Optimal red:blue ratio of full spectrum LEDs for hydroponic pakchoi cultivation in plant factory

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Abstract: Pakchoi, a popular leafy vegetable in China, is expected to be planted in plant factories with artificial lighting (PFALs). In order to examine the effects of different red and blue light ratios (R:B ratio) on growth, photosynthesis, and absorption spectrum of plant leaves, and to analyze the energy use efficiency, the pakchoi (*Brassica Chinensis* L. cv. Xiazhijiao) was cultivated hydroponically under white LEDs with R:B ratios of 0.9 (L0.9) and 1.8 (L1.8), white plus red LEDs with R:B ratios of 2.7 (L2.7) and 4.0 (L4.0) for 40 d, respectively. The results showed that the leaf length and width were significantly greater in the L0.9 treatment than in other treatments, and the dry weight per plant increased by over 33% when R:B ratio decreased from 4.0 to 0.9. The net photosynthesis rates of pakchoi leaves ranged from 9.2 to 9.6 μmol/(m^2·s) under different lighting conditions, which had no significant difference. The biggest difference in the spectrum absorptance of pakchoi leaves was expressed in green light waveband, and the highest absorption of plant leaves was under L0.9 and L1.8 treatments. The light energy use efficiency (LUE), photon yield (PY), and energy yield (EY) in L0.9 were over 25% higher than that in the other treatments, while there was no significant difference in the electrical energy use efficiency (EUE). In conclusion, an optimal light quality to cultivate pakchoi in PFALs was the white LEDs with R:B ratio of 0.9, and this finding could provide a promising lighting environment to hydroponic pakchoi yield and energy use efficiency.

Keywords: pakchoi, R:B ratio, yield, absorption spectrum, energy use efficiency

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1 Introduction

As the living standards of Chinese people have improved, fresh and nutritious vegetables have become a preferable option for more and more consumers. Pakchoi (*Brassica chinensis* L.), a vegetable species of *Brassicaceae*, is one of the favorite leafy vegetables of the Chinese, especially in North China[1]. The pakchoi is rich in dietary fiber, vitamins C and carotenoid, making it an ideal choice for leafy vegetables. Because of its unstable supply, uneven quality, and difficulties in storage and transportation, it is necessary to provide a new way for high yield and quality pakchoi production. Plant factory with artificial lighting (PFALs) is expected to realize year-round clean cultivation of high-quality leafy vegetables[2]. It was reported that there were currently more than 500 PFALs worldwide in production, and most of them were used to plant leafy vegetables, mainly lettuce[3]. Pakchoi is a leafy vegetable with a short growth cycle, which has a large potential to be cultivated in PFALs. A suitable lighting environment could be favorable for producing hydroponic pakchoi with high yield and quality in PFALs.

Lighting is an important factor that could influence plant morphology, photosynthesis, and growth. Therefore, it is vital to explore the most efficient lighting environment for growing plants. Moreover, light quality as a signal could impact leaves shape, chlorophyll content, secondary metabolic products accumulation, etc.[4] In previous studies, the research on the effect of light quality on the growth of leafy vegetables has been mainly focused on red and blue light. The suitable R:B ratio of LED light varies among different leafy vegetables. Agarwal et al.[5] explored the impact of monochromatic red light, monochromatic blue light, and the mixture of red LEDs and blue LEDs with ratios of red light to blue light (R:B ratio) of 3, 1, and 1/3 on spinach, which revealed that too much blue light or red light were both to the disadvantage of biomass accumulation and photosynthesis. Pennisi et al.[6] proved that R:B ratio of 3 could improve the growth, physiological, metabolic functions, and resource use efficiency of sweet basil. R:B ratio of 12 could improve the growth of lettuce by stimulating morphological and physiological responses[7]. However, in recent years some researchers have revealed that long hour lighting of monochromatic red light, monochromatic blue light, and the mixture of red and blue LEDs with different R:B ratios often affect the growth of plants, which may cause the reduction of output of leafy vegetables comparing with full spectrum LEDs[8-10]. Although chlorophyll mainly absorbed blue and red light to supply energy for photosynthesis, green light was observed to reach deeper mesophyll[11], which might contribute to enhancing photosynthesis and biomass accumulation[12-14]. Compared with blue and red light, white LED has higher color rendering, which supported the identification of plant diseases and reduced the difficulty of plant management[15-18], besides, the cost of white LED packages is now

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80% lower than that of the red LEDs. As a result, the proportion of white LEDs in horticultural fixtures was increased to 60%[19]. Similarly, a rising number of PFALs are also using full spectrum LEDs in practice, but which kind of spectral composition of full spectrum LEDs is suitable for the cultivation of leafy vegetables remains to be discussed[20-23].

The light energy absorbed by the plant will eventually be converted partially into chemical energy. Thus, the increased chemical energy of plants is all provided by electric energy, as artificial lighting is the only source of plant photosynthesis in PFALs. Although using PFAL could improve plant productivity to generate profit, it is still hard to cover the extreme capital and operation cost in commercial production. In order to cosmically extend the PFAL application, the electricity consumption of artificial lighting which currently takes 70%-80% of total consumption for year-round cultivation should be reduced[24-26]. An optimal lighting environment could decrease the lighting consumption accounts by increasing the yield and nutritional value of plants. Besides, R:B ratio is not only a significant index for studying the physiological response of plants, but it also means that the efficacy of the luminaire is different. Thus, the impact of R:B ratio on the consumption of electricity for lighting is worth exploring and it is a key issue for its commercial prospect.

