiment. We took samples of 10 g in fresh mass and crushed them in the mortar. The crushed material was placed in a measuring beaker and 50 cm^3 of the extraction solution was topped up. For plants of the Brassicaceae family, this solution was prepared as follows: 1 g of potassium permanganate and 0.6 cm^3 of concentrated sulfuric acid were dissolved in a 1% solution of aluminum–potassium alum, and the volume of the solution was brought up to 1000 cm^3. Then, the material obtained in the measuring beaker was mixed for 3 min in the magnetic stirrer. The concentration of the nitrate ions in the suspension was measured using the ion-meter "Itan" (Tom'analit, Tomsk, Russia).

2.7. Measurement of Chlorophyll Fluorescence Parameters and Vegetation Indices

To measure the activity of the light stage of photosynthesis, a portable fluorimeter, PAR-FluorPen FP 110-LM/D (Photon Systems Instruments, Drásov, Czech Republic), was used to detect active chlorophyll fluorescence and was further analyzed using the PAM method or OJIP test. The PAR-FluorPen FP 110-LM/D consists of a detector (PIN photodiode with a narrow band filter, working optical range from 667 to 750 nm) and a blue LED emitter (maximum about 455 nm), and a sensor of ambient light. To assess the photosynthetic efficiency of photosystem II (Fv/Fm), the leaf was preliminarily dark-adapted for at least 20 min. To determine the spectral reflectance of the leaves, a portable PolyPen RP 410/UVIS meter (Czech Republic) was used. The spectra of nine plants were measured in each lighting variant and at each cultivation period. Three spectral measurements were carried out on different leaves of each individual plant. Using the PolyPen RP 410 UVIS program, the main reflectance indicators and the vegetation index were calculated.

2.8. Energy Intensity Calculation

The cost of electricity for the production of 1 g mustard plant fresh mass was calculated as the ratio of the total electricity consumed by lamps for 30 days per the total mass of all plants under the illuminator of this type.

2.9. Statistical Data Processing

All experiments were carried out threefold. Statistical processing of measurement results and plotting were performed in Python 3.9. To estimate statistical significance, the Independent two-sample T-test was used with $p < 0.05$ significance levels.

3. Results

3.1. Morphology

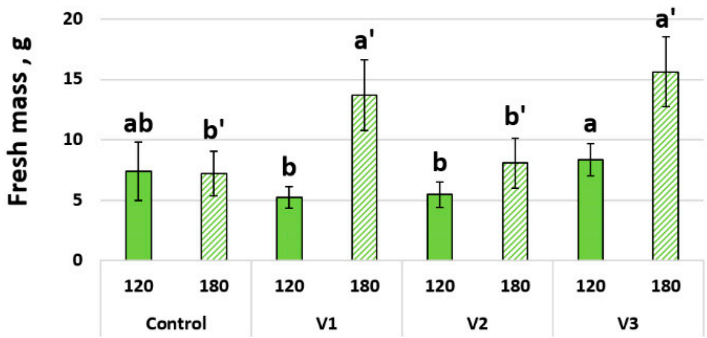
The measurement results of the morphological parameters of the red leaf mustard plants on the 30th day after their germination are shown in Figure 2. Statistical analysis of the data obtained showed the reliability of differences in terms of fresh mass and leaf surface area. At a PFD of 180 µmol m^{-2} s^{-1}, the fresh mass and leaf area indicators were higher in all experimental variants.

(a)

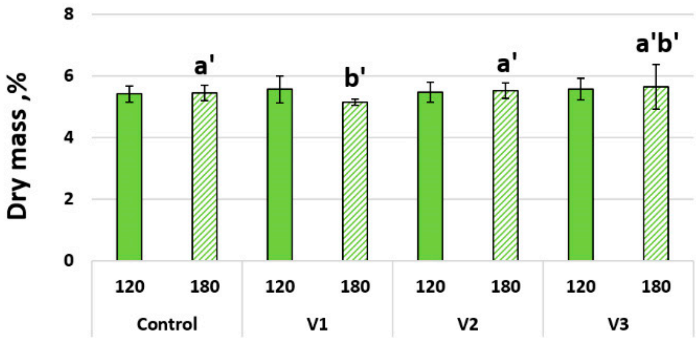
(b)

Figure 2. Red leaf mustard (*Brassica juncea* L.) plants of the "Red Hill" variety under 120 µmol m^{-2} s^{-1} PFD (**a**) and 180 µmol m^{-2} s^{-1} PFD (**b**) on 30th day of cultivation.

