Effects of light quality on growth and development of cucumber seedlings in controlled environment

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Abstract: Conventional light sources have been successfully used to cultivate a wide variety of horticultural crops. However, they are of limited use due to uncontrollability of spectra and energy inefficiency. Light-emitting diodes (LEDs) emerged with tremendous potential in controlled environment agriculture due to their energy efficiency, longevity, and spectral specificity, but the effects of different types of LEDs on plant growth and development must be examined. In this study, cucumber (*Cucumis sativus* L. cv. Zhongnong 26) seedlings were grown under four different lighting treatments that each delivered a photosynthetic photon flux density of 200 μmol/m^2·s at plant canopy including triphosphate fluorescent lamps (TF), high-frequency fluorescent lamps (HF), white LEDs (WL), and red and blue LEDs (RBL). Cucumber seedlings were grown in a growth chamber at (25.0±1.5)°C with 12-hour light and 12-hour dark for 30 days after sowing, and data were subsequently collected. Seedlings grown under the WL were 45%, 12%, and 40% taller than those grown under the TF, HF and RBL, respectively. The leaf area was 23% smaller under the TF than under the HF. The shoot dry weight was 16%-22% lower under the TF than under the other lighting treatments. The transplants grown under the RBL had the lowest root dry weight and root to shoot ratio. The seedling quality index was similar among all the lighting treatments. The LEDs treatment yielded more total dry weight with unit electric power compared to the fluorescent lamps. The chlorophyll content was 13%-15% higher in plants grown under the HF and WL than that under the TF and RBL. Plants grown under the WL and RBL had greater photosynthetic rate, transpiration rate, and stomatal conductance than those grown under the TF and HF. It was concluded that high quality cucumber seedlings can be efficiently produced under the broad-spectrum WL that emit a reasonable amount of blue, green and red light, and the lack of green light and/or high ratio of red to blue light under the RBL may cause undesired plant attributes.

Keywords: blue light, chlorophyll, cucumber seedlings, controlled environment, gas exchange, green light, light-emitting diode, red light

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1 Introduction

Proper photosynthetic lighting for indoor cultivation in controlled environments has enhanced crop productivity in increasingly populated regions, space-based missions, and bioregenerative life support facilities[1]. The spectral characteristics of electric light sources must fulfill physiological requirements of plants for photosynthesis and photomorphogenic development[2]. However, spectral distributions of a wide range of conventional light sources, such as fluorescent, metal halide, and high-pressure sodium lamps, are predetermined and may not be optimal for species-specific light requirements. Light-emitting diodes (LEDs) emerged with great potential for horticultural lighting due to their

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energy efficiency, longevity, and application flexibility[3]. Moreover, LEDs are suitable for research and commercial applications in controlled environments as a result of their low radiated heat output and capability of spectral adaptation[4]. Facilitated with LEDs, which can be tailored to emit photons at specific wavelengths, photobiological research can precisely define the functions of light quality without confounding spectral irradiance[5,6]. Therefore, LEDs allow for optimal spectral distributions, thereby promoting plant growth with considerable life span and energy efficiency[7]. Endeavors to transition from conventional light sources to LEDs were accompanied by numerous inventions, such as LED replacement for fluorescent light tubes[8], a combination of fluorescent and LED lighting system[9], and retrofit LED lamps for fluorescent fixtures without ballast[10].

Researchers have been striving to clarify the influence of light quality on growth, morphology, development, and photosynthesis of different plant species[11-14]. A combination of red (R) and blue (B) LEDs can be generally advantageous for plant cultivation[15-17]. For example, the dry weight of lettuce (*Lactuca sativa* L. cv. Outredgeous) grown under R+B LEDs (R to B light ratio, R:B=9) was greater than under triphosphor fluorescent lamps[18]. However, the dry weight of *Withania somnifera* grown under R+B LEDs (R:B=1) was approximately 42% lower than under fluorescent lamps[15]. Another study showed that a high R:B resulted in greater dry weight of lettuce 'Sunmang' than a low R:B or fluorescent and high-pressure sodium lamps, and the inclusion of B light was crucial to avoid abnormal leaf shape and low antioxidant phenolic compound accumulation[19]. Due to discrepancies in previous studies, comparisons of R+B LEDs and various conventional fluorescent lamps are needed.

