Research Article **Open Access**

Barbara Frąszczak*, Monika Gąsecka, Anna Golcz, Renata Zawirska-Wojtasiak

The effect of radiation of LED modules on the growth of dill (*Anethum graveolens* L.)

DOI 10.1515/biol-2016-0008
Received November 26, 2014; accepted February 12, 2016

Abstract: Light quality is thought to affect the growth and development of plants. We examined how light influences the growth and content of some chemical compounds in dill (*Anethum graveolens* L.). The plants were grown under different light quality. The share of orange and green light in the spectrum was constant and amounted to 10% for either colour. In the first combination (A, 70/10), there was 70% of red light and 10% of blue light. Other combinations had the following proportions: B 60/20, C 50/30, D 40/40 and E 30/50 of red and blue light. The PPFD was about 155 μmol m^{-2} s^{-1}. Blue light inhibited the elongation growth as well as leaf area. It had positive influence on the accumulation of dry mass, glucose and fructose in the herb. In the combinations with higher percentage of red light the plants were characterised by higher content of essential oils, macronutrients and zinc. To sum up, we can say that the proportion of red and blue light has significant influence on the morphological qualities, chemical composition and dynamics of photosynthesis in these plants. On the other hand, the selection of spectral composition of LEDs will depend on the result we want to achieve.

Keywords: light quality, LEDs, physiological indices, essential oils, photosynthetic rate (Pn), stomatal conductance (gs), macro-micronutrients

***Corresponding author: Barbara Frąszczak,** Department of Vegetable Crops, Poznań University of Life Sciences, ul. Dąbrowskiego 159, 60-597 Poznań, Poland, E-mail: barbaraf@up.poznan.pl
Monika Gąsecka, Department of Chemistry, Poznań University of Life Sciences, ul. Dąbrowskiego 159, 60-597 Poznań, Poland
Anna Golcz, Department of Plant Nutrition, Poznań University of Life Sciences, ul. Dąbrowskiego 159, 60-597 Poznań, Poland
Renata Zawirska-Wojtasiak, Institute of Food Technology of Plant Origin, Poznań University of Life Sciences, ul. Dąbrowskiego 159, 60-597 Poznań, Poland

1 Introduction

According to published literature, plants can complete their life cycle under red LEDs alone, however higher production of biomass and greater photosynthetic capacity due to blue and red light combinations was observed in many papers [1-4]. The absence of one of these light wavebands causes photosynthetic inefficiencies [5]. Apart from that, the ratio of blue, red and far red is important for the normal photomorphogenesis of various plants [6]. As demonstrated in studies, the combination of red and blue LEDs has proved to be an effective lighting source for several crops [7]. However, the effects of different combinations of red and blue light on the growth and development of plants have not yet been fully investigated. Yorio et al. [8] suggested that 10% of blue light would be an acceptable level for the growth of lettuce, spinach and radish. Other studies have demonstrated that the combination of red and blue light at 1:1 ratio was found to be more effective for the growth of cherry tomato plants [9,10]. The aforementioned publications suggest that one combination of red and blue light would not be favourable to all species and stages of plant development as the reactions of plants are very different, depending on the species.

The combination of red and blue light is the most effective photosynthetic waveband. Red light is important for the accumulation of starch in the photosynthetic apparatus [11]. Blue light is important for photosynthesis, chloroplast development and chemical composition of plants, but the response is highly dependent on the dosage of blue light [5]. However, even healthy plants grown under red and blue LEDs alone appear purplish grey [6]. The addition of green light in combination with red and blue LEDs may increase the plant growth, since green light can better penetrate into the plant canopy than red or blue light [12]. There is not much information about the effect of orange light in literature and the data is contradictory [13]. The authors observed that orange light added to the combination of red and blue light decreased the growth of tomato transplants. The plants were not high, but their hypocotyls were elongated and relatively

thin. The abovementioned studies show that in order to guarantee the normal growth and development of plants cultivated under artificial light, it is necessary to create spectrally balanced LED systems.

The aim of this study was to evaluate the effect of different combinations of LED red and blue light with orange and green light added on the growth, physiological indices and chemical composition of dill plants.

2 Experimental Procedures

2.1 Growth conditions and plant material

Pot experiments were carried out in a growing room at the Poznań University of Life Sciences, Poland. The plants grew in five different combinations with varying percentage of red and blue light and a fixed amount of green and orange light. The lighting parameters used in each treatment are shown in Figure 1 and Table 1. The plants were cultivated in a growing room with five separate tables having different spectral distributions. Thus, the plants had exactly the same growth conditions. The tables measured approxmiately 1 m^2. Above each table, LED flexible strips (LSX 5300, type SMD, Seoul Semiconductor, South Korea) were hung. The LED panel consisted of 60 flexible strips with 60 LEDs per meter. Photoperiods were adjusted by a control system, whereas lighting was adjusted manually. The photosynthetic photon flux density (PPFD) amounted to about 155 µmol m^{-2} s^{-1} at the top of the plants and was measured with a quantum sensor (PAR-10, Sanopan, Poland). The spectral distribution of light treatments was measured with a spectroradiometer BLACK-Comet CXR, 280-900 nm (UV-VIS by StellarNet Inc.). The

Table 1. Major light wavelength of different light combinations and flux densities.

