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Effect of Daily Light Integral on Cucumber Plug Seedlings in Artificial Light Plant Factory

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Abstract: In a controlled environment, in an artificial light plant factory during early spring or midsummer, vegetable seedlings can be uniform, compact, and high quality. Appropriate light parameters can speed up the growth of seedlings and save on production costs. Two experiments were carried out in this study: (1) cucumber seedling growth under different daily light integrals (DLIs) (5.41–11.26 mol·m^{-2}·d^{-1}) and optimum DLI for seedling production were explored (experiment 1: Exp. 1); (2) under the same DLI selected by Exp. 1, the effects of different light intensities and photoperiods on cucumber seedlings were investigated (experiment 2: Exp. 2). The root biomass, root-to-shoot ratio, seedling index, and shoot dry matter rate increased as the DLI increased from 5.41 to 11.26 mol·m^{-2}·d^{-1}, while the shoot biomass and leaf area decreased in Exp. 1. The cucumber seedlings became more compact as DLI increased, but more flowers developed after transplanting when the DLI was 6.35 mol·m^{-2}·d^{-1}. Under the optimal DLI (6.35 mol·m^{-2}·d^{-1}), the optimal intensity was 110–125 µmol·m^{-2}·s^{-1}, and the optimal photoperiod was 14–16 h, in which plant biomass, shoot dry matter rate, seedling index, and photochemical efficiency were higher.

Keywords: daily light integral; cucumber seedling; seedling quality; flower development

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1. Introduction

The daily light integral (DLI) is the total amount of photosynthetic light delivered to plants each day [1,2]. The DLI is an important environmental parameter for plants and displays stronger correlation with vegetative growth parameters than with photoperiod and light intensity [3,4]. Many studies have shown that a suitable DLI could promote the growth and development of plants, such as the germination rate of photoblastic seeds [5], shoot and root biomass [6–9], stem diameter [10,11], leaf area and leaf number [12], and the differentiation of flower buds [4,13,14].

The production of high-quality seedlings with characteristics of higher biomass, compactness and adequate leaf area in a short cultivation period is the target of producers. However, this constitutes a significant challenge under insufficient scrutiny [15,16]. Many operations use supplemental lighting to increase DLI under low irradiance to accelerate growth and improve the morphology of seedlings in typical greenhouses [17–19]. Cucumber seedlings became more compact and vigorous, with characteristics of a short hypocotyl length, large leaf area, and high biomass under a high DLI [19,20]. Increases in DLI during the seedling stage have been also reported to accelerate subsequent floral initiation and decrease the time to the first flowering after transplant [13,21,22]. The number of tomato floral buds and days to flowering increased corresponding to the decrease in the shading before anthesis [23].

However, higher DLI is correlated with more illuminating apparatus and electric energy consumption. Additionally, superfluous DLI with a high light intensity or long photoperiod may cause damage to the photosynthetic system and inhibits the production

of photosynthates [24,25]. For example, high DLI results in a decrease in photosystem II (PSII) activity, thus leading to the low production of lettuce [26]. The total fresh mass and total dry mass of spinach were higher when DLI was 17.3 mol·m^{-2}·d^{-1} compared with 20.2 mol·m^{-2}·d^{-1} [27]. These reductions in biomass may result in a reduced source of flower bud formation, since it has been previously demonstrated that flower initiation requires a certain amount of photoassimilates [8]. Extra DLI did not further increase the flowering rate or floral bud number in some bedding plants [28–30]. Therefore, an optimal DLI which can only just meet the demand of seedling growth and facilitate late flower bud differentiation should be selected by the producer for energy-saving purposes.

Under the same DLI, a longer photoperiod is more beneficial to the growth of plants. The plant height, shoot dry mass, root dry mass and chlorophyll content index of rudbeckia seedlings were larger with longer photoperiods [18]. A longer photoperiod with the same DLI increased the light interception, chlorophyll content index, quantum yield of photosystem II, and aboveground biomass of lettuce and mizuna [31,32].

Under artificial light conditions, DLI is completely supplied by lamps and varies via changing the light intensity or photoperiod. Due to the controllable illumination parameters, DLI parameters for plants are more reliable and can be used for plant cultivation and research with higher accuracy. Exploring the optimum DLI and illumination parameters is conducive to the scheduling and improvement of profitability.

Cucumber is cultivated worldwide, and its seedling stage is crucial for subsequent growth and development. Scarce research has been conducted on the effects of DLI from sole-source (SS) lighting on cucumber plug seedlings. Therefore, the objectives of our study were to determine the optimal DLI by investigating the morphology, biomass, chlorophyll fluorescence, and subsequent flower development of cucumber plug seedlings (Exp. 1); then the effects of different illumination intensities and times on the quality of cucumber seedlings were further investigated under the optimal DLI selected in Exp. 1, and the appropriate light parameters for cucumber plug seedlings were finally selected (Exp. 2).

2. Materials and Methods

2.1. Plant Material

In both Exp. 1 and 2, seeds of cucumber 'Yuexiu No.3' were place onto humid cotton in an incubator for 2 days. The temperature and relative humidity were set to 25 °C and 80%, respectively. The germinated seeds were sown into plug trays (50-cell size (28 mL)) in a substrate with peat, coconut coir and perlite (6: 3: 1, v: v: v) and placed into a walk-in growth chamber at the College of Horticulture of South China Agricultural University, Guangzhou. Each tray was a repeat. Each experiment conducted four treatments, in which three repeats were concluded. Before cotyledons were fully expanded after sowing, 800 ± 50 mL tap water was added to each tray every second day. Once cotyledons were fully expanded, 800 ± 50 mL 1/4 strength modified Hoagland and Arnon's nutrient solution was added to each tray every second day to provide (in mg·L^{-1}) 53 nitrogen (N), 40 calcium (Ca), 59 potassium (K), 8 phosphorus (P), 25 magnesium (Mg), 33 sulphur (S), 0.56 iron (Fe), 0.5 boron (B), 0.5 manganese (Mn), 0.05 zinc (Zn), 0.01 molybdenum (Mo) and 0.005 copper (Cu) until the emergence of the second true leaf. Then, 800 ± 50 mL 1/2 strength modified Hoagland and Arnon's nutrient solution was added to each tray every second day until sampling.

2.2. Growth Chamber Environment

All the plug trays were placed on steel shelves in two vertical layers in a walk-in growth chamber, with an average daily temperature of 25 °C, relative humidity (RH) of 75%, and average carbon dioxide (CO_2) concentration of 400 μmol·mol^{-1}.

2.3. Sole-Source Lighting Treatments

Adjustable LED lamps of red (655–660 nm):blue (455–460 nm) = 1:1 (R_1:B_1) (Unihero technology Co. Ltd., Huizhou, China) were placed above the steel shelves providing

sole-source lighting with different photosynthetic photon flux densities (PPFDs) and photoperiods. The spectra for PPFD at 200 μmol·m^{-2}·s^{-1} are shown in Figure 1. Two experiment lighting treatments were conducted as follows. Exp. 1: the average total photon flux was delivered from sole-source light-emitting diodes (LEDs) with light ratios (%) of red/blue 50:50 to achieve target light intensities of 125 to 200 μmol·m^{-2}·s^{-1} with 12–16 h photoperiods. Four gradients of DLIs in each run set from 7.47 to 11.26 mol·m^{-2}·s^{-1} (run 1) and from 5.41 to 8.43 mol·m^{-2}·s^{-1} (run 2), respectively (Table 1). Exp. 2: target light intensities were of the same light ratios as Exp. 1, of 110–175 μmol·m^{-2}·s^{-1}, with 10–16 h photoperiods, and four lighting treatments were conducted with the same DLI (6.35 mol·m^{-2}·d^{-1}) selected by Exp. 1 (Table 2).