The most widely used white (W) LEDs typically incorporate phosphor coatings over B LEDs[20,21]. They can be used to efficiently grow radish (*Raphanus sativus* L. cv. Cherry Belle), soybean (*Glycine max* L. cv. Hoyt), and wheat (*Triticum aestivum* L. cv. Perigee), but warm-, neutral-, and cool-W LEDs emitting various amounts of B light that altered plant development differently[22]. The addition of W light to R+B LEDs promoted biomass accumulation of Boston lettuce but did not affect chlorophyll and carotenoid content[23]. However, W LEDs need to be evaluated against conventional light sources and other LEDs to determine their prospects in sole-source horticultural lighting.

The objective of this study was to examine the effects of R+B LEDs, W LEDs, and two different types of fluorescent lamps on growth and photosynthesis of cucumber seedlings. The results can be used to facilitate design of spectrally appropriate, efficacious lighting systems for plant seedling cultivation in controlled environments.

2 Materials and methods

2.1 Plant material and environmental control

Seeds of cucumber (*Cucumis sativus* L. cv. Zhongnong 26) were sown in 72-cell plug trays containing a commercial horticultural medium with 60% vermiculite, 20% peat and 20% perlite. One seed was sown per cell in all trays, and the germination rate exceeded 98%. The trays were subsequently transferred to a growth chamber, where two trays were placed under each of four separate lighting treatments. An environmental control system in the ventilated growth chamber maintained air temperature, relative humidity, and CO_2 concentration at (25.0±1.5)°C, (60±5)% and (500±50) μmol/m^2·s, respectively. The Hoagland nutrient solution[24,25] was regularly supplied from the bottom of the trays after two true leaves of 80% seedlings unfolded.

2.2 Lighting treatments

The following four different lighting treatments were delivered as triphosphor fluorescent lamps (TF, peak wavelength=442 nm) (Beijing Panasonic Lighting Corp., Beijing, China), high-frequency fluorescent lamps (HF, peak wavelength=604 nm) (Beijing Panasonic Lighting Corp., Beijing, China), white LEDs (WL, peak wavelength=604 nm) (Tianjin Jinya Electronic Inc., Tianjin, China), and R+B LEDs (RBL, peak wavelength=658 nm) (Tianjin Jinya Electronic Inc., Tianjin, China). The two types of fluorescent lamps were considered as controls. Each lighting treatment was designated to a random layer on a shelf to avoid light contamination from adjacent treatments. All lamps in above lighting treatments were controlled by an environmental control computer and operated daily to deliver a photoperiod of 12 h from 08:00 to 20:00. Spectral output of each light source was measured at an interval of 2 nm between 300-1100 nm using a spectroradiometer (LI-1800, LI-COR Biosciences, Lincoln, NE, USA), and the measurements were averaged from six different spots at plant height under each lighting treatment (Table 1). The photosynthetic photon flux density (PPFD, 400-700 nm) was adjusted to approximately 200 μmol/m^2·s (8.6 mol/m^2·d) at plant height in all lighting treatments. Light intensities of B (400-500 nm), green (G, 500-600 nm), R (600-700 nm), and far red (FR, 700-800 nm) were integrated, and the phytochrome photoequilibrium (P_{FR}/P_{R+FR}) was determined for each lighting treatment as described by Sager et al.[26] (Table 1).

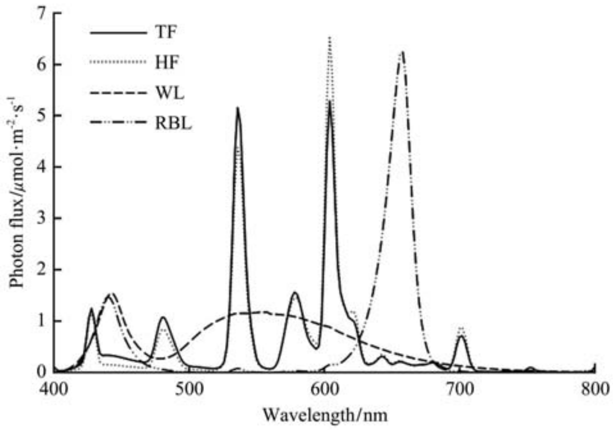

Figure 1 Spectral distributions of different lighting treatments between 400-800 nm