The best lighting option for fresh mass accumulation and the largest leaf surface area was observed under the spectrum ratio red–blue (V3). The increase in fresh mass was 71.6% (Figure 3a), and in leaf surface area it was 51.8% (Figure 3c). In terms of dry mass (Figure 3b) and number of leaves (the data are not shown), there were no significant differences between the variants in the experiment. Based on the dry mass indicator, the plants of all variants were not inferior to each other in terms of nutritional properties.



(**a**)



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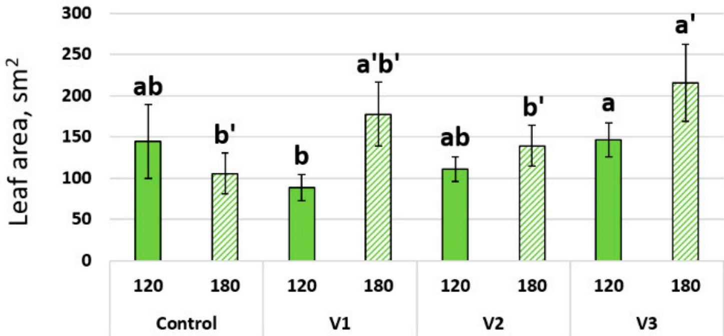

(**c**)

Figure 3. Fresh mass (**a**), dry mass (**b**) and leaf surface area (**c**) of red leaf mustard (*Brassica juncea* L.) plants of the "Red Hill" variety on 30th day of cultivation. The data shown are the means and the vertical bars indicate standard errors (n = 5). Statistically significant differences within p = 0.05. The different letters indicate significant differences among groups.

By the 30th day of red mustard cultivation, flowering was not observed in any of the light options. This was facilitated by the optimal length of daylight hours; therefore, in this case, a high proportion of the green part of the spectrum is not required to prevent flowering [49].

In the variant V3, the shares of the far-red and green LEDs are small and plant shadow avoidance reaction [17] was not observed; this is due to the greater photosynthetic activity of red and blue light. The largest leaf surface area was observed in all treatments at PFD 180 µmol m^{-2} s^{-1}; this observation coincides with other studies [30].

3.2. Biochemical Analysis of Leaves

The content of the main photosynthetic pigments is shown in Figure 4. In terms of the carotenoid ratio to total chlorophyll (1:5), we can say that the plants of all variants in the experiment were in the active growth phase and had no signs of aging. In relation to chlorophyll a to chlorophyll b (3:1), it can be concluded that mustard plants of all variants in the experiment did not suffer from a lack of illumination. An increase in the total level of PFD had no significant effect on the concentration of photosynthetic pigments. The best light variations for total chlorophyll content were V3 with light intensity 120 and 180 µmol m^{-2} s^{-1} and V2 with light intensity 120 µmol m^{-2} s^{-1}. In another study conducted on mustard microgreens, total integrated chlorophyll of higher values was observed at the spectral ratio B 13%, R 87% (without addition of G or FR) as compared to B 9%, R 84%, FR 7% and B 8%, G 18%, R74% spectral ratios [34]. It is possible that the negative effect of FR on the total chlorophyll content rises with increasing PPF; therefore in the V2 variant and at 120 µmol m^{-2} s^{-1} PFD, higher chlorophyll content was observed.

