Morphology, growth, and physiological traits of greenhouse cucumber seedlings as affected by supplementary white and blue LEDs

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Abstract: Supplemental lighting can be applied in the greenhouse to obtain high-quality seedlings when the solar daily light integral (DLI) is insufficient. However, there is no optimal strategy for the supplementary light provided by white and blue light-emitting diodes (LEDs) with the same DLI in cucumber (*Cucumis sativus* L.) seedling production grown in the greenhouse in early spring. The objective of the study was to determine changes in morphology, photosynthesis, growth, and physiological characteristics in greenhouse-grown cucumber seedlings (cv. Tianjiao No. 5) depending on different supplementary fractions (28.5%, 33.5%, 38.5%, 43.5%, and 48.5%) of blue light (B) under constant DLI provided by combinations of white (B28.5% included) and blue LEDs, and cucumber seedlings were grown with sunlight only were set as the control. The results documented that supplementary light resulted in compact and robust greenhouse-grown cucumber seedlings with higher chlorophyll content and net photosynthetic rate compared to those grown without supplementary light. The plant height and hypocotyl length of cucumber seedlings decreased quadratically with an increase of blue light fractions provided by combinations of white and blue LEDs. Additionally, the leaf area and stem diameter of cucumber seedlings increased first and a decreased trend was observed subsequently with the increasing fraction of blue light in a quadratic function. Similar trends were found in root architecture (e.g., root length, root surface area, and root volume) and root activity of cucumber seedlings; however, no significant differences were exhibited as blue light fraction increased from 38.5% to 43.5% provided by supplementary light. Stem firmness and cellulose content increased by 26.2% and 23.4%, respectively, as 15% blue light was added to white LEDs. In conclusion, the 43.5% blue light created by supplementary broad-spectrum white and blue LEDs resulted in compact and stoutest cucumber seedlings along with well-developed root system and higher stem firmness, thus improving the mechanical strength of the greenhouse-grown cucumber seedlings for transplanting.

Keywords: blue light, hypocotyl length, photosynthetic capacity, stem firmness, supplementary light

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1 Introduction

Vegetable seedling production is a main and basic aspect of crop production, which affects the subsequent growth, crop yield, and economic benefits after transplanting. With the rapid development of the plug seedling industry, more than 680 billion vegetable seedlings are in demand in China[1]. Therein, cucumber (*Cucumis sativus* L.) is one of the main horticultural crops in the world and ranks first in China in terms of annual production, which accounted for 79.8% of the world's cucumber production in 2020[2].

Delicate management was needed for raising high-quality vegetable seedlings; nevertheless, the excessive elongation of hypocotyl[3], thinner stem[4], and lower dry weight[3,5] of vegetable seedlings often exhibited under the short photoperiod and low light intensity in insufficient sunlight seasons (e.g., autumn-winter period or early spring). Many commercial producers or managers use plant growth regulators to deal with this problem; however, alternative methods are required in consideration of the regulatory restrictions and the possibility of environmental pollution[6,7]. Recently, farmers have been paying more attention to 'light fertilization' compared to nutrition and water fertilization[8]. Thus, providing supplementary artificial lighting to plug seedlings was considered to be an effective way to solve the above-mentioned problem and produce high-quality seedlings.

In recent years, light-emitting diodes (LEDs) have replaced conventional lighting technologies (e.g., high-pressure sodium, fluorescent, and incandescent lamps) in many protected environments as a result of the short response time, energy-saving possibilities, and spectral configuration flexibility, thus leading to rapid technological evolution in the horticultural lighting industry[9]. Supplementary light intensity or light duration with different daily light integrals (DLIs) provided by LEDs were investigated in grafted watermelon seedlings[8], grafted tomato seedlings[10], and Cos lettuce[11] grown in the greenhouse, suggesting that the optimal supplementary light could lead to robust and compact plants grown under weak light conditions. Additionally, different light qualities also resulted in different influences on the growth and development of vegetable seedlings. Previous reports demonstrated that white LEDs with broadband spectra had great potential to promote crop yield or nutritional quality in lettuce[12] and pepper seedling[13] compared to fluorescent lights or red plus blue LEDs, respectively. Lin et al.[14] observed that supplemental white LEDs in red plus

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blue LEDs led to higher crispness and sweeter taste of lettuce as a result of the increased accumulation of sugars. In addition, white LEDs had generally similar influences on ornamental seedling growth and electric energy consumption compared to red plus blue lights[15]. White LEDs were applied as supplemental light in cucumber seedling[5], *Rudbeckia* seedling[16], *Codonopsis lanceolata* seedling[17], and grafted tomato seedling[4] production in greenhouses.

