Growth, nutritional quality, and energy use efficiency in two lettuce cultivars as influenced by white plus red versus red plus blue LEDs

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Abstract: Red plus blue light-emitting diodes (LEDs) are commonly applied in plant factories with artificial lighting due to photosynthetic pigments, which absorb strongly in red and blue light regions of the spectrum. However, plants grown under natural environment are used to utilizing broad-wide spectrum by long-term evolution. In order to examine the effects of addition light added in red plus blue LEDs or white LEDs, green and purple leaf lettuces (*Lactuca sativa* L. cv. Lvdie and Ziya) were hydroponically cultivated for 20 days under white LEDs, white plus red LEDs, red plus blue LEDs, and red plus blue LEDs supplemented with ultraviolet, green or far-red light, respectively. The results indicated that the addition of far-red light in red plus blue LEDs increased leaf fresh and dry weights of green leaf lettuce by 28% and 34%, respectively. Addition of ultraviolet light did not induce any differences in growth and energy use efficiency in both lettuce cultivars, while supplementing green light with red plus blue LEDs reduced the vitamin C content of green leaf lettuce by 44% and anthocyanin content of purple leaf lettuce by 30% compared with red plus blue LEDs, respectively. Spectral absorbencies of purple leaf lettuce grown under red plus blue LEDs supplemented with green light were lower in green light region compared with those grown under red plus blue LEDs, which was associated with anthocyanin contents. White plus red LEDs significantly increased leaf fresh and dry weights of purple leaf lettuce by 25%, and no significant differences were observed in vitamin C and nitrate contents compared with white LEDs. Fresh weight, light and electrical energy use efficiencies of hydroponic green and purple leaf lettuces grown under white plus red LEDs were higher or no significant differences compared with those grown under red plus blue LEDs. In conclusion, white plus red LEDs were suggested to substitute for red plus blue LEDs in hydroponic lettuce (cv. Lvdie and Ziya) production in plant factories with artificial lighting.

Keywords: plant factory, hydroponic lettuce, light-emitting diodes (LED), light energy use efficiency, artificial lighting, absorption spectrum, anthocyanin content, photosynthetic pigments
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1 Introduction

Chlorophylls and carotenoids are two classes of photosynthetic pigments in higher plants, which are used for light absorption that drive photosynthesis[1]. Chlorophyll a and chlorophyll b are dominant pigments in leaf cells, which absorb strongly in red (main absorption peak at 625-675 nm) and blue (main absorption peak at 425-475 nm) regions of the spectrum[2]. Previous studies indicated that plant leaves absorbed over 90% red and blue lights and approximately 70% green light[1,3], demonstrating that red and blue lights are mostly absorbed by leaves. The chlorophyll pigments in vegetable leaves are sensitive to light quality, and may have variety-specific differences[4]. Chlorophyll contents were higher in lettuce (*Lactuca sativa* L.) grown under monochrome blue light than those grown under monochrome red light[5,6], while opposite results were observed in tomato plants[7]. In addition, chlorophyll content[5], fresh weight[8], and nutritional quality[8,9] of plants exposed to combination of red and blue lights were higher compared with monochrome red light. Therefore, suitable light quality provide by mixed red and blue lights were widely examined by previous studies in lettuce[5,10,11], sweet basil[12], pak choi[13], and spinach[14].

In commercial horticulture industry, light-emitting diodes (LEDs) have tremendous potentiality owing to flexibility of spectral configuration, long life spans, and high energy conversion efficiency[15]. Lettuce is a major crop cultivated worldwide and it has been a model crop in studying its responses to LED quality[16-18]. Red and blue LEDs seem to be more suitable for lettuce production as a result of the maximum absorption spectrum of chlorophylls[5,19]. However, plants grown under natural environment are used to utilizing broad-wide spectrum by long-term evolution[20,21]. Except for red and blue lights, other parts of spectrum also affect plant growth and metabolites accumulation. Green light can penetrate upper leaves and could be absorbed by chloroplasts in the abaxial side[22]. Kim et al.[23] observed that green leaf lettuce grown under red and blue LEDs

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supplemented with 24% green light had higher leaf fresh weight than those grown without green light. Net photosynthetic rate of lettuce leaf increased when red light supplemented with 10% green light but decreased when same fraction of green light was added in red and blue LEDs[24]. Addition of 8% green light with 68% red light led to bigger leaf area and higher leaf fresh weight in red leaf lettuce (cv. Sunmang), but not in green leaf lettuce (cv. Grand Rapid TBR) compared with lettuce grown with 66% red light[25]. Far-red light promotes plant growth by increasing leaf expansion instead of photosynthetic reaction[26,27]. Leaf and root fresh weights of red oakleaf lettuce (cv. Cherokee) seedlings increased significantly when far-red light was added to red and blue LEDs, but not in green butterhead lettuce (cv. Rex)[28]. Similar trends were found in dry weight of red leaf lettuce (cv. Outredgeous) when far-red light was supplemented with red LEDs[29]. Ultraviolet (UV) light is applied for stimulating phytochemicals biosynthesis in plants grown under controlled environment due to its short wavelength and high energy[30,31]. Total anthocyanin, flavonoid and phenolic contents of red leaf lettuce exposed to UV light increased remarkably than those without UV light[32]. Similar results were also reported by Lee et al.[30]. These studies suggested that growth and nutritional quality of plants could be regulated by supplemental other lights and different cultivars have various morphological and physiological responses to light quality.