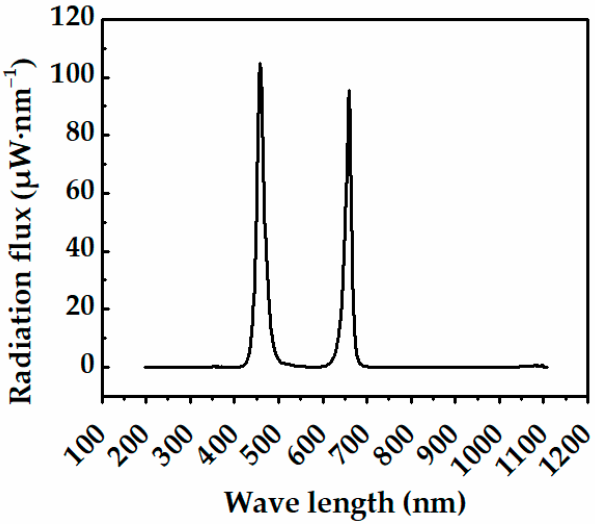


Figure 1. Spectral quality of 200 μmol·m^{-2}·s^{-1} from SS LEDs with light ratios (%) of red/blue 50:50.

Table 1. Illumination parameters of different treatments in Exp. 1.

Treatments	Light Intensity * (μmol·m^{-2}·s^{-1})	Photoperiod (h)	Average DLI * (mol·m^{-2}·d^{-1})
Run 1	148.17 ± 2.75	14	7.47 ± 0.14
	148.00 ± 2.22	16	8.52 ± 0.13
	199.33 ± 2.50	14	10.05 ± 0.13
	195.43 ± 1.72	16	11.26 ± 0.10
Run 2	125.14 ± 1.06	12	5.41 ± 0.05
	126.00 ± 1.69	14	6.35 ± 0.09
	151.57 ± 1.13	14	7.64 ± 0.06
	146.43 ± 0.87	16	8.43 ± 0.05

* The data represent the mean ± SE of 10 spots under lights in each treatment.

Table 2. Four combinations with different light intensities and photoperiods that achieve the same DLI in Exp. 2.

Treatments	Light Intensity * (μmol·m^{-2}·s^{-1})	Photoperiod (h)	Average DLI * (mol·m^{-2}·d^{-1})
T1	111.17 ± 0.48	16	6.40 ± 0.03
T2	125.17 ± 1.90	14	6.31 ± 0.10
T3	146.00 ± 1.32	12	6.31 ± 0.06
T4	176.67 ± 1.33	10	6.36 ± 0.05

* The data represent the mean ± SE of 10 spots under lights in each treatment.

2.4. Morphology and Growth Measurement

The morphology and growth of cucumber plug seedlings in both Exp. 1 and 2 were measured on the 26th day after sowing. Six seedlings of each repeat (i.e., 18 seedlings per

DLI treatment) were randomly selected and measured to determine the hypocotyl length, stem diameter, total leaf area, shoot fresh mass, shoot dry mass, root fresh mass, and root dry mass. The fresh mass of seedlings was recorded by an electronic balance, and the dry mass was recorded after seedlings were heated to de-enzyme at 105 °C, then dried at 80 °C until steady.

Seedling index = (stem diameter/hypocotyl length + root dry mass/shoot dry mass) × total dry mass × 10 [33], root-to-shoot ratio = root dry mass/shoot dry mass, leaf area ratio = total leaf area/shoot dry mass, and shoot dry matter rate = shoot dry mass/shoot fresh mass were calculated [11,34].

2.5. Physiological Characteristics and Photosynthesis Pigment Content

The soluble sugar content was extracted and analyzed by anthrone colorimetry. A 0.5 g amount of leaf fresh sample was added to a test tube with 10 mL of distilled water, and then it was extracted in boiling water for 30 min. The extract was filtered into a 25 mL volumetric flask, the test tube and residue were rinsed repeatedly, and the volume was maintained to scale. An amount of 0.1 mL of the sample extract was absorbed into a 20 mL graduated test tube, followed by adding 1.9 mL of distilled water, 0.5 mL of ethyl anthrone acetate reagent and 5 mL of concentrated sulfuric acid. The solution was fully oscillated and cooled down to room temperature. The absorbance was measured at 630 nm by using a UV-spectrophotometer [35].

The soluble protein content was extracted and analyzed by Coomassie Brilliant Blue methods. Amount of 0.5 g of fresh leaf sample and 5 mL of distilled water were ground into a homogenate and centrifuged at 10,000× *g* for 10 min at 4 °C. After mixing 0.3 mL of supernatant and 0.7 mL of distilled water, 5 mL of Coomassie Brilliant Blue G-250 solution (0.1 g/L) was added to the mixture. After 2 min, the absorbance at 595 nm was determined by using a UV-spectrophotometer [35].

The content of photosynthesis pigment was determined by an acetone–ethanol blend method. An amount of 0.2 g of leaf with removed veins was placed into a test tube containing 20 mL of acetone and ethanol (1:1, *v:v*), and extracted under dark conditions. The absorbance at 663, 645 and 440 nm was determined by using a UV-spectrophotometer after the leaves turned white. Chlorophyll a (Chl a) content ($mg \cdot g^{-1}$) = (12.70 × A_{663} − 2.69 × A_{645}) × 20 mL/(1000 × 0.2 g); chlorophyll b (Chl b) content ($mg \cdot g^{-1}$) = (22.90 × A_{645} − 4.86 × A_{663}) × 20 mL/(1000 × 0.2 g); total chlorophyll (Total Chl) content ($mg \cdot g^{-1}$) = (8.02 × A_{663} + 20.20 × A_{645}) × 20 mL/(1000 × 0.2 g); carotenoid content ($mg \cdot g^{-1}$) = (4.70 × A_{440} − 2.17 × A_{663} − 5.45 × A_{645}) × 20 mL/(1000 × 0.2 g) [36].

2.6. Chlorophyll Fluorescence

Chlorophyll fluorescence was measured by MINI-PAM-II (WALZ company, Germany), and the actinic illumination was set at 286 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Leaves were dark-acclimated for 20 min with the manufacturer's plastic and foam clips before measurements were recorded. Six seedlings of each repeat were randomly selected and measured, and the locus was the second true leaf of each seedling. The photochemical quenching indexes (qP and qL), the non-photochemical quenching indexes (qN and NPQ), photic injury non-photochemical quenching quantum yield (Y(NO)), photoprotection non-photochemical quenching quantum yield (Y(NPQ)) and PSII conversion efficiency of light energy (Φ_{PSII}), and maximal photochemical efficiency of PSII in the dark (Fv/Fm) were measured.