Previous studies indicated that blue (B) light can stimulate cotyledon expansion, inhibit hypocotyl elongation, and influence the stomatal opening of plants[18,19]. For instance, Snowden et al.[20] indicated that stem length and leaf area index of tomato plants decreased with an increase in blue light fractions. Similar trends were also observed in cucumber plants[21], basil plants[22], and radish plants[23]. Additionally, Clavijo-Herrera et al.[24] found that stomatal conductance and specific leaf area (SLA) of lettuce increased under higher blue light fractions. However, previous studies evaluated the impacts of different fractions of blue light combined with red light in lettuce[25,26], red cabbage[27], cucumber seedling[21], and sweet basil[28]. Chen et al.[29] observed that white light with supplemental blue light (15%) with the same light intensity led to shorter plant height and thicker stem diameter of ‘Green Oak Leaf’ lettuce cultivated in a fully controlled growth chamber. However, the information on how different fractions of blue light combined with the white spectrum can alter the morphological and physiological properties of greenhouse-grown cucumber seedlings is still lacking.

Thus, the objectives of this study were to evaluate the influences of different percentages of blue light added in white LEDs as supplementary light under constant DLI on photosynthetic characteristics, biomass accumulation, root architecture, and stem firmness of greenhouse-grown cucumber seedlings. The results are expected to provide guidelines for the light management strategies of supplementary light for greenhouse-grown cucumber seedling production during the autumn-winter period or early spring.

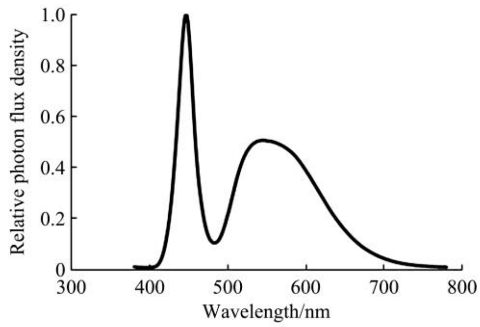
2 Materials and methods

2.1 Plant materials and growth conditions

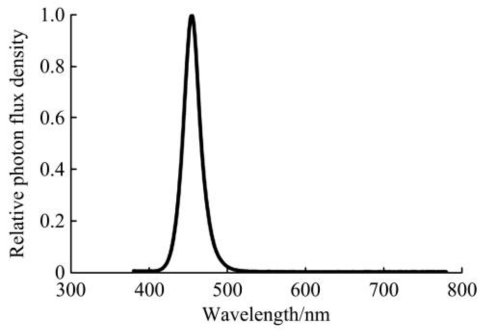
Seeds of cucumber (*Cucumis sativus* L. cv. Tianjiao No. 5) were sown in 72-cell plug trays containing a mixture of vermiculite, peat, and perlite (3:1:1, v/v/v). Plug trays were placed in a Venlo-type greenhouse with a floor area of 2736 m^2 in Qingdao Agricultural University, Qingdao, Shandong Province, China, for 21 d. The air temperature and relative humidity in the greenhouse were maintained at (24±2)℃/(17±1)℃ and 60%-70% during the light/dark period, respectively. Plants were regularly irrigated with Hoagland’s nutrient solution (EC=1.8-2.0 mS/cm, pH=6.0-6.5) with the following components (mg/L): $Ca(NO_3)_2 \cdot 4H_2O$, 945; KNO_3, 607; $MgSO_4 \cdot 7H_2O$, 493; $NH_4H_2PO_4$, 115; Na_2Fe-EDTA, 30; $MnSO_4 \cdot H_2O$, 2.13; $CuSO_4 \cdot 5H_2O$, 0.08; $ZnSO_4 \cdot 7H_2O$, 0.22; H_3BO_3, 2.86; and $(NH_4)_6Mo_6O_{24} \cdot 4H_2O$, 0.02. The management of cucumber seedlings was applied based on Yan et al.[5]