Table 1 Spectral characteristics of different lighting treatments

Treatment	Photosythetic photon flux density/μmol·m^{-2}·s^{-1}					Percentage/%				Light ratio		
	PPFD (400-700 nm)	Blue (B,400-500 nm)	Green (G, 500-600 nm)	Red (R, 600-700 nm)	Far red (FR,700-800 nm)	PPFD	B	G	R	R:FR	R:B	P_R/P_{R+FR}
TF	205	39	90	76	7	100	19	44	37	10	2	0.840
HF	197	28	81	88	9	100	14	41	45	10	3	0.845
WL	203	55	103	45	5	100	27	51	22	9	1	0.824
RBL	198	40	2	157	0	100	20	1	79	317	4	0.879

2.3 Data collection

The experiment was replicated twice in time with all data collected from eight seedlings randomly selected from each lighting treatment 30 d after seeds sowing. Transplant height was measured from the media surface to the meristem tip. Stem diameter was measured at three positions on the stem using a vernier caliper. Shoot and root fresh weight was measured using an electronic scale (FA1204B, Bioon Group, Shanghai, China). Shoot and root dry weight was measured after seedlings were dried in a drying oven at 105°C for 3 h and subsequently at 80°C for 72 h. To measure leaf area, all leaves of each seedling were scanned using a leaf area meter (LI-3000, LI-COR Biosciences, Lincoln, NE, USA). To evaluate and predict overall seedling survival and growth, seedling quality index suggested by Dickson et al.[27] was calculated as follows: weight/(height-diameter quotient+shoot-root ratio). Chlorophyll contents were measured using a UV/VIS spectrophotometer (UV-2100, Unico Inc., Shanghai, China). The second completely unfolded true leaf below the meristem on each seedling was sampled for measuring chlorophyll contents. Arnon's[28] equations for calculation of chlorophyll extracted in 80% acetone were used with absorbance levels at 663 nm and 645 nm obtained from the spectrophotometer. Gas exchange parameters including the net photosynthetic rate, transpiration rate, intercellular CO_2 concentration, and stomatal conductance were measured by using a portable photosynthesis system (LI-6400, LI-COR Biosciences, Lincoln, NE, USA) containing a leaf chamber with a standard light source. In the leaf chamber, PPFD, air temperature, airflow speed, and CO_2 concentration were set at 250 μmol/m^2·s, 20°C, 500 μmol/s, and 400 μmol/mol, respectively. Instantaneous water use efficiency was calculated by dividing the net photosynthetic rate with the transpiration rate as described by Polley[29]. The electric energy used by lamps in each lighting treatment was measured using a portable electronic power meter (PowerBay-SSM, Shenzhen Northmeter Co., Ltd., Shenzhen, China).

2.4 Data analysis

Data were analyzed with the SAS (SAS Institute, Inc., Cary, NC, USA) means (PROC MEANS), mixed (PROC MIXED), and glimmix (PROC GLIMMIX) procedures, and pairwise comparisons between treatments were performed using Tukey's honest significant difference test ($p<0.05$).

3 Results and discussion

3.1 Growth characteristics under different lighting environment

The lamp type had a significant impact on seedling height, stem diameter and leaf area (Table 2). Cucumber seedlings under the WL were tallest, followed by the HF, and then the TF and RBL. Stem diameter was greater under the HF and WL than under the TF and RBL. Leaf area of plants under the TF was 23% smaller compared with the HF. Accumulation of biomass was affected by different lighting treatments. Shoot dry weight under the TF was 16%-22% less than that under all the other treatments, whereas root dry weight was 30% greater under the WL than under the RBL. Root to shoot ratio was higher under the TF than under the RBL. Irrespective of distinct growth characteristics under different treatments, the seedling quality index was similar.

Table 2 Growth parameters of cucumber seedlings grown under different lighting treatments

Parameter	Treatment			
	TF	HF	WL	RBL
Seedling height/cm	5.1 c	6.6 b	7.4 a	5.3 c
Stem diameter/mm	3.77 b	4.39 a	4.24 a	3.55 b
Leaf area/cm^2	88.8 b	115.6 a	99.9 ab	102.3 ab
Shoot dry weight/g	0.32 b	0.39 a	0.41 a	0.38 a
Root dry weight/mg	62.8 ab	63.6 ab	66.9 a	51.4 b
Root to shoot ratio	0.195 a	0.166 ab	0.166 ab	0.135 b
Seedling quality index	0.0206 a	0.0211 a	0.0200 a	0.0193 a

Note: Means followed by different letters in the same row are significantly different by Tukey's honest significant difference test ($p<0.05$).

