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Article

Evaluation of Air Temperature, Photoperiod and Light Intensity Conditions to Produce Cucumber Scions and Rootstocks in a Plant Factory with Artificial Lighting

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Abstract: Air temperature and light conditions are important factors not only to produce high-quality seedlings but also to promote energy efficiency in a plant factory with artificial lighting. In this study, we conducted two experiments in order to investigate the favorable conditions of air temperature, light intensity and photoperiod for the production of cucumber scions and rootstocks in a plant factory with artificial lighting. Cucumber scions and rootstocks were cultivated in two combined treatments: the combination of three different levels of difference between the day and night temperature (DIF), 25/20, 26/18 and 27/16 °C and five different light intensity conditions of photosynthetic photon flux, 50, 100, 150, 200 and 250 μmol·m^{-2}·s^{-1} was set for the first experiment, and the combination of three different photoperiod conditions, 12, 16 and 20 h·d^{-1} and five different light intensity conditions, 50, 100, 150, 200 and 250 μmol·m^{-2}·s^{-1} was set for the second experiment. In the air temperature and light intensity treatments, the hypocotyl elongation of cucumber scions and rootstocks was affected more largely by light intensity than DIF. The highest DIF treatment (27/16 °C) affected negatively on the accumulation of dry mass. On the contrary, the smallest DIF treatment (25/20 °C) was favorable for seedling growth due to lesser stress by rapid change of air temperature between photo- and dark-period. In the photoperiod and light intensity treatments, an increased DLI (daily light integral) promoted the growth of scions and rootstocks. Under the same DLI condition, the growth of scions and rootstocks increased with increasing photoperiod and decreasing light intensity. In both of experiments, while the dry weight increased with increasing the light intensity, the light use efficiencies were reduced by increasing the light intensity. Considering the growth and quality of seedlings and energy efficiency, the optimal environment conditions were represented by 25/20 °C of air temperature, 150 μmol·m^{-2}·s^{-1} of light intensity and 16 h·d^{-1} of photoperiod.

Keywords: DIF; DLI; grafting; PPF; seedling

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1. Introduction

Even though vegetable grafted seedlings have been widely applied across the world to improve soil-borne disease resistance, adverse environment tolerance, fruit quality and yield [1–3], commercial grafted seedling growers have been confronting difficulties to produce high quality of grated seedlings due to the climate change. Production of grafted seedlings generally requires higher consideration and complexity than non-grafted seedlings production [4]. Especially, proper size, uniformity and quality of scions and rootstocks are essential to enhance grafting work efficiency and success rate. Additionally, in the aspect of grafting work management, scions and rootstocks are necessary to be produced regularly within a certain production period all year round. However, the production of scions and rootstocks in the context of climate change has been challenging to follow a right schedule of grafted seedling production and shipment process with high quality of seedlings, as the climate change has affected horticultural crop production [5].

A plant factory with artificial lighting (PFAL) has been positively considered as an alternative to produce horticultural crops against the climate change era [6]. PFAL can control environment conditions of light, temperature, humidity, carbon dioxide and water artificially without outside weather consideration. Therefore, various plants have been studied from seedlings, leafy vegetables, herbs, medicinal plants and pot flowers and several commercial companies have been actively running PFALs in the world [7].

In order to maximize plant productivity in a PFAL, it is critical to determine optimal ranges of each environment conditions related to plant growth and development by considering resource use efficiency. Plant growth and development are generally affected by environment factors including temperature, light quality and intensity, photoperiod, relative humidity and CO_2 concentration [8]. In addition, those environment factors are affected inter-relatedly each other [9]. Furthermore, a PFAL utilizes external resources, especially electricity, to control environment conditions [10]. Therefore, the optimal environment conditions in a PFAL should be considered with not only for one or two single factors but also for integrated several factors with resource use efficiency.

The research on the utilization of PFAL for seedling production has been conducted since the early 1990s and focused on the investigation of proper environment conditions for the seedling production in a PFAL. Recently, many studies on the utilization of LED (light emitting diode) in a PFAL were conducted. Control of seedling growth in a PFAL in terms of hypocotyl length, stem diameter, dry matter and compactness is important to improve grafting success rate by manipulating environment conditions [11]. Hence, identification of optimal environment conditions for plant seedling production is essential. In addition, understanding combination of environment factors each other is crucial to obtain maximum productivity in a PFAL. However, most of researchers investigated the plant response under the environment conditions with control of only single environment factor in a PFAL, and these results is difficult to apply the commercial seedling production in a PFAL.

In general, air temperature, photoperiod and light intensity have been known as principal actuators among the various environment factors for plant growth and development, especially biomass production [12,13], and also those environment factors can be easily controlled in a PFAL. Temperature and light conditions affect interactively on plant growth, therefore, an appropriate environment condition for seedling production in a PFAL should be manipulated considering the interaction of multiple environment factors.

Therefore, this study aimed to evaluate the effects of air temperature, photoperiod and light intensity on growth of cucumber scions and rootstocks cultivated in a PFAL. Growth characteristics and seedling quality with light use efficiency analysis were compared to each treatment. 30 different combinations between air temperature, photoperiod and light intensity treatments were investigated to determine optimal conditions of air temperature, photoperiod and light intensity for the production of cucumber scions and rootstocks in a PFAL.

2. Materials and Methods

2.1. Plant Materials and Growth Conditions

Cucumber scions, 'Joeunbaegdadagi' (*Cucumis sativus* L.; Farm Hannong Co. Ltd., Seoul, Korea) and figleaf gourd rootstocks, 'Heukjong' (*Cucurbita ficifolia* Bouché; Sakata Korea Co. Ltd., Seoul, Korea), were sown in 162–cell plug tray (W 280 × L 540 × H 48 mm) filled with the commercial growing media (Hungnong Bio Co. Ltd., Farm Hannong, Seoul, Korea). The cucumber scions and rootstocks were irrigated and germinated in a dark condition with continuous air temperature (28 °C) and relative humidity (100%). The periods of germination of cucumber scions and rootstocks were 36 and 60 h, respectively. After germination, the cucumber scions and rootstocks were cultivated for 6 days in a PFAL (Figure 1). All the treatments were maintained at CO_2 concentration 400 μmol·mol^{-1} and relative humidity 70/85% (day/night) with white LED lamps (Future Green Co., Ltd., Hwaseong, Korea) and sub-irrigated using the nutrition solution with pH 5.5 and EC (electrical conductivity) 1.4 dS·m^{-1}. The composition of nutrient solution was: 12 meq L^{-1} NO_3-N, 0.7 meq L^{-1} NH_4-N, 2 meq L^{-1} P, 7 meq L^{-1} K, 5 meq L^{-1} Ca, 2 meq L^{-1} Mg, 2 meq L^{-1} SO_4-S, 3.0 mg L^{-1} Fe, 0.5 mg L^{-1} Mn, 0.05 mg L^{-1} Zn, 0.5 mg L^{-1} B, 0.02 mg L^{-1} Cu and 0.01 mg L^{-1} Mo.

