



Article

The Combinations of White, Blue, and UV-A Light Provided by Supplementary Light-Emitting Diodes Promoted the Quality of Greenhouse-Grown Cucumber Seedlings

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Abstract: Insufficient solar light in winter inside the greenhouse may lead to a lower quality of vegetable seedlings, and supplemental light is an effective technique to solve this problem. This study evaluated the impacts of supplementary white (W)-light-emitting diodes (LEDs), ultraviolet A LEDs (UV-A), white and blue LEDs (WB), the combinations of white and UV-A LEDs (W-UVA), and white, blue, and UV-A LEDs (WB-UVA) on the leaf morphology, photosynthetic traits, biomass accumulation, root architecture, and hormone content of cucumber (*Cucumis sativus* L. cv. Tianjiao No. 5) seedlings grown in the greenhouse. The results indicated that supplementary LED lighting led to a decreased plant height, shorter hypocotyl length, bigger leaf area, and thicker leaf compared with those grown with solar light only, regardless of light quality. The shoot fresh weight, root fresh weight, and seedling quality index of cucumber seedlings grown under the combinations of white, blue, and UVA radiations increased by 30.8%, 3.2-fold, and 1.8-fold, respectively, compared with those grown with natural light only. However, no significant differences were exhibited in the biomass accumulation of greenhouse-grown cucumber seedlings between the control and the UVA treatment. The cellulose content and stem firmness of greenhouse-grown cucumber seedlings grown under the combinations of white, blue, and UVA radiations increased by 49.9% and 13.1%, respectively, compared with those grown under white light only. Additionally, the cytokinin content of cucumber seedlings was promoted by over 36.7% by applying supplementary light. In summary, the combinations of white, blue, and UVA radiations led to compact morphological characteristics, superior mechanical properties, and preferable growth performance, which could be applied as an available lighting strategy to obtain the desired morphological and quality properties of vegetable seedlings.



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1. Introduction

Cucumbers (*Cucumis sativus* L.) are widely cultivated worldwide as an important vegetable variety with a world production of 91.2 million tons in 2021 [1]. Prior studies have indicated that the quality of vegetable seedlings influenced the subsequent growth and yield of mature plants at harvest [2,3], and the annual demand of cucumber seedlings in China is 47 billion plants [4]. Therefore, producers focus on various environmental factors that affect the yield and quality of cucumber seedlings during the production process. In addition, the growing conditions in the protected horticulture (e.g., greenhouse or plant factory with artificial lighting) are superior compared with the open field as a result of the fact that growers could adjust the environmental elements based on the crop needs, which was beneficial for cultivation of high-quality vegetable seedlings.

Light is one of the most important variables for plant growth and development, and there are three dimensions of light to be noticed: light quality, light intensity, and pho-

toperiod [5]. Previous studies have indicated that lower light intensity was not conducive to plant growth and development. For instance, Pennisi et al. [6] found that lower light intensity reduced the leaf functionality of lettuce, which resulted in reduced nutritional content, and lower antioxidant capacity, phenolics, and flavonoids concentrations. Similar results were also observed in sweet basil [7], broccoli microgreens [8], and dwarf tomato [9]. Recently, more researchers paid attention to the daily light integral (DLI) and observed that increasing the DLI within limits could improve the growth status of plants and promote the accumulation of nutrients in plants [10–12]. Additionally, increasing the DLI in seasons with insufficient light could increase the stem firmness of cucumber seedlings, which was beneficial for mechanized transplanting [13].

Light quality also has significant impacts on the formation and composition of plant organic matter [14,15]. For instance, red light is efficient in driving plant photosynthesis compared with other wavelengths [16]; blue light promoted the synthesis of chlorophyll in cucumber, wheat, and spinach [17,18]. Many researchers have reported that red plus blue LEDs are the most important parts of spectral regions for plant growth [19]. Therefore, red plus blue lights provided by light-emitting diodes (LEDs) were commonly applied or investigated by researchers in leafy vegetables [20,21], vegetable seedlings [22,23], and herbs [24,25] grown in the greenhouse or plant factory with artificial lighting. However, white LEDs exhibited similar or preferable influences on plant growth and energy use efficiency compared with red plus blue LEDs [26,27], and white LEDs created a “friendly” light environment to human eyes [9,28]. Thus, white LEDs or white LEDs combined with other wavelengths were investigated in lettuce [28], spinach [29], and grafted tomato transplants [30]. Generally, the hypocotyl of vegetable seedlings would elongate under low light conditions, and the reduction in blue light had a similar response in plants [31]. However, the circumstances of increased tomato plant compactness and reduced stem elongation occurred with the increase in blue light [18,32]. The suitable combinations of supplementary white and blue lights were investigated by Yan et al. [13] in greenhouse-grown cucumber seedlings and the results indicated that the plant height and hypocotyl length of cucumber seedlings decreased with the increased blue fraction of supplementary light; however, the stem diameter and leaf area of cucumber seedlings increased first and then decreased with the increased blue fraction, and similar trends were observed in the biomass accumulation of cucumber seedlings.

The impacts of ultraviolet (UV) radiation on the plant morphology and physiological characteristics of plants were investigated by researchers in recent years. The majority of the UV radiation part is UV-A radiation (315–400 nm), which accounts for 98–99% of the ultraviolet radiation reaching the Earth’s surface [33,34]. The UV-A radiation affected the growth, photosynthesis, and specific substance contents of plants [34]. Zhang et al. [35] indicated that UV-A functions had similar effects in maintaining leaf photosynthetic function as compared with blue light. In addition, previous reports have shown that supplementing certain amounts of UV-A to visible radiation (400–700 nm) promoted plant biomass accumulation compared with those grown without supplements [36].