Light colour	Wavelength	Light-emitting diodes (LEDs) PFD* (µmol m^{-2} s^{-1})				
		Treatment				
		A**(70/10)	B (60/20)	C (50/30)	D (40/40)	E (30/50)
UV	320–380	0.0	0.0	0.0	0.0	0.0
Blue	380–495	17.4	33.6	46.4	62.6	78.2
Green	495–570	14.6	14.6	14.6	14.6	14.6
Yellow- Orange	570–620	15.0	15.0	15.0	15.0	15.0
Red	620–700	107.8	93.2	77.1	63.7	46.4
Far Red	700–780	0.1	0.09	0.09	0.08	0.08
Total	320–780	154.9	156.6	153.2	155.7	154.3

*PFD: Photon Flux Density, **A – name of combination, 70- red light fraction (%), 10 – blue light fraction (%)

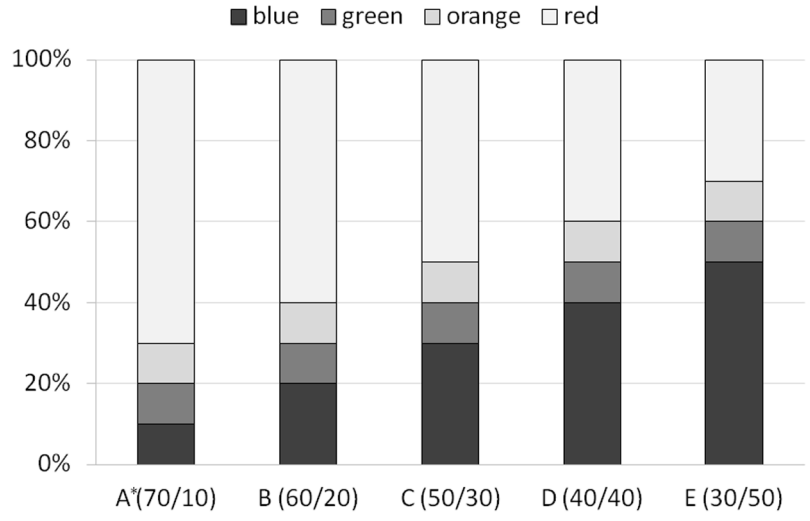

Figure 1. The percentage of each light colour in treatments. A* – name of combination, 70- red light fraction (%), 10 – blue light fraction (%).

measurements were made 15 cm under the lamps, more or less at the height of the plant tops. A 16-hour photoperiod and a day/night temperature of 23/18°C were maintained. A relative humidity was 65-70%.

'Ambrozja', a dill (*Anethum graveolens* L.) cultivar, was seeded in a white peat bedding substrate (Klassmann-Deilman, Germany). After germination, the dill plants were cultivated for 28 days (four weeks). The number of plants grown in a single pot was similar, i.e. 40 (± 5) plants. They were grown in pots with a capacity of 280 cm^3 and a cultivation area of 49 cm^2. The plants were watered on capillary mats every other day.

2.2 Biometric measurements

The plants were evaluated every 7 days during vegetation, for the first time - seven days after germination and later on the 14th, 21st and 28th day after the germination. Harvesting involved hand cutting of the plants close to the surface of the substrate. After the harvest, the weight of the fresh matter of the plants in every pot was determined. In addition, the plant height, length of the hypocotyl and the area of leaves were also measured (ten plants per pot, four pots per treatment). A scanner (Mustek 1200 UB) and the *Skwer* program (*IksmodaR*, Poland) were used to calculate the area of leaves.

Dry mass composition was determined by drying the material to a constant weight at 105°C for 24 h (PN-90/A-75101/03).

2.3 Chemicals

At harvest, after 28 days of cultivation, plant samples were collected for chemical analyses.

2.3.1 Saccharide content in the herb

Sugars were extracted from leaf samples weighing approximately 1.5 g for 60 min with 10 mL of ethanol/water mixture (80:20, v/v) at 80°C [14]. The extract was filtered through AP 200 1300 glass fibre pre-filters (Millipore). After solvent evaporation, 1 ml of mobile phase (acetonitrile/water, 75:25, v/v) was added and the extracts were analysed with a Waters Alliance 2695 Chromatograph coupled with a Waters RI detector 2414. The acetonitrile/water mobile phase (75:25, v/v) was used at a flow rate of 1.0 mL min^{-1} to separate soluble sugars (fructose, glucose and sucrose) on a Supelcosil LC NH_2 column.

2.3.2 Phenolic compounds in herb

The leaves were ground to a fine powder in liquid nitrogen. Phenolic compounds were then extracted twice with 10 mL of methanol and centrifuged. The total phenolic content was determined using Folin-Ciocalteu reagent as described by Dong et al. [15] with some modifications. The standard solution and the extract were mixed with 0.1 mL of Folin-Ciocalteu's reagent. After 3 min, 1 mL of 10% Na_2CO_2 solution was added. After 30 min of incubation at room temperature, absorbance was measured with a Cary 300 Bio UV-Vis spectrophotometer at a wavelength λ=765 nm. The total phenolic content was expressed as milligrams of gallic acid per gram of dry extract.

Prior to analysis, dried methanolic extracts of samples were dissolved in 1 ml of methanol. HPLC analysis was performed using a Waters Alliance 2695 chromatograph coupled with a Waters 2996 photodiode array detector. Chromatographic separation was performed on an RP C-18 column, 250 × 4 mm × 5 μm, with acetonitrile: 2% aqueous acetic acid mixture (pH=2) used as an elution phase (gradient). The concentration of phenolic acids was determined with an internal standard at wavelengths λ= 280 nm (gallic, chlorogenic, caffeic and p-coumaric acids) or λ=320 nm and 280 nm (ferulic and t-cinnamic acids), myricetin - $C_{15}H_{10}O_8$ λ=320 nm. Compounds were identified by comparing the retention time of the analysed peak with the retention time of the standard and by adding a specific amount of the standard to the samples under analysis and repeating the analysis. The detection level was 1 μg/g. The retention times of the assayed acids were as follows: gallic acid 8.85 min, chlorogenic acid 21.60 min, caffeic-26.19, p-coumaric acid 40.20 min. The detection limit was 1 mg/kg.