2.7. Flowering in Cucumber Plant after Transplant

As a supplementary experiment, only the run 2 in Exp. 1 was carried out for flowering statistics. After DLI treatments, nine cucumber seedlings from each DLI treatment were transplanted into a growth bag (15 cm diameter, 15 cm height) filled with substrate of peat, coconut coir and perlite (6:3:1, v:v:v). Plants were watered with 1/2 strength Hoagland and Arnon's nutrient solution before the first flower bloom, and then full strength nutrient solution. The days to first flower bloom from transplant, node of the first male flower, male

flower number, node of first female flower, female flower number on main stem, number of lateral branches, and total female flower number under the 15th node were recorded at 60 days after the transplant.

2.8. Statistical Analysis

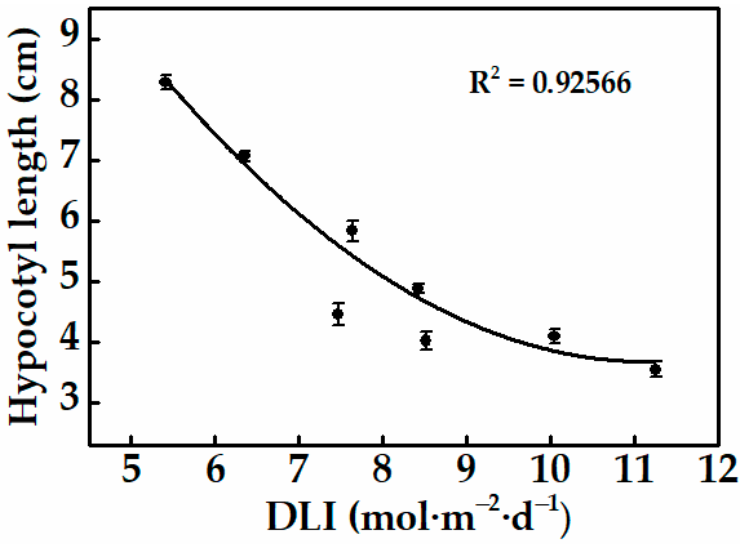
Data were analyzed by one-way ANOVA using PASW Statistics 18.0. Duncan's multiple range test at $p < 0.05$ was used to determine significant treatment differences. The plotting and fitting of monomial and binomial response functions were conducted using Origin 8.6.

3. Results

3.1. Experiment 1

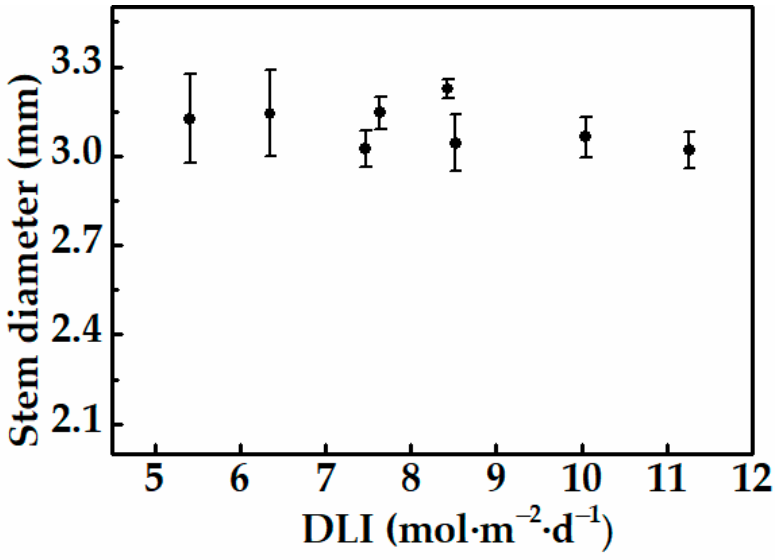
3.1.1. Morphology and Growth of Cucumber Plug Seedlings

The morphology and growth of cucumber plug seedlings were affected by DLI. The hypocotyl length and leaf area of cucumber plug seedlings showed the same trend as DLI increased. Hypocotyl length decreased from 8.28 to 3.55 cm, while the leaf area decreased from 123.15 to 56.07 cm^2, as DLI increased from 5.41 to 11.26 $mol \cdot m^{-2} \cdot d^{-1}$ (Figure 2a,c). The stem diameter of cucumber plug seedlings was not affected by DLI (Figure 2b). Shoot fresh mass and dry mass decreased as DLI increased from 5.41 to 11.26 $mol \cdot m^{-2} \cdot d^{-1}$. The root fresh mass and dry mass first increased and then decreased as the DLI increased, peaking at 8.43 $mol \cdot m^{-2} \cdot d^{-1}$ (Figure 3a). The root-to-ratio and seedling index first increased and then remained steady with the increase in DLI. At a lower DLI, the leaf area ratio decreased significantly with an increased DLI, but it remained at a low value under higher DLIs. The shoot dry mass rate increased from 0.073 to 0.095 as the DLI increased from 5.41 to 11.26 $mol \cdot m^{-2} \cdot d^{-1}$ (Figure 3b).

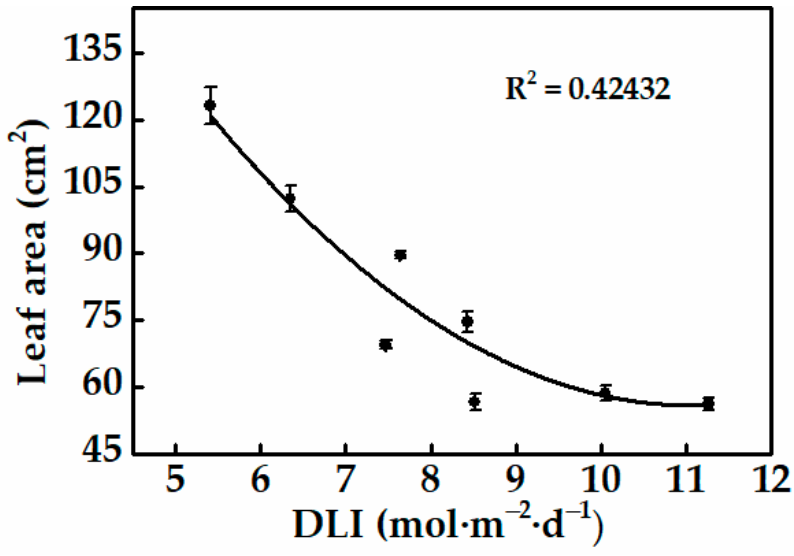


(a)

Figure 2. *Cont.*



(**b**)



(**c**)

Figure 2. Relationships between DLI and (**a**) hypocotyl length, (**b**) stem diameter and (**c**) leaf area of cucumber seedlings. Each symbol represents the mean of 18 plants in each treatment, and error bars represent SEs of means. Fitting formula shown in supplementary section.

3.1.2. Physiological Characteristics and Photosynthesis Pigment Content of Cucumber Plug Seedlings

The soluble sugar content of cucumber plug seedlings increased by 8.72 mg·g^{-1} linearly as the DLI increased from 5.41 to 11.26 mol·m^{-2}·d^{-1} (Figure 4a). When the DLI was in the range of 6.35–8.52 mol·m^{-2}·d^{-1}, the soluble protein remained high but then fell dramatically beyond this range (Figure 4b). All the photosynthesis pigment contents were negatively correlated with DLI (Figure 5).