Figure 1. Cucumber scions (**a**) and rootstocks (**b**) cultivated in a PFAL.

2.2. Temperature and Light Treatments

2.2.1. Air Temperature and Light Intensity Treatments (Exp. 1)

To determine optimal conditions of air temperature and light intensity, the cucumber scions and rootstocks were cultivated in a PFAL under 15 different treatments consisting of three air temperature levels of 25/20, 26/18 and 27/16 °C and five light intensities of photosynthetic photon flux (PPF) 50, 100, 150, 200 and 250 μmol·m^{-2}·s^{-1} with 16 h photoperiod. Three PFALs with multi-layer (5 shelves) cultivation system were used for this experiment. Three air temperature treatments were applied in each PFAL, and 5 light intensity treatments were applied in each shelve of multi-layer cultivation system. All the air temperature conditions were maintained average temperature as 23.3 °C with 25.3 ± 0.5/20.1 ± 0.7, 25.8 ± 0.8/18.4 ± 1.3 and 26.9 ± 1.3/16.5 ± 1.9 °C, respectively (Figure 2). Light intensities for 50, 100, 150, 200 and 250 μmol·m^{-2}·s^{-1} treatments were maintained as 47.0 ± 2.5, 95.9 ± 2.7, 148.0 ± 4.9, 195.5 ± 6.9 and 250.3 ± 8.7 μmol·m^{-2}·s^{-1}, respectively (Figure 3).

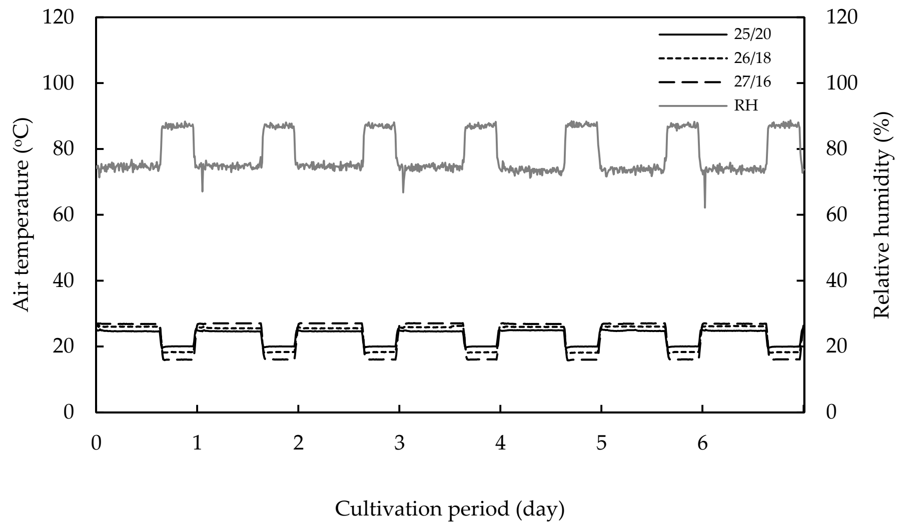

Figure 2. Changes of air temperature and relative humidity conditions applied in a PFAL.

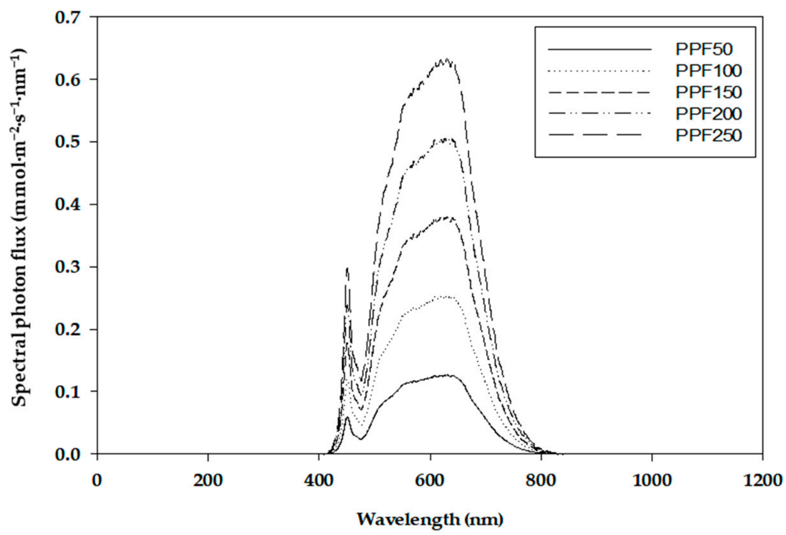

Figure 3. Spectral distribution properties of light intensity conditions applied in a PFAL.

2.2.2. Photoperiod and Light Intensity Treatments (Exp. 2)

To determine optimal conditions of photoperiod and light intensity, the cucumber scions and rootstocks were cultivated in a PFAL under 15 different treatments combined with three photoperiods of 12, 16 and 20 h and five PPF light intensities of 50 (47.4 ± 3.6), 100 (98.2 ± 5.4), 150 (150.6 ± 4.0), 200 (198.0 ± 8.0) and 250 (251.2 ± 10.8) µmol·m^{-2}·s^{-1}. Air temperature was maintained at 25.2 ± 0.7/20.2 ± 0.9 °C (photo/dark period). This experiment was conducted in three PFALs with multi-layer (5 shelves) cultivation system. Three photoperiod treatments were applied in each PFAL, and 5 light intensity treatments were applied in each shelve of multi-layer cultivation system.