2.2 Treatment design

The average DLI of natural light in the Venlo-type greenhouse was 7.0 mol/(m^2 d) during the experimental period. A supplementary light provided by LEDs with DLI of 4.5 mol/(m^2 d) was applied in the cucumber seedlings based on our previous study[5], corresponding with supplementary light intensity and duration of 125 μmol/(m^2 s) and 10 h/d, respectively. The supplementary lighting time in the morning and the afternoon was the same. The spectrum of treatments was adjusted by replacing part of the broadband white LEDs with blue LEDs (Weifang Hengxin Electric Appliance Co., Ltd, Weifang, China). The cucumber seedlings grown under different supplementary fractions (28.5%, 33.5%, 38.5%, 43.5%, and 48.5%) of blue light under constant DLI provided by combinations of white and blue LEDs, and cucumber seedlings grown with sunlight only were set as the control (DLI at 7.0 mol/(m^2 d) from sunlight only). A spectrometer (PG100N, United Power Research Technology Corporation, Taiwan, China) was used to measure the spectral distribution of the LED lamps (Figure 1) at the plant canopy. The percentage of blue (B, 400-499 nm), green (G, 500-599 nm), and red (R, 600-700 nm) lights of white LEDs were 28.5%, 49.1%, and 22.4%, respectively. Each treatment had three plug trays, and each tray had 72 cucumber seedlings, which were considered as one replication.



a. White light emitting-diodes



b. Blue light emitting-diodes

Figure 1 Relative photon flux density of different supplementary light sources used in the experiment

2.3 Growth measurements

2.3.1 Plant morphology and growth characteristics

Six uniform plants with two true leaves were randomly selected at 21 d after sowing for the measurements. The plant height, stem diameter, total leaf area, fresh and dry weights of cucumber seedlings were measured according to Yan et al.[5] The plant roots were washed twice carefully with distilled water, and subsequently scanned by a scanning system (V800, Seiko Epson Corp., Nagano, Japan). SLA of cucumber seedling was calculated based on Dou et al.[30]

2.3.2 Measurements of photosynthetic performance

A portable photosynthetic instrument (LI-6400XT, Li-Cor Inc., Lincoln, NE, USA) with a leaf chamber (6400-02B) was used to measure photosynthetic characteristics of cucumber seedling. Light intensity, leaf temperature, gas flow, and CO_2 concentration of the leaf chamber were controlled at 400 μmol/(m^2 s), 25℃, 500 μmol/s, and 400 μmol/mol, respectively. A chlorophyll meter (SPAD-502 Plus, Konica Minolta Inc., Tokyo, Japan) was used to measure the relative chlorophyll contents of cucumber seedlings.

2.3.3 Measurement of root activity, stem firmness, and cellulose content of cucumber seedling

The cellulose of cucumber stems and root activity of plants were measured by the Updegraff method[31] and the triphenyl tetrazolium chloride (TTC) method[32], respectively. A texture analyzer (TMS-Pro, Food Technology Corporation, Virginia, USA) equipped with a 2 mm diameter probe was used to measure stem firmness of cucumber seedling.

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). Regressions between treatments and morphological characteristics of cucumber seedlings were conducted using Microsoft Excel 2016 software. Principal component analysis (PCA) was used to compare the effects of different light treatments based on the first and second principal components from all the plant traits.

3 Results

3.1 Relative chlorophyll content and photosynthesis of greenhouse-grown cucumber seedlings as affected by supplementary white and blue light-emitting diodes

Relative chlorophyll contents and photosynthetic characteristics were significantly affected by supplementary light and different supplementary fractions of blue light (Table 1). The relative chlorophyll content of cucumber seedlings grown with supplementary white LEDs combined with 15% blue LEDs (WB15) was 9.3% higher than those grown with supplementary white LEDs only. Additionally, the net photosynthetic rate and transpiration rate of cucumber seedlings increased by 14.7% and 44.9% as 15% blue light was added in white LEDs. Whereas no significant differences in net photosynthetic rate were observed as supplementary blue light fraction increased from 33.5% (WB5) to 43.5% (WB15). A similar trend was also found in stomatal conductance of cucumber leaves.