Our previous study investigated the proper proportion created by white and blue LEDs for growth of greenhouse-grown cucumber seedlings [37]; nevertheless, hardly any studies have reported the influences of supplementary white or white plus blue LEDs combined with UV-A on the leaf morphology, pigment content, photosynthetic traits, biomass accumulation, root architecture, and hormone contents of cucumber seedlings grown in the greenhouse. The results could provide guidelines for the regulation of supplemental light strategies for greenhouse-grown cucumber seedlings produced in winter, early spring, or seasons with insufficient sunlight.

2. Materials and Methods

2.1. Plant Materials

Cucumber seedlings (*Cucumis sativus* L. cv. Tianjiao No. 5) were grown in 72-cell plug trays containing a mixture of 60% vermiculite, 20% peat, and 20% perlite. One seed

was used per cell, plug trays were placed in a Venlo-type greenhouse with a floor area of 2736 m² in Qingdao Agricultural University, Qingdao, Shandong Province, China, at a temperature of (24 ± 1) °C/(16 ± 1) °C during the day/night period, and the relative humidity was maintained at 60–70%, for 22 days. Hoagland's nutrient solution was used for cucumber seedlings during the experimental period, and the management of seedlings was reported by our previous study [13].

2.2. Treatment Design

The average daily light intensity of sunlight inside the Venlo-type greenhouse was 128 μmol m⁻² s⁻¹ during the experimental period (19 November–11 December 2021), with an average DLI of 5.0 mol m⁻² d⁻¹. Considering the suitable DLI and supplementary duration [13] for growth of cucumber seedlings, they were grown under supplemental DLI at 6.5 mol m⁻² d⁻¹ with a light intensity and photoperiod at 180 μmol m⁻² s⁻¹ and 10 h d⁻¹, respectively, created by white LEDs (W) (Weifang Hengxin Electric Appliance Co., Ltd., Weifang, China), ultraviolet A LEDs (UV-A) (Xiamen Lumigro Technology Co., Ltd., Xiamen, China), the combinations of white and blue LEDs (WB) (Weifang Hengxin Electric Appliance Co., Ltd., Weifang, China), the combinations of white and UV-A LEDs (W-UVA), and the combinations of white, blue, and UV-A LEDs (WB-UVA), respectively. The ratio of combinations of blue and white LEDs and the spectral distribution of the LEDs were applied based on our previous study [37] and the supplemental light intensity of UV-A light was 15 μmol m⁻² s⁻¹. Additionally, cucumber seedlings grown with natural light only was set as the control (DLI at 5.0 mol m⁻² d⁻¹). The experiment was arranged in a randomized complete block design with three replications, and 72 seedlings were applied in each replication in this experiment.

2.3. Growth Measurements

2.3.1. Plant Morphology and Growth Traits

The plant height, hypocotyl length, and stem diameter of cucumber seedlings were measured using a ruler and digital caliper (Shanghai Tool Factory Co., Ltd., Shanghai, China). Fresh and dry weights, and the root architecture of cucumber seedlings were measured based on Yan et al. [13]. Seedling quality index and specific leaf area were calculated according to Han et al. [38] and Dou et al. [7].

2.3.2. Determinations of Photosynthetic Performance

Photosynthetic performances of cucumber seedlings were determined by a portable photosynthetic measuring system (LI-6400XT, Li-Cor Inc., Lincoln, NE, USA) with a leaf chamber (6400-02B), according to Yan et al. [13]. The apparent mesophyll conductance (g_m) and stomatal limitation value (L_s) were calculated according to Wang et al. [20]. A chlorophyll meter (SPAD-502 Plus, Konica Minolta Inc., Tokyo, Japan) was applied to determine the relative chlorophyll contents of cucumber seedlings.

2.3.3. Measurement of Root Activity, Stem Firmness, and Cellulose Content of Cucumber Seedling

The triphenyl tetrazolium chloride (TTC) method and the Updegraff method were applied to determine the root activity and cellulose content of cucumber seedlings, according to Li [39] and Updegraff [40], respectively. The stem firmness of cucumber stems was determined according to Yan et al. [13].

2.3.4. Measurement of Hormone Content of Cucumber Seedlings

The fully expanded cucumber leaf was flash-frozen and ground in liquid nitrogen and then transferred to a freezer with –80 °C for storage. The cytokinin contents of cucumber seedlings were quantified by a competitive Enzyme-linked immunosorbent assay (ELISA) technique, according to Aguilar et al. [41].

2.3.5. Supplementary Light Use Efficiency

Supplementary light use efficiency was estimated based on the increase in fresh weight, according to Wei et al. [42] and Wang et al. [12].

2.4. Statistical Analysis

Statistical analysis was conducted using the SPSS 18.0 software (IBM, Inc., Chicago, IL, USA). The least significant difference (LSD) test was performed across all treatments at $p < 0.05$. The data were exhibited as the mean \pm standard deviation (SD) values. The heat map was performed using the TBtools (<https://github.com/CJ-Chen/TBtools>, accessed on 25 September 2022) based on Chen et al. [43]. We calculated the Euclidean distance among samples and the complete clustering method was applied according to Gao et al. [8].