Considering carbohydrate accumulation and energy use efficiency, white LEDs were suggested to substitute for fluorescent lamps in lettuce production in plant factory with artificial lighting[33]. White plus red LEDs were found more suitable for growth of hydroponic lettuce compared with fluorescent lamps at seedling stage[27] and its subsequent cultivation stage[17]. Chen et al.[20] also indicated that white plus red LEDs resulted in vigorous and compact lettuce than those grown under white LEDs alone and inferred that lettuce yield would increase with more red light added in white LEDs. However, excess red light may have negative influences on lettuce growth and phytochemical accumulation. Yan et al.[34] examined proper red light amounts (24.4% red light) added in white LEDs for purple leaf lettuce production in consideration of growth, nutritional values, and energy use efficiencies. However, few studies compared white plus red LEDs and red plus blue LEDs in photosynthetic pigments, absorption spectrum and energy use efficiency in different lettuce cultivars.

In order to find out suitable LED quality provided by white plus red LEDs or red plus blue LEDs, chlorophyll contents, growth, spectral characteristics of lettuce leaf, nutritional quality, and energy use efficiency of green and purple leaf lettuces were investigated in a plant factory with artificial lighting. The results can be a practical way for tailoring LEDs in lettuce production in different cultivars.

2 Materials and methods

2.1 Plant materials and growth conditions

Seeds of green and purple leaf lettuces (*Lactuca sativa* L. cv. Lvdie and Ziya) were sown in sponge cube (23 mm × 23 mm × 23 mm) filled with deionized water, and then were put in plastic containers (520 mm × 360 mm × 90 mm) in a walk-in growth chamber (China Agricultural University, Beijing, China). Seven day-old lettuce seedlings were divided into 128-cell trays and then cultivated continuously for 13 days. Uniform lettuce seedlings were selected randomly and then transplanted to hydroponic beds (1200 mm × 900 mm × 70 mm) with 4 mm thickness, which were made of acrylonitrile butadiene styrene. Each bed held 35 plants at 20 days after sowing. According to previous study[27], light intensity at 200 μmol/(m^2·s) with a 16 h/d photoperiod provided by white plus red LEDs with a red light to blue light ratio (R:B ratio) of 2.2 were applied during seedling stage. Air temperature and relative humidity were maintained at (22±1)°C/(18±1)°C and (65%±5%)/(75%±10%) at photoperiod/dark period, respectively. CO_2 concentration was maintained at (800±50) μmol/mol at photoperiod and without control at dark period. The hydroponic lettuces were harvest at 20 days after transplanting.

Yamasaki lettuce nutrient solution was used and provided by the following components, mg/L: $Ca(NO_3)_2·4H_2O$, 236; KNO_3, 404; $MgSO_4·7H_2O$, 123; $NH_4H_2PO_4$, 57; Fe-DTPA (7%), 28.571; $MnSO_4·H_2O$, 0.615; $CuSO_4·5H_2O$, 0.039; $ZnSO_4·7H_2O$, 0.088; H_3BO_3, 1.127; $(NH4)_6Mo_6O_{24}·4H_2O$, 0.013, respectively. The electrical conductivity and pH of Yamasaki lettuce nutrition solution were adjusted at 1.0-1.2 mS/cm and 6.0-6.5, respectively. Tap water were applied to irrigate lettuce seedlings once a day after 2 days after sowing. 1/4 strength and 1/2 strength of Yamasaki lettuce nutrient solution were used at cotyledon stage and 1-2 true leaves stage, respectively. A full strength of Yamasaki lettuce nutrient solution was applied upon unfolding of the 2nd true leaf and the nutrient solution was replaced every 7 days during growth period.

2.2 LED lighting treatments

Lettuce were grown under six kinds of LED quality provided by white LEDs with a R:B ratio of 0.9 (W), white plus red LEDs with a R:B ratio of 2.2 (WR), red plus blue LEDs with a R:B ratio of 4.6 (RB). Ultraviolet (RBUV), green (RBG) or far-red LEDs (RBFr) were added to red plus blue LEDs with R:B ratios of 5.1, 5.4, and 5.6, respectively. LEDs mentioned above were manufactured by Beijing Lighting Valley Technology Co., Ltd. and with alternating current supply. A mirror-like stainless steel plate (1200 mm × 900 mm × 0.4 mm) was installed above LEDs. The wall was made of aluminum plastic plate with small holes for ventilation. Spectral distributions of above light environment were measured by a fiber spectrometer (AvaField-2, Avantes Inc., The Netherland) at 15 cm below the LED lamps with wavebands ranging from 300 nm to 800 nm (Figure 1). The photon flux of ultraviolet (UV, 300-399 nm), blue (B, 400-499 nm), green (G, 500-599 nm), red (R, 600-699 nm) and far-red (Fr, 700-800 nm) lights were integrated based on the spectral distributions (Table 1).