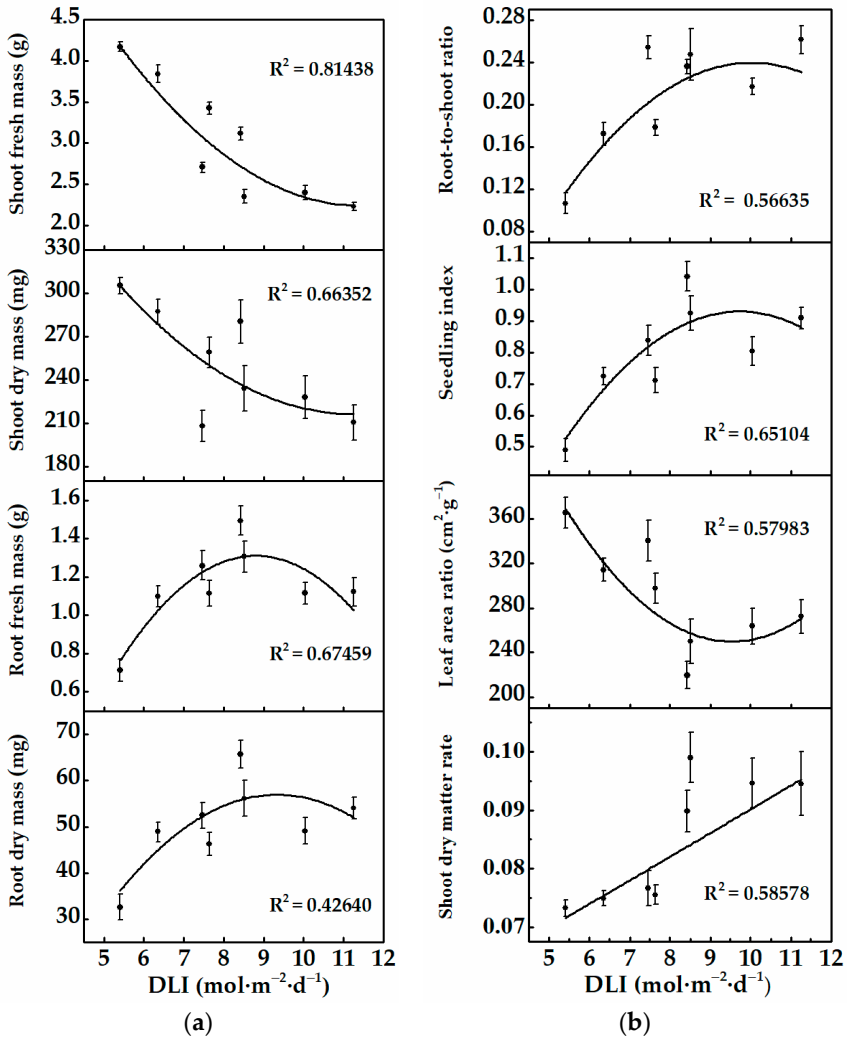


Figure 3. Relationships between DLI and (**a**) shoot fresh and dry mass, root fresh and dry mass, (**b**) root-to-shoot ratio, seedling index, leaf area ratio, and shoot dry matter rate of cucumber seedlings. Each symbol represents the mean of 18 plants in each treatment, and error bars represent SEs of means. Fitting formula shown in supplementary section.

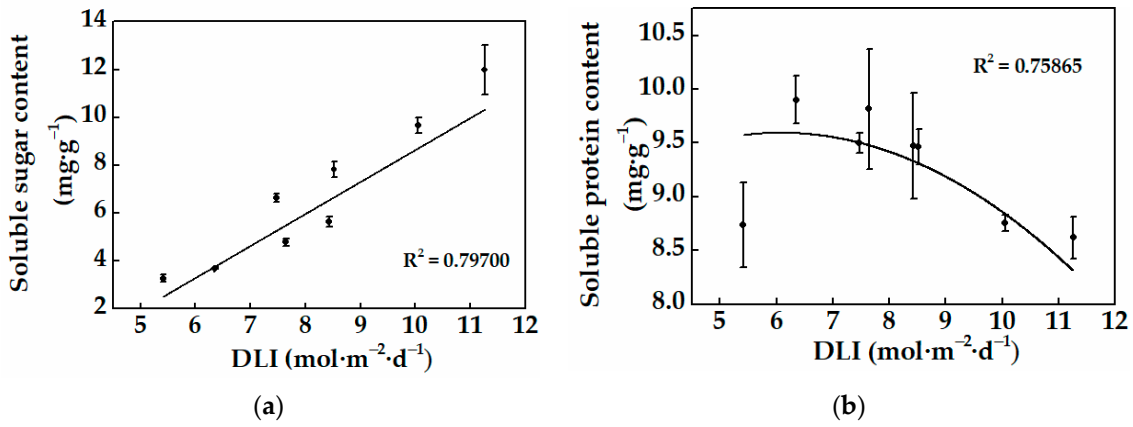


Figure 4. Relationships between DLI and (**a**) soluble sugar content and (**b**) soluble protein content of cucumber seedlings. Each symbol represents the mean of three repeats in each treatment, and error bars represent SEs of means. Fitting formula shown in supplementary section.

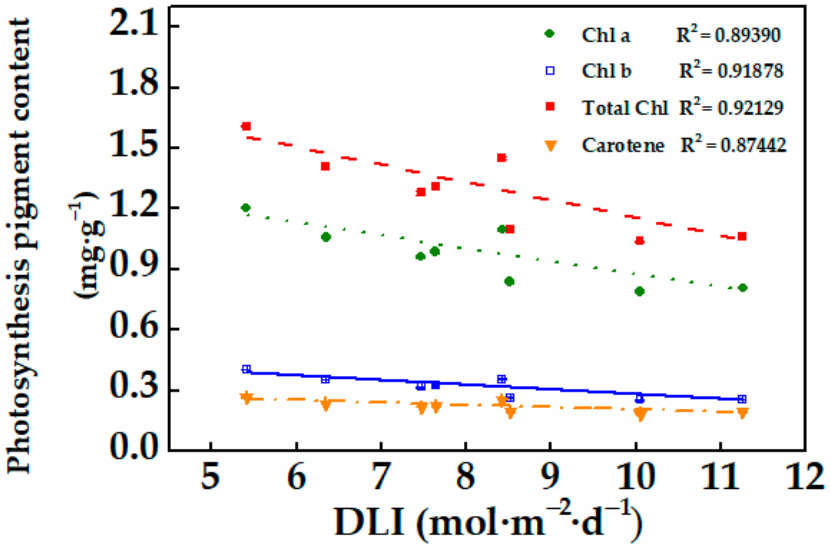


Figure 5. Relationships between DLI and photosynthesis pigment content of cucumber seedlings. Each symbol represents the mean of three repeats in each treatment, and error bars represent SEs of means. Fitting formula shown in supplementary section.

3.1.3. Flowering in Cucumber Plant after Transplant

The days to the first flower bloom from transplant, and the node of the first male and female flowers (data not shown) were unaffected by DLI. When DLI was about 6.35 mol·m^{-2}·d^{-1}, more male flowers, female flowers and lateral branches appeared (Table 3).

Table 3. The effect of DLI on cucumber plant flowering after transplant of cucumber plug seedlings in run 2 *.