Table 1 Photosynthetic characteristics of greenhouse-grown cucumber seedlings grown under different supplementary fractions of blue (B) light provided by combinations of white (W) and blue light-emitting diodes (LEDs)

Treatments	SPAD value	Net photosynthetic rate/μmol m^{-2} s^{-1}	Stomatal conductance /mol m^{-2} s^{-1}	Substomatal CO_2 concentration /μmol mol^{-1}	Transpiration rate /mmol m^{-2} s^{-1}
Control	35.1±3.0^{c}	4.6±0.1^{c}	0.047±0.003^{c}	227±8^{ab}	0.88±0.04^{c}
W	42.0±3.3^{b}	9.5±0.1^{b}	0.096±0.008^{b}	218±11^{b}	1.78±0.11^{b}
WB5	42.2±0.3^{b}	11.0±0.2^{a}	0.132±0.006^{a}	237±5^{ab}	2.39±0.11^{a}
WB10	44.0±2.1^{ab}	11.1±1.0^{a}	0.140±0.029^{a}	242±13^{a}	2.52±0.42^{a}
WB15	45.9±2.7^{a}	10.9±0.9^{a}	0.119±0.006^{ab}	242±18^{a}	2.58±0.53^{a}
WB20	43.6±1.0^{ab}	9.5±1.0^{b}	0.094±0.016^{b}	226±22^{ab}	1.87±0.27^{b}

Note: Different letters in the same column indicate significant differences at the 5% level, according to LSD test; Control, cucumber seedlings grown with sunlight only; the data in treatment symbols indicated the blue light fraction provided by blue LEDs added in the white LEDs.

3.2 Effects of supplementary blue light fraction on leaf morphology, root architecture and growth of greenhouse-grown cucumber seedlings

Plant height and hypocotyl length of cucumber seedlings decreased quadratically with increasing supplementary fraction of blue light (Figure 2). Plant height and hypocotyl length decreased by 13.3% and 31.3% as supplementary fraction of blue light increased from 28.5% (W) to 48.5% (WB20), respectively. Leaf area and stem diameter of cucumber seedlings increased first and decreased subsequently following a quadratic function. Cucumber seedlings grown under 43.5% (WB15) of supplementary blue light led to bigger leaf area and thinner stem diameter than those grown with 28.5% blue light (W). SLA of cucumber seedlings decreased with the application of supplementary light; however, opposite results were observed in seedling quality index. Cucumber seedling grew under supplementary 10%-15% blue light provided by blue LEDs resulted in higher seedling quality index compared with other treatments (Table 2).

In general, supplementary light led to higher fresh and dry weights of greenhouse-grown cucumber seedlings than those grown with sunlight only (Table 2). Shoot fresh weight, root fresh weight, shoot dry weight and root dry weight of cucumber seedling grown with supplementary white LEDs increased by 34.2%, 193.3%, 46.1%, and 120.0%, respectively, compared with those grown without supplementary light. Cucumber seedlings grown under 43.5% blue light (WB15) provided by supplementary LEDs resulted in higher shoot and root dry weights of cucumber seedlings compared to other treatments.

Root morphology and root activity of cucumber seedlings were significantly impacted by supplementary LEDs (Figure 3). Root length, root surface area, and root volume of cucumber seedlings increased by more than 3.0-folds as supplementary LEDs were applied in the greenhouse. Root length of cucumber seedlings increased gradually as blue light fraction provided by supplementary light increased from 28.5% (W) to 43.5% (WB15). However, no significant differences were observed in root length between WB10 and WB15. Similar results were also observed in root surface area and root volume. Cucumber seedlings grown under WB15 exhibited highest root activity compared with those grown under other treatments.