The purpose of this study was to determine the effects of different R:B ratios in full spectrum LED fixtures on the photomorphosis and the growth of hydroponic pakchoi by researching photosynthetic rate, chlorophyll content, spectral characteristics of leaves, and energy use efficiency. The results of this study would be used to give guidance on the management of light conditions for hydroponic pakchoi production in PFALs.

2 Materials and methods

2.1 Plant materials

Seeds of pakchoi (*Brassica chinensis* L. cv. Xiazhijiao) were soaked in 10% (V/V) sodium hypochlorite solution for 30 min to sterilize, followed by a rinse with water. Solid and plump seeds were selected and sown in moist sponge cubes (L25 mm × W25 mm × H25 mm). All the cubes were placed in plastic containers (L520 mm × W360 mm × H90 mm) which were held proper amount of deionized water and covered by plastic sheets with holes for moisturization. Two days after sowing, the deionized water was replaced by Japanese horticultural experimental nutrient solution at standard concentration when buds emerged. Japanese horticultural experimental nutrient solution was used with pH of 6.0-6.5 and EC of 2.2-2.5 mS/cm and provided by the following components, mg/L: $Ca(NO_3)_2·4H_2O$, 944; KNO_3, 808; $MgSO_4·7H_2O$, 492; $NH_4H_2PO_4$, 152; Na_2Fe_7-EDTA, 30; H_3BO_3, 2.86; $MnSO_4·4H_2O$, 2.13; $ZnSO_4·7H_2O$, 0.22; $CuSO_4·5H_2O$, 0.08; $(NH_4)_6Mo_7O_{24}·4H_2O$, 0.02. Twenty days after sowing, the pakchoi seedlings developing four leaves and one shoot were transplanted to 128-cell trays with a planting density of 108 plants/m. All plants were harvested at 40 d after sowing and six plants from each treatment were randomly selected for measurement. All the treatments were repeated three times.

2.2 Environmental conditions

All experiments were performed in small PFAL rooms. Four multistory stainless steel cultivation shelves were set to cultivate plants. Each cultivation shelf held five Acrylonitrile-butadiene-styrene (ABS) cultivation beds (L1200 mm×W900 mm×H70 mm) with 54 uniform holes (Φ20 mm) for transplanted pakchoi.

During the pregermination stage, air temperature and relative humidity were set as (25±1)°C and 75%±5% without lighting. During the cultivation stage, air temperature and relative humidity were turned to (25±1)°C/(20±1)°C and (65±5)%/(75±5)% respectively during the light period/dark period. Meanwhile, CO_2 concentration was maintained at (800±50) μmol/mol during the light period and uncontrolled during the dark period.

2.3 Lighting treatments

The lighting environment was provided by four types of LED luminaires (Beijing Lighting Valley Technology Co., Beijing, China), white LEDs with R:B ratios of 0.9 (L0.9) and 1.8 (L1.8), white plus red LEDs with R:B ratios of 2.7 (L2.7) and 4.0 (L4.0). The color temperatures of white LEDs in L0.9 and L2.7 were 6500 K, and those in L1.8 and L2.7 were 4000 K. The photoperiod was set to 12 h/d with photon flux density (PFD) of 250 μmol/(m^2·s). The light intensity and spectral distributions were tested by a fiber spectrometer (AvaSpec-ULS2048, Avantes Inc., Apeldoorn, The Netherlands) at 15 cm under the lamps (Figure 1) varying from 300-800 nm. The analysis of light quality was based on the photon flux of ultraviolet light (UV, 300-399 nm), blue light (B, 400-499 nm), green light (G, 500-599 nm), red light (R, 600-699 nm) and far-red light (Fr, 700-800 nm), and the R:B ratio was integrated by the photon flux of red light waveband to blue light waveband (Table 1).

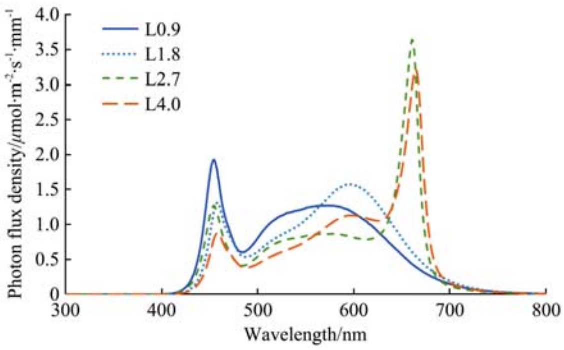


Figure 1 Spectral distributions of LED lighting environment at light intensity of 250 μmol/(m^2·s) provided by white LEDs with R:B ratio of 0.9 and 1.8, white plus red LEDs with R:B ratio of 2.7 and 4.0, respectively.