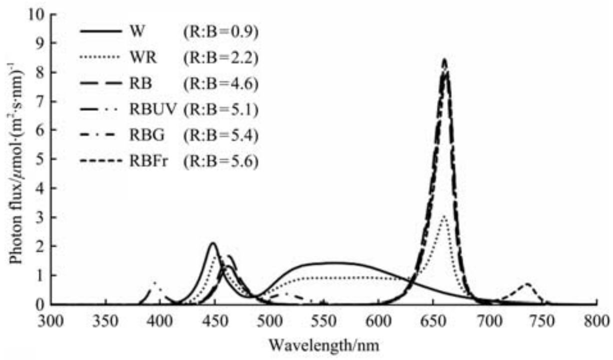


Figure 1 Spectral distribution of LED lighting environment at light intensity of 250 μmol/(m^2·s) provided by white LEDs (W), white plus red LEDs (WR), red plus blue LEDs (RB), and red plus blue LEDs supplemented with ultraviolet (RBUV), green (RBG), or far-red light (RBFr), respectively

Table 1 Spectral distributions of white LEDs (W), white plus red LEDs (WR), red plus blue LEDs (RB), and red plus blue LEDs supplemented with ultraviolet (RBUV), green (RBG), or far-red light (RBFr), respectively

Wavelength/nm		Spectral distribution/%					
		W	WR	RB	RBUV	RBG	RBFr
Photon flux	(300-800 nm)	100.0	100.0	100.0	100.0	100.0	100.0
Ultraviolet light	(300-399 nm)	0.0	0.0	0.0	3.4	0.0	0.0
Blue light	(400-499 nm)	27.0	20.4	17.7	15.7	14.8	13.9
Green light	(500-599 nm)	46.9	33.9	0.6	0.5	5.0	0.4
Red light	(600-699 nm)	24.2	44.1	81.5	80.2	80.0	78.1
Far-red light	(700-800 nm)	1.9	1.6	0.2	0.2	0.2	7.6
R:B		0.9	2.2	4.6	5.1	5.4	5.6
R:Fr		12.7	27.6	-	-	-	10.3

Note: Data are photon flux-based compositions of ultraviolet, blue, green, red and far-red lights. R:B, red light to blue light ratio. R:Fr, red light to far-red light ratio.

2.3 Measurements

2.3.1 Chlorophyll contents and photosynthetic characteristic of hydroponic lettuce leaves

Six uniform plants were randomly chosen in each treatment. The 3rd fully expanded leaf from the top was used for chlorophyll contents and photosynthetic characteristic measurements. Approximate 0.1 g of lettuce leaves were cut into small pieces and extracted in 80% acetone for 48 h. The absorbance of the extract at wavelength 663 nm and 645 nm were measured with a UV-VIS spectrophotometer (UV3150, Shimatsu Corporation, Japan). Chlorophyll a and chlorophyll b contents were calculated according to Arnon[35] and were used to calculate total chlorophyll content. A portable photosynthesis system (LI-6400XT, LI-COR Inc., USA) were applied to measure net photosynthetic rate. The light intensity, leaf temperature and CO_2 concentration in the leaf chamber (equipped with in-built red and blue LEDs) were controlled at 250 μmol/(m^2·s), 22°C, and 800 μmol/mol, respectively.

2.3.2 Spectral characteristics of hydroponic lettuce leaves

Five uniform lettuce plants were randomly selected in each treatment, and one side of the main vein of the third fully expanded leaf from the top was measured for the spectral characteristics. The spectral transmittance and reflectance of lettuce leaves were examined by above UV-VIS spectrophotometer with scanning wavelength range from 300 nm to 800 nm. The spectral absorbances of lettuce leaves were calculated by the transmittance and reflectance.

2.3.3 Growth characteristics of hydroponic lettuces

Six uniform lettuce plants were randomly selected at harvest (20 days after transplanting) in each treatment. Fresh leaf and roots were oven-dried at 105°C for 3 h and subsequently set to 80°C until constant weight. Fresh and dry weights of the lettuce leaf and roots were measured by an electronic analytical balance (FA1204B, Bioon Group, China).