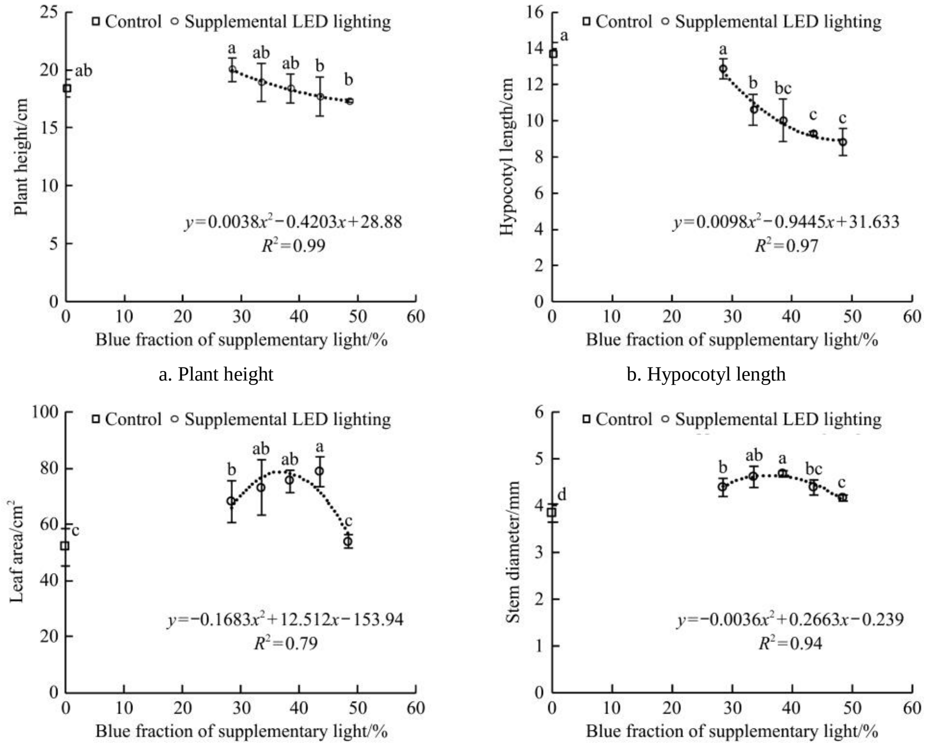
3.4 Stem firmness and cellulose content of greenhouse-grown cucumber seedlings

Stem firmness and cellulose content of cucumber seedlings grown in the greenhouse were significantly influenced by supplementary light (Figure 4). Stem firmness and cellulose content of cucumber seedlings grown with supplementary light increased by more than 30% and 40% compared with those grown without supplementary light, respectively. Generally, stem firmness and cellulose content of cucumber seedlings increased as the blue light fraction increased from 33.5% (WB5) to 43.5% (WB15), and decreased subsequently as blue light fraction increased more than 43.5%. However, no remarkable differences were found in these two parameters between WB10 and WB15.

3.5 Principal component analysis

PCA was conducted to indicate the impacts of different blue light fractions provided by supplementary white and blue LEDs on the growth of cucumber seedlings. PCA1 and PCA2 explained 79.9% and 12.5% of total variability, respectively (Figure 5). The studied populations were placed into four groups (WB15, WB5 and

WB10, W, Control, and WB20). The Control and WB15 were clearly distinguished from each other along PC1. The results were consistent with our results above in that the cucumber seedlings grown between Control and WB15 exhibited more drastic changes.



a. Plant height b. Hypocotyl length

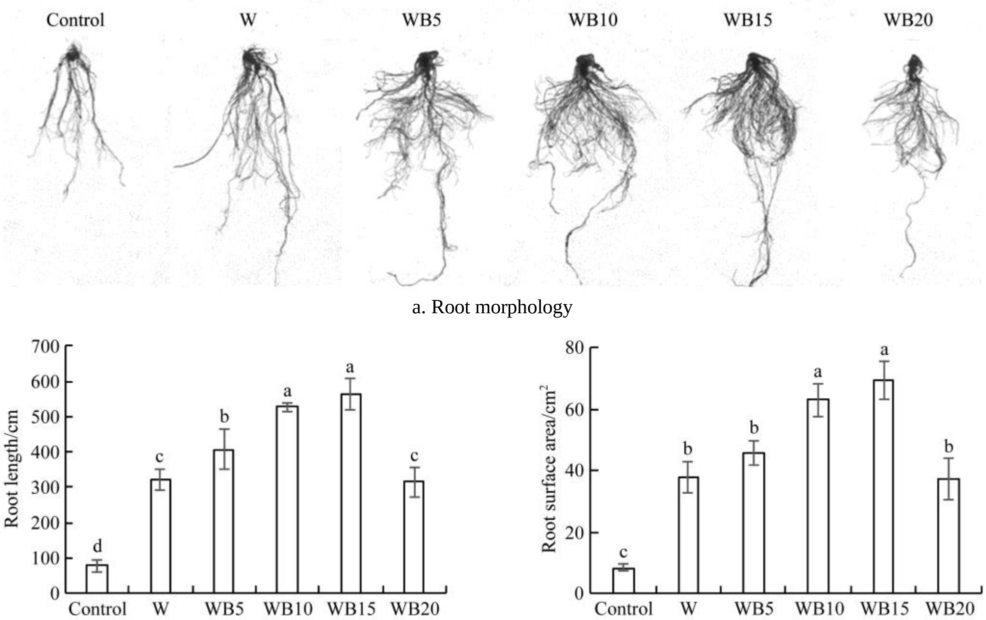
c. Leaf area d. Stem diameter

Note: Means followed by different letters within each parameter are significantly different based on least significant difference (LSD) test (p<0.05).