2.3.3 Analysis of essential oils (GC/MS, Chiral GC)

Essential oils were isolated from 1 g of dill by hydrodistillation with a Deryng laboratory glass apparatus of the Polish Pharmacopeia [16]. The distillation took 3 h. Before distillation, 1.5 mg of the internal standard (pentadecane) was added together with 0.3 mL of xylene, used as the extraction solvent.

A Hewlett-Packard HP 6890 gas chromatograph with a split/splitless injector and FID detector was used for analyses. Compounds were separated with a DB-5 capillary column (30 m × 0.32 mm × 0.25 μm). The analysis parameters on the DB-5 column were as follows: initial temperature 40°C (for 1 min), then 8°C/min to 230°C/min. Hydrogen was used as a carrier gas at a flow rate of 1.6 mL/min.

The amount of volatiles was calculated based on the known amount of the internal standard added to the sample prior to the distillation.

The identity of the separated compounds was confirmed with an Agilent 7890 chromatograph coupled to an Agilent 5957 VLASD mass detector.

2.3.4 Macro- and micronutrients in the herb

In order to assay for N, P, K, Ca, Mg and Na the plant material was mineralised in concentrated sulfuric acid, while for analyses of total S, Fe, Mn, Zn and Cu - in a mixture of nitric and perchloric acids (3:1, v/v). After mineralisation of the plant material the following determinations were performed: N-total using the distillation method according to Kjeldahl in a Parnas Wagner apparatus; P - colorimetrically with ammonia molybdate; S by nephelometry and K, Ca, Mg, Na, Fe, Mn, Zn, Cu using flame atomic absorption spectroscopy (FAAS, on a Carl Zeiss Jena apparatus).

2.4 Net photosynthetic rate

Photosynthesis was measured with a gas exchange measurement system (LCpro+, ADC BioScientific). Gas exchange was measured with a custom-made leaf chamber (6.25 cm^2). After steady-state rates of A (photosynthetic rate) had been recorded (approx. 1 h), the leaves were removed from the chamber and the leaf area was measured. The second youngest, but fully developed leaves were used for measurements (n = 5). Photosynthesis was measured in the conditions that the plants were grown. The measurements were taken on the 26- 28^{th} days of cultivation.

2.5 Statistical analysis

The experiments were carried out in five combinations and in two cultivation cycles. There were 4 replicates in each cycle. Three pots were treated as one replicate. The analyses of the chemical composition and dry mass content were performed in four replicate for both cycles. The analyses of the content of essential oils and macro- and micronutrients were performed in two replicates, but they were not analysed statistically. The results presented in this study are the means of two cycles. The significance of the impact of the light source on the plant characteristics was determined with ANOVA. Differences between the means were estimated with the Newman-Keuls test at the level of significance $\alpha = 0.05$. All statistical analyses were carried out with the *Statistica* program (StatSoft, Poland).

2.6 Physiological indices

The dry mass and leaf area data were used to determine the following physiological indices of growth: relative growth rate (RGR), net assimilation rate (NAR), leaf area index (LAI) and specific leaf area (SLA), as described by Hunt [17]. The values of indices refer to individual pots. The relative growth rate (RGR) index was calculated using the following formula: $RGR = (\ln W_2 - \ln W_1)(t_2 - t_1)$, where W_2 and W_1 refer to the plant dry mass (g) at times t_2 and t_1, respectively. The net assimilation rate (NAR) is the increase of biomass per unit of time and per any unit of measurement of magnitude of the assimilation organs: $NAR = dW/(A \cdot dt)$, where A = area of assimilation organs (dm^2), dW = dry mass increment (g), dt = time of cultivation (day). The leaf area index (LAI) refers to the area of the leaf surface in relation to the floor area taken up by all plants. It was calculated using the following formula: LAI = A/P, where: A – plant assimilation area (dm^2), P – floor area (dm^2). Specific leaf area (SLA) is defined as the ratio between the leaf area and the dry mass of leaves: $SLA = L_A/L_W$, where L_A = leaf area (dm^2), L_W = dry mass of leaves (g).

3 Results

Table 2 summarizes the changes in dill biomass when exposed to the different ratios of red and blue light. The length of the hypocotyl and the height of the plants were directly proportional to the amount of red light with maximum length and height seen with the highest red light condition (A, 70/10). However, the influence of the spectral composition of light on the fresh mass of dill was not so definite, especially during the first three weeks of cultivation. After 28 days the greatest amount of both fresh and dry mass was observed in combination C (50/30). During the entire period of cultivation, the plants exposed to higher percentage of blue light (E, 30/50) were characterised by high yield of dry mass. During the first week, there were no significant differences in the leaf area between the combinations. In subsequent weeks, the leaf area was the smallest in combination E (30/50). Thus, the plants showed distinct growth responses to different light-quality treatments.

There was greater content of nitrogen, phosphorus, potassium, calcium and zinc observed in the combinations with greater amounts of red light (Table 3). The content of

Table 2. The morphological characteristics of dill plants grown under different spectral composition of light.