2.3.4 Nutritional quality of hydroponic lettuces

Samples were randomly chosen from fresh leaves of six uniform lettuce plants in each treatment. Leaf samples were cut into small pieces and mixed for measuring vitamin C, nitrate, and anthocyanin contents. 2,6-dichlorophenol indophenol titration method[36], coloration method of sulfosalicyclic acid[37], and spectrometric method[38] were applied to examine vitamin C, nitrate and anthocyanin contents of hydroponic lettuce leaves, respectively. Nitrate content was determined by above UV-VIS spectrophotometer at wavelength of 410 nm for absorbance, anthocyanin content was calculated by the absorbance of extraction solution at wavelength of 530 nm and 600 nm.

2.3.4 Light and electrical energy use efficiencies

Light energy use efficiency (LUE) and electrical energy use efficiency (EUE) were calculated according to Kozai and Niu[39], which were defined as: LUE = $f\times D$/PAR and EUE = $h\times$LUE. Where, f is conversion factor from dry mass to chemical energy (about 20 MJ/kg), D is the dry mass increase rate of lettuce plants, kg/(m^2·h), PAR is the photosynthetically active radiation, MJ/(m^2·h), h is the conversion coefficient from electrical energy to PAR energy. From practical measurement, h in white LEDs, white plus red LEDs, red plus blue LEDs, and red plus blue LEDs supplemented with ultraviolet, green, or far-red light were 0.455, 0.368, 0.343, 0.332, 0.333 and 0.337, respectively. Power consumption of LED lights in each treatment were measured by smart metering (TP9004, Shenzhen Northmeter Co., Ltd., China) and used for calculating power consumption based on 100 g fresh weight of leaves or 1 g dry weight of all plant by Zhang et al.[17].

2.4 Statistical analysis

Statistical analysis was performed with SPSS 18.0 software (IBM, Inc., Chicago, IL, USA) followed by the least significant difference (LSD) test to compare the means between treatments (p<0.05). The results were reported as the mean ± standard deviation (SD) values.

3 Results and discussion

3.1 Chlorophyll contents, photosynthesis, and spectral characteristics of hydroponic lettuce leaves

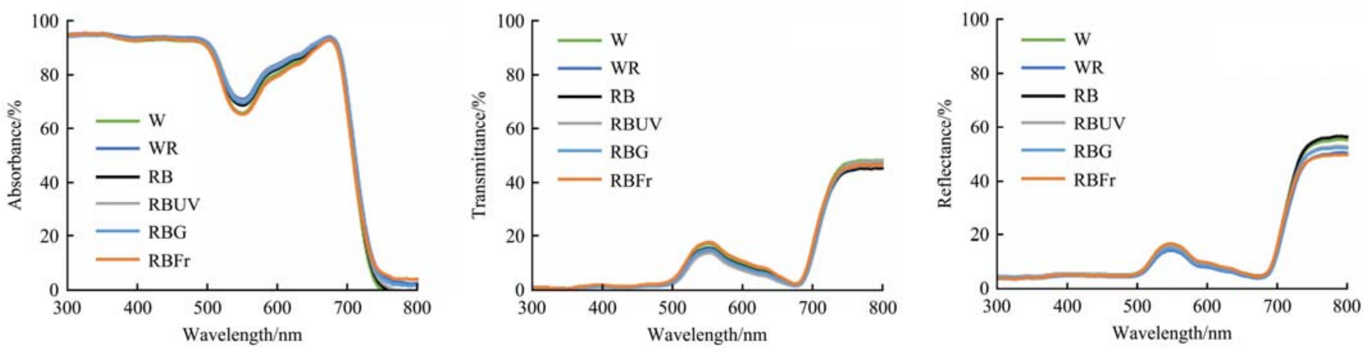
Lettuce grown under red plus blue LEDs supplemented with UV, green or far-red light did not exhibit significant differences in chlorophyll contents compared with red plus blue LEDs, irrespective of lettuce cultivars (Table 2). Similar trends were found in net photosynthetic rate of green leaf lettuce. However, net photosynthetic rate of purple leaf lettuce grown under red plus blue LEDs supplemented with 4.4% green light was lower compared with those grown under red plus blue LEDs, which was attributed to the fact that green light was not effectively absorbed by upper leaves (Figure 2). Kang et al.[24] observed that net photosynthetic rate of green leaf lettuce was significantly decreased when 10% green light were added in red plus blue LEDs. However, when 5% and 24% green lights were added in red plus blue LEDs and white plus red LEDs, respectively, no remarkable differences were found in chlorophyll contents and net photosynthetic rate of green leaf lettuce[23,40]. Meanwhile, net photosynthetic rate of purple leaf lettuce grown under red plus blue LEDs supplemented with green light was lower compared with those grown under red plus blue LEDs, although no significant differences were observed in chlorophyll contents of purple leaf lettuce between two treatments. This may due to the differences of carotenoids contents, which acted as auxiliary photoreceptors of chlorophyll with main absorption spectrum in blue region[2]. No remarkable differences were observed in chlorophyll contents and net photosynthetic rate of two lettuce cultivars grown under red plus blue LEDs and white plus red LEDs, which was consistent with the study reported by Mickens et al.[41]