Figure 2 Relationships between different fractions of blue light provided by supplementary light emitting-diodes (LEDs) and morphological characteristics of cucumber seedlings grown in the greenhouse for 21 d after sowing

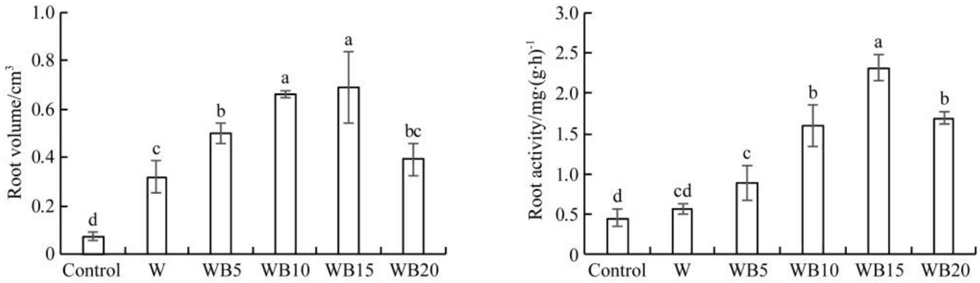
Table 2 Growth and morphological characteristics of greenhouse-grown cucumber seedlings grown under various combined fractions of white (W) and blue (B) light-emitting diodes (LEDs)

Treatments	Shoot fresh weight /g plant^{-1}	Root fresh weight /g plant^{-1}	Shoot dry weight /g plant^{-1}	Root dry weight /g plant^{-1}	Specific leaf area /cm^2 mg^{-1}	Seedling quality index
Control	3.8±0.2^b	0.165±0.028^c	0.241±0.027^c	0.015±0.002^c	0.496±0.049^a	0.021±0.001^c
W	5.1±0.3^a	0.484±0.086^b	0.352±0.025^b	0.033±0.006^b	0.381±0.009^{bc}	0.048±0.005^b
WB5	4.9±0.4^a	0.606±0.070^{ab}	0.402±0.063^{ab}	0.043±0.003^b	0.378±0.026^{bc}	0.053±0.007^b
WB10	4.9±0.5^a	0.705±0.122^a	0.413±0.053^{ab}	0.065±0.014^a	0.321±0.037^c	0.104±0.021^a
WB15	4.9±0.3^a	0.694±0.126^a	0.421±0.104^a	0.058±0.012^a	0.369±0.026^{bc}	0.095±0.013^a
WB20	4.0±0.5^b	0.435±0.094^b	0.320±0.054^{bc}	0.033±0.007^b	0.411±0.085^b	0.044±0.009^b



a. Root morphology

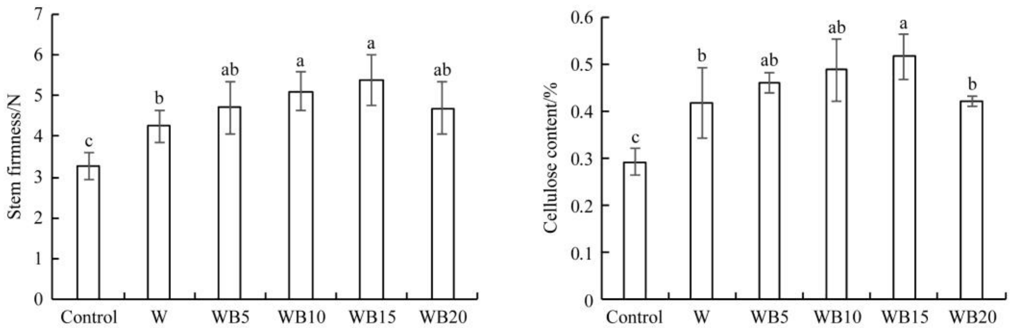
b. Root length c. Root surface area



d. Root volume e. Root activity

Note: Means followed by different letters within each parameter are significantly different based on least significant difference (LSD) test (p<0.05).