2.3. Growth of Cucumber Scions and Rootstocks

Growth characteristics, such as hypocotyl length, stem diameter, leaf area, shoot fresh weight and dry weight, of the cucumber scions and rootstocks were investigated after 6 days of cultivation in a PFAL. In Korea, cucumber seedlings are grafted by single cotyledon splice grafting method and rootstocks are used after cutting root. Therefore, we investigated the growth of only shoot parts in cucumber scions and rootstocks in this study. To compare seedling quality and dry matter productivity by the temperature, photoperiod and light intensity treatments, compactness, leaf area index (LAI), leaf area ratio (LAR) and light use efficiency (LUE) were calculated using the following formulae, respectively:

$$\text{Compactness} = \frac{shoot\ dry\ weight\ (\text{mg})}{hypocotyl\ length\ (\text{cm})}$$

$$\text{LAI} = \frac{leaf\ area\ (\text{cm}^2)}{plug\ tray\ area\ (\text{cm}^2)}$$

$$\text{LAR} = \frac{leaf\ area\ (\text{cm}^2)}{shoot\ dry\ weight\ (\text{g})}$$

$$\text{LUE} = \frac{shoot\ dry\ weight\ (\text{g})}{light\ integral\ (\text{mol}\cdot\text{m}^{-2})}$$

2.4. Statistical Analysis

A randomized block design with 7 samples and 3 replications was applied in this study. All experimental data for each treatment were analyzed by two-way ANOVA with the general linear model (GLM) via SAS (Enterprise Guide 7.1, SAS Institute Inc., Cary, NC, USA) and represented significance differences at $p < 0.05$, 0.01 and 0.001. In addition, Tukey's honestly significant difference (HSD) tests ($p < 0.05$) were conducted to compare any significant difference among various treatments.

3. Results

3.1. The Effect of Air Temperature and Light Intensity Conditions on the Growth of Cucumber Scions and Rootstocks in a PFAL (Exp. 1)

Morphological characteristics of cucumber scions and rootstocks cultivated in a PFAL were highly affected by the air temperature and light intensity treatments (Figure 4). The hypocotyl length of cucumber scions and rootstocks was affected mainly by light intensity, and increasing the light intensity decreased the hypocotyl length of cucumber scions and rootstocks (Tables 1 and 2). The leaf area of cucumber scions and rootstocks increased by increasing the light intensity in the range of 50–150 μmol·m^{-2}·s^{-1}, however, the leaf area did not increase in the light intensity of 200 and 250 μmol·m^{-2}·s^{-1}. Increasing the DIF could not promote the hypocotyl elongation of cucumber scions and rootstocks.

Table 1. Growth of cucumber scions as affected by the different air temperature and light intensity at 6 days after cultivation in a PFAL.

Air Temperature (°C)	PPF (μmol·m^{-2}·s^{-1})	Hypocotyl Length (cm)		Stem Diameter (mm)		Leaf Area (cm^2)		Shoot Fresh Weight (g)		Shoot Dry Weight (g)	
25/20	50	7.8	bc [z]	1.5	d	13.7	de	0.60	de	0.027	gh
	100	8.2	b	1.7	ab	19.0	a	0.88	a	0.044	ef
	150	7.0	d	1.8	a	19.6	a	0.85	a	0.052	cd
	200	5.2	fg	1.7	ab	18.0	ab	0.74	b	0.053	cd
	250	3.9	ij	1.6	b–d	16.1	bc	0.68	b–d	0.061	ab
26/18	50	9.2	a	1.5	cd	13.0	e	0.67	b–d	0.027	gh
	100	6.8	de	1.6	a–d	15.8	c	0.67	b–d	0.037	f
	150	6.3	e	1.7	ab	16.2	bc	0.71	bc	0.044	e
	200	4.7	gh	1.7	ab	16.0	bc	0.65	cd	0.055	b–d
	250	4.8	gh	1.7	ab	16.5	bc	0.71	bc	0.064	a
27/16	50	7.1	cd	1.4	e	8.6	f	0.42	g	0.022	h
	100	5.5	f	1.5	cd	11.7	e	0.49	fg	0.029	g
	150	5.6	f	1.7	a–c	16.4	bc	0.70	bc	0.057	bc
	200	4.4	hi	1.6	b–d	15.6	cd	0.64	cd	0.054	b–d
	250	3.7	j	1.5	cd	13.6	de	0.55	ef	0.049	de
Significance											
Air temperature (A)		***		***		***		***		***	
Light intensity (B)		***		***		***		***		***	
Interaction (A × B)		***		***		***		***		***	

[z] Means for 3 replicates with 7 samples within each column followed by the same letters are not significantly different according to Tukey's HSD test at $p < 0.05$. *** = significant at $p < 0.001$.

Table 2. Growth of cucumber rootstocks as affected by the different air temperature and light intensity at 6 days after cultivation in a PFAL.

Air Temperature (°C)	PPF ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	Hypocotyl Length (cm)		Stem Diameter (mm)		Leaf Area (cm^2)		Shoot Fresh Weight (g)		Shoot Dry Weight (g)	
25/20	50	8.1	bc [z]	2.5	a–d	39.3	cd	2.80	b–d	0.155	de
	100	5.8	e	2.3	d–f	37.8	cd	2.36	ef	0.152	d–f
	150	8.0	bc	2.6	ab	49.9	a	3.26	a	0.190	a–c
	200	6.3	e	2.5	a–c	47.4	a	2.90	a–c	0.174	a–d
	250	6.4	e	2.6	a	50.0	a	3.16	ab	0.194	ab
26/18	50	9.4	a	2.4	c–e	30.1	e	2.45	d–f	0.139	ef
	100	7.4	cd	2.3	ef	33.6	de	2.34	ef	0.141	ef
	150	8.0	bc	2.5	a–c	45.2	ab	3.03	a–c	0.170	cd
	200	7.3	d	2.5	b–d	46.8	a	3.15	ab	0.184	a–c
	250	6.2	e	2.6	a–c	47.7	a	3.01	a–c	0.198	a
27/16	50	8.3	b	2.3	d–f	23.3	f	2.11	fg	0.138	ef
	100	6.2	e	2.2	f	21.9	f	1.76	g	0.131	f
	150	7.7	b–d	2.5	a–c	46.0	ab	3.04	ab	0.171	b–d
	200	6.3	e	2.6	ab	38.8	cd	2.50	de	0.168	cd
	250	5.9	e	2.5	a–c	40.7	bc	2.66	c–e	0.185	a–c
Significance											
Air temperature (A)		***		***		***		***		***	
Light intensity (B)		***		***		***		***		***	
Interaction (A × B)		***		NS		***		***		NS	

[z] Means for 3 replicates with 7 samples within each column followed by the same letters are not significantly different according to Tukey's HSD test at $p < 0.05$. NS: non-significant, *** = significant at $p < 0.001$.