Cucumber seedlings were taller under the WL than under the RBL. Broad-band W light promoted the stem elongation of cucumber seedlings more effectively than R+B light[14]. Similarly, the hypocotyl length of *Arabidopsis* seedlings was greater under R+G+B light than under growth-inhibitory R+B light, suggesting the addition of G light antagonized R and B light effects on stem elongation[30]. Cucumber seedlings under the HF (14% B light) were taller than those grown under the TF (19% B light) and RBL (20% B light) possibly due to less inhibitory effect of B light. The hypocotyl elongation of *Arabidopsis* [31], lettuce[32-34], and radish seedlings[35] was inhibited as the B light intensity increased. Although the stem length of lettuce was remarkably suppressed by B light, that of eggplant increased as B light intensity increased, indicating the effect of B light on stem elongation is species specific[36]. Overall, differences in extension growth may result from varied proportions of both G and B light.

Leaf area under the RBL was similar with that under all the other lighting treatments with the addition of G light, suggesting that including 41% to 51% G light did not affect leaf area. Similarly, the presence of 51% and 0% G light had the same effect on the leaf area of lettuce[13]. The leaf area of cherry tomato seedlings under the R+B light and R+B+G light (14% G light) was also similar[14]. Supplementing W light with G light to increase the percentage of G light from 52% to 70% did not affect the leaf length and width of lettuce[33]. However, the leaf area of lettuce increased when a small fraction (24%) of G light was added to R+B light and reduced when the percentage of G light was increased from 24% to 51% and 86%[13]. Therefore, leaf area may only be promoted if an optimum amount of G light is delivered. In our study, the leaf area of cucumber seedlings under the HF (R:B=3) was greater than that under the TF (R:B=2). Consistently, a higher R:B resulted in greater leaf area of lettuce[19,37,38], spinach[38], pea[39], radish[22,35] and soybean[22].

The shoot and root dry weight of lettuce under a high R:B ratio of 3 or 7 was greater than that under a low R:B ratio of 1 or 2[19]. Similarly, the shoot dry weight of cucumber seedlings under the HF (R:B=3) and RBL (R:B=4) was greater than that under the TF (R:B=2). However, the shoot dry weight under the WL (R:B=1) was greater than that under the TF possibly due to the presence of more G light under the WL. It was reported that the shoot dry weight of lettuce under R+B+G light (24% G light) was greater than that under R+B light[13]. Yorio et al.[40] reported that radish and spinach grown under cool-W fluorescent lamps gained greater root dry weight than those under R LEDs + 10% B fluorescent lamps, suggesting that a high B light intensity might be required in favor of the root dry weight, and optimal growth might be restrained under R+B light due to lacking of some other wavelengths. Therefore, a broad spectrum including the highest amount of B light under the WL may contribute to greater root dry weight under the WL than under the RBL. As the R:B decreased, the root to shoot ratio increased in cucumber[41] and lettuce[19].

3.2 Chlorophyll content under different lighting environment

Chlorophyll a, chlorophyll b and total chlorophyll content of cucumber seedlings grown under the HF and WL were higher than under the TF and RBL (Figure 2). However, the ratio of chlorophyll a/b was higher under the TF and RBL than under the HF and WL. The total chlorophyll content of lettuce was higher while the chlorophyll a/b was lower under W light than that under R+B light[37], in agreement with our results. However, the effect of light quality on chloroplast development is strongly dependent on plant species[42], as evidenced by different responses of lettuce, spinach, and komatsuna[38]. The low chlorophyll content under the RBL might also result from a high R:B ratio of 4. Lettuce grown under a high R:B ratio of 7 had lower total chlorophyll content compared with those grown under a low R:B ratio of 1, 2 or 3[19].