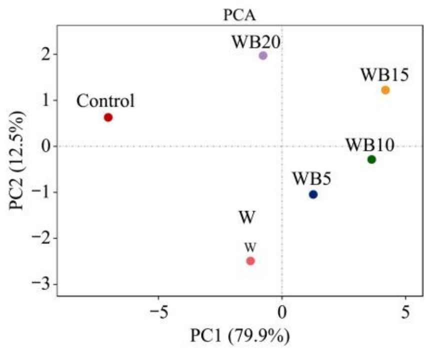
Figure 3 Effects of supplementary lighting provided by different combinations of white (W) and blue (B) light emitting-diodes (LEDs) on root morphology and root activity of cucumber seedlings grown in the greenhouse for 21 d after sowing



a. Stem firmness b. Cellulose content

Note: Means followed by different letters within each parameter are significantly different based on least significant difference (LSD) test (p<0.05).

Figure 4 Stem firmness and cellulose content of greenhouse-grown cucumber seedlings as influenced by different proportions of supplemental blue and white light emitting-diodes (LEDs) for 21 d after sowing



Note: PC1 or PC2 on the axes indicates the principal component 1 or 2, and the percentages in parentheses represent the relative contributions of these two principal components to the total variation in the data

Figure 5 Component scores for different lighting treatments on greenhouse-grown cucumber seedlings at 21 d after sowing

4 Discussion

Light quality and quantity influence morphological characteristics of plants to adapt to changeable light conditions. In this study, we compared leaf morphology, root architecture, growth characteristics of greenhouse-grown cucumber seedlings under the same supplementary DLI to assess to what extent their response distinctly to supplementary white and blue LEDs. In general, supplementary light resulted in bigger leaf area and thicker stems of cucumber seedlings (Figure 2). Similar results were observed in grafted watermelon seedlings[8], cucumber seedlings[33], and tomato plants[34]. Insufficient light usually led to slender and stretchy plants with longer hypocotyl, etiolated and thin stems[5,35], which was undesirable for cultivation of high-quality seedlings. On the contrary, increasing DLI via supplementary light promoted plant growth with robust and compact features. According to the study of Ji et al.[36], total leaf area and stem diameter of cucumber seedlings (cv. Jintong and Yunv) increased as DLI increased from 4.3 to 13.0 mol/(m^2 d); however, Yan et al.[37] observed that leaf length and the ratio of leaf length to leaf width of lettuce seedlings decreased in a logarithmic way with increasing DLI (10.08 to 14.40 mol/(m^2 d)). These differences may be dependent on the species, a DLI threshold, or other environmental factors. For instance, He et al.[38] observed that the leaf area of sweet potato seedlings increased first and decreased subsequently in a quadratically function as DLI increased from 8.6 to 20.2 mol/(m^2 d), regardless of light quality. Our results demonstrated that plant height and hypocotyl length of greenhouse-grown cucumber seedlings decreased quadratically as blue light fraction of supplementary LEDs increased from 28.5% to 48.5% (Figure 2). A similar trend was reported by Hernández et al.[39], who observed that increasing blue light fraction up to 75% decreased plant height of tomato seedlings linearly. This phenomenon may be attributed to cryptochrome photoreceptors, which have maximal absorption in the blue light range with the peak of approximately 450 nm. Additionally, blue light is related with gibberellin (GA) inactivation of the seedlings, thus affecting the stem elongation of plants[40]. Stem elongation suppression of plants was mediated by the GA reduction and blue light photoreceptors were related to the transcriptional regulation of GA metabolic enzyme genes.

High-quality seedlings often exhibit high photosynthetic capacity and well-developed leaves and roots[36,41]. Treatments with supplementary light resulted in higher chlorophyll content associated with higher net photosynthetic rate, stomatal conductance, and transpiration rate compared with those grown without supplementary light (Table 1). Higher chlorophyll content showed that plants possess more chloroplasts per unit leaf area, determining the photosynthetic enzymes numbers. Moreover, high stomatal conductance could increase CO_2 supply into plant leaves, increasing the net photosynthetic rate and electron transport rate of plants[42]. Previous studies also indicated that chlorophyll content of plants was proportional to blue light amount[43]. However, the impacts of blue light on horticultural plants are also related to the proportion, the background light or other light quality. For instance, Kang et al.[44] observed that leaf photosynthetic rate of lettuce increased and then decreased as blue light fraction increased from 0 to 30% when combined with red light; however, no significant differences were observed in treatments with different fractions of blue light when 10% green light were added in the combination of red and blue light. The differences may cause by the low absorbance of green light, which reduces the leaf stomatal conductance of plants. Furthermore, Clavijo-Herrera et al.[24] found that stomatal conductance of lettuce grown in a walk-in growth chamber increased linearly as blue light fraction of red-blue LEDs increased from 0 to 100%, as blue light regulates the intracellular guard cell signaling of plants. Similar trends were also found in greenhouse-grown lettuce[11], cucumber seedlings[5], and melon plants[45].