Treatments	Days after germination			
	7	14	21	28
	Length of hypocotyl (cm)			
A** (70/10)	5.8 a*	5.8 a	6.5 a	6.9 a
B (60/20)	3.1 c	3.9 b	3.9 c	5.8 b
C (50/30)	3.2 c	3.5 c	3.8 c	4.5 c
D (40/40)	3.7 b	3.9 b	4.3 b	4.7 c
E (30/50)	3.8 b	4.1 b	4.3 b	5.1 c
	Length of plant (cm)			
A (70/10)	9.6 a	12.3 a	14.3 a	16.3 a
B (60/20)	8.3 b	10.4 b	12.2 b	16.2 a
C (50/30)	7.7 b	9.7 bc	12.6 b	13.4 bc
D (40/40)	8.0 b	9.1 c	12.1 b	14.2 b
E (30/50)	8.1 b	8.9 c	12.1 b	13.0 c
	Fresh mass (g pot^{-1})			
A (70/10)	1.1 a	2.8 cd	4.9 b	9.9 b
B (60/20)	0.9 b	3.9 ab	5.4 ab	8.2 c
C (50/30)	0.6 c	2.4 d	6.9 a	11.2 a
D (40/40)	1.1 a	4.2 a	6.1 ab	10.0 b
E (30/50)	0.9 b	3.3 bc	5.9 ab	8.31 c
	Dry mass (g pot^{-1})			
A (70/10)	0.11 ab	0.26 d	0.51 c	1.03 b
B (60/20)	0.11 ab	0.35 c	0.33 d	1.09 b
C (50/30)	0.09 b	0.22 d	0.72 b	1.26 a
D (40/40)	0.10 ab	0.55 a	0.76 b	0.94 b
E (30/50)	0.13 a	0.47 b	0.93 a	1.29 a
	Leaf area (dm^2)			
A (70/10)	0.66 a	0.71 a	0.96 ab	1.61 b
B (60/20)	0.68 a	0.70 a	1.04 a	1.74 a
C (50/30)	0.60 a	0.69 a	1.02 a	1.69 ab
D (40/40)	0.64 a	0.54 b	1.04 a	1.75 a
E (30/50)	0.60 a	0.30 c	0.87 b	1.45 c

* – the values followed by the same letters for an individual factor do not differ significantly at $\alpha = 0.05$
**A – name of combination, 70- red light fraction (%), 10 – blue light fraction (%)

iron and manganese was greater in the combinations with increasing amounts of blue light, except for combination D (40/40). The plants growing in that combination were characterised by the greatest content of copper.

Essential oils were the greatest in the combination with the highest percentage of red light and it decreased as the percentage of red light decreased in consecutive combinations (Table 4). The total amount of aromatic compounds in the dill herb ranged from 0.85 mg/g to 1.96 mg/g, where phellandrene was the dominant compound in terms of quantity (70.6 – 88.3%)

Phenolics were not significantly affected by light treatments in our experiment (Table 5).

Among simple saccharides, fructose content was the highest (Table 6). There was about 50% less glucose whereas sucrose was the lowest – about 6%, when compared to fructose. The fructose content was the greatest in the combinations with higher amounts of blue light, i.e. in combinations C (50/30) and D (40/40) whereas higher glucose was noticed in combinations D (40/40) and E (30/50). The content of sucrose was the greatest in the combination with the highest amount of red light, i.e. A (70/10).

The highest photosynthetic efficiency was observed in combinations B (60/20) and C (50/30) (Table 7). The plants in combination D (40/40) were characterised by the highest stomatal conductance.

During the initial period, the RGR and NAR values were the greatest in the combinations with a high percentage of blue light (D 40/40, E 30/50) (Figure 2). In

Table 3. Macro- and micronutrient content in dill herb depending on the spectral compositions of light.

Treatments	N	P	K	Ca	Mg	Na	S	Fe	Mn	Zn	Cu
				(% DW)					(ppm)		
A* (70/10)	3.26	0.87	4.23	2.43	0.61	0.06	0.38	121.95	83.10	182.35	12.65
B (60/20)	3.21	0.96	4.51	2.48	0.65	0.04	0.38	126.10	146.10	180.70	12.25
C (50/30)	2.94	0.72	3.65	2.28	0.68	0.04	0.42	181.15	182.55	143.90	11.60
D (40/40)	3.12	0.88	4.41	2.38	0.46	0.06	0.39	138.60	134.60	159.20	13.50
E (30/50)	3.17	0.84	4.26	2.19	0.42	0.06	0.40	188.75	200.35	152.90	12.65

*A – name of combination, 70- red light fraction (%), 10 – blue light fraction (%)

Table 4. Essential oils in the dill herb as a function of the spectral composition of light.

Essential oils ($mg \times g^{-1}$ FW)	Treatments				
	A* (70/10)	B (60/20)	C (50/30)	D (40/40)	E (30/50)
total	1.96	1.26	0.85	0.99	1.05
phellandrene	1.73	1.08	0.60	0.78	0.88

*A – name of combination, 70- red light fraction (%), 10 – blue light fraction (%)

Table 5. Phenolic acids in the dill herb as a function of the spectral compositions of light.