The light absorption of lettuce leaf was mainly in red (600-699 nm) and blue light (400-499 nm) regions with absorbance peaks at about 680 nm and then drastically decreased at wavelengths more than 680 nm for both cultivars (Figure 2). The absorption spectrum of lettuce leaves grown under different LEDs were similar in blue and red regions, but significant differences were observed in green (500-599 nm) region in purple leaf lettuce. The spectrum absorbances of lettuce leaves were lower in green light regions owing to higher transmittance and reflectance in this region. Purple leaf lettuce grown under red plus blue LEDs and red plus blue supplemented with green light had highest and lowest absorbances in green light region among all treatment, respectively. These differences were attributed to the facts that lettuce grown under red plus blue LEDs contained higher anthocyanin contents than those grown under red plus blue LEDs supplemented with green light (Figure 3). Similar trends were reported by previous studies[42,43], demonstrating that the differences of absorption spectrum in green light region was due to anthocyanin contents. Addition of 4.4% green light in red plus blue LEDs increased the reflectance of purple lettuce leaves, and the reflectance in green light region was significantly higher than that in red and blue light region, suggesting that more fraction of visible light passed through upper leaves. The results were consistent with the previous study reported by Son and Oh[25], who observed that lettuce grown under LEDs containing green light exhibited a higher transmittance in green wavelength than red and blue wavelength.

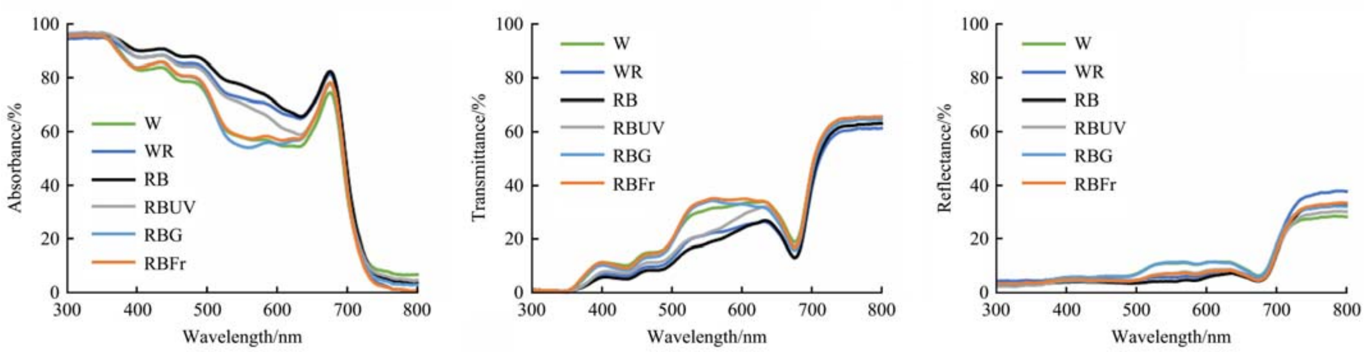
Table 2 Chlorophyll contents and photosynthetic characteristics of hydroponic green and purple leaf lettuces (cv. Lvdie and Ziya) grown under white LEDs (W), white plus red LEDs (WR), red plus blue LEDs (RB), and red plus blue LEDs supplemented with ultraviolet (RBUV), green (RBG), or far-red light (RBFr), respectively

Lettuce cultivar	Lighting treatment	Chlorophyll a content /mg·g^{-1}	Chlorophyll b content /mg·g^{-1}	Total chlorophyll content /mg·g^{-1}	Net photosynthetic rate /μmol·m^{-2}·s^{-1}
cv. Lvdie (Green leaf)	W	1.01±0.34 NS	0.31±0.10 NS	1.32±0.44 NS	11.3±0.7 NS
	WR	1.05±0.20 NS	0.34±0.06 NS	1.39±0.26 NS	10.8±0.6 NS
	RB	0.98±0.24 NS	0.32±0.08 NS	1.30±0.31 NS	12.0±1.4 NS
	RBUV	1.12±0.32 NS	0.36±0.10 NS	1.48±0.42 NS	11.7±1.6 NS
	RBG	0.96±0.27 NS	0.30±0.08 NS	1.26±0.35 NS	11.2±0.7 NS
	RBFr	0.94±0.21 NS	0.31±0.07 NS	1.26±0.27 NS	11.5±1.0 NS
cv. Ziya (Purple leaf)	W	0.51±0.07 a	0.16±0.02 a	0.66±0.09 a	6.3±0.6 b
	WR	0.39±0.13 ab	0.12±0.04 b	0.51±0.17 ab	7.0±0.6 ab
	RB	0.37±0.11 ab	0.11±0.03 bc	0.48±0.13 b	7.9±0.4 a
	RBUV	0.35±0.11 b	0.11±0.03 bc	0.46±0.14 b	6.8±1.4 ab
	RBG	0.38±0.05 ab	0.11±0.01 bc	0.48±0.06 b	6.2±1.1 b
	RBFr	0.26±0.04 b	0.08±0.01 c	0.34±0.05 b	6.4±1.9 ab

Note: Different letters in the same column indicate significant differences at the 5% level, according to LSD's multiple comparison (*n* = 6).