The root quality directly impacts the growth and development of vegetable seedlings after transplanting, influencing the crop yield and economic benefit[5,8]. Yan et al.[5] observed that root surface area, root volume, and root activity of cucumber seedlings grown with supplementary white LEDs increased by more than 5-folds, 10-folds, and 42.5%, compared with those grown without supplementary light. In general, root architecture of greenhouse-grown cucumber seedlings increased as blue light fraction increased from 28.5% (W) to 38.5% (WB10); however, no significant differences were observed in root length, root surface area, and root volume as blue light fraction increased from 38.5% (WB10) to 43.5% (WB15). On the contrary, excess blue light in supplementary LEDs reduced the root development, as well as the root activities of cucumber seedlings (Figure 3). Similarly, Li et al.[46] observed that root activity of peanut plants increased as blue light fraction increased from 30% to 50%, and then decreased as blue light fraction increased from 50% to 70%. However, no remarkable differences were found in root length and root activity of rapeseed plantlet grown under different combinations of red and blue light[47], suggesting a species-specific behavior.

Carbohydrate accumulation in response to lighting environment often follows an optimum way, and light stress may occur when it excessed the maximum value. Generally, the proper supplementary lighting promoted biomass accumulation and leaf quality in cucumber seedlings. Our results indicated that shoot and root dry weights increased first and then decreased with the increased blue light fraction provided by the supplementary LEDs. Similarly, Gómez and Mitchell[48] observed that shoot dry weight of tomato seedlings grown in a glass-glazed greenhouse was promoted as 5% of supplementary blue light fraction added in the red light, and no significant differences were observed as blue light fraction increased from 5% to 20%. However, too much blue light reduced shoot fresh weight of tomato seedlings as blue light fraction increased from 50% to 75% in red plus blue LEDs[39]. In the study of Hitz et al.[49], who observed that dry weight and leaf area of soybean plants increased as fraction of blue light provided by red-blue LEDs increased from 15% to 27.5%, and a decreased trend was found as blue light fraction was more than 27.5%. In general, the increase in dry biomass accumulation in response to the supplementary light may be attributed to the augmented chlorophyll content and net photosynthetic rate. The decrease in carbohydrate accumulation at high fraction of blue light (>43.5%) observed in this study may be due to the decrease in leaf area, which affects the light interception and subsequent biomass assimilation. This was because biomass assimilation of plants is also associated with leaf morphology (e.g., leaf number, leaf area) and net photosynthetic rate throughout the growth cycle.

Mechanical parameters (e.g., hardness, firmness, or softness) of plants or food appear to be fairly straightforward, suggesting the resistance scale of the objects to the applied compressive forces[50]. Our results indicated that supplementary light promoted the stem firmness of greenhouse-grown cucumber seedlings by more than 30%, which was consistent with the results reported by Yan et al.[5] A positive correlation trend between stem firmness and cellulose contents of cucumber seedlings were also observed in this study (Figure 4). The relatively higher stem firmness and cellulose content of vegetable seedlings were beneficial for mechanized transplanting, thus improving the survival rate of seedlings.

5 Conclusions

The findings of this study confirmed that the seedling quality of greenhouse-grown cucumber was significantly improved by supplementary LEDs. Additionally, different supplementary fractions of blue light provided by white and blue LEDs significantly influenced the leaf morphology, root architecture, photosynthetic characteristics, growth, and stem firmness of greenhouse-grown cucumber seedlings. Our results revealed that cucumber seedlings grown under 43.5% blue light created by supplementary broad-spectrum white and blue LEDs resulted in compact and stoutest seedlings along with well-developed root system and higher stem firmness, thus improving the mechanical strength of the greenhouse-grown cucumber seedlings for transplanting.

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