DLI/mol·m^{-2}·d^{-1}	Days to First Flower Bloom from Transplant	Male Flower Number	Female Flower Number of Main Stem	Number of Lateral Branches	Total Female Flower Number
5.41	39.83 ± 0.75 ^{a}	46.00 ± 4.47 ^{b}	1.17 ± 0.17 ^{b}	1.00 ± 0.26 ^{b}	2.17 ± 0.31 ^{b}
6.35	39.00 ± 0.26 ^{a}	57.33 ± 2.60 ^{a}	1.17 ± 0.17 ^{b}	2.50 ± 0.43 ^{a}	3.67 ± 0.56 ^{a}
7.64	38.83 ± 0.31 ^{a}	50.33 ± 3.87 ^{a,b}	1.33 ± 0.21 ^{a}	2.17 ± 0.54 ^{a,b}	3.50 ± 0.43 ^{a,b}
8.43	40.00 ± 0.45 ^{a}	39.83 ± 2.24 ^{b}	1.33 ± 0.21 ^{a}	1.33 ± 0.42 ^{a,b}	2.67 ± 0.42 ^{a,b}

* Presented values are means ± SEs (n = 9). ^{a,b} Different lowercase letters indicate statistically differences among treatments ($p < 0.05$).

3.2. Experiment 2

3.2.1. Morphology and Growth of Cucumber Plug Seedlings

Under the same DLI, the hypocotyl length, stem diameter and shoot fresh mass were independent of changes in illumination strength and time (supplementary section and Figure 6a). The shoot dry mass, root fresh mass and root dry mass decreased by 50.24, 310.00 and 15.13 mg, respectively, as the light intensity increased from 111 to 177 μmol·m^{-2}·s^{-1} and the photoperiod decreased from 16 to 10 h (Figure 6a). Two sets of low light intensities and long photoperiods (T1 and T2) had a higher root-to-shoot ratio, seedling index, shoot dry matter rate and lower leaf area ratio (Figure 6b).

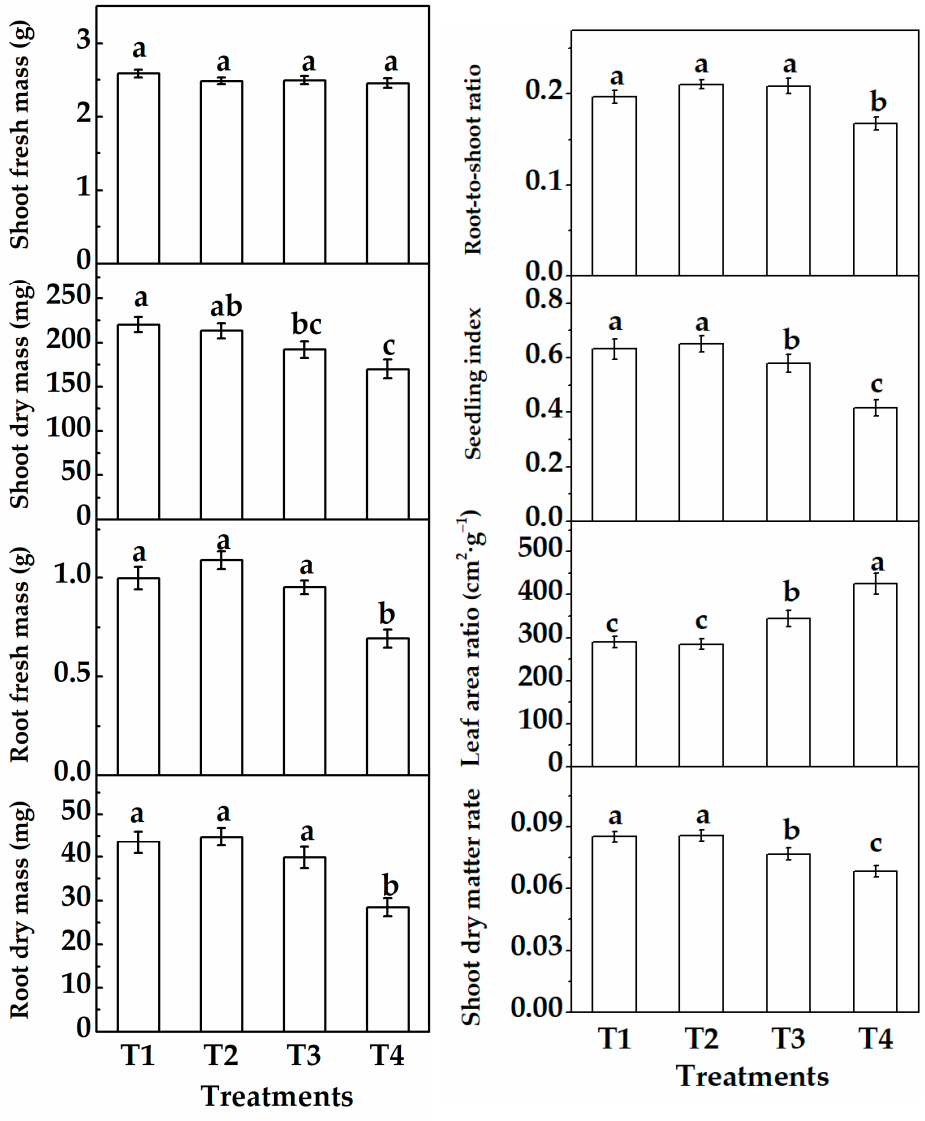
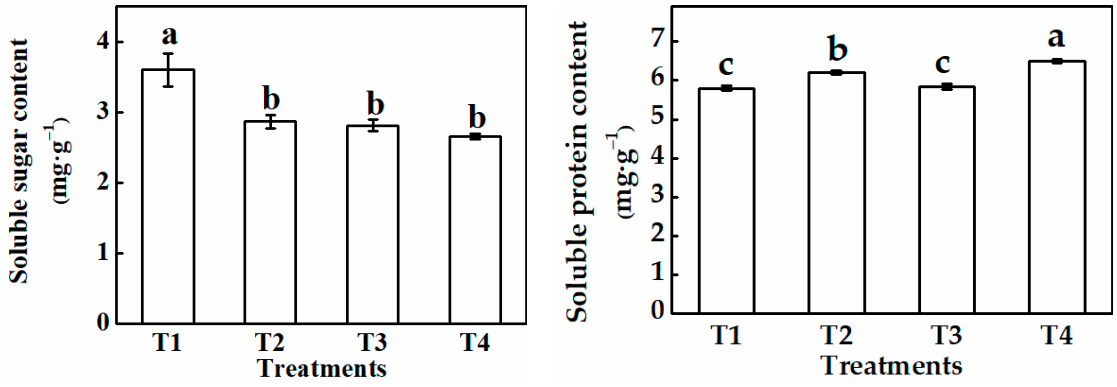


Figure 6. The effects of different light intensities and photoperiods on (**a**) shoot fresh and dry mass, root fresh and dry mass (**b**) root-to-shoot ratio, seedling index, leaf area ratio, and shoot dry matter rate of cucumber seedlings. Different letters indicate statistically significant differences among treatments ($p \leq 0.05$). Error bars show SEs ($n = 18$).

3.2.2. Physiological Characteristics of Cucumber Plug Seedlings

The soluble sugar content was the highest in T1, and there were no significant differences in the other three treatments. The soluble sugar content in T1 was 25.66%, 27.95%, and 35.42% higher than in T2, T3, and T4, respectively (Figure 7a). There was no obvious pattern between the content of soluble protein with the variation of illumination parameters under the same DLI (Figure 7b).