Treatments	Phenolic		
	vanillic acid ($ng \times g^{-1}$ FW.)	syringic acid ($ng \times g^{-1}$ FW.)	total (mg GAE$\times g^{-1}$ FW.)
A** (70/10)	536.69 a*	791.73 a	85.87 a
B (60/20)	550.60 a	809.65 a	92.28 a
C (50/30)	566.57 a	842.60 a	85.19 a
D (40/40)	542.31 a	799.69 a	95.90 a
E (30/50)	566.68 a	834.07 a	95.77 a

* – the values followed by the same letters for an individual factor do not differ significantly at $\alpha = 0.05$
**A – name of combination, 70- red light fraction (%), 10 – blue light fraction (%)

Table 6. Simple saccharide content of dill herb as a function of the spectral composition of light.

Treatments	Sacharider		
	Fructose ($\mu g \times g^{-1}$ FW.)	Glucose ($\mu g \times g^{-1}$ FW.)	Sucrose ($\mu g \times g^{-1}$ FW.)
A** (70/10)	2197.7 ab*	1040.9 b	153.4 a
B (60/20)	2025.9 b	1122.9 ab	117.0 ab
C (50/30)	2232.4 a	1054.4 b	135.3 ab
D (40/40)	2319.0 a	1212.3 a	121.5 ab
E (30/50)	2054.0 b	1264.5 a	101.3 b

* – the values followed by the same letters for an individual factor do not differ significantly at $\alpha = 0.05$
**A – name of combination, 70- red light fraction (%), 10 – blue light fraction (%)

Table 7. The effect of different light treatment on the net photosynthetic rate (Pn) and stomatal conductance (gs) of dill plants.

Treatments	Net photosynthetic rate (μmol CO_2 h^{-1} $plant^{-1}$)	Stomatal conductance (mol·m^{-2}·s^{-1})
A** (70/10)	21.2 b*	0.38 b
B (60/20)	26.8 a	0.34 b
C (50/30)	25.6 a	0.31 b
D (40/40)	20.5 b	0.50 a
E (30/50)	20.3 b	0.35 b

* – the values followed by the same letters for an individual factor do not differ significantly at α = 0.05
**A – name of combination, 70- red light fraction (%), 10 – blue light fraction (%)

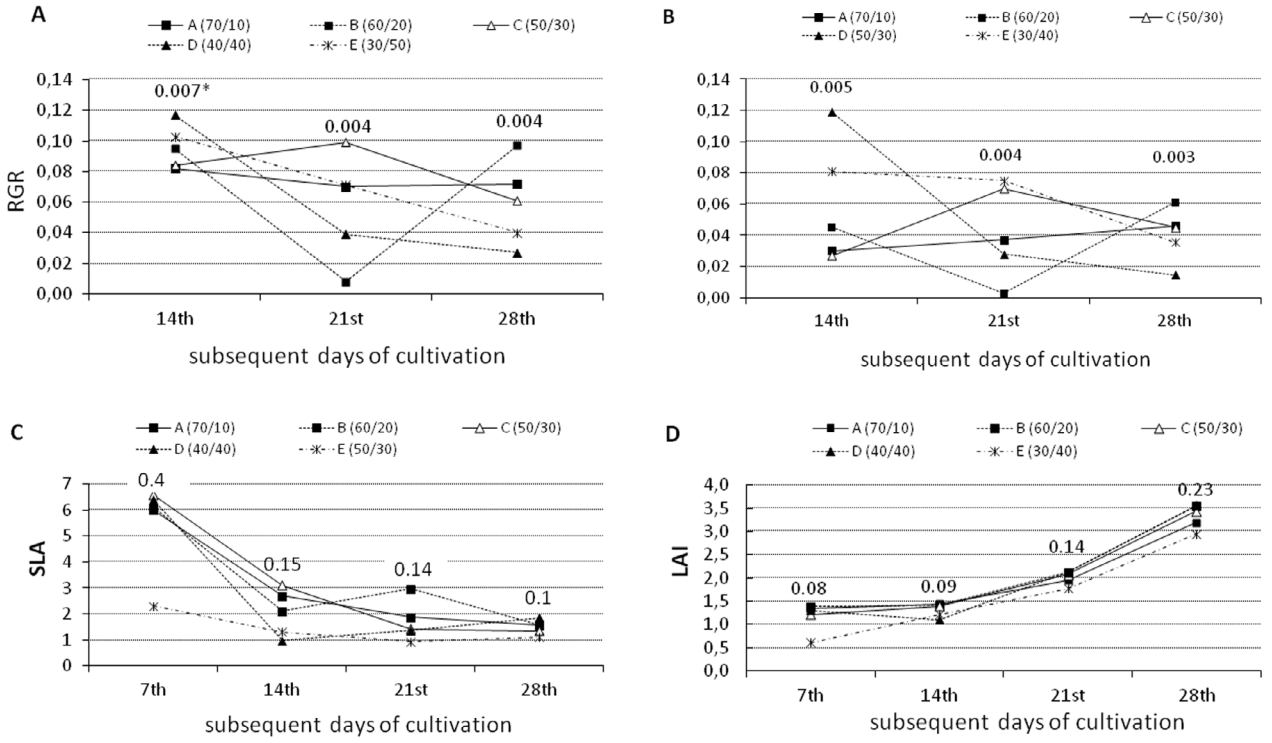

Figure 2. The effect of different light treatment on (a) RGR – relative growth rate index; (b) NAR – net assimilation rate; (c) SLA – specific leaf area; (d) LAI – leaf area index. *LSD – least significant differences at α = 0.05 A – name of combination, 70- red light fraction (%), 10 – blue.

the next week of growth, there was a very big decrease in the RGR and NAR indices for those combinations. On the last day of cultivation the highest value of both indices was observed in combination B (60/20). During the whole period of cultivation the plants in combination A (70/10) were characterised by the smallest changes in the values of both indices. The values of both the SLA and LAI index were the lowest in the combination with the highest share of blue light (E 30/50). During the entire period of cultivation, both indices (SLA and LAI) had high values in the combinations with a higher share of red light (A-C), and in the last week – also in combination D (40/40).