Table 1 Spectral distribution of LED lighting environment at light intensity of 250 μmol/(m^2·s) provided by white LEDs with R:B ratio of 0.9 and 1.8, white plus red LEDs with R:B ratio of 2.7 and 4.0, respectively

Wavelength/nm		Spectral distribution/%			
		L0.9	L1.8	L2.7	L4.0
Photon flux	300-800 nm	100.0	100.0	100.0	100.0
Ultraviolet light	300-399 nm	0.0	0.0	0.0	0.0
Blue light	400-499 nm	27.0	19.1	18.1	13.2
Green light	500-599 nm	46.9	44.5	31.8	31.8
Red light	600-699 nm	24.2	33.9	48.6	53.0
Far-red light	700-800 nm	1.9	2.5	1.4	2.0
R:B		0.9	1.8	2.7	4.0

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

2.4 Growth measurements of hydroponic pakchoi

2.4.1 Growth characteristics

All the fully expanded true leaves were counted as leaf number, and stem length, leaf length and leaf width of hydroponic pakchoi (fifth or sixth fully expanded leaf from the apical shoot) were measured from each treatment at 40 d. The fresh weights of the shoots and roots were measured by centesimal balance, and all these material was de-enzyme in an oven at 105°C for 3 h, then dried to constant weight at 80°C, and the dry weights were measured by an electronic analytical balance (FA1204B, Bioon Group, China).

2.4.2 Photosynthetic characteristics

A portable photosynthesis system (LI-6400XT, LI-COR Biosciences Corporation, Lincoln, NE, USA) was used to measure the stomatal conductance, intercellular CO_2 concentration, transpiration rate, and net photosynthesis rate (P_n) of hydroponic pakchoi leaves. Relevant parameters of 6400-02B leaf chamber including PFD, leaf temperature, CO_2 concentration, and air flow were set at 250 μmol/(m^2·s), 25°C, 800 μmol/mol, and 500 μmol/s, respectively.

2.4.3 Chlorophyll contents

Pakchoi leaves from the same leaf position were selected and cut up as samples. Around 0.1 g of sample was weighed and then put into 10 mL 95% ethanol extract. After extracting in dark conditions, the solution was detected for absorbance at the wavelength of 470 nm, 649 nm, and 665 nm by an ultraviolet spectrophotometer (UV-1700, AUCY Scientific Inc., Shanghai, China), respectively. The chlorophyll contents were calculated according to the method in reference[27].

2.4.4 Plant leaves spectral characteristics

The spectra of light reflection and transmission were measured from the adaxial and abaxial surfaces of pakchoi leaves by an integrating sphere of UV-VIS spectrophotometer (UV3150, Shimatsu Corporation, Japan), and the wavelength was set from 300 nm to 800 nm when the wavelength interval was set at 1 nm. The measurement positions were chosen to be in the middle of the leaf blade beside the main leaf vein for 4 scans and the average values were taken as the measurement results. Absorbance was calculated as subtraction of reflectance and transmittance from 100%.

2.4.5 Energy use efficiency

Light energy use efficiency (LUE) was defined as the ratio of the increase in chemical energy of the whole plant to the total amount of light energy received at the plant community surface by the plant in a unit of time (a week or a cultivation cycle). Electrical energy use efficiency (EUE) was referred to as the ratio of the increase in chemical energy of the whole plant to the total consumption of electric energy for lighting in a unit of time (a week or a cultivation cycle)[26]. The definition of photon yield (PY) was the ratio of the increase in fresh weight of the vendible part of one plant to the total amount of photons (300-800 nm) received at the plant community surface by the plant in a unit of time (a week or a cultivation cycle). Energy yield (EY) represented the ratio of the increase in fresh weight of the vendible part of one plant to the total electricity consumption for lighting per plant in a unit of time (a week or a cultivation cycle)[28].

LUE, EUE, PY, EY were calculated by the following equations:

$$\text{LUE}=f\cdot D/R \tag{1}$$

$$\text{EUE}=f\cdot D/E \tag{2}$$

$$\text{PY}=\text{FW}/\text{OTLI} \tag{3}$$

$$\text{EY}=\text{FW}/\text{OPLI} \tag{4}$$

where, f is the conversion factor from dry mass to chemical energy (about 20 MJ/kg)[25]; D is the dry mass accumulation rate of unit area, kg/(m^2·h); R is the light radiation (300-800 nm) at 15 cm under the lamps, MJ/(m^2·h), which was measured by a fiber spectrometer (AvaSpec-ULS2048, Avantes Inc., Apeldoorn, The Netherlands); E is the total consumption of electricity for lighting, MJ/(m^2·h), which was measured by smart metering (TP9004, Shenzhen Northmeter Co., Ltd., China); FW is the fresh weight of the vendible part of one plant, g; OTLI is the average number of light quantum received at 15 cm under the lamps during growth per plant, mol; OPLI is the average energy consumption of lighting by a single plant during growth per plant, kW·h.

2.5 Statistical analysis

IBM SPSS Statistics 26 (IBM Corporation, Chicago, IL, USA) was used for statistical analysis. The comparisons were conducted by Duncan's multiple range test selected from significant one-way ANOVA (p<0.05). The results were recorded as mean±standard deviation values (n=6).