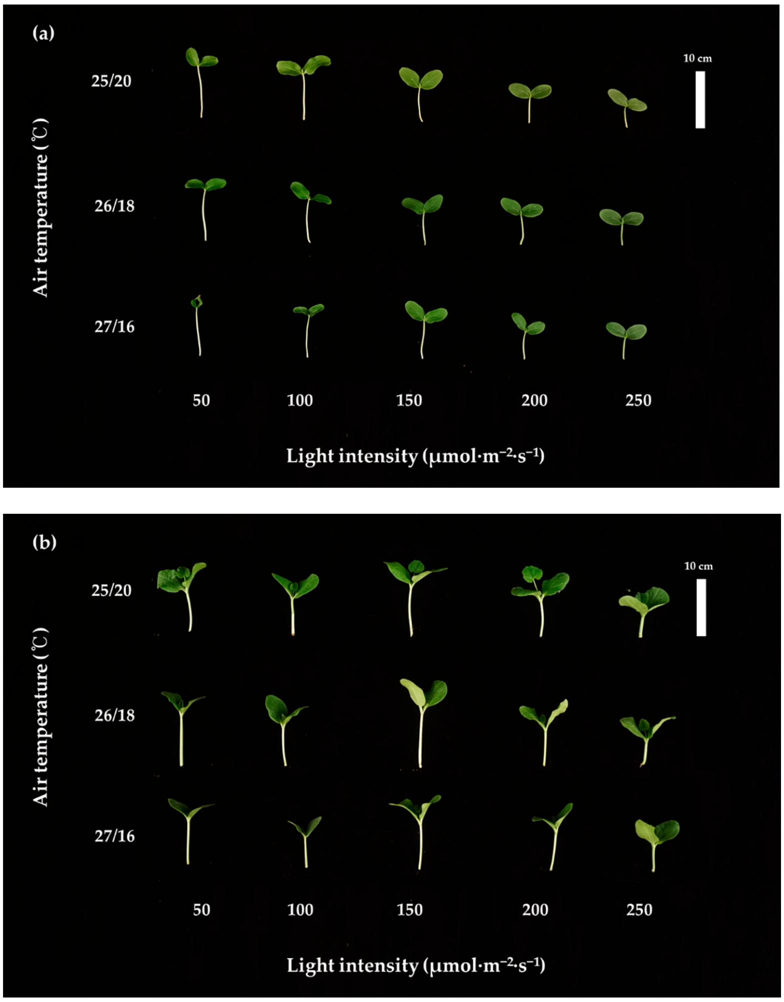

Figure 4. Cucumber scions (**a**) and rootstocks (**b**) cultivated under different air temperature and light intensity conditions in a PFAL.

In the air temperature and light intensity treatments, the dry weight of cucumber scions showed distinct logarithmic growth models as the light intensity increased from 50 to 250 μmol·m^{-2}·s^{-1}, and the dry weight of rootstocks were linearly increased (Figure 5). The compactness of cucumber scions and rootstocks showed the positive linear correlation with the light intensity. As PPF increased, the effects of PPF on dry weights and compactness of cucumber scions and rootstocks were diminished between the air temperature treatments, except the dry weight of rootstocks at 27/16 °C. The dry weight of cucumber scions and rootstocks at 27/16 °C were relatively lagged behind compared to 25/20 °C and 26/18 °C.

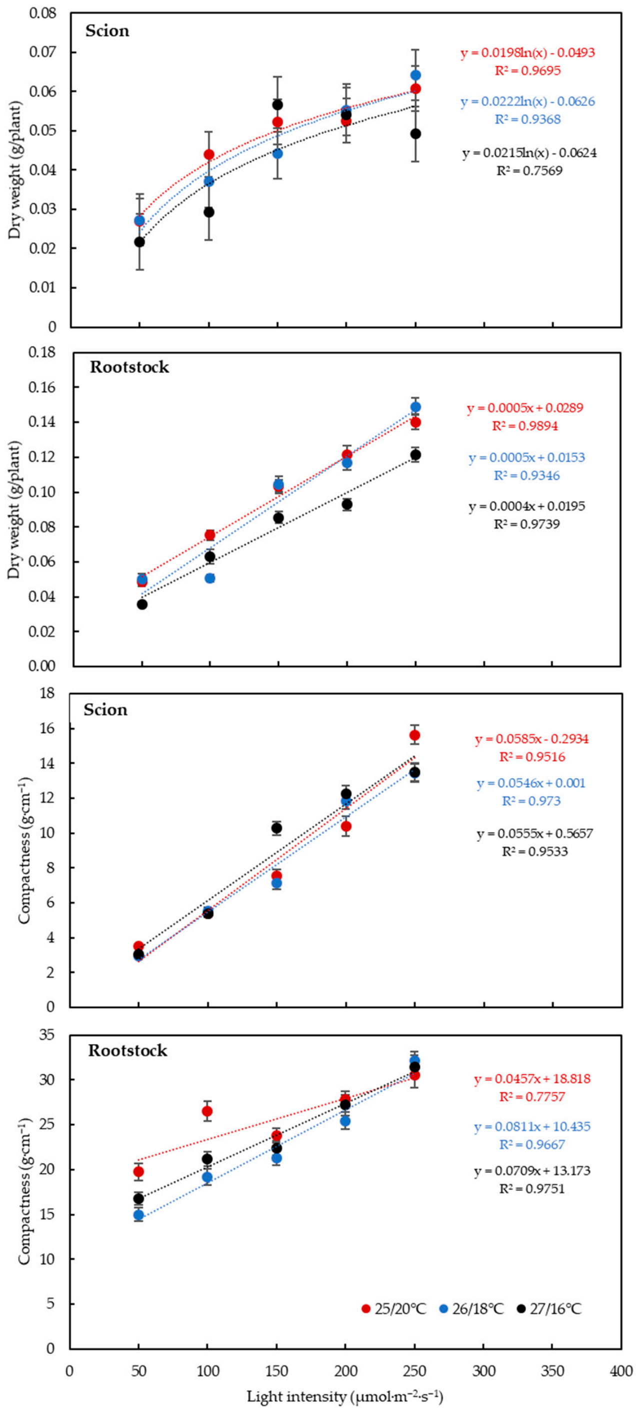

Figure 5. Regression analyses of the dry weight and compactness of cucumber scions and rootstocks as affected by the different air temperature and light intensity treatments in a PFAL. The values of each point represent means for 3 replicates with 7 samples and standard errors.

Most of LARs and LAIs at each light intensity treatments, except the LARs of cucumber scions at 250 μmol·m^{-2}·s^{-1} and rootstocks at 150 μmol·m^{-2}·s^{-1}, were decreased as the DIF increased (Figure 6). Even though the LARs of cucumber scions showed a clear downward trend as the light intensity increased, those of rootstocks did not show clear difference between the light intensity treatments. The LAIs of cucumber rootstocks tend to increase by increasing the light intensity and increasing the DIF affected negatively on the LAIs of cucumber scions and rootstocks.