(**a**) (**b**)

Figure 7. The effects of different light intensities and photoperiods on (**a**) soluble sugar and (**b**) soluble protein content of cucumber seedlings. Different letters indicate statistically significant differences among treatments ($p \leq 0.05$). Error bars show SEs ($n = 9$).

3.2.3. Photosynthesis Pigment Content and Chlorophyll Fluorescence of Cucumber Plug Seedlings

When the light intensity increased and the photoperiod decreased, the contents of chlorophyll and carotenoid tended to increase (data shown in supplementary section). As the light intensity increased and the photoperiod decreased, the photochemical quenching indexes (qP and qL) and Φ_{PSII} all showed a downwards trend, and the decreased range from T3 to T4 was sharp, and there were significant differences among the four treatments. The non-photochemical quenching indexes (qN and NPQ) and Y(NPQ) increased first then decreased later, which was the largest in T3. Y(NO) showed an increasing trend with the increase in light intensity and shortening of the photoperiod, and T4 was 146.84%, 144.89%, and 117.27% higher than T1, T2, and T3, respectively. The Fv/Fm of T4 was the smallest, and there was no difference among T1, T2, and T3 (Table 4).

Table 4. The effects of different light intensities and photoperiods on chlorophyll fluorescence of cucumber seedlings *.

Treatment	Photochemical Quenching		Non-Photochemical Quenching		Y(NO)	Y(NPQ)	Φ_{PSII}	Fv/Fm
	qP	qL	qN	NPQ				
T1	0.63 ± 0.01 ^{a}	0.39 ± 0.01 ^{a}	0.62 ± 0.01 ^{b}	1.11 ± 0.04 ^{b}	0.29 ± 0.00 ^{c}	0.32 ± 0.01 ^{c}	0.39 ± 0.01 ^{a}	0.78 ± 0.00 ^{a}
T2	0.58 ± 0.01 ^{b}	0.35 ± 0.00 ^{b}	0.65 ± 0.01 ^{a,b}	1.23 ± 0.05 ^{a,b}	0.29 ± 0.00 ^{c}	0.36 ± 0.01 ^{b}	0.35 ± 0.01 ^{b}	0.77 ± 0.00 ^{a}
T3	0.40 ± 0.02 ^{c}	0.21 ± 0.01 ^{c}	0.66 ± 0.01 ^{a}	1.31 ± 0.07 ^{a}	0.33 ± 0.01 ^{b}	0.42 ± 0.01 ^{a}	0.25 ± 0.01 ^{c}	0.78 ± 0.01 ^{a}
T4	0.12 ± 0.01 ^{d}	0.05 ± 0.00 ^{d}	0.31 ± 0.01 ^{c}	0.31 ± 0.02 ^{c}	0.71 ± 0.01 ^{a}	0.22 ± 0.01 ^{d}	0.07 ± 0.00 ^{d}	0.64 ± 0.02 ^{b}

* Presented values are means ± SEs ($n = 18$). $^{a–d}$ Different lowercase letters indicate statistically differences among treatments ($p < 0.05$).

4. Discussion

Under low irradiance conditions, plants extend stems and leaves to capture more light energy, and are prone to thin branches and leaves [34,37]. Increasing DLI along with low irradiance can effectively inhibit plants spindling growth (elongated hypocotyl, thin stem diameter) of cucumber seedling [17]. As the DLI increased, the hypocotyl length and leaf area decreased in this study, but the stem diameter remained at 3–3.3 cm.

With the increased DLI, cucumber seedling quality improved in some respects (Figure 3b). High-quality vegetable seedlings are usually compact and fully rooted transplants with a higher seedling index ratio and root-to-shoot ratio [15]. Hurt et al. [38] found that when DLI was increased to about 10 mol·m^{-2}·d^{-1}, the seedling quality index of five annual bedding plants was significantly improved. The root-to-shoot ratio of new guinea impatiens, geranium, and petunia cuttings were increased as DLI increased [11]. In this study, the root-to-shoot ratio and seedling index increased as DLI increasing from 5.4 to 8.5 mol·m^{-2}·d^{-1}, then, became stable due to the decrease of root dry mass with DLI continuing to increase. A lower leaf area

ratio and a higher shoot dry matter rate are also regarded as high quality, which represents a higher proportion of structural materials and carbohydrates per of unit fresh weight [34]. As the DLI increased, the leaf area ratio of eight kinds of bedding plants (i.e., ageratum, begonia, impatiens, marigold, petunia, salvia, vinca, and zinnia) decreased, while the shoot dry matter rate increased [34]. This phenomenon also occurred with the *Tecoma stans* [16], impatiens cuttings [37], *Heuchera americana* [39], lettuce [40], and *brassica* microgreens [41].

High-quality seedlings exhibit luxuriant growth both before and post-transplant growth, which is mainly due to a higher shoot fresh and dry mass. Generally, increasing DLI can promote the accumulation of shoot biomass [41,42]. However, there was a negative correlation between DLI and biomass in this study. It is possible that higher DLIs exceeded the amount required for cucumber seedlings. As in Ji's [20] experiment, when DLI exceeded 14.4 mol·m^{-2}·d^{-1}, the correlation between the fresh mass and dry mass of the shoot in three cucumber seedlings and DLI changed from positive to negative. The promotion of DLI to flower development is usually accompanied by an increased shoot biomass [23,28,34,43]. Leaf area reached 500 cm^2, and dry mass reached 3 g, which were prerequisite for the flowering of tomato seedlings, revealing that some level of photoassimilates is necessary for floral initiation [23]. In this study, the decreased shoot biomass and leaf area with a higher DLI might have slowed down the development of cucumber seedlings, which stunted flower development after transplant. Therefore, the optimal DLI for cucumber seedlings at the nursery stage was 6.35 mol·m^{-2}·d^{-1}, in which there is a higher shoot biomass and better floral initiation.

Under the optimal DLI (6.35 mol·m^{-2}·d^{-1}) screened by Exp. 1, a further exploration of appropriate lighting parameters combining different light intensities and photoperiods of cucumber seedlings was conducted. Under the same DLI, the variation of the light intensity and photoperiod mainly influences dry matter accumulation [44]. In this study, the shoot dry mass decreased with the increased light intensity and the reduction in the photoperiod, while there was no significant change in shoot fresh mass. Additionally, the combined treatment of a high light intensity and short photoperiod was not conducive to thicker leaves and stronger seedlings (Figure 6b).

In Exp. 2, the chlorophyll fluorescence parameters were consistent with the growth conditions, and also demonstrated that the combination of a low light intensity and long photoperiod was more favorable for the growth of cucumber seedlings. Under the same photoperiod, as PPFD increased, Φ_{PSII} decreased in three species (*Ipomea batatas*, *Lactuca sativa*, and *Epipremnum aureum*) [45]. This phenomenon was also found in lettuce and mizuna under the same DLI, which meant that most PSII reaction centers were closed at high PPFDs [31,46]. In this study, Φ_{PSII} decreased as PPFD increased, resulting in a decline in photosynthate. NPQ and Y(NPQ) increased first and then decreased, indicating that with the increase in light intensity and the shortening of the photoperiod, the photoprotection mechanism of cucumber seedlings was activated, but the excessive light intensity destroyed the PSII and reduced the photoprotection ability of cucumber seedlings [47]. Meanwhile, Y(NO) showed that the degree of light damage was severe in T4. Due to the low light intensity requirements, these combinations (low light intensities and long light durations) can also reduce capital expenses by reducing the cost of light fixtures [18,31].