3 Results and discussion

3.1 Growth characteristics of hydroponic pakchoi

Different R:B ratio of LED could affect the morphology and biomass accumulation of hydroponic pakchoi (Figure 2). The results indicated that the leaf number, stem length, leaf length, and leaf width were significantly greater in L0.9 than in other treatments after 40 d of cultivation, which was 10.2%-28.8% higher (Table 2). L1.8, L2.7, and L4.0 treatments did not show significant difference in hydroponic pakchoi morphology. Pakchoi grown under L0.9 treatment were higher than ones grown under L1.8, L2.7, and L4.0 in shoot/root fresh and dry weights, especially in shoot weights. Therefore, L0.9 treatment was beneficial to the organic accumulation of hydroponic pakchoi.

Figure 2 Effect of LED light quality on the morphology of hydroponic pakchoi after 40 d cultivation

Table 2 Morphology and biomass of hydroponic pakchoi grown under LED lighting environment at light intensity of 250 μmol/(m^2·s) provided by white LEDs with R:B ratios of 0.9 and 1.8, white plus red LEDs with R:B ratios of 2.7 and 4.0, respectively, for 40 d after sowing

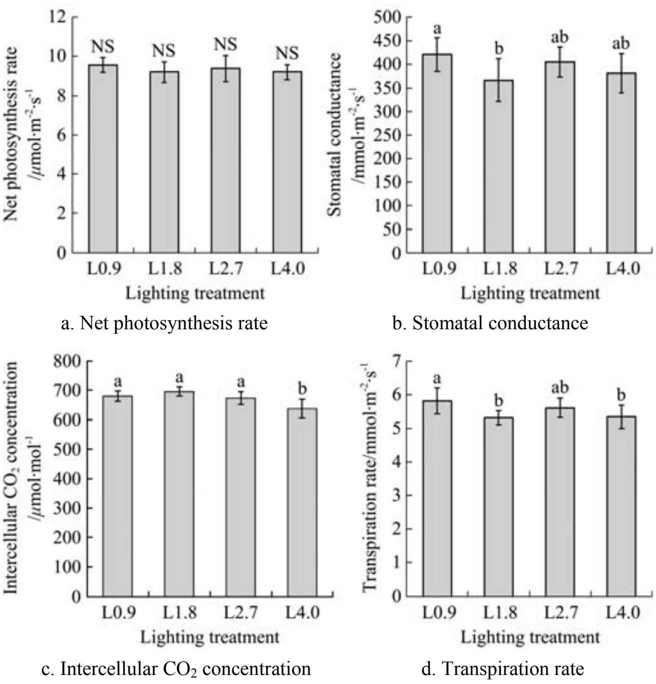
Lighting treatment	Leaf number	Stem length/cm	Leaf length/cm	Leaf width/cm	Shoot fresh weight/g	Root fresh weight/g	Shoot dry weight/g	Root dry weight/g
L0.9	13.5±0.6^{NS}	6.6±1.1^{a}	12.7±0.7^{a}	8.8±0.7^{a}	47.41±7.39^{a}	2.27±0.52^{a}	2.27±0.31^{a}	0.18±0.05^{NS}
L1.8	12.0±1.9^{NS}	4.8±0.7^{b}	10.9±0.5^{b}	7.6±0.3^{b}	29.12±4.32^{b}	1.79±0.34^{ab}	1.68±0.26^{b}	0.15±0.02^{NS}
L2.7	11.6±1.3^{NS}	4.7±0.3^{b}	11.0±0.8^{b}	7.9±0.4^{b}	25.17±3.26^{b}	1.56±0.35^{b}	1.74±0.20^{b}	0.16±0.03^{NS}
L4.0	12.5±1.4^{NS}	5.0±0.4^{b}	10.9±1.0^{b}	7.7±0.5^{b}	25.91±4.48^{b}	1.58±0.34^{b}	1.50±0.21^{b}	0.14±0.02^{NS}

Note: Different letters in the same column indicate significant differences (p<0.05), NS represents no significant difference in the same column.

The results showed that a relatively higher fraction of blue light was a benefit to the subsequent growth of hydroponic pakchoi. The cause of higher biomass accumulation was probably that the expanded leaf area under L0.9 could increase photosynthetic products, which conforms with the previous studies[7,29]. Meanwhile, the responses of plant morphology and biomass accumulation to R:B ratio were related to species, and the suitable percentage of red and blue light varied among different brassicaceous vegetables. Mickens et al.[30] observed that the fresh shoot weight of red pakchoi had no significant difference between the white LEDs treatments and the white plus red LEDs treatments. Ying et al.[31] explored the influence of blue light fraction in red and blue LEDs on yield of four *Brassicaceae* microgreens including cabbage, kale, arugula, and mustard, and no significant difference was observed in fresh and dry yield of kale, arugula, and mustard under different percentages of blue light from 0-30%, while, the fresh and dry weight reached a plateau at 15% blue light in cabbage planting[31].