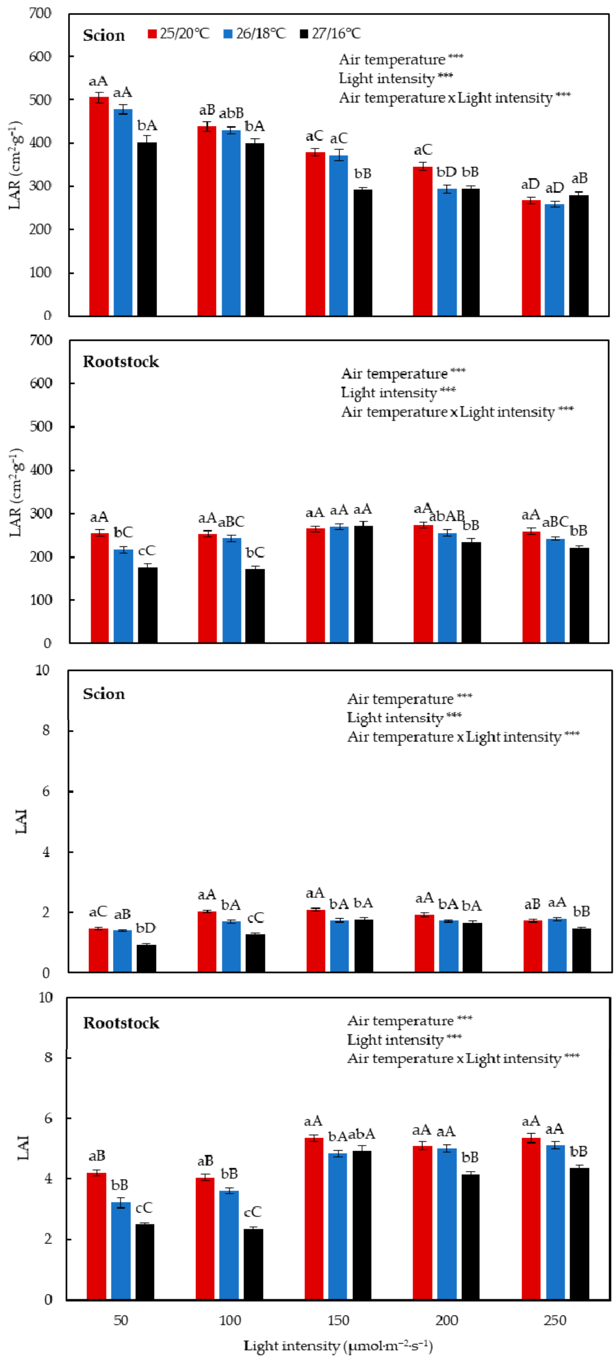

Figure 6. Leaf area ratio (LAR) and leaf area index (LAI) of cucumber scions and rootstocks as affected by the different air temperature and light intensity treatments in a PFAL. The error bar indicates the standard error of the mean for 3 replicates with 7 samples. *** indicates significant differences at $p < 0.001$. Values with different letters differ significantly at the 95% level according to Tukey's HSD test. Lowercase letters compares air temperature treatments for each light intensity treatment. Uppercase letters compare light intensity treatments for each air temperature treatment.

The LUEs were decreased as the light intensity increased except the LUE of cucumber scions at the 150 μmol·m^{-2}·s^{-1} and 27/16 °C treatment (Figure 7). The LUEs of rootstocks showed sharp reductions from 50 to 100 μmol·m^{-2}·s^{-1}, and the LUEs of cucumber scions and rootstocks decreased by increasing the DIF in the low intensity treatments (50 and 100 μmol·m^{-2}·s^{-1}).

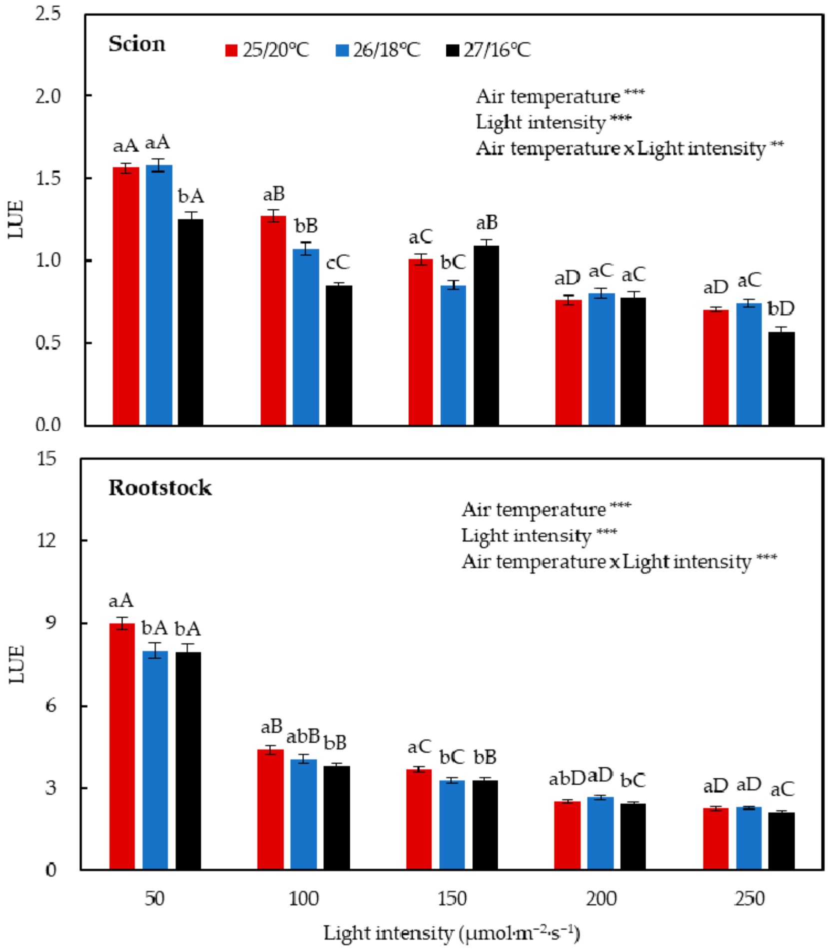

Figure 7. Light use efficiency (LUE) of cucumber scions and rootstocks as affected by the different air temperature and light intensity treatments in a PFAL. The error bar indicates the standard error of the mean for 3 replicates with 7 samples. ** and *** indicate significant differences at $p < 0.01$ and 0.001, respectively. Values with different letters differ significantly at the 95% level according to Tukey's HSD test. Lowercase letters compares air temperature treatments for each light intensity treatment. Uppercase letters compare light intensity treatments for each air temperature treatment.