3. Results

3.1. Impacts of Supplementary Light on Morphological Performances of Greenhouse-Grown Cucumber Seedlings

Morphological characteristics of greenhouse-grown cucumber seedlings were significantly impacted by supplementary light (Table 1). In general, cucumber seedlings grown with natural light only exhibited a higher plant height, longer hypocotyl, and smaller leaf area compared with those grown with supplementary light; however, no significant differences were found in stem diameter, leaf width, and leaf area of cucumber seedlings grown between the control and the UV-A treatments. Cucumber seedlings grown with combinations of supplementary white, blue, and UV-A light exhibited the shortest plant height and smallest specific leaf area, which decreased by 39.8% and 47.7%, respectively, compared with those grown with natural light only. The stem diameter and leaf area of greenhouse-grown cucumber seedlings grown in the WB-UVA treatment increased by 33.3% and 44.6% compared with those grown under the control treatment, respectively.

3.2. Impacts of Supplementary Light on Photosynthetic Performances of Cucumber Seedlings Cultivated in the Greenhouse

The SPAD value, net photosynthetic rate, substomatal CO₂ concentration, transpiration rate, and apparent mesophyll conductance of cucumber seedlings cultivated with sunlight only were significantly lower than those cultivated with supplementary light (Table 2). However, no significant differences were found in these parameters of cucumber seedlings grown between WB and WB-UVA treatments. The SPAD value, net photosynthetic rate, and transpiration rate of cucumber seedlings grown in the WB-UVA treatment increased by 39.1%, about 1.2- and 2.7-fold compared with those cultivated without supplementary light, respectively.

3.3. Impacts of Supplementary Light on Growth Characteristics and Root Architecture on Greenhouse-Grown Cucumber Seedlings

Fresh and dry weights of greenhouse-grown cucumber seedlings were significantly influenced by supplementary light (Table 3). Fresh and dry weights of cucumber seedlings were significantly increased by using white LEDs alone or the combinations of white and other LEDs. No significant differences were observed in these above parameters in cucumber seedlings grown between supplemented UVA light and the control. The shoot fresh weight, root fresh weight, and seedling quality index of cucumber seedlings grown in the WB-UVA treatment increased by 30.8%, about 3.2- and 1.8-fold, compared with those grown with natural light only, respectively.

Table 1. Morphological performances of greenhouse-grown cucumber seedlings cultivated under supplementary light provided by white (W), UV-A light-emitting diodes (LEDs), and various combinations of W, blue (B), and UV-A LEDs; cucumber seedlings grown without supplementary light were used as control.

Treatments	Plant Height (cm)	Hypocotyl Length (cm)	Stem Diameter (mm)	Leaf Length (cm)	Leaf Width (cm)	Leaf Area (cm ²)	Specific Leaf Area (cm ² mg ⁻¹)							
Control	18.6 ± 2.2	a	13.8 ± 1.4	a	3.6 ± 0.4	b	6.6 ± 0.6	c	30.7 ± 3.1	c	0.501 ± 0.035	a		
W	14.0 ± 1.0	bc	8.5 ± 0.4	c	4.7 ± 0.3	a	7.4 ± 0.3	b	7.9 ± 0.4	b	38.8 ± 2.1	c	0.305 ± 0.013	c
UVA	15.8 ± 0.3	b	12.1 ± 0.6	b	3.7 ± 0.2	b	7.3 ± 0.1	b	6.7 ± 0.3	c	33.5 ± 2.2	c	0.415 ± 0.031	b
WB	12.7 ± 1.0	cd	8.6 ± 0.6	c	4.8 ± 0.4	a	7.7 ± 0.2	ab	8.4 ± 0.3	a	42.9 ± 3.6	ab	0.271 ± 0.021	cd
W-UVA	13.5 ± 1.3	c	8.5 ± 0.7	c	4.9 ± 0.2	a	7.3 ± 0.4	b	8.0 ± 0.4	ab	39.4 ± 2.8	b	0.278 ± 0.012	cd
WB-UVA	11.2 ± 0.4	d	7.1 ± 0.5	d	4.8 ± 0.4	a	8.0 ± 0.1	a	8.4 ± 0.2	ab	44.4 ± 2.4	a	0.262 ± 0.013	d

Note: Different letters within each parameter were significantly different tested by the least significant difference (LSD) test at $p < 0.05$.

Table 2. Photosynthetic characteristics of cucumber seedlings cultivated in the greenhouse under supplementary light provided by white (W), UV-A light-emitting diodes (LEDs), and various combinations of W, blue (B), and UV-A LEDs; cucumber seedlings cultivated without supplementary light were used as control.