3.2 Photosynthesis of hydroponic pakchoi leaves

Although the morphology of hydroponic pakchoi showed different responses to R:B ratio, there was no significant difference among P_n of hydroponic pakchoi leaves under varied treatments, which were at 9.2 to 9.6 μmol/(m^2·s) (Figure 3). The highest stomatal conductance was observed under L0.9 treatment at 421 mmol/(m^2·s) which was 12.8% higher than L1.8 treatment. Intercellular CO_2 concentration is another important issue having an impact on photosynthesis, and the intercellular CO_2 concentration was lower at 637 μmol/mol under L4.0 treatment while the results were similar under L0.9, L1.8, and L2.7 treatments in this study. Transpiration rate was also the highest under L0.9 treatment and 8% higher than L1.8 and L4.0 treatments approximately. Hernández et al.[32] found that with the fraction of blue light increased from 10% to 80%, the P_n of cucumber leaf showed an increasing tendency. Yan et al.[20] reported that P_n of hydroponic lettuce was higher as the R:B ratio decreased from 3.6 to 0.9 with the same daily light integrals. Chang et al.[33] gave a contrary result, as they found that the P_n of *Brassica napus* L. decreased with the increase of the blue light fraction from 25% to 100%.



a. Net photosynthesis rate b. Stomatal conductance

c. Intercellular CO_2 concentration d. Transpiration rate

Figure 3 Net photosynthesis rate, stomatal conductance, intercellular CO_2 concentration, transpiration rate of hydroponic pakchoi leaves grown for 40 d under white LEDs at R:B ratios of 0.9 and 1.8, white plus red LEDs at R:B ratios of 2.7 and 4.0, respectively

3.3 Chlorophyll contents and spectral characteristics of hydroponic pakchoi leaves

The pigment contents of hydronic pakchoi leaves had no obvious response to light quality. The total chlorophyll and carotenoid contents of hydroponic pakchoi leaves reached the highest level under L2.7, respectively, and there was no significant difference in chlorophyll b content. Meanwhile, carotenoid content of pakchoi leaves under L2.7 treatment was observed around 20% higher than in other treatments. The total chlorophyll contents of pakchoi were the highest under blue light followed by that under white light[34], while the highest contents of chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids of Brassica napus were all observed under red light followed by those under white light[35].

Table 3 Pigment contents of hydroponic pakchoi leaves grown under LED lighting environment at a light intensity of 250 μmol/(m^2·s) provided by white LEDs with R:B ratios of 0.9 and 1.8, white plus red LEDs with R:B ratios of 2.7 and 4.0, respectively

Lighting treatment	Chlorophyll a content /mg·g^{-1}	Chlorophyll b content /mg·g^{-1}	Total chlorophyll content/mg·g^{-1}	Chlorophyll a/b	Carotenoid content /mg·g^{-1}
L0.9	1.41±0.15^b	0.52±0.06^{NS}	1.93±0.20^b	2.70±0.04^{NS}	0.26±0.04^b
L1.8	1.51±0.16^{ab}	0.57±0.08^{NS}	2.08±0.25^{ab}	2.65±0.09^{NS}	0.26±0.04^b
L2.7	1.63±0.12^a	0.61±0.07^{NS}	2.24±0.18^a	2.67±0.15^{NS}	0.32±0.03^a
L4.0	1.43±0.12^b	0.53±0.05^{NS}	1.97±0.17^{ab}	2.69±0.08^{NS}	0.25±0.04^b

Note: Different letters in the same column indicate significant differences (p<0.05), NS represent no significant difference in the same column.

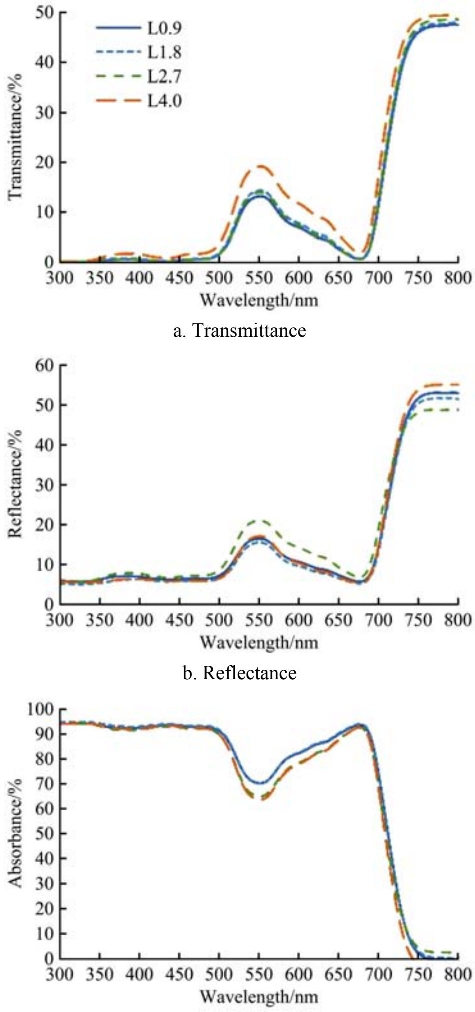
The light transmittance, reflection, and absorptance of hydroponic pakchoi leaves under different LED light quality showed similar trends that most red, blue, and ultraviolet light was absorbed, part of green light, and nearly all of the far-red light was transmitted and reflected (Figure 4). The absorptance spectrum of hydroponic pakchoi leaves was consistent with previous studies[36,37] and mainly influenced by photosynthetic pigments absorbing light with varied efficiency at different wavelengths[21].