3.2. The Effect of Photoperiod and Light Intensity Conditions on the Growth of Cucumber Scions and Rootstocks in a PFAL (Exp. 2)

The different photoperiod and light intensity conditions in a PFAL affected significantly on the morphological characteristics of cucumber scions and rootstocks (Figure 8). The hypocotyl length of cucumber scions and rootstocks decreased by increasing the photoperiod and light intensity (Tables 3 and 4), therefore, increasing the DLI reduced the hypocotyl elongation of cucumber scions and rootstocks. The stem diameter, leaf area, shoot fresh and dry weight tend to increase by increasing the DLI, and the leaf area of cucumber scions and rootstocks increased by increasing the photoperiod. Under the same DLI conditions, the shoot dry weight of cucumber scions and rootstocks was higher in the longer photoperiod and lower light intensity treatment.

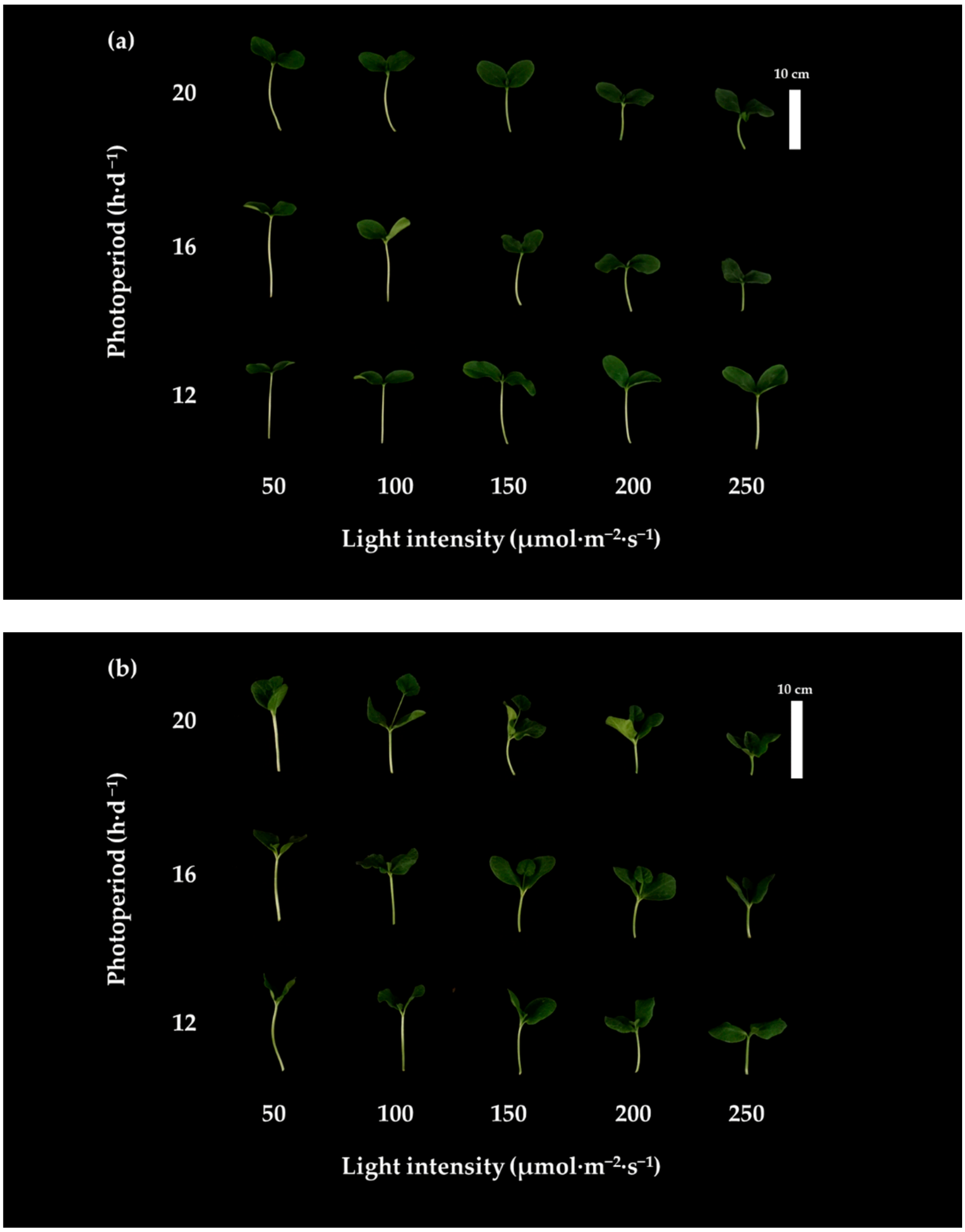

Figure 8. Cucumber scions (**a**) and rootstocks (**b**) cultivated under different photoperiod and light intensity conditions in a PFAL.

In the photoperiod and light intensity treatments, there is a logarithmic relationship between the dry weight of cucumber scions and the light intensity, and the dry weight of rootstocks and the compactness of cucumber scions and rootstocks were linearly increased as the light intensity increased (Figure 9). The dry weight and compactness of cucumber scions and rootstocks at each light intensity significantly increased as the photoperiod increased from 12 to 20 h·d^{-1}. In addition, the differences of dry weights and compactness of cucumber scions and rootstocks between the photoperiod treatments were gradually increased as the light intensity increased. All coefficients of dry weights and compactness were the highest at 20 h·d^{-1}.

Table 3. Growth of cucumber scions as affected by the different photoperiod and light intensity at 6 days after cultivation in a PFAL.