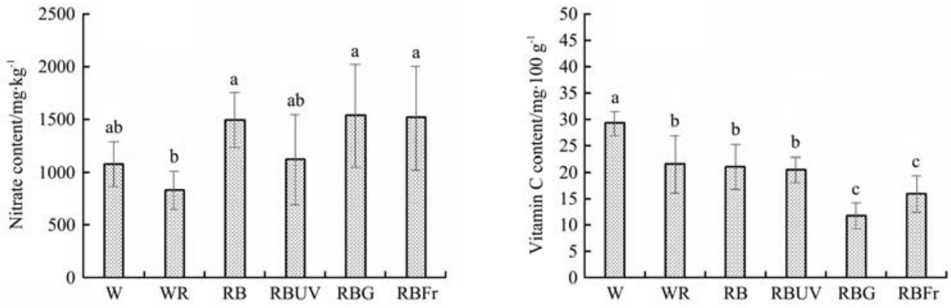


a. cv. Lvdie

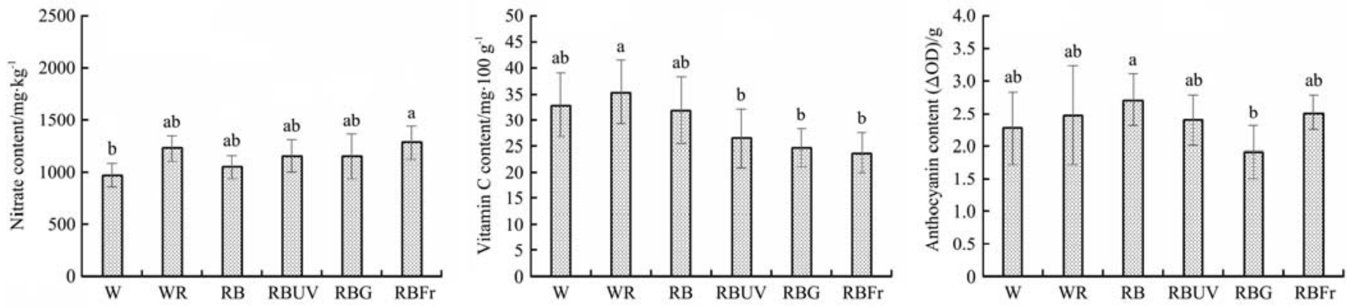


b. cv. Ziya

Figure 2 Spectral characteristics of hydroponic green and purple leaf lettuces (cv. Lvdie and Ziya) grown under white LEDs (W), white plus red LEDs (WR), red plus blue LEDs (RB), and red plus blue LEDs supplemented with ultraviolet (RBUV), green (RBG), or far-red light (RBFr), respectively



a. cv. Lvdie



b. cv. Ziya

Figure 3 Nitrate, vitamin C and anthocyanin contents of hydroponic green and purple leaf lettuces (cv. Lvdie and Ziya) grown under white LEDs (W), white plus red LEDs (WR), red plus blue LEDs (RB), and red plus blue LEDs supplemented with ultraviolet (RBUV), green (RBG), or far-red light (RBFr), respectively

3.2 Growth of hydroponic lettuces

No significant differences were observed in leaf fresh weight of purple leaf lettuce grown under red plus blue LEDs supplemented with UV, green or far-red light compared with those grown under red plus blue LEDs. However, leaf fresh weight of green leaf lettuce increased significantly by 22.9% and 27.5% when 4.4% green light and 7.4% far-red light were added in red plus blue LEDs, respectively (Table 3). The results demonstrated that different colored lettuces may have various responses to LED quality. Meng and Runkle[28] observed that supplemental far-red light in red plus blue LEDs resulted in higher leaf and root fresh weights of red oakleaf lettuce seedlings (cv. Cherokee), however, no significant differences were found in green butterhead lettuce seedlings (cv. Rex). Addition of far-red light in white fluorescent lamps also increased leaf fresh weight of red leaf lettuce (cv. Red Cross) by 28.2%[16]. This may due to the facts that addition of far-red light leads to the lighting environment with a lower R:Fr ratio, which acts as a signal for plants and leads to shade-avoidance responses, such as increases shoot elongation and induces larger leaves. As a result, far-red light promoted the biomass accumulation by increasing lettuce leaves area and thereby increasing the area of light interception[26,27]. Lee et al.[44] observed that leaf and root fresh weights of red leaf lettuce grown under LEDs with lower R:Fr ratio at 1.2 were 1.3 and 1.6 times higher than those grown under higher R:Fr ratio at 4.1. Addition of 4.4% green light or 3.4% UV light had no significant effects in leaf and root dry weights in both lettuce cultivars (Table 3). Similarly, Kim et al.[40] observed that no significant differences were found in leaf area, total chlorophyll contents, and leaf dry weight of lettuce when 5% green light were added in red plus blue LEDs. Additional of 9% green light in white LEDs also did not lead to any differences in chlorophyll contents, fresh and dry weights of lettuce at 28 days after sowing[41]. The results were likely due to the facts that too small fraction or amount of supplemental light in LEDs would not induce any differences in carbohydrate accumulation.