4 Discussion

Red and blue lights have the greatest impact on the plant growth because they are the major energy sources for photosynthetic CO_2 assimilation in plants [18]. According to Averchev et al. [19], for the growth of plants the appropriate ratio between red and blue light is 7:1, where the PPFD is 350-400 μmol m^{-2} s^{-1}. In their study, the plants which grew under the light with the aforementioned proportion (combination A, 70/10) were characterised by the greatest height and length of hypocotyl. This must have been caused by the low amount of blue light in that

combination, which strongly reduces the growth of shoots in some plants [20, 21]. It is noteworthy that especially in the initial period of growth the smallest length of hypocotyl was observed in combinations B (60/20) and C (50/30). Thus, we can assume that the two proportions of light are particularly favourable to dill when it is necessary to prevent excessive shooting of plants during the initial growth period. 28 days after the emergence, plants from the combinations with the increasing share of blue light (C, D, E) were characterised by a significantly shorter length of hypocotyl than the plants from the first two combinations, where the proportion of blue light was much lower than the proportion of red light. In the study by Samuolienė et al. [22], 5% of blue light added to red light was not sufficient to inhibit excessive elongation of radish. A considerable reduction in the length of hypocotyl was noticed when blue light proportion reached 10% .

It is known that blue light is important for leaf expansion and it enhances the leaf area and biomass production [5, 23]. In our study, combination C (50/30) was characterised by the greatest fresh mass of plants in the last week. Some authors have suggested that the combination of red and blue light at a 1:1 ratio might promote fresh and dry weight in many plant species [9, 24]. Our research also revealed the positive influence of this combination (D 40/40) on the fresh mass of dill, but only for the first three measurements. The authors suppose that increasing the amount of blue light at the expense of red light causes a decrease in the fresh mass of plants. In this study, blue light also caused a higher content of dry weight in the dill herb. Yorio et al. [8] reported that when lettuce, radish and spinach were grown under red LEDs, the accumulation of dry weight was lower than when the plants were grown under red LEDs + 10% BF light.

Observations from other studies suggest that when red [25] or blue and green light [26] were added, there was an increase in phenols in the plant under study. In our study, we did not observe the influence of diversified spectral composition of light on the content of phenols. The differences between the proportions of blue and red light may have been too small to affect the synthesis of phenols.

Supplemental blue light with red light significantly increased the photosynthetic rate when compared to red light only [27, 28]. We observed that the CO_2 assimilation rate (Pn) was the greatest when there were large amounts of red and blue light, i.e. in combinations B (60/20) and C (50/30). In the other combinations, where the amount of blue light increased and the amount of red light decreased, Pn was much lower. We can conclude that the addition of blue light increases Pn but only if there is enough red light in the spectrum.

Several studies have shown that under blue light plants have a higher stomatal conductance (gs) than under other lights [29, 30]. However, it is not always correlated with an increase in Pn [30]. A similar reaction was observed in this study. The highest gs value was observed in combination D (40/40), but was characterised by a lower Pn value than in the other combinations.

Red light was found to have significant influence on the content of essential oils and phellandrene. According to Soylu et al. [31], the aroma of dill herb oil from the leaves and stems is caused by phellandrene and dill ether. In the study by Nishioka et al. [32], the content of essential oils in Japanese mint was higher in the red light treatment than in the blue and green light treatment. However, the concentration of *l*-menthol was not affected by the light quality. In that study, the percentage of individual enantiomers did not differ depending on the spectral composition of light. However, the amount and composition of essential oils also depend on the height of the plant and they usually increase as the plant becomes more mature [33]. According to Callan et al. [34], the high density of plants in the initial growth period increases the amount of phellandrene and pinene, as compared with carvone. To sum up, we can say that red light might have positive effect on the production of essential oils in dill.

The influence of the applied light combinations on the content of macro- and micronutrients in leaves was diversified. Potassium was the prevalent macronutrient. According to Słupski et al. [35], potassium prevailed in ash, leaves and whole dill plants. The lowest content of N, P and K in leaves was observed in combination C (50/30), which was also characterised by the greatest photosynthesis intensity and the highest content of fresh weight. The plants grown in that combination were also characterised by the high content of Mg, Fe and S and low content of Zn and Cu. Matsuda et al. [27] found that rice plants grown under red light in combination with blue light had higher content of total nitrogen (N) in leaves than those grown under red light alone. They also observed a positive correlation between the content of nitrogen (N) in leaves and stomatal conductance and the dynamics of photosynthesis. We did not observe this correlation in our study, which may have been caused by small differences in the content of nitrogen between individual combinations. The absence of a correlation may also have been caused by the low PPFD level, because according to Hirose and Werger [36], the positive correlation between the photosynthetic rate and the content of N in leaves is gradually lost as the PPFD decreases.

It is known that light conditions have considerable influence on the content of sugar in leaves [37]. The content

of glucose and fructose was the highest in the combinations with a greater share of blue light. On the other hand, the content of sucrose did not differ significantly depending on the applied combination. Many authors report that the addition of blue light stimulates the synthesis of simple saccharides in plants [19, 30].