With the increased DLI, the photosynthetic pigment showed a linear declining trend, which confirmed that leaves gained more light capture ability by increasing the chlorophyll content under lower DLIs [48,49]. The relative chlorophyll content of cucumber leaves of different ages decreased upon increasing the DLI, and the apparent quantum yield decreased according to the light response curve [50]. The chlorophyll content was positively correlated with shoot biomass in Exp. 1 and negatively correlated with shoot biomass in Exp. 2, which reveal that the chlorophyll content only represents the adaptability of plants to environmental changes and had no direct relationship with the amount of photosynthate produced by plants [49].

Plant leaves adapt to light conditions not only anatomically and morphologically, but also biochemically [48]. The increase of soluble sugar content increased the plant

resistance to some extent [51]. Previous research has shown that increasing DLI promotes the accumulation of soluble sugar in lettuce [40]. Higher DLIs and longer photoperiods may be more beneficial to improve the resistance of cucumber seedlings. These might be future research perspectives.

5. Conclusions

In conclusion, within the range of 5.41–11.26 mol·m^{-2}·d^{-1}, the increment in DLI was conducive to a compact morphology but inhibited the shoot biomass of cucumber plug seedlings. The optimal DLI in an artificial light condition was 6.35 mol·m^{-2}·d^{-1}, for which the leaf area and shoot biomass were relatively high, and floral initiation was accelerated in the subsequent stage. Under the condition of optimal DLI (6.35 mol·m^{-2}·d^{-1}), the combinations of low light intensities and long photoperiods are more conducive to the accumulation of root growth and whole plant dry matter, with a relatively high seedling index and thicker leaves. Therefore, the optimal light intensity was 110–125 μmol·m^{-2}·s^{-1}, and the optimal photoperiod was 14–16 h for cucumber plug seedlings.

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References

1. Faust, J.E.; Logan, J. Daily Light Integral: A research review and high-resolution maps of the United States. *HortScience* **2018**, *53*, 1250–1257. [CrossRef]
2. Christiaens, A.; Lootens, P.; Roldán-Ruiz, I.; Pauwels, E.; Gobin, B.; Van Labeke, M.C. Determining the minimum daily light integral for forcing of azalea (*Rhododendron simsii*). *Sci. Hortic.* **2014**, *177*, 1–9. [CrossRef]
3. Lee, J.H. *Vegetative Growth and Inflorescence Emergence of Phalaenopsis 'Mantefon' as Affected by Photoperiod, Light Intensity, and Daily Light Integral*; Seoul National University: Seoul, Korea, 2018.
4. Lee, H.B.; Lee, J.H.; An, S.K.; Park, J.H.; Kim, K.S. Growth characteristics and flowering initiation of *Phalaenopsis* Queen Beer 'Mantefon' as affected by the daily light integral. *Hortic. Environ. Biote.* **2019**, *60*, 637–645. [CrossRef]
5. Zhang, S.; Pan, X.; Ma, L.; Zhang, Y. Influence of light on germination and seedling status of *Centipeda herba*. *Seed* **2016**, *35*, 91–93.
6. Walters, K.J.; Curry, C.J. Effects of nutrient solution concentration and daily light integral on growth and nutrient concentration of several basil species in hydroponic production. *HortScience* **2018**, *53*, 1319–1325. [CrossRef]
7. Currey, C.J.; Hutchinson, V.A.; Lopez, R.G. Growth, morphology, and quality of rooted cuttings of several herbaceous annual bedding plants are influenced by photosynthetic daily light integral during root development. *HortScience* **2012**, *47*, 25–30. [CrossRef]
8. Warner, R.M.; Erwin, J.E. Effect of photoperiod and daily light integral on flowering of five *Hibiscus* sp. *Sci. Hortic.* **2003**, *97*, 341–351. [CrossRef]
9. Solis-Toapanta, E.; Gómez, C. Growth and photosynthetic capacity of basil grown for indoor gardening under constant or increasing daily light integrals. *HortTechnology* **2019**, *29*, 880–888. [CrossRef]
10. Baumbauer, D.A.; Schmidt, C.B.; Burgess, M.H. Leaf lettuce yield is more sensitive to low daily light integral than kale and spinach. *HortScience* **2019**, *54*, 2159–2162. [CrossRef]
11. Currey, C.J.; Lopez, R.G. Biomass Accumulation and allocation, photosynthesis, and carbohydrate status of new guinea impatiens, geranium, and petunia cuttings are affected by photosynthetic daily light integral during root development. *J. Amer. Soc. Hort. Sci.* **2015**, *140*, 542–549. [CrossRef]
12. Kelly, N.; Choe, D.; Meng, Q.; Runkle, E.S. Promotion of lettuce growth under an increasing daily light integral depends on the combination of the photosynthetic photon flux density and photoperiod. *Sci. Hortic.* **2020**, *272*, 1–8. [CrossRef]