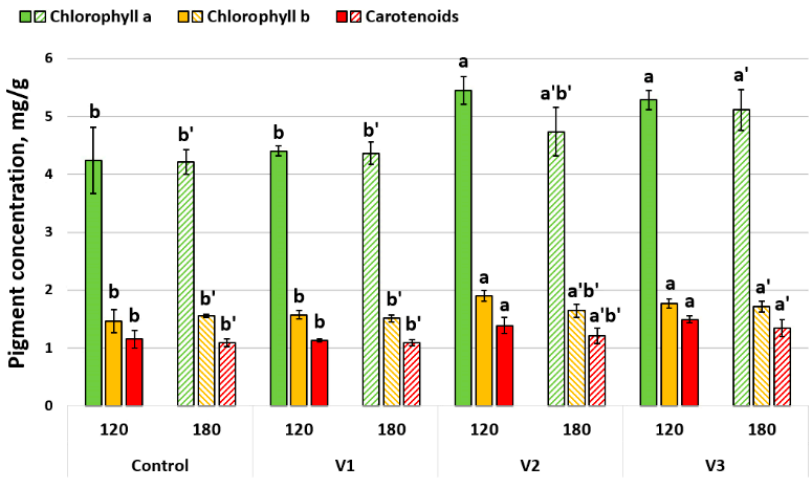

Figure 4. Pigments concentration in red leaf mustard (*Brassica juncea* L.) plants of the "Red Hill" variety on 30th day of cultivation. The data shown are the means and the vertical bars indicate standard errors (n = 5). Statistically significant differences within $p \leq 0.05$. The different letters indicate significant differences among groups.

The nitrate concentration is inversely correlated with the PFD total level (Figure 5). For all variants in the experiment, a PFD of 120 µmol m^{-2} s^{-1} is above the maximum concentration allowable for leafy greens in the Russian Federation [50], so it is unacceptable to use this level of illumination.

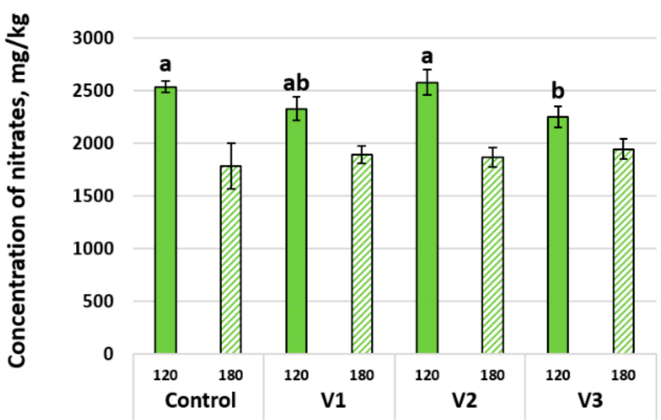

Figure 5. Concentration of nitrates in red leaf mustard (*Brassica juncea* L.) plants of the "Red Hill" variety on 30th day of cultivation. The data shown are the means and the vertical bars indicate standard errors (n = 5). Statistically significant differences within $p \leq 0.05$. The different letters indicate significant differences among groups.

It is known that the combination of red and blue lights with a high share of blue light (25% and higher) can be effective at reducing the nitrate content in the mustard microgreens [38,51]. At the stage before harvesting, the simultaneous increase of PPFD (up to 300 µmol m^{-2} s^{-1}) and blue light share significantly reduces the nitrates concentration in the plants of the Tatsoy cabbage (*Brassica rapa* subsp. *narinosa*) [52]. Additionally, a decreased PPFD value results in the highest nitrate content in the mustard microgreens [53]. In our experimental variants, the share of the G-radiation in the total illumination did not correlate with the nitrate content, in contrast to the studies conducted on lettuce plants [22].

3.3. Chlorophyll Fluorescence Parameters and Measurements of Vegetation Indexes

Figure 6 shows the effect of different lighting options, when growing mustard, on the effective quantum yield (Qy) of photochemical reactions of photosystem II, non-photochemical quenching (NPQ), and photochemical fluorescence quenching coefficient (Qp), which show the state of the plant photosynthesis system. NPQ is a mechanism employed by plants to protect themselves from excessive light intensity. In the V3 variant, an increase in NPQ was observed with an increase in PFD from 120 µmol m^{-2} s^{-1} to 180 µmol m^{-2} s^{-1}, which indicates that at a PFD 120 µmol m^{-2} s^{-1}, the photosynthetic apparatus of the plant was not in saturation, in contrast to other options, where NPQ remained practically unchanged with increasing PFD. On petunia plants, it was found that, under the blue–red spectrum, plant leaves have a lower index Qy [54] than in variants with a white diodes addition, but in our study the blue–red spectrum (V3) had no significant effect on red mustard's Qy index.