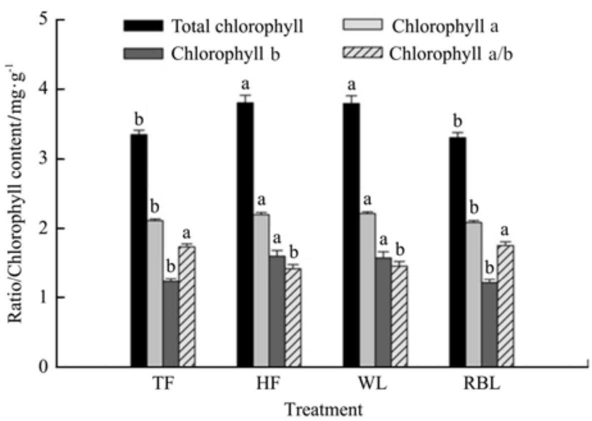

Figure 2 Chlorophyll content and ratio of chlorophyll a/b of cucumber seedlings grown under different lighting treatments.

3.3 Photosynthetic parameters under different lighting environment

Photosynthetic parameters of cucumber seedlings were significantly influenced by different lighting treatments (Table 3). Net photosynthetic rate, transpiration rate, and stomatal conductance were higher in cucumber seedlings grown under the WL and RBL than under the HF and TF. Higher intercellular CO_2 concentration exhibited in cucumber seedlings grown under the WL compared with the HF. Cucumber seedlings under the TF and HF had higher instantaneous water use efficiency than those under the WL. Since light intensity was similar in all lighting treatments with the same photoperiod, light quality was responsible for differences in growth, morphology and photosynthesis among the lighting treatments in this study. FR light was minimal under all lighting treatments. The R to FR light ratio was similar under the TF, HF, and WL. The phytochrome photoequibrilium (P_R/P_{R+FR}) was similar under all lighting treatments, ranging between 0.82 and 0.88, and thus was not considered a factor causing morphogenic differences.

Table 3 Photosynthetic parameters of cucumber seedlings grown under different lighting treatments

Parameter	Treatment			
	TF	HF	WL	RBL
Net photosynthetic rate/μmol·m^{-2}·s^{-1}	5.49b	5.74b	7.25a	6.88 a
Transpiration rate/mmol·m^{-2}·s^{-1}	2.06b	2.15b	4.61a	3.53 a
Stomatal conductance/mol·m^{-2}·s^{-1}	0.08b	0.08b	0.23a	0.16 a
Intercellular CO_2 concentration/μmol·mol^{-1}	376ab	366b	415a	383 ab
Instantaneous water use efficiency	2.96a	2.96a	1.85b	2.37ab

Note: Means followed by different letters in the same row are significantly different by Tukey's honest significant difference test (p<0.05).

3.4 Energy consumption

Listed lamp power does not always accurately indicate actual energy consumption in a circuit (Table 4). The LED lamps are more energy efficient than the fluorescent lamps. Although there was no significant difference in total dry weight under the HF, WL and RBL, total dry weight per kilowatt hour was the highest under the RBL, followed by the WL, and then the TF and HF (Table 4). The W LED lamps integrating a reasonable spectral distribution are more effective and efficient in obtaining desired plant attributes than conventional fluorescent lamps. The LEDs yielded more dry weight with unit electric power compared with traditional fluorescent lamps. Other factors such as initial costs, light output, efficiency, and other lighting characteristics along with spectral composition should be taken into consideration when designing a lighting system for commercial production of transplants. Therefore, LED lamps were more suitable for using in seedling production under artificial lighting.

Table 4 Dry weight with unit electric power calculated from cucumber seedlings grown under different lighting treatments with corresponding energy consumption measured

Parameter	Treatment			
	TF	HF	WL	RBL
Listed lamp power/W	36	32	18	30
Lamp number	6	6	10	6
Actual power used/W	184	260	159	135
Total dry weight/g	0.38 b	0.46 a	0.48 a	0.43 ab
Total dry weight with unit electric power/g·(kW·h)$^{-1}$	2.08 c	1.76 c	3.01 b	2.82 a

Note: Means followed by different letters in the same row are significantly different by Tukey's honest significant difference test ($p<0.05$).

4 Conclusions

The results indicated that light quality significantly influence growth and morphology of cucumber seedlings. Plants grown under the WL and RBL had greater biomass, chlorophyll contents and photosynthetic ability than those grown under the TF and HF. The LEDs yielded more total dry weight with unit electric power compared with the fluorescent lamps. It is concluded that high quality cucumber seedlings can be efficiently produced under the broad-spectrum WL that emit a reasonable amount of blue, green and red light, and the lack of green light and/or high ratio of red to blue light under the RBL may cause undesired plant attributes.

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