Pakchoi leaves under L4.0 treatment showed higher transmittance of green and red light. Meanwhile, the leaves under L2.7 treatment showed higher reflectance in the same range as a result of its high content of chlorophyll. The calculation results showed that the absorptance of lower R:B (L0.9 and L1.8) treatments kept more than 70% when the wavelength light was between 500 nm and 680 nm. The minimal absorptance of pakchoi leaves under L2.7 and L4.0 treatments was at around 64% in the same range.

The largest absorptance gap among different treatments was observed in the interval of 530-570 nm. Besides, the pakchoi leaves under L0.9 and L1.8 treatments absorbed more light in these wavelengths, which could result in higher biomass of plant, and the growth of pakchoi under L0.9 was enhanced. The blue light could contribute to anthocyanin accumulated in the leaves[38], and hydroponic pakchoi leaves under L0.9 and L1.8 treatments showed high absorption of green light might related to the high content of anthocyanin[21,39].

3.4 Energy use efficiency of hydroponic pakchoi

LUE, PY, and EY of hydroponic pakchoi were significantly higher in L0.9 treatment, which reached 0.058, 12.52 g/mol, and 75.09 g/kW·h, respectively, and there was no significant difference between L1.8, L2.7, and L4.0. The PY in L0.9 treatment were 38.6%, 47.0%, and 45.4% more than those in L1.8, L2.7, and L4.0, respectively. Nevertheless, the effects of light



a. Transmittance

b. Reflectance

c. Absorbance

Figure 4 Transmittance, reflectance and absorbance of hydroponic pakchoi leaves grown under white LEDs at R:B ratios of 0.9 and 1.8, white plus red LEDs at R:B ratios of 2.7 and 4.0, respectively

quality on EUE of pakchoi had no significant difference. The photon efficacy of LED fixtures used for L0.9 treatment was lower than other treatments, which led to more LED fixtures fixed. Therefore, the total energy consumption for lighting of L0.9 treatment was higher than others, although the biomass of pakchoi in L0.9 was 28.9% at least higher than other treatments. The EUE of hydroponic pakchoi had no significant difference among all treatments. Kozai[25] indicated that the maximum theoretical value of LUE of PFAL was 0.1, and the LUE was between 0.043 and 0.058 in this study, having a gap with the theoretical value.

When the daily light intensity is controlled, PY is only affected by yield, while LUE depends also on the absorption and utilization of photosynthetic photons for plants. Meanwhile, the photoelectric conversion coefficient was quite different in terms of the types of LED fixtures that influenced EUE and EY strongly. Yan et al.[20-21] observed LUE and EUE of lettuce would increase with the improvement of R:B ratio, and when the R:B ratio increased from 0.9 to 2.2, LUE and EUE were improved from 0.022 to 0.032 and from 0.0099 to 0.1177, respectively. Pennisi et al.[40] investigated that with R:B ratio increasing from 0.5 to 3.0, the light electricity consumption of lettuce production based on leaf fresh weight increased by 44%. A similar result was found in basil whose light electricity consumption based on fresh weight decreased from 83.0 to 23.2 g/kW when the R:B ratio increased from 0.7 to 5.5[41]. Consistent with the previous researches, when the cultivation lighting environment was offered by lower R:B ratio treatments, better yield, and energy use efficiency of hydroponic pakchoi were detected compared with the outcomes of the other treatments. The dry weight of pakchoi under L0.9 was 26%-33% higher than other treatments, which also led to higher LUE.

Table 4 Energy use efficiency of hydroponic pakchoi grown under LED lighting environment at light intensity of 250 μmol/(m^2·s) provided by white LEDs with R:B ratios of 0.9 and 1.8, white plus red LEDs with R:B ratios of 2.7 and 4.0, respectively

Lighting treatment	Light energy use efficiency	Electrical energy use efficiency	Photon yield /g·mol^{-1}	Energy yield /g·kWh^{-1}
L0.9	0.058±0.008^{a}	0.0199±0.0029^{NS}	12.52±0.34^{a}	75.09±2.04^{a}
L1.8	0.045±0.007^{b}	0.0167±0.0024^{NS}	7.69±1.14^{b}	51.89±7.70^{b}
L2.7	0.048±0.006^{b}	0.0196±0.0024^{NS}	6.64±0.86^{b}	50.45±6.53^{b}
L4.0	0.043±0.005^{b}	0.0169±0.0021^{NS}	6.84±1.18^{b}	51.93±8.98^{b}

Note: Different letters in the same column indicate significant differences (p<0.05), NS represent no significant difference in the same column.

4 Conclusions

Suitable R:B ratio could promote the growth of hydroponic pakchoi and improve energy use efficiency. The white LED with R:B ratio of 0.9 could achieve much higher biomass of pakchoi than R:B ratios of 1.8, 2.7, and 4.0. L0.9 could promote the expansion of leaves and photosynthesis. Lower R:B ratios at 0.9 and 1.8 could help increase the light absorption capacity of pakchoi leaves. The LUE, PY, and EY were much higher in L0.9 than those in other treatments. Considering the yield and quality of hydroponic pakchoi and energy use efficiency, it is suggested that full spectrum LED with R:B ratio of 0.9 could be selected to provide a proper lighting condition for hydroponic pakchoi production.