A higher red light fraction combined with blue or white light led to higher yield of lettuce[5,34], pepper seedlings[45], and sweet basil[12]. White plus red LEDs resulted in higher leaf and root weights of purple leaf lettuce compared with white LEDs, but no significant differences were observed in green leaf lettuce. Previous studies indicated that 14.0%[41], 18.0%[20] and 24.4%[34] red lights added in white LEDs resulted in higher yield of lettuces. However, when white fluorescent lamps were applied as base lighting source, supplemental 33.4% red light had no remarkable influences in fresh and dry weights of red leaf lettuce[16]. Green leaf lettuce grown under white and white plus red LEDs were 22.6% and 25.9% higher in leaf fresh weight than those grown under red plus blue LEDs. However, no significant differences were observed in leaf and root fresh weights of purple lettuce grown under red plus blue LEDs and white plus red LEDs (Table 3). Mickens et al.[41] found that fresh weight of lettuce was higher exposed to white LEDs with 32.0% red light or white plus red LEDs with 46.0% red light than those exposed to red plus blue LEDs with 60.0% red light. Similarly, Han et al.[46] observed that leaf area and total fresh weight of lettuce grown under broad white or narrow white LEDs were higher than those grown under red plus blue LEDs. Leaf fresh weight of green and red leaf lettuces grown under warm white LEDs with 54.6% red light also led to higher yield than those grown under red plus blue LEDs with 66.7% red light[47]. These studies indicated that white or white plus red LEDs resulted in similar or higher carbohydrate accumulation of lettuce than red plus blue LEDs, which could be used for lettuce production in different cultivars.

3.3 Nutritional values of hydroponic lettuce

Supplementation of UV, green or far-red light in red plus blue LEDs did not affect nitrate contents in green and purple leaf lettuces (Figure 3). No significant differences were observed in anthocyanin content in purple lettuce when UV light with light intensity of 8.5 μmol/(m^2·s) or far-red light with light intensity of 18.5 μmol/(m^2·s) were added in red and blue LEDs, respectively (Figure 3). Similarly, Samuoliene et al.[48] found that addition of

UV light with light intensity of 4 μmol/(m^2·s) did not induce any discrepancies in anthocyanin content. However, the results were slightly different from previous study reported by Li and Kubota[16], who found that anthocyanin contents were significantly increased by 11.2% and decreased by 40.5% when UV light with light intensity of 16.3 μmol/(m^2·s) and far-red light with light intensity of 154 μmol/(m^2·s) were added in white LEDs, respectively. The differences were probably attributed to the amount of the light supplemented and the remaining spectral composition or cultivars. Supplementary green light in red plus blue LEDs reduced vitamin C content by 44.3% in green leaf lettuce and anthocyanin content by 29.5% in purple leaf lettuce. Previous studies indicated that addition of 1.7%[29] or 17.8%[16] green light had no additional effects on anthocyanin contents. No significant differences were found in vitamin C and anthocyanin contents in both lettuce cultivars grown under white plus red LEDs and red plus blue LEDs. There were no remarkable discrepancies in nitrate, vitamin C and anthocyanin contents in purple leaf lettuce grown under white LEDs and white plus red LEDs. The results were consistent with previous studies, who found that supplemental 33.4% red light in white fluorescent lamps[16] and supplemental 14.1% red light in white plus red LEDs[17] did not have remarkable effects in anthocyanin content and nitrate contents of lettuce, respectively.

3.4 Energy use efficiencies of LED lighting for hydroponic lettuces production

Optimal spectrum of LEDs should be carefully selected to maximize the carbohydrate accumulation and in consideration of energy use efficiencies of plants. Supplementation of UV, green or far-red light in red plus blue LEDs had no significantly effects in power consumption based on fresh and dry weights of purple leaf lettuce, LUE and EUE (Table 4). However, addition of far-red light in red plus blue LEDs resulted in lower consumption based on fresh and dry weights of green leaf lettuce, and higher LUE and EUE. The results were attributed to the facts that addition of far-red light in red plus blue LEDs led to higher lettuce yield. No significant differences were observed in energy use efficiencies of purple leaf lettuce between red plus blue LEDs and white plus red LEDs. However, white plus red LEDs led to higher LUE and EUE of green leaf lettuce than those exposed to red plus blue LEDs. LUE and EUE of purple leaf lettuce grown under white plus red LEDs were 45.5% and 18.2% higher than those grown under white LEDs, respectively, which were consist with previous study reported by Yan et al.[34], who found that LUE and EUE increased by more than 22.7% and 7.1% when 24.4% red light were added in white LEDs, respectively.