Photoperiod ($h \cdot d^{-1}$)	PPF ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	Hypocotyl Length (cm)		Stem Diameter (mm)		Leaf Area (cm^2)		Shoot Fresh Weight (g)		Shoot Dry Weight (g)	
12	50	2.2	8.3	b [z]	1.3	e	7.7	h	0.47	i	0.023	j
	100	4.3	6.3	e–g	1.3	de	10.0	h	0.47	i	0.027	j
	150	6.5	9.2	a	1.6	bc	16.3	e–f	0.84	d–g	0.045	fg
	200	8.6	7.5	bc	1.7	bc	17.0	e–f	0.85	c–f	0.051	ef
	250	10.8	5.7	f–h	1.7	bc	16.1	e–f	0.76	f–h	0.048	ef
16	50	2.9	9.3	a	1.3	e	14.6	g	0.74	gh	0.030	ij
	100	5.8	7.0	c–e	1.5	cd	18.8	b–d	0.82	e–g	0.039	gh
	150	8.6	7.1	cd	1.7	bc	21.3	a	1.00	b	0.055	de
	200	11.5	5.8	f-h	1.6	bc	14.4	g	0.68	h	0.054	de
	250	14.4	5.3	h	1.7	bc	15.2	gf	0.71	h	0.064	bc
20	50	3.6	8.3	b	1.6	bc	18.0	c–e	0.87	c–e	0.037	hi
	100	7.2	7.6	bc	1.7	b	19.9	a–c	0.93	b–d	0.051	ef
	150	10.8	6.5	d–f	1.6	bc	19.9	a–c	0.86	c–f	0.060	cd
	200	14.4	5.9	f–h	1.7	b	20.4	ab	0.94	bc	0.070	b
	250	18.0	5.6	gh	1.9	a	21.8	a	1.15	a	0.078	a
			Significance									
	Photoperiod (A)		***		***		***		***		***	
	Light intensity (B)		***		***		***		***		***	
	Interaction (A × B)		***		***		***		***		***	

[z] Means for 3 replicates with 7 samples within each column followed by the same letters are not significantly different according to Tukey's HSD test at $p < 0.05$. *** = significant at $p < 0.001$.

Table 4. Growth of cucumber rootstocks as affected by the different photoperiod and light intensity at 6 days after cultivation in a PFAL.

Photoperiod ($h \cdot d^{-1}$)	PPF ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	Hypocotyl Length (cm)		Stem Diameter (mm)		Leaf Area (cm^2)		Shoot Fresh Weight (g)		Shoot Dry Weight (g)	
12	50	2.2	10.9	a [z]	2.4	d	36.8	f	2.82	e–g	0.147	i
	100	4.3	9.6	b	2.5	cd	43.9	e	3.01	d–f	0.156	f–i
	150	6.5	8.9	bc	2.6	a–c	46.9	de	3.34	a–d	0.172	e–i
	200	8.6	8.8	bc	2.7	ab	51.2	a–d	3.54	ab	0.184	c–e
	250	10.8	8.4	cd	2.6	a–d	50.8	a–d	3.30	b–d	0.170	e–i
16	50	2.9	9.5	b	2.5	b–d	35.6	f	2.66	fg	0.150	hi
	100	5.8	7.8	de	2.6	a–d	35.1	f	2.53	g	0.154	g–i
	150	8.6	8.9	bc	2.6	a–d	48.8	b–e	3.29	b–d	0.184	c–e
	200	11.5	7.9	de	2.6	a–c	47.2	c–e	3.12	c–e	0.182	d–f
	250	14.4	6.6	f	2.7	ab	52.2	a–d	3.27	b–d	0.198	b–d
20	50	3.6	8.2	cd	2.7	a	49.5	a–e	3.50	a–c	0.174	d–g
	100	7.2	7.4	ef	2.6	a–c	55.3	a	3.54	ab	0.180	d–g
	150	10.8	7.3	ef	2.7	ab	53.2	a–c	3.43	a–c	0.209	a–c
	200	14.4	7.2	ef	2.8	a	55.0	a	3.72	a	0.223	ab
	250	18.0	4.9	g	2.7	a	53.9	ab	3.35	a–d	0.235	a
			Significance									
	Photoperiod (A)		***		***		***		***		***	
	Light intensity (B)		***		***		***		***		***	
	Interaction (A × B)		***		*		***		***		**	

[z] Means for 3 replicates with 7 samples within each column followed by the same letters are not significantly different according to Tukey's HSD test at $p < 0.05$. *, ** and *** = significant at $p < 0.05$, 0.01 and 0.001, respectively.

The LARs and LAIs from the photoperiod and light intensity treatments were difficult to find general growth and decline trends (Figure 10). The LARs of cucumber scions and rootstocks did not show any trend, expect the downward trends of cucumber rootstocks by increasing the photoperiod at 200 and 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