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)	Apparent Mesophyll Conductance (mol m ⁻² s ⁻¹)	Stomatal Limitation Value							
Control	36.3 ± 2.1	d	5.2 ± 0.2	d	0.06 ± 0.01	d	243 ± 24	b	0.78 ± 0.09	d	0.025 ± 0.004	d	0.40 ± 0.06	a
W	46.3 ± 1.8	b	9.6 ± 0.6	b	0.19 ± 0.02	b	295 ± 8	a	2.16 ± 0.04	b	0.031 ± 0.002	c	0.24 ± 0.02	c
UVA	39.1 ± 3.5	c	6.8 ± 0.3	c	0.10 ± 0.01	c	281 ± 25	a	1.17 ± 0.15	c	0.026 ± 0.002	d	0.31 ± 0.03	b
WB	50.5 ± 1.7	a	10.8 ± 0.4	a	0.24 ± 0.03	a	300 ± 8	a	2.65 ± 0.22	a	0.036 ± 0.001	b	0.24 ± 0.02	c
W-UVA	47.9 ± 1.4	ab	10.1 ± 0.6	b	0.19 ± 0.03	b	293 ± 14	a	2.13 ± 0.32	b	0.033 ± 0.002	bc	0.24 ± 0.03	c
WB-UVA	50.5 ± 1.5	a	11.2 ± 0.8	a	0.22 ± 0.02	ab	295 ± 12	a	2.39 ± 0.21	ab	0.039 ± 0.004	a	0.23 ± 0.02	c

Note: Different letters within each parameter were significantly different tested by the least significant difference (LSD) test at $p < 0.05$.

Table 3. Fresh and dry weights of greenhouse-grown cucumber seedlings cultivated under supplementary light provided by white (W), UV-A light-emitting diodes (LEDs), and various combinations of W, blue (B), and UV-A LEDs; cucumber seedlings grown with natural light only were used as control.

Treatments	Shoot Fresh Weight (g Per Plant)	Root Fresh Weight (g Per Plant)	Shoot Dry Weight (g Per Plant)	Root Dry Weight (g Per Plant)	Seedling Quality Index					
Control	2.92 ± 0.13	d	0.45 ± 0.03	d	0.198 ± 0.030	c	0.016 ± 0.002	d	0.025 ± 0.003	c
W	3.49 ± 0.44	bc	1.17 ± 0.09	c	0.283 ± 0.020	b	0.040 ± 0.005	bc	0.055 ± 0.006	b
UVA	3.05 ± 0.27	cd	0.44 ± 0.01	d	0.216 ± 0.026	c	0.015 ± 0.001	d	0.022 ± 0.002	c
WB	4.09 ± 0.19	a	1.42 ± 0.18	b	0.316 ± 0.014	ab	0.045 ± 0.006	b	0.065 ± 0.009	ab
W-UVA	4.13 ± 0.10	a	1.09 ± 0.09	c	0.339 ± 0.038	a	0.037 ± 0.004	c	0.057 ± 0.005	b
WB-UVA	3.82 ± 0.45	ab	1.90 ± 0.18	a	0.348 ± 0.046	a	0.059 ± 0.009	a	0.069 ± 0.008	a

Note: Different letters within each parameter were significantly different tested by the least significant difference (LSD) test at $p < 0.05$.

The root architecture of greenhouse-grown cucumber seedlings was remarkably influenced by supplementary light (Figure 1). The root length, root area, and root volume of cucumber seedlings grown with supplementary WB-UVA light increased by 184.9%, 219.0%, and 266.7% compared with those grown with natural light only, respectively. Similarly, no significant differences were found in these parameters in cucumber seedlings grown between the control and UVA treatment. The root activity of cucumber seedlings exposed to WB and WB-UVA treatments was significantly higher compared with other treatments, which increased by 3.8 and 3.6 times compared with the control.