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[References]

[1] Han W, Huang L, Owojori O J. Foliar application of zinc alleviates the heat stress of pakchoi (*Brassica chinensis* L.). Journal of Plant Nutrition, 2020; 43: 194–213.

[2] Kozai T. Towards sustainable plant factories with artificial lighting (PFALs) for achieving SDGs. Int J Agric & Biol Eng, 2019; 12(5): 28–37.

[3] Kozai T. Current status of plant factories with artificial lighting (PFALs) and smart PFALs. In: Smart Plant Factory: The Next Generation Indoor Vertical Farms, Singapore: Springer Singapore, 2018; pp.3–13.

[4] Pattison P M, Tsao J Y, Brainard G C, Bugbee B. LEDs for photons, physiology and food. Nature, 2018; 563(7732): 493–500.

[5] Agarwal A, Dutta Gupta S, Barman M, Mitra A. Photosynthetic apparatus plays a central role in photosensitive physiological acclimations affecting spinach (*Spinacia oleracea* L.) growth in response to blue and red photon flux ratios. Environmental and Experimental Botany, 2018; 156: 170–182.

[6] Pennisi G, Blasioli S, Cellini A, Maia L, Crepaldi A, Braschi I, et al. Unraveling the role of red:blue LED lights on resource use efficiency and nutritional properties of indoor grown sweet basil. Frontiers in Plant Science, 2019; 10: 305. doi:10.3389/fpls.2019.00305.

[7] Wang J, Lu W, Tong Y, Yang Q. Leaf morphology, photosynthetic performance, chlorophyll fluorescence, stomatal development of lettuce (*Lactuca sativa* L.) exposed to different ratios of red light to blue light. Frontiers in Plant Science, 2016; 7: 250. doi: 10.3389/fpls.2016.00250.

[8] Chen X, Guo W, Xue X, Wang L, Qiao X. Growth and quality responses

of 'Green Oak Leaf' lettuce as affected by monochromic or mixed radiation provided by fluorescent lamp (FL) and light-emitting diode (LED). Scientia Horticulturae, 2014; 172: 168–175.

[9] Nguyen D T P, Kitayama M, Lu N, Takagaki M. Bioactive compound accumulation and growth of coriander (*Coriandrum sativum* L.) under different types of white LED lights in plant factory. Acta Horticulturae, 2020; 1296: 921–928.

[10] Mickens M A, Skoog E J, Reese L E, Barnwel P L, Spencer L E, Massa G D, et al. A strategic approach for investigating light recipes for 'Outredgeous' red romaine lettuce using white and monochromatic LEDs. Life Sciences in Space Research, 2018; 19: 53–62.

[11] Sun J U O W, Nishio J N, Vogelmann T C. Green light drives CO_2 fixation deep within leaves. Plant & Cell Physiology, 1998; 39(10): 1020–1026.

[12] Claypool N B, Lieth J H. Green light improves photosystem stoichiometry in cucumber seedlings (*Cucumis sativus*) compared to monochromatic red light. Plants, 2021; 10(5): 824. doi: 10.3390/plants10050824.

[13] Li L, Tong Y, Lu J, Li Y, Yang Q. Lettuce growth, nutritional quality, and energy use efficiency as affected by red-blue light combined with different monochromatic wavelengths. HortScience, 2020; 55(5): 613–620.

[14] Samuolienė G, Viršilė A, Haimi P, Miliauskienė J. Photoresponse to different lighting strategies during red leaf lettuce growth. Journal of Photochemistry and Photobiology B, Biology, 2020; 202: 111726. doi: 10.1016/j.jphotobiol.2019.111726.

[15] Westmoreland F M, Kusuma P, Bugbee B. Cannabis lighting: Decreasing blue photon fraction increases yield but efficacy is more important for cost effective production of cannabinoids. PloS One, 2021; 16(3): e0248988. doi: 10.1371/journal.pone.0248988.

[16] Both A, Bugbee B, Kubota C, Lopez R G, Mitchell C, Runkle E S, et al. Proposed product label for electric lamps used in the plant sciences. HortTechnology, 2017; 27(4): 544–549.

[17] Yan Z, He D, Niu G, Zhai H. Evaluation of growth and quality of hydroponic lettuce at harvest as affected by the light intensity, photoperiod and light quality at seedling stage. Scientia Horticulturae, 2019; 248: 138–144.

[18] Park Y, Runkle E S. Spectral effects of light-emitting diodes on plant growth, visual color quality, and photosynthetic photon efficacy: White versus blue plus red radiation. PloS One, 2018; 13(8): 0202386. doi: 10.1371/journal.pone.0202386.

[19] Kusuma P, Pattison P M, Bugbee B. From physics to fixtures to food: current and potential LED efficacy. Horticulture Research, 2020; 7: 56. doi: 10.1038/s41438-020-0283-7.