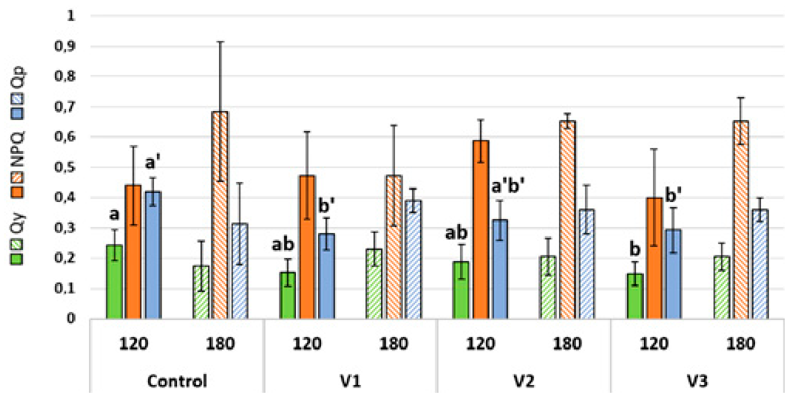

Figure 6. Chlorophyll fluorescence parameters in red mustard plants of the "Red Hill" variety on 30th day of cultivation depending on the type of radiation: Qy—effective quantum yield of photochemical reactions of photosystem II of light-adapted plants, non-photochemical quenching (NPQ), Qp—coefficient of photochemical fluorescence quenching. The different letters indicate significant differences among groups.

The maximal photochemical efficiency of photosystem II ($(F_m - F_o)/F_m$) (data not shown) had no significant differences between the variants and was in the range of 0.83 ÷ 0.84, which means that the photosynthetic apparatus was not damaged in the plants and they did not suffer from light stress [55].

Using a portable spectroradiometer, some vegetation indices were determined (Figure 7). A normalized difference vegetation index (NDVI) serves as an indicator of the plant's state and shows the total amount of green vegetation. PRI is a photochemical reflection index associated with the xanthophyll cycle, which allows us to determine the stress state of the plant's photosynthetic apparatus. (R780-R710)/(R780-R680) is the reflectance index associated with the concentration of chlorophylls [56,57]. The leaf reflection coefficients did not differ significantly from each other in the variants of the experiment, which may be due to slight differences between the variants in the concentrations of pigments (Figure 4), morphological parameters of the plants, and anatomical features of the leaf structure [57].

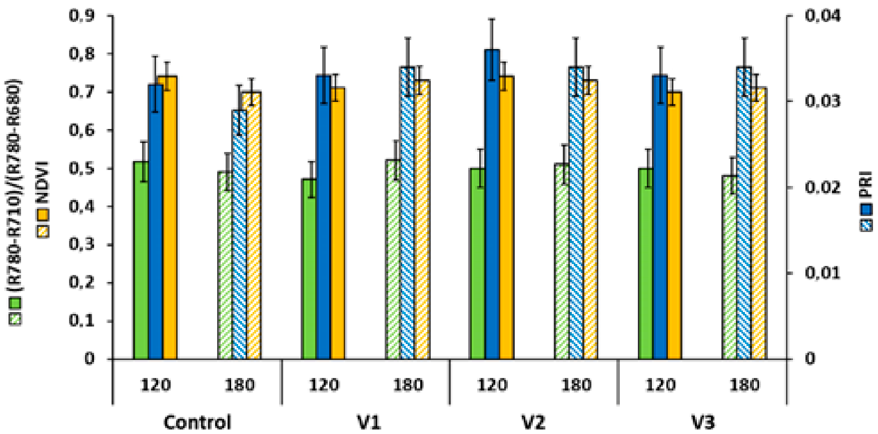

Figure 7. Reflection coefficients of red leaf mustard (*Brassica juncea* L.) plants of the "Red Hill" variety on 30th day of cultivation.

The leaf reflection coefficients did not differ significantly from each other in the variants of the experiment, which may be due to slight differences between the variants in the concentrations of pigments (Figure 4).