The growth of plants is the result of interaction between environmental factors and biomass allocation parameters determining the potential RGR [38]. The RGR was correlated with its physiological (NAR) component. The high RGR and NAR values after 14 days of growth in the combinations where the share of blue light was greater than the share of red light may have resulted from the fact that blue light is a good light source for chlorophyll induction in the initial growth period [39]. According to Hogewoning et al. [5], a higher content of chlorophyll is related to the higher ratio of blue light in the light source. Furthermore, supplemental blue light with red light significantly increased the photosynthetic rate and plant biomass [28]. It is noteworthy that the RGR and NAR were negatively correlated with the morphological indices (SLA, LAI). The lowest values of these indices were observed in the combination with the highest share of blue light, which strongly inhibits the growth of many plant species [21,40].

5 Concluding remarks

The ratio of red and blue light at 60/20 and 50/30 ratios was most favourable for the dynamics of growth and Pn intensity of dill plants. A higher percentage of red light in the spectrum also had a positive influence on the accumulation of essential oils and macronutrients in the dill herb. On the other hand, a higher amount of blue light noticeably inhibited excessive elongation of plants and the area of leaves, but it increased the amount of fructose and glucose. Thus, the spectral composition of light applied to plants at the initial growth stage will largely depend on the planned effects.

Conflict of interest: Dr Frąszczak has nothing to disclose

References

[1] Zhang S., Ma K., Chen L., Response of photosynthetic plasticity of *Paeonia suffruticosa* to changed light environments. Environ. Exp. Bot., 2003, 49, 2, 121-133

[2] Goins G.D., Yorio N.C., Sanwo M.M., Brown C.S., Sager J.C., Photomorphogenesis, photosynthesis, and seed yield of wheat plants grown under red light-emitting diodes (LEDs) with and without supplemental blue lighting. J. Exp. Bot., 1997, 48, 1407-1413

[3] Lee S.-H., Tewari R.K., Hahn E.-J., Peak K.-Y., Photon flux density and light quality induces changes in growth, stomatal development, photosynthesis and transpiration of *Withania Somfifera* (L.) Duanl., plantlets. Plant Cell Tiss. Organ Cult., 2007, 90, 141-151

[4] Matsuda R., Ohasshi-Kaneko K., Fujiwara K., Kurata K., Analysis of the relationship between blue-light photon flux density and the photosynthetic properties of spinach (*Spinacia oleracea* L.) leaves with regard to the acclimation of photosynthesis to growth irradiance. Soil Sci. Plant Nutr., 2007, 53, 459-465

[5] Hogewoning S.W., Trouwborst G., Maljaars H., Poorter H., Ieperen W.V. Harbinson, J., 2010. Blue light dose-responses of leaf photosynthesis, morphology, and chemical composition of *Cucumis sativus* grown under different combinations of red and blue light. J. Exp. Bot. 61, 3107-3117

[6] Kim H.H., Wheeler R.M., Sager J.C., Goins G.D., Norikane J.H., Evaluation of lettuce growth using supplemental green light with red and blue light-emitting diodes in a controlled environment – A review of research at Kennedy Space Center. Acta Hortic., 2006, 711, 111-119

[7] Kim H.H., Wheeler R.M., Sager J.C., Yorio N.C., Light-emitting diodes as an illumination source for plants: a review of research at Kennedy Space Center. Habitation, 2005, 10, 71-78

[8] Yorio N.C., Goins G.D., Kagie H.R., Wheeler R.M., Sager J.C., Goins G.D., Improving spinach, radish, and lettuce growth under red light-emitting diodes (LEDs) with blue light supplementation. HortScience., 2001, 36, 380-383

[9] Liu X.Y., Guo S.R., Xu Z.G., Jiao X.L., Takafumi T., Regulation of chloroplast ultrastructure, cross-section anatomy of leaves and morphology of stomata of cherry tomato by different light irradiations of LEDs. HortScience., 2011, 46, 217-221

[10] Fan X.X., Xu Z.G., Liu X.Y., Tang C.M., Wang L.W., Han H.L., Effects of light intensity on the growth and leaf development of young tomato plants grown under a combination of red and blue light. Sci. Hortic., 2013, 153, 50-55

[11] Sæbø A., Krekling T., Appelgren M., Light quality affects photosynthesis and leaf anatomy of birch plantlets *in vitro*. Plant Cell Tissue Organ Cult., 1995, 41, 177-185

[12] Folta K.M, Maruhnich S.A., Green light: a signal to slow down or stop. J. Exp. Bot., 2007, 58, 12, 3099-3111

[13] Brazaitytė A., Duchovskis P., Urbonavičiūtė A., Samuolienė G., Jankauskienė J., Sakalauskaitė J., et al., The effect of light-emitting diodes lighting on the growth of tomato transplants. Zemdirbyste – Agriculture, 2010, 97, 2, 89-98

[14] Johansen H.N., Glitso V., Knutsen K.E.B., Influence of extraction solvent and temperature on the quantitative determination of oligosaccharides from plant materials by high-performance liquid chromatography. J. Agr. Food Chem., 1996, 44, 1470-1474

[15] Dong J., Zhang M., Lu L., Sun L., Xu M., Nitric oxide fumigation stimulates flavonoid and phenolic accumulation and enhances antioxidant activity of mushroom. Food Chem., 2012, 135, 3, 1220-1225

[16] Polish Pharmacopoeia, IV, Warszawa, 2002

[17] Hunt R., Plant Growth Curves, the functional approach to plant growth analysis, Edward Arnold, Sheffield, 1982, 16-46