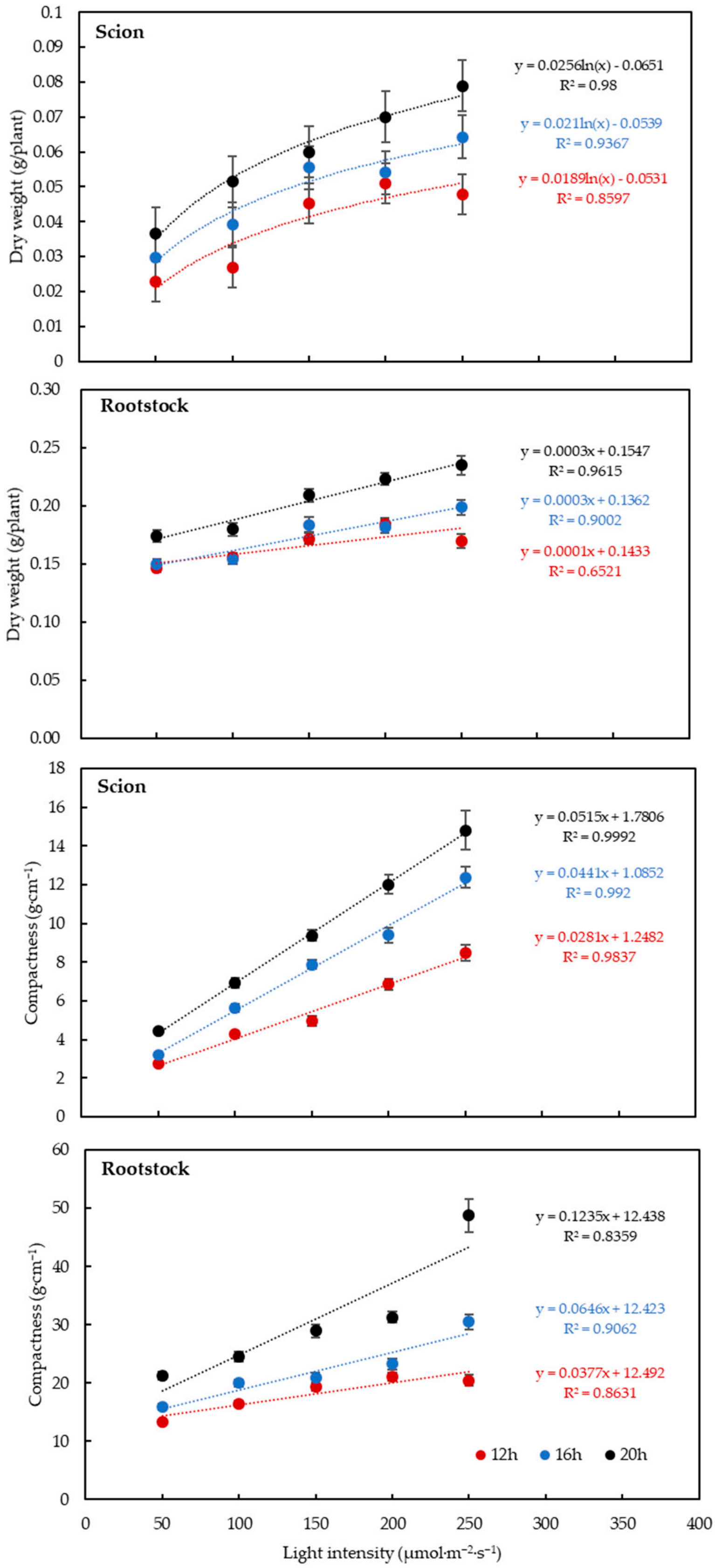

Figure 9. Regression analyses of the dry weight and compactness of cucumber scions and rootstocks as affected by the different air temperature and light intensity treatments in a PFAL. The values of each point represent means for 3 replicates with 7 samples and standard errors.

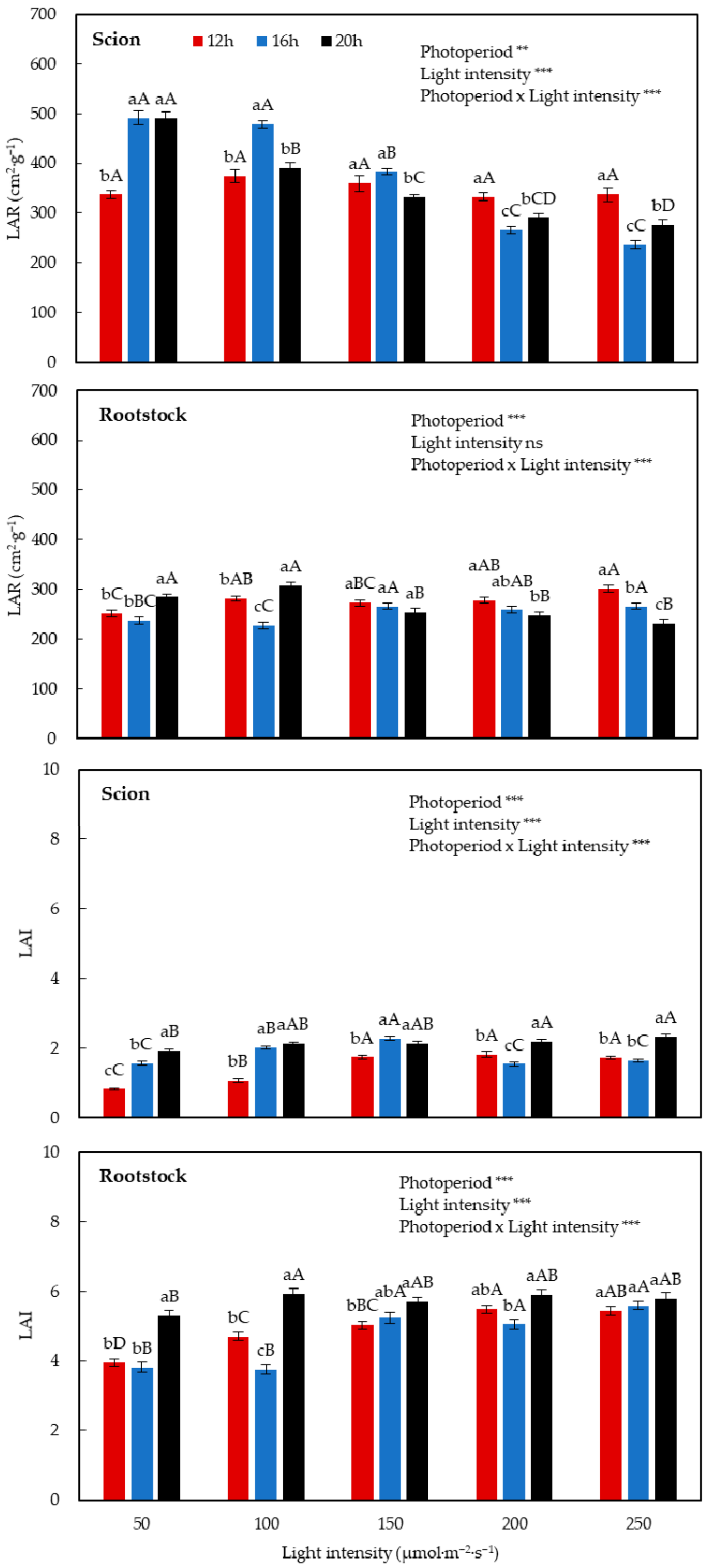

Figure 10. Leaf area ratio (LAR) and leaf area index (LAI) of cucumber scions and rootstocks as affected by the different photoperiod and light intensity treatments in a PFAL. The error bar indicates the standard error of the mean for 3 replicates with 7 samples. **, *** and 'ns' indicate significant differences at $p < 0.01$, 0.001 and non-significant differences, respectively. Values with different letters differ significantly at the 95% level according to Tukey's HSD test. Lowercase letters compares photoperiod treatments for each light intensity treatment. Uppercase letters compare light intensity treatments for each photoperiod treatment.

3.3. The LUEs of Cucumber Scions and Rootstocks as Affected by Air Temperature, Light Intensity and Photoperiod Conditions in a PFAL

The LUEs were decreased as the light intensity increased in the photoperiod and light intensity treatments, except the LUEs of cucumber scions in the 12 h·d^{-1} of photoperiod treatments (Figure 11). The differences of LUEs among the photoperiod regimes were not shown in cucumber scions, however, the LUEs of rootstocks showed more significant differences among the photoperiod regimes. In cucumber scions, the LUEs at 50 and 250 µmol·m^{-2}·s^{-1} were not significantly different among the photoperiod treatments, and the LUE at 150 µmol·m^{-2}·s^{-1} was exceptionally higher than that at 100 µmol·m^{-2}·s^{-1} in the 12 h·d^{-1} of photoperiod.