Table 3 Fresh and dry weights of hydroponic green and purple leaf lettuces (cv. Lvdie and Ziya) grown under white LEDs (W), white plus red LEDs (WR), red plus blue LEDs (RB), and red plus blue LEDs supplemented with ultraviolet (RBUV), green (RBG), or far-red light (RBFr), respectively

Lettuce cultivar	Lighting treatment	Leaf fresh weight /g per plant		Root fresh weight /g per plant		Leaf dry weight /g per plant		Root dry weight /g per plant	
cv. Lvdie (Green leaf)	W	79.22±5.10	a	12.89±0.67	a	3.46±0.48	ab	0.63±0.06	ab
	WR	81.33±10.73	a	12.54±2.66	ab	3.72±0.84	a	0.66±0.12	a
	RB	64.61±7.10	b	10.67±1.65	b	2.79±0.42	b	0.46±0.05	b
	RBUV	71.23±11.45	ab	10.83±2.15	b	2.96±0.51	b	0.56±0.07	b
	RBG	79.43± 6.22	a	11.61±1.05	ab	3.48±0.32	ab	0.55±0.07	b
	RBFr	82.39±11.80	a	13.56±0.80	a	3.73±0.73	a	0.62±0.10	ab
cv. Ziya (Purple leaf)	W	38.46±2.27	b	6.91±0.17	c	1.91±0.11	c	0.31±0.03	c
	WR	48.12±8.68	a	8.15±0.99	b	2.46±0.42	b	0.40±0.03	ab
	RB	51.53±4.28	a	9.32±0.92	ab	2.87±0.19	a	0.40±0.04	ab
	RBUV	48.83±1.87	a	9.27±1.23	ab	2.90±0.48	a	0.42±0.05	ab
	RBG	48.74±3.49	a	8.05±1.30	bc	2.60±0.25	ab	0.36±0.04	b
	RBFr	47.76±4.37	a	10.06±1.54	a	2.65±0.27	ab	0.45±0.05	a

Note: Different letters in the same column indicate significant differences at the 5% level, according to LSD's multiple comparison (n = 6).

Table 4 Energy use efficiencies of hydroponic green and purple leaf lettuces (cv. Lvdie and Ziya) grown under white LEDs (W), white plus red LEDs (WR), red plus blue LEDs (RB), and red plus blue LEDs supplemented with ultraviolet (RBUV), green (RBG), or far-red light (RBFr), respectively

Lettuce cultivar	Lighting treatment	Power consumption based on fresh weight/kWh per 100g FW	Power consumption based on dry weight/kWh per 1g DW	Light energy use efficiency	Electrical energy use efficiency
cv. Lvdie (Green leaf)	W	1.25±0.09 b	0.28±0.03 b	0.041±0.005 ab	0.0185±0.0023 a
	WR	1.47±0.20 b	0.32±0.06 b	0.045±0.003 a	0.0163±0.0012 ab
	RB	1.83±0.13 a	0.42±0.06 a	0.036±0.005 b	0.0125±0.0017 c
	RBUV	1.72±0.28 a	0.41±0.07 a	0.039±0.007 ab	0.0129±0.0021 c
	RBG	1.47±0.14 b	0.35±0.02 ab	0.046±0.004 a	0.0151±0.0014 b
	RBFr	1.38±0.18 b	0.32±0.05 b	0.045±0.005 a	0.0151±0.0017 b
cv. Ziya (Purple leaf)	W	2.53±0.12 NS	0.52±0.03 a	0.022±0.001 b	0.0099±0.0006 b
	WR	2.42±0.36 NS	0.44±0.06 b	0.032±0.004 a	0.0117±0.0016 a
	RB	2.24±0.12 NS	0.41±0.02 b	0.036±0.002 a	0.0122±0.0006 a
	RBUV	2.39±0.12 NS	0.45±0.02 b	0.034±0.001 a	0.0114±0.0004 a
	RBG	2.41±0.20 NS	0.46±0.05 b	0.033±0.003 a	0.0111±0.0011 ab
	RBFr	2.29±0.24 NS	0.42±0.05 b	0.036±0.003 a	0.0112±0.0012 ab

Note: Different letters in the same column indicate significant differences at the 5% level, according to LSD's multiple comparison (n = 6).

4 Conclusions

Growth, nutritional quality, and energy use efficiency of hydroponic lettuce could be strategically changed by supplemental selected lights in red plus blue LEDs or white LEDs. Moreover, lighting environment management for hydroponic lettuce production is also associated with different leaf color. Fresh weight, light and electrical energy use efficiencies of hydroponic lettuces grown under white plus red LEDs were higher or no significant differences compared with those grown under red plus blue LEDs. In conclusion, white plus red LEDs was suggested to substitute for red plus blue LEDs in hydroponic lettuce (cv. Lvdie and Ziya) production in plant factory with artificial lighting.

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