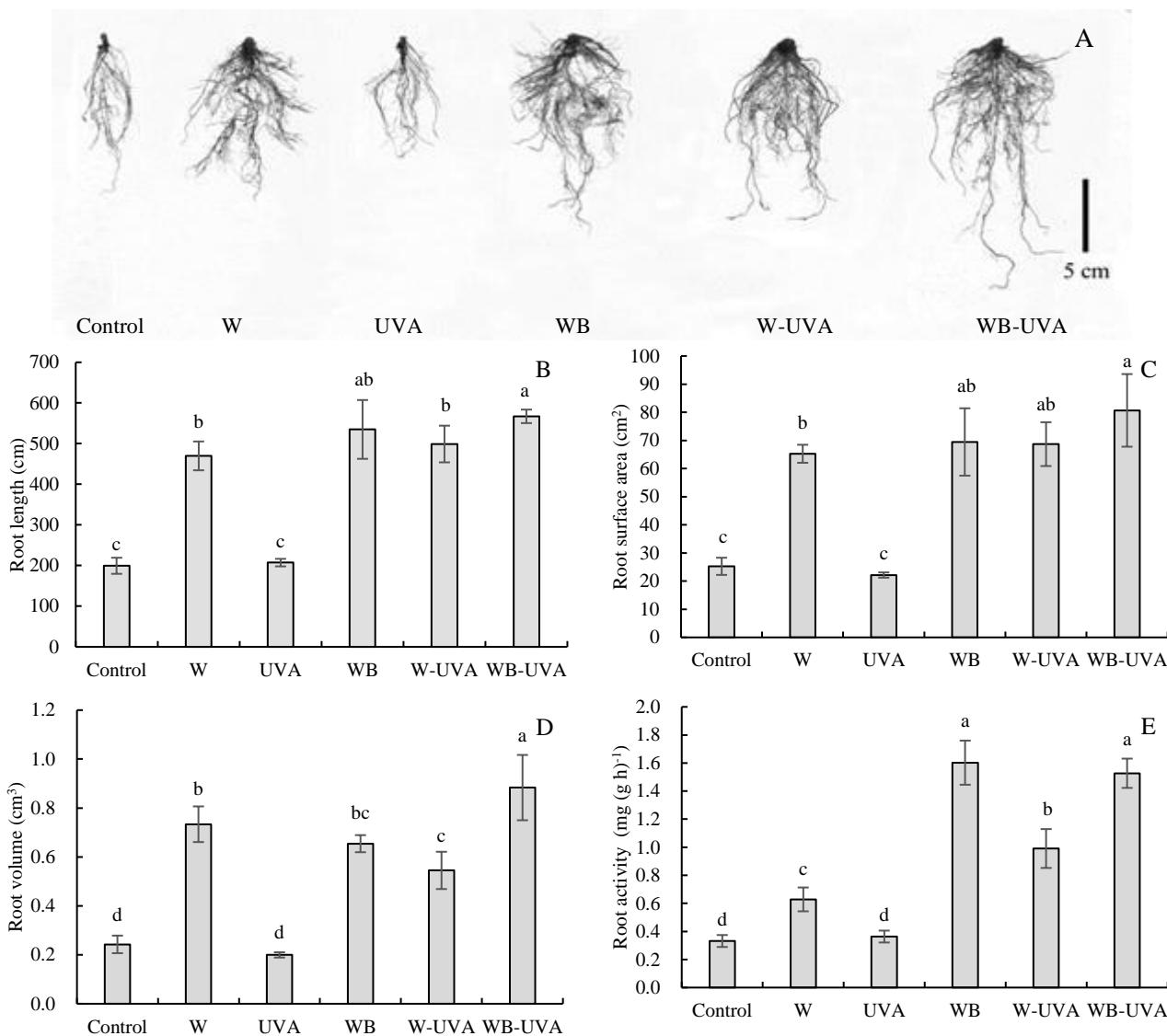


Figure 1. Effects of supplementary light provided by white (W), UV-A light-emitting diodes (LEDs), and various combinations of W, blue (B), and UV-A LEDs (A) on root morphology (A), root length (B), root surface area (C), root volume (D), and root activity (E) of greenhouse-grown cucumber seedlings cultivated for 22 days after sowing; cucumber seedlings grown without supplementary light were used as control. Different letters within each parameter were significantly different tested by the least significant difference (LSD) test at $p < 0.05$.

3.4. Influences of Supplementary Light on Stem Firmness and Cellulose Content of Greenhouse-Grown Cucumber Seedlings

The stem firmness and cellulose content of greenhouse-grown cucumber seedlings cultivated with supplementary light were higher than those cultivated with sunlight only

(Figure 2). The stem firmness and cellulose content of cucumber seedlings grown under the combination of white, blue, and UVA light were 1.9- and 2.7-times higher compared with cucumber seedlings grown with supplementary white LEDs, respectively. In addition, UVA light also led to higher stem firmness and cellulose contents of greenhouse-grown cucumber seedlings.

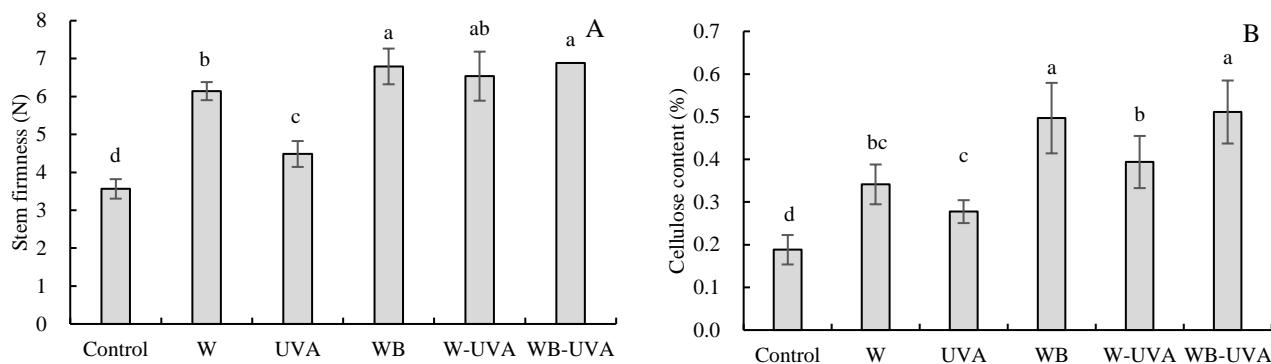


Figure 2. Effects of supplementary light provided by white (W), UV-A light-emitting diodes (LEDs), and various combinations of W, blue (B), and UV-A LEDs on stem firmness (A) and cellulose content (B) of greenhouse-grown cucumber seedlings cultivated for 22 days after sowing; cucumber seedlings grown without supplementary light were used as control. Different letters within each parameter were significantly different tested by the least significant difference (LSD) test at $p < 0.05$.

3.5. Hormone Content of Cucumber Seedlings Cultivated in the Greenhouse as Affected by Supplementary Light

The hormone contents of cucumber seedlings grown in the greenhouse reacted differently by different supplementary light treatments (Figure 3). The cytokinin content of cucumber seedlings cultivated with supplemental light increased remarkably compared with those grown with natural light only. Clearly, UVA light was effective in promoting the cytokinin content of cucumber seedlings. Moreover, the cytokinin content of cucumber seedlings grown with WB-UVA increased by 1-fold compared with those grown under the control treatment.

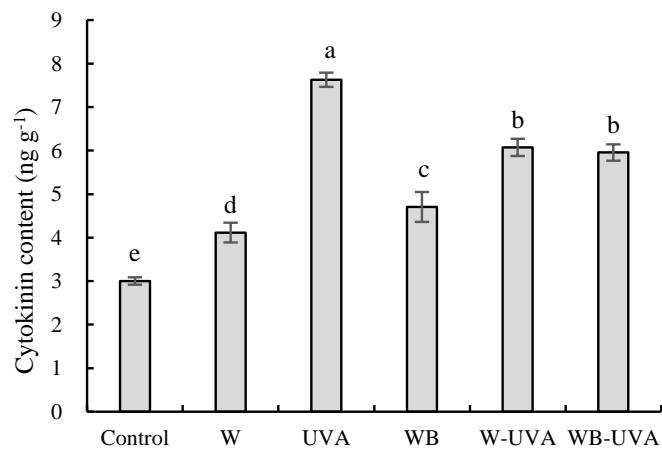


Figure 3. Impacts of supplementary light provided by white (W), UV-A light-emitting diodes (LEDs), and various combinations of W, blue (B), and UV-A LEDs on cytokinin content of greenhouse-grown cucumber seedlings cultivated for 22 days after sowing; cucumber seedlings grown without supplementary light were used as control. Different letters within each parameter were significantly different tested by the least significant difference (LSD) test at $p < 0.05$.

3.6. Supplementary Light Use Efficiency of Greenhouse-Grown Cucumber Seedlings

The supplementary light use efficiency of greenhouse-grown cucumber seedlings was significantly affected by supplementary LEDs (Figure 4). Supplementary white and UVA LEDs led to the lowest and highest supplementary light use efficiency in greenhouse-grown cucumber seedling production, respectively. In addition, the supplementary light use efficiency of cucumber seedlings cultivated under supplementary white LEDs increased by over 70% compared with those grown under the WB or WB-UVA treatments. No significant differences were found in supplementary light use efficiency in cucumber seedlings grown under the WB, W-UVA, and WB-UVA treatments.

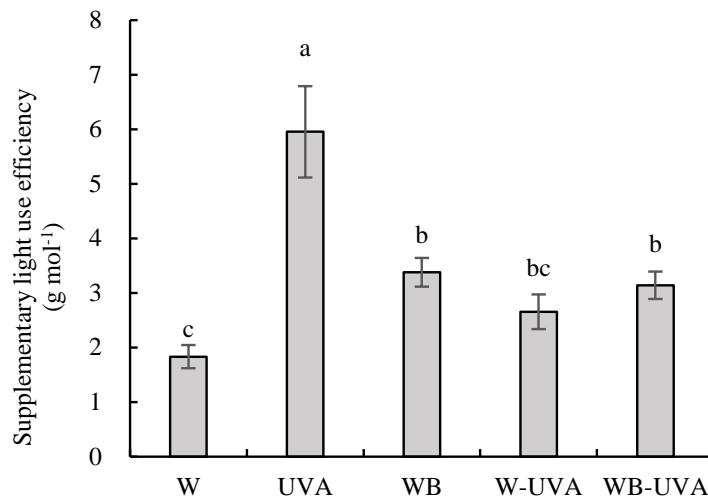


Figure 4. Supplementary light use efficiency of greenhouse-grown cucumber seedlings cultivated under supplementary white (W), UV-A light-emitting diodes (LEDs), and various combinations of W, blue (B), and UV-A LEDs at 22 days after sowing; cucumber seedlings grown without supplementary light were used as control. Different letters within each parameter were significantly different tested by the least significant difference (LSD) test at $p < 0.05$.

3.7. Heat Map Analysis

A heat map was applied to analyze the response among the tested parameters and exhibited a broad view of the influences of the supplementary lights on greenhouse-grown cucumber seedlings (Figure 5). The WB and the WB-UVA clusters were the closest to each other, the W and the W-UVA clusters were the closest to each other, and the control and the UVA clusters were the closest to each other. In addition, the control and WB-UVA treatment showed opposite responses in most of the measured parameters. Plant height and hypocotyl length were negatively related to the combinations of W-UVA, WB-UVA, and WB. However, the leaf area, root activity, root fresh weight, dry weight, and other indexes were positively related to the combinations of different lights. From the heat map, we could determine that different light combinations had different impacts on the growth indicators of cucumber seedlings. WB-UVA was characterized by a higher leaf area, shoot dry weight, gm, and biomass accumulation of the cucumber seedlings. WB-UVA had a better performance than UVA, W, and W-UVA in the morphological characteristics, photosynthetic properties, growth characteristics, and root architecture of greenhouse-grown cucumber seedlings.

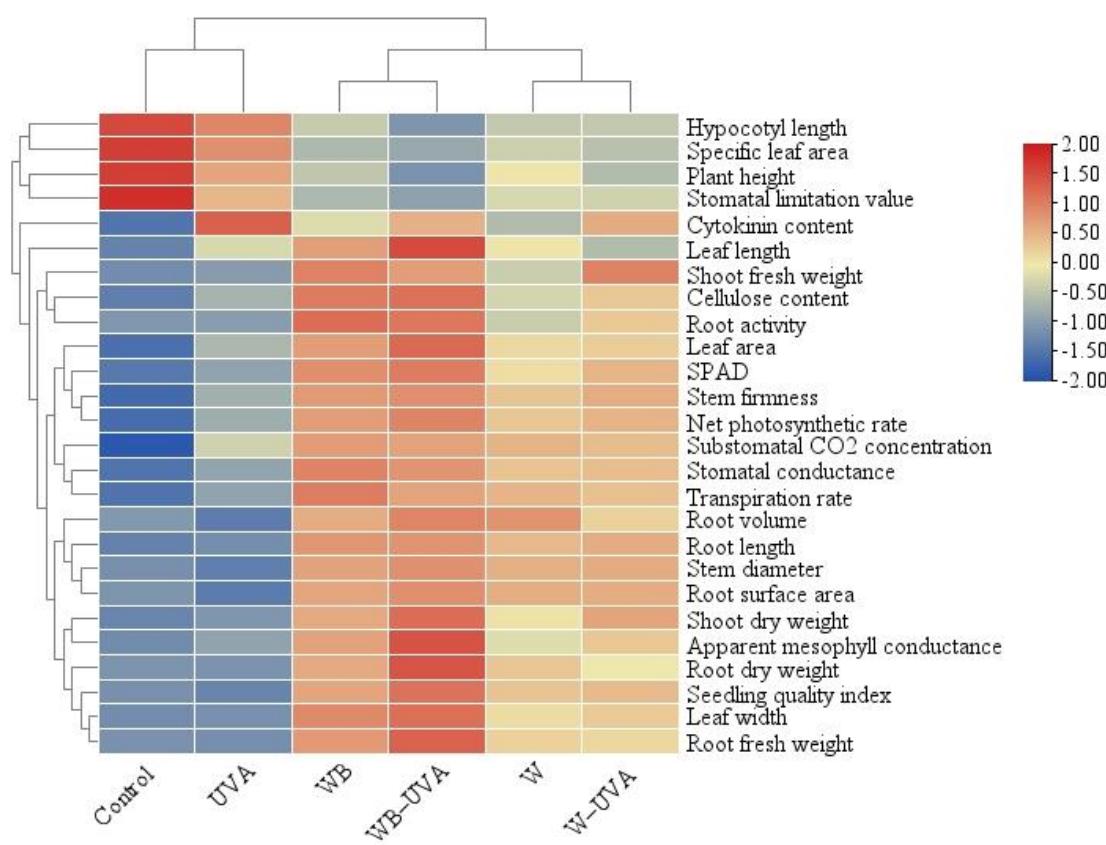


Figure 5. Cluster heat map analysis of greenhouse-grown cucumber seedlings for 22 days after sowing as influenced by white (W), UV-A light-emitting diodes (LEDs), and various combinations of W, blue (B), and UV-A LEDs. Blue and pure red indicated an increase and a decrease in the response parameters, respectively.

4. Discussion

Appling supplementary light in the greenhouse had become an indispensable method to improve the growth conditions and quality of plants grown in seasons or latitudes with insufficient solar light, and different light qualities had distinctly different biological effects on plants [42,44]. In this study, supplementary lighting led to a decreased plant height, shorter hypocotyl length, and bigger leaf area compared with those grown with solar light only. Moreover, the changes in morphology of plants were also related to the spectral composition of supplementary lights. The stem diameter and leaf area of greenhouse-grown cucumber seedlings cultivated in the WB-UVA treatment increased by 33.3% and 44.6% compared with those grown with natural light only, respectively. In addition, UVA radiation led to lower plant height, shorter hypocotyl length, and thicker leaves of cucumber seedlings compared with those cultivated with natural light only (Table 1). The results were similar with the previous studies reporting that UV radiation would lead to plants with larger internode diameters and shorter internodes [45,46]. In addition, Zhang et al. [35] observed that UVA radiation resulted in a bigger leaf area and smaller specific leaf area of tomato plants. Moreover, blue light significantly promoted the leaf expansion of plants [23]; when blue and UV lights were applied in the meantime, the elongation of the main stem of cucumber seedlings could be inhibited through activating cryptochromes [47], and the stem diameter and leaf area of plants could be promoted significantly. Similarly, Azad et al. [21] observed that the plant height of leaf lettuce decreased with the increase in blue light fraction, and a higher blue light fraction resulted in a compact leaf arrangement with green color and small petioles of lettuce, which was regulated by cryptochromes [31].

Different types of light sources, such as energy and signal sources, significantly affected plant photomorphogenesis [48]. It could be found that photosynthetic traits of the greenhouse-grown cucumber seedlings were changed remarkably when exposed to different combinations of supplementary light (Table 2). The results indicated that UVA radiation affected the plant chlorophyll contents significantly, and some studies had shown that UVA radiation could promote the increase in total chlorophyll content in lettuce, barley seedlings, and broccoli sprouts under greenhouse cultivation conditions [49–51]. Moreover, chlorophyll contents of plants directly influenced the photosynthesis process, and they were affected by the light quality [52]. In this study, the SPAD value, net photosynthetic rate, and transpiration rate of cucumber seedlings cultivated with supplementary light increased substantially compared with those cultivated with sunlight only, and supplementary lights with more blue light fraction led to a higher net photosynthetic rate and transpiration rate, indicating that increasing the DLI and blue light increased the photosynthetic characteristics of plants. Similar results were also found in lettuce [21] and grafted watermelon seedlings [53]. In addition, it could be observed that UVA radiation affected the photosynthetic process of cucumber seedlings between the control and UVA treatments, but not observed in W vs. W-UVA, and WB vs. WB-UVA, which may be related with the supplementary light intensity or background light. Gao et al. [54] indicated that UVA radiation improved the actual photochemical efficiency of photosystem II, thus increasing the growth of Chinese kale. Simultaneously, the enhancement of photosynthetic activity by UVA radiation was caused by the re-absorption of UVA-induced blue-green fluorescence [50]. However, Kang et al. [36] found that the net photosynthesis rate of tomato seedlings was unaffected by UVA radiation when supplemented with red plus blue lights. This difference may be caused by the supplementary light intensity, the background light quality, or the plant species.

The light spectral composition affected the biomass accumulation of plants, and different vegetable varieties responded differently to the light spectrum [55]. Supplemental LED lighting improved the quality of vegetable seedlings by increasing the DLI in the greenhouse, where a 1% increase in DLI may lead to a 1% increase in the yields of fruit vegetable, which may be due to the increased Cytochrome b6f complex and Rubisco contents in plants [56,57]. Our study indicated that supplementing with UVA radiation alone unaffected the biomass accumulation of cucumber seedlings, but the combination of UVA with white light, or white plus blue lights significantly increased the biomass accumulation of greenhouse-grown cucumber seedlings. Additionally, the seedling quality index of greenhouse-grown cucumber seedlings cultivated in the WB-UVA treatment was significantly higher compared with other treatments, except for the cucumber seedlings grown with supplementary white and blue LEDs, indicating that UVA light was beneficial to the growth of cucumber seedlings when it was used in conjunction with other LEDs. Root architecture is also a vital trait in evaluating seedling quality, as well-rooted vegetable seedlings are more appropriate to support transport conditions [44]. Little research has been conducted on the root architecture of greenhouse-grown cucumber seedlings cultivated under various supplementary lights. Yan et al. [13] found that the root growth of cucumber seedlings was increased by supplementary white LEDs, and similar trends were also found in the root length, root surface area, root volume, and root activity of cucumber seedlings. Moreover, our results showed that no remarkable differences were observed in the aforementioned parameters of greenhouse-grown cucumber seedlings grown between the control and UVA treatment, which may be caused by the supplementary DLI.

The stem firmness and cellulose content of plants indicated the mechanical properties of plants [58]. Vegetable seedlings with a higher cellulose content characterized the good lodging resistance of their stems, which was convenient for vegetable grafting and transplanting. It can be seen in this study that the stem firmness and cellulose content of greenhouse-grown cucumber seedlings cultivated with supplementary light were higher than those cultivated without supplementary light. This change could improve the mechanical properties of greenhouse-grown cucumber seedlings and was conducive

for transplanting. Similar results could be found in the research of Yan et al. [13]. In addition, the stem firmness and cellulose content of cucumber seedlings were improved by supplementary blue light.

The hormone contents in the plant reflected the degree of the physiological process of the plant. Cytokinins are a major class of phytohormones, which play a vital role in the retardants of leaf senescence, flower bud differentiation, and root growth [59,60]. From the results of this study, it could be found that different light qualities had remarkable impacts on the hormone content of cucumber seedlings, and the cytokinin content of greenhouse-grown cucumber seedlings cultivated with supplementary light increased compared with those grown with sunlight only. Chory et al. [61] suggested that adding higher contents of cytokinin to dark-grown seedlings led to de-etiolation, suggesting that etiolation depended on low levels of cytokinin. In general, blue and UVA radiations promoted the synthesis of cytokinin of cucumber seedling. Similarly, Marchetti et al. [62] indicated that cytokinin reactivation was delayed in the absence of blue light.

Supplementary light use efficiency should be considered due to the increased electricity consumption [63], which could be applied to estimate the effectiveness of supplementary light sources for cultivating crops in the protected horticulture. Our results indicated that cucumber seedlings grown in the UVA light led to the highest supplementary light use efficiency as a result of the small amount of light used in the treatment. However, the increased lighting use efficiency should also be considered with the growth performances of plants [12,28]. From the perspective of energy saving, no remarkable differences were found in supplementary light use efficiency in greenhouse-grown cucumber seedlings cultivated in the WB, W-UVA, and WB-VUA treatments, which were significantly higher as compared with those grown in the W treatment.

From the results of the heat map, the effects of different combinations of supplementary LEDs on cucumber seedlings varied greatly, and the appropriate combinations of supplementary LEDs could promote the growth of plants. It showed that UVA could not promote the growth of cucumber seedlings when it was used alone (the control vs. the UVA). However, when it was combined with white light or white and blue lights, the growth status of cucumber seedlings had been significantly improved as compared with those grown with natural light only, including morphological characteristics, biomass, and photosynthetic characteristics. This result is consistent with previous studies, which believed that UVA can be used in conjunction with blue light to promote plant growth [36,64,65]. Moreover, the promotion effects were more obvious when cucumber seedlings were grown under the combinations of blue, white, and UVA lights, especially on the growth characteristics and photosynthetic properties.

5. Conclusions

Supplementary lighting remarkably affected the leaf morphology, growth, and physiological traits of greenhouse-grown cucumber seedlings. In addition, different light spectra had significant and diverse influences on the growth of cucumber seedlings. Combinations of white, blue, and UVA radiations led to compact morphological characteristics, superior mechanical properties, and preferable growth performance, which could be used as an effective tool to obtain the desired morphological and quality properties of targeted plants. It also promoted photosynthetic processes and hormone synthesis of greenhouse-grown cucumber seedlings, which was suitable as supplementary lighting sources in the seasons with insufficient light.

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