3.4. Energy Intensity

The electricity costs for the production of 1 g of mustard leaf at 30 days of cultivation were calculated (Figure 8). The lowest value of consumed energy was in variant V3 with a PFD of 180 µmol m^{-2} s^{-1} (77 Wt h/g). The highest value was observed in the V1 variant at a PFD of 120 µmol m^{-2} s^{-1} (190 Wt h/g). It can be associated with the efficiency of plant photon absorption of different spectral ranges. In the V3 variant, the irradiators contained mainly red and blue LEDs, which have the highest photon output of any LED available [58]. In addition, blue and red light are well absorbed by chlorophylls and carotenoids. The V3 variant was distinguished by a higher concentration of these photosynthetic pigments.

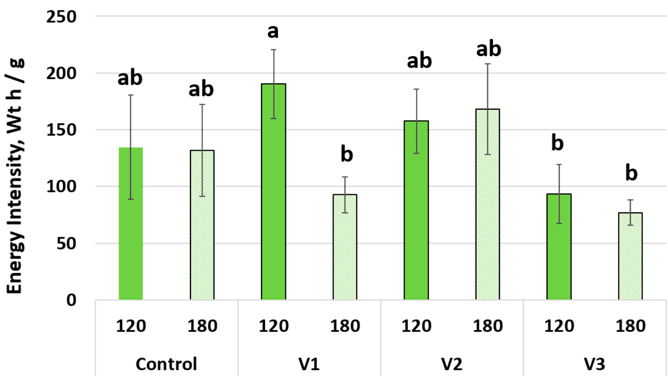

Figure 8. Energy intensity of cultivation of red leaf mustard (*Brassica juncea* L.) plants of the "Red Hill" variety on 30th day. The data shown are the means and the vertical bars indicate standard errors (n = 5). Statistically significant differences within $p \leq 0.05$. The different letters indicate significant differences among groups.

4. Discussion

Plants mainly absorb blue light and red light, which indicates the possibility of growing with red and blue LEDs [59]. Therefore, lettuce [60–62], radishes [63] and tomatoes [64] have been studied by numerous researchers using a combination of red and blue light. In this study, under red–blue LEDs, mustard leaf had a larger leaf area and fresh weight by 50% and 70%, respectively. Control and V2 plants had the lowest leaf area and fresh weight due to a higher green light PFD percentage (30%). In addition to red and blue LEDs, green and far red diodes were added to the growth chambers, as a combination of blue, red, green and far red light in small amounts is most suitable for crop growth [65]. Similar systems, for example, are installed on the International Space Station [66], at the Chinese space laboratory, Tiangong II [63], at the Vegetable Production System [66–71] and in the Advanced Plant Habitat [72].

It is well known that high and low light intensities, regardless of the spectral composition, inhibit the efficiency of photosynthesis, in particular the effective quantum yield [71]. In our work, we used different light intensities of 120 and 180 μmol photons m^{-2} s^{-1}; 120 μmol photons m^{-2} s^{-1} was not enough to completely saturate the photosynthetic apparatus of plants, as evidenced by an increase in NPQ and a decrease in Qy in leaves. It was also shown that in all experimental cases there was a decrease in NPQ and Qp. This is due to the presence of green and far red light in the spectrum, which stabilizes the photosynthetic apparatus and reduces the amount of photodamage in photosystem II [72]. Furthermore, the addition of a small amount of green light and far red light has been shown to save plants from photoinhibition when exposed to prolonged light [73,74]. These results show that our LED system is able to improve the growth and development of mustard.

5. Conclusions

When growing red mustard of the 'Red Hill" variety, the best lighting option was the red–blue (V3) with an irradiation intensity of 180 μmol m^{-2} s^{-1}. This intensity meets the needs of mustard plants, and the spectral composition, with the highest proportion of blue and red illumination among the selected options, contributes to the formation of compact dense rosettes of leaves with a larger leaf area and fresh mass. Additional illumination of plants with green and far-red light in variants with the addition of white LEDs for mustard did not contribute to an increase in fresh mass, in contrast to other studies of green crops [15]. The addition of green and far red radiation to blue–red light in various proportions at the same level of PFD, in contrast to studies on microgreens [39], had a negative effect on plant fresh mass, leaf surface area and photosynthetic activity. In future studies we are going to identify the optimal proportion of blue and red light and variety-specific reactions when growing red mustard of various varieties.

The results obtained will be useful for the optimization of the artificial lighting parameters of red mustard cultivation in urban farms.

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