13. Graver, J.K.; Boldt, J.K.; Lopez, R.G. Radiation intensity and quality from sole-source light-emitting diodes affect seedling quality and subsequent flowering of long-day bedding plant species. *HortScience* **2018**, *53*, 1407–1415.
14. Owen, W.G.; Meng, Q.W.; Lopez, R.G. Promotion of flowering from far red radiation depends on the photosynthetic daily light integral. *HortScience* **2018**, *53*, 1–7. [CrossRef]
15. Randall, W.C.; Lopez, R.G. Comparison of supplemental lighting from high-pressure sodiumlamps and light-emitting diodes during bedding plant seedling production. *HortScience* **2014**, *49*, 589–595. [CrossRef]
16. Torres, A.P.; Lopez, R.G. Photosynthetic daily light integral during propagation of *Tecoma stans* influences seedling rooting and growth. *HortScience* **2011**, *46*, 282–286. [CrossRef]
17. Zhang, Y.; Dong, H.; Song, S.; Su, W.; Liu, H. Morphological and physiological responses of cucumber seedlings to supplemental led light under extremely low irradiance. *Agronomy* **2020**, *10*, 1698. [CrossRef]
18. Elkins, C.; van Iersel, M.W. Longer photoperiods with the same daily light integral improve growth of rudbeckia seedlings in a greenhouse. *HortScience* **2020**, *55*, 1676–1682. [CrossRef]
19. Hernández, R.; Kubota, C. Growth and morphological response of cucumber seedlings to supplemental red and blue photon flux ratios under varied solar daily light integrals. *Sci. Hortic.* **2014**, *173*, 92–99. [CrossRef]
20. Ji, F.; Wei, S.; Liu, N.; Xu, L.; Yang, P. Growth of cucumber seedlings in different varieties as affected by light environment. *Int. J. Agric. Biol. Eng.* **2020**, *13*, 73–78. [CrossRef]
21. Oh, W.; Runkle, E.S.; Warner, R.M. Timing and duration of supplemental lighting during the seedling stage influence quality and flowering in petunia and pansy. *HortScience* **2010**, *45*, 1332–1337. [CrossRef]
22. Pramuk, L.A.; Runkle, E.S. Photosynthetic daily light integral during the seedling stage influences subsequent growth and flowering of *Celosia*, *Impatiens*, *Salvia*, *Tagetes*, and *Viola*. *HortScience* **2005**, *40*, 1336–1339. [CrossRef]
23. Wang, R.; Gui, Y.; Zhao, T.; Ishii, M.; Eguchi, M.; Xu, H.; Li, T.; Iwasaki, Y. Determining the relationship between floral initiation and source–sink dynamics of tomato seedlings affected by changes in shading and nutrients. *HortScience* **2020**, *55*, 457–464. [CrossRef]
24. Velez-Ramirez, A.I.; Dünner-Planella, G.; Vreugdenhil, D.; Millenaar, F.F.; van Ieperen, W. On the induction of injury in tomato under continuous light: Circadian asynchrony as the main triggering factor. *Funct. Plant Biol.* **2017**, *44*, 597–611. [CrossRef]
25. Fan, X.; Xu, Z.; Liu, X.; Tang, C.; Wang, L.; Han, X. Effects of light intensity on the growth and leaf development of young tomato plants grown under a combination of red and blue light. *Sci. Hortic.* **2013**, *153*, 50–55. [CrossRef]
26. Fu, W.; Li, P.; Wu, Y. Effects of different light intensities on chlorophyll fluorescence characteristics and yield in lettuce. *Sci. Hortic.* **2012**, *135*, 45–51. [CrossRef]
27. Gao, W.; He, D.; Ji, F.; Zhang, S.; Zheng, J. Effects of daily light integral and LED spectrum on growth and nutritional quality of hydroponic spinach. *Agronomy* **2020**, *10*, 1082. [CrossRef]
28. Lopez, R.G.; Runkle, E.S. Photosynthetic daily light integral during propagation influences rooting and growth of cuttings and subsequent development of new guinea impatiens and petunia. *HortScience* **2008**, *43*, 2052–2059. [CrossRef]
29. Blanchard M, G. *Manipulating Light and Temperature for Energy-Efficient Greenhouse Production of Ornamental Crops*; Michigan State University: East Lansing, MI, USA, 2009.
30. Hutchinson, V.A.; Currey, C.J.; Lopez, R.G. Photosynthetic daily light integral during root development influences subsequent growth and development of several herbaceous annual bedding plants. *HortScience* **2012**, *47*, 856–860. [CrossRef]
31. Palmer, S.; van Iersel, M.W. Increasing growth of lettuce and mizuna under sole-source LED lighting using longer photoperiods with the same daily light integral. *Agronomy* **2020**, *10*, 1659. [CrossRef]
32. Mao, H.; Hang, T.; Zhang, X.; Lu, N. Both multi-segment light intensity and extended photoperiod lighting strategies, with the same daily light integral, promoted *Lactuca sativa* L. growth and photosynthesis. *Agronomy* **2019**, *9*, 857. [CrossRef]
33. Bai, Y.; Shi, W.; Xing, X.; Wang, Y.; Jin, Y.; Zhang, L.; Song, Y.; Dong, L.; Liu, H. Study on tobacco vigorous seedling indexes model. *Sci. Agri. Sin.* **2014**, *47*, 1086–1098.
34. Faust, J.E.; Holcombe, V.; Rajapakse, N.C.; Layne, D.R. The effect of daily light integral on bedding plant growth and flowering. *HortScience* **2005**, *40*, 645–649. [CrossRef]
35. Li, H.S. *Principles and Techniques of Plant Physiological and Biochemical Experiments*; Higher Education Press: Beijing, China, 2000.
36. Hao, J.J.; Kang, Z.L.; Yu, Y. *Experimental Techniques for Plant Physiology*; Chemical Industrial Press: Beijing, China, 2007.
37. Currey, C.J.; Lopez, R.G. Biomass accumulation, allocation and leaf morphology of *impatiens hawker* 'Magnum Salmon' cuttings is affected by photosynthetic daily light integral in propagation. *Acta Hortic.* **2012**, *956*, 349–356. [CrossRef]
38. Hurt, A.; Lopez, R.G.; Craver, J.K. Supplemental but not photoperiodic lighting increased seedling quality and reduced production time of annual bedding Plants. *HortScience* **2019**, *54*, 289–296. [CrossRef]
39. Garland, K.F.; Burnett, S.E.; Day, M.E.; van Iersel, M.W. Influence of substrate water content and daily light integral on photosynthesis, water use efficiency, and morphology of *Heuchera americana*. *J. Amer. Soc. Hort. Sci.* **2012**, *137*, 57–67. [CrossRef]
40. Gent, M.P.N. Effect of daily light integral on composition of hydroponic lettuce. *HortScience* **2014**, *49*, 173–179. [CrossRef]
41. Gerovac, J.R.; Craver, J.K.; Boldt, J.K.; Lopez, R.G. Light intensity and quality from sole-source light-emitting diodes impact growth, morphology, and nutrient content of *Brassica* microgreens. *HortScience* **2016**, *51*, 497–503. [CrossRef]
42. Kjaer, K.H.; Ottosen, C.; Jørgensen, B.N. Timing growth and development of *Campanula* by daily light integral and supplemental light level in a cost-efficient light control system. *Sci. Hortic.* **2012**, *143*, 189–196. [CrossRef]
43. Hutchinson, V.A. *Photosynthetic Daily Light Integral During Vegetative Propagation and Finish Stages Influence Growth and Development of Annual Bedding Plant Species*; Purdue University: West Lafayette, IN, USA, 2012.

44. Vaid, T.M. *Improving the Scheduling and Profitability of Annual Bedding Plant Production by Manipulating Temperature, Daily Light Integral, Photoperiod, and Transplant Size*; Michigan State University: East Lansing, MI, USA, 2012.
45. Zhen, S.; van Iersel, M.W. Photochemical acclimation of three contrasting species to different light levels: Implications for optimizing supplemental lighting. *J. Amer. Soc. Hort. Sci.* **2017**, *142*, 346–354. [CrossRef]
46. Elkins, C.; Van Iersel, M.W. Longer photoperiods with the same daily light integral increase daily electron transport through photosystem II in lettuce. *Plants* **2020**, *9*, 1172. [CrossRef]
47. Murchie, E.H.; Lawson, T. Chlorophyll fluorescence analysis: A guide to good practice and understanding some new applications. *J. Exp. Bot.* **2013**, *64*, 3983–3998. [CrossRef]
48. Dou, H.; Niu, G.; Gu, M.; Masabni, J.G. Responses of sweet basil to different daily light integrals in photosynthesis, morphology, yield, and nutritional quality. *HortScience* **2018**, *53*, 496–503. [CrossRef]
49. Dai, Y.; Shen, Z.; Liu, Y.; Wang, L.; Hannaway, D.; Lu, H. Effects of shade treatments on the photosynthetic capacity, chlorophyll fluorescence, and chlorophyll content of *Tetrastigma hemsleyanum* Diels et Gilg. *Enviro. Exp. Bot.* **2009**, *65*, 177–182. [CrossRef]
50. Pettersen, R.I.; Torreand, S.; Gislerød, H.R. Effects of leaf aging and light duration on photosynthetic characteristics in a cucumber canopy. *Sci. Hortic.* **2010**, *125*, 82–87. [CrossRef]
51. Du, X.; Huang, P.; Yang, M. Phosphorus fertilizers on the growth and resistance physiology of Eucalyptus *urophylla*×*Eucalyptus* grandis DH3229 seedlings. *J. For. Environ.* **2020**, *40*, 526–533.