[18] Lin K.-H., Huang M.-Y., Huang W.-D., Hsu M.-H., Yang Z.-W., Yang C.-M., The effects of red, blue, and white light-emitting

diodes on the growth, development, and edible quality of hydroponically grown lettuce (*Lactuca sativa* L. var. *capitata*). Scientia Hort., 2013, 150, 86-91

[19] Avercheva O.V., Berkovich Yu.A., Erokhin A.N., Zhigalova T.V., Pogosyan S.I., Smolyanina S.O., Growth and photosynthesis of chinese cabbage plants grown under light-emitting diode-based light source. Russ. J. Plant Physiol., 2009, 56, 1, 14-21

[20] Johkan M., Shoji K., Goto F., Hashida S., Yoshihara T., Blue light-emitting diode light irradiation of seedlings improves seedling quality and growth after transplanting in red leaf lettuce. HortScience., 2010, 45, 1809-1814

[21] Islam M.A., Kuwar G., Clarke J.L., Blystad D-R., Gislerød H.R., Olsen J.E., Torre S., Artificial light from light emitting diodes (LEDs) with a high portion of blue light results in shorter poinsettias compared to high pressure sodium (HPS) lamps. Sci. Hortic., 2012, 147, 136-143

[22] Samuolienė G., Sirtautas R., Brazaitytė A., Sakalauskaitė J., Sakalauskienė S., Duchovskis P., The impact of red and blue light-emitting diode illumination on radish physiological indices. Cent. Eur. J. Biol., 2011, 6, 5, 821-828

[23] Li H.M., Xu Z.G., Tang C.M., Effect of light emitting diodes on growth and morphogenesis of upland cotton (*Gossypium hirsutum* L.) plantlets in vitro. Plant Cell Tissue Organ Cult., 2010, 103, 155-163

[24] Kim S.J., Hahn E.J., Heo J.W., Paek K.Y., Effects of LEDs on net photosynthetic rate, growth and leaf stomata of Chrysanthemum plantlets in vitro. J. Sci. Hortic., 2004b, 101, 143-151

[25] Li Q., Kubota C., Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environ. Exp. Bot., 2009, 67, 59-64

[26] Lee N.Y., Lee M.-J., Kim Y.-K., Park J.-C., Park H.-K., Choi J.-S., et al., Effect of light emitting diode radiation on antioxidant activity of barley leaf. J. Korean Soc. Appl. Biol. Chem., 2010, 53, 658–690

[27] Matsuda R., Ohashi-Kaneko K., Fujiwara K., Goto E., Kurata K., Photosynthetic characteristics of rice leaves grown under red light with or without supplemental blue light. Plant Cell Physiol., 2004, 45, 12, 1870-1874

[28] Kim H.H., Goins G.D., Wheeler R.M., Sager J.C., Stomatal conductance of lettuce grown under or exposed to different light qualities. Ann. Bot., 2004a, 94, 691-697

[29] Shimazaki K.I., Doi M., Assmann S.M., Kinoshita T., Light regulation of stomatal movement. Annu. Rev. Plant Biol., 2007, 58, 219–247

[30] Wang H., Gu M., Cui J., Shi K., Zhou Y., Yu J., Effects of light quality on CO_2 assimilation, chlorophyll-fluorescence quenching, expression of Calvin cycle genes and carbohydrate accumulation in *Cucumis sativus*. J. Photoch. Photobio. B., 2009, 96, 30-37

[31] Soylu S., Soylu E.M., Evrendilek G.A., Chemical composition and antibacterial activity of essential oils of bitter fennel (*Foeniculum vulgare Mill. var. vulgare*) and dill (*Anethum graveolens* L.) against the growth of food-borne and seedborne patho genic bacteria. Ital. J. Food Sci., 2009, 3, 21, 347-355

[32] Nishioka N., Nishimura T., Ohyama K., Sumino M., Malayeri S.H., Goto E., et al., 2008. Light quality affected growth and contents of essential oil components of Japanese mint plants. Acta Hortic., 797, 431-436

[33] Lisewska Z., Kmiecik W., Słupski J., Content of basic components and volatile oils in green dill as depending on the height and usable parts of plants. J. Food Quality, 2007, 30, 281-299

[34] Callan N.W., Johnson D.L., Westcott M.P., Welty L.E., H. Ind. Crop. Prod., 2007, 25, 282-287

[35] Słupski J., Lisewska Z., Kmiecik W., Contents of macro and microelements in fresh and frozen dill (*Anethum graveolens* L.). Food Chem. 2005, 91, 737-743

[36] Hirose T., Werger M.J.A., Nitrogen use efficiency in instantaneous and daily photosynthesis of leaves in the canopy of a *Solidago altissima* stand. Physiol. Plant. 1987, 70, 215-222

[37] Wingler A., Purdy S., MacLean J.A., Pourtau N., The role of sugars in integrating environmental signals during the regulation of leaf senescence. J. Exp. Bot. 2006, 57(2), 391-399

[38] Galmés J., Cifre J., Medrano H., Flexas J., Modulation of relative growth rate and its components by water stress in Mediterranean species with different growth forms. Oecologia, 2005, 145, 21-31

[39] Wu M.-C., Hou C.-Y., Jiang C.-M., Wang Y.-T., Wang C.-Y., Chen H.-H., et al., A novel approach of LED light radiation improves the antioxidant activity of pea seedlings. Food Chem., 2007, 101, 1753-1758

[40] Hirai T., Amaki W., Watanabe H., Action of blue or red monochromatic light on stem intermodal growth depends on plant species. Acta Hortic., 2006, 711, 345-349