[20] Yan Z, He D, Niu G, Zhou Q, Qu Y. Growth, nutritional quality, and energy use efficiency of hydroponic lettuce as influenced by daily light integrals exposed to white versus white plus red light-emitting diodes. HortScience, 2019; 54(10): 1737–1744.

[21] Yan Z, He D, Niu G, Zhou Q, Qu Y. Growth, nutritional quality, and energy use efficiency in two lettuce cultivars as influenced by white plus red versus red plus blue LEDs. Int J Agric & Biol Eng, 2020; 13(2): 33–40.

[22] Cope K R, Bugbee B. Spectral effects of three types of white light-emitting diodes on plant growth and development: absolute versus relative amounts of blue light. HortScience, 2013; 48(4): 504–509.

[23] Kong Y, Nemali A, Mitchell C, Nemali K. Spectral quality of light can affect energy consumption and energy-use efficiency of electrical lighting in indoor lettuce farming. HortScience, 2019; 54(5): 865–872.

[24] Kozai T, Niu G, Takagaki M. Plant factory: An indoor vertical farming system for efficient quality food production. Second edition, 2020; 405p.

[25] Kozai T. Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. Proceedings of the Japan Academy. Series B, Physical and Biological Sciences, 2013; 89(10): 447–461.

[26] Kozai T, Niu G. Plant factory as a resource-efficient closed plant production system. In: Plant factory an indoor vertical farming system for efficient quality food production second edition, 2020; pp.93–115.

[27] Lichtenthaler H K, Wellburn A R. Determination of total carotenoids and chlorophylls a and b of leaf in different solvents. Biochemical Society Transactions, 1983; 11: 591–592.

[28] Chung H, Chang M, Wu C, Fang W. Quantitative evaluation of electric light recipes for red leaf lettuce cultivation in plant factories. HortTechnology, 2018; 28(6): 755–763.

[29] Agarwal A, Dutta Gupta S, Barman M, Mitra A. Photosynthetic apparatus plays a central role in photosensitive physiological acclimations affecting spinach (*Spinacia oleracea* L.) growth in response to blue and red photon flux ratios. Environmental and Experimental Botany, 2018; 156: 170–182.

[30] Mickens M A, Torralba M, Robinson S A, Spencer L E, Romeyn M W, Massa G D, et al. Growth of red pak choi under red and blue, supplemented white, and artificial sunlight provided by LEDs. Scientia Horticulturae, 2019; 245: 200–209.

[31] Ying Q, Kong Y, Jones-Baumgardt C, Zheng Y. Responses of yield and appearance quality of four *Brassicaceae* microgreens to varied blue light proportion in red and blue light-emitting diodes lighting. Scientia Horticulturae, 2020; 259: 108857. doi: 10.1016/j.scienta.2019.108857.

[32] Hernández R, Kubota C. Physiological responses of cucumber seedlings under different blue and red photon flux ratios using LEDs. Environmental and Experimental Botany, 2016; 121: 66–74.

[33] Chang S X, Li C X, Yao X Y, Song C, Jiao X L, Liu X Y, et al. Morphological, photosynthetic, and physiological responses of rapeseed leaf to different combinations of red and blue lights at the rosette stage. Frontiers in Plant Science, 2016; 7: 1144. doi: 10.3389/fpls.2016.01144.

[34] Fan X, Xue F, Song B, Chen L, Xu G, Xu H. Effects of blue and red light on growth and nitrate metabolism in pakchoi. Open Chemistry, 2019; 17(1): 456–464.

[35] Saleem M H, Rehman M, Fahad S, Tung S A, Iqbal N, Hassan A, et al. Leaf gas exchange, oxidative stress, and physiological attributes of rapeseed (*Brassica napus* L.) grown under different light-emitting diodes. Photosynthetica, 2020; 58(3): 836–845.

[36] McCree K J. The action spectrum, absorptance and quantum yield of photosynthesis in crop plants. Agricultural Meteorology, 1972; 9: 191–216.

[37] Li Q, Kubota C. Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environmental and Experimental Botany, 2009; 67(1): 59–64.

[38] Lee J W, Kang W H, Park K S, Son J E. Spectral dependence of electrical energy-based photosynthetic efficiency at single leaf and canopy levels in green- and red-leaf lettuces. Horticulture, Environment, and Biotechnology, 2017; 58(2): 111–118.

[39] Liu J, van Iersel M W. Photosynthetic physiology of blue, green, and red light: Light intensity effects and underlying mechanisms. Frontiers in Plant Science, 2021; 12: 619987. doi: 10.3389/fpls.2021.619987.

[40] Pennisi G, Orsini F, Blasioli S, Cellini A, Crepaldi A, Braschi I, et al. Resource use efficiency of indoor lettuce (*Lactuca sativa* L.) cultivation as affected by red:blue ratio provided by LED lighting. Scientific Reports, 2019; 9(1): 14127. doi: 10.1038/s41598-019-50783-z.

[41] Piovene C, Orsini F, Bosi S, Sanoubar R, Bregola V, Dinelli G, et al. Optimal red:blue ratio in led lighting for nutraceutical indoor horticulture. Scientia Horticulturae, 2015; 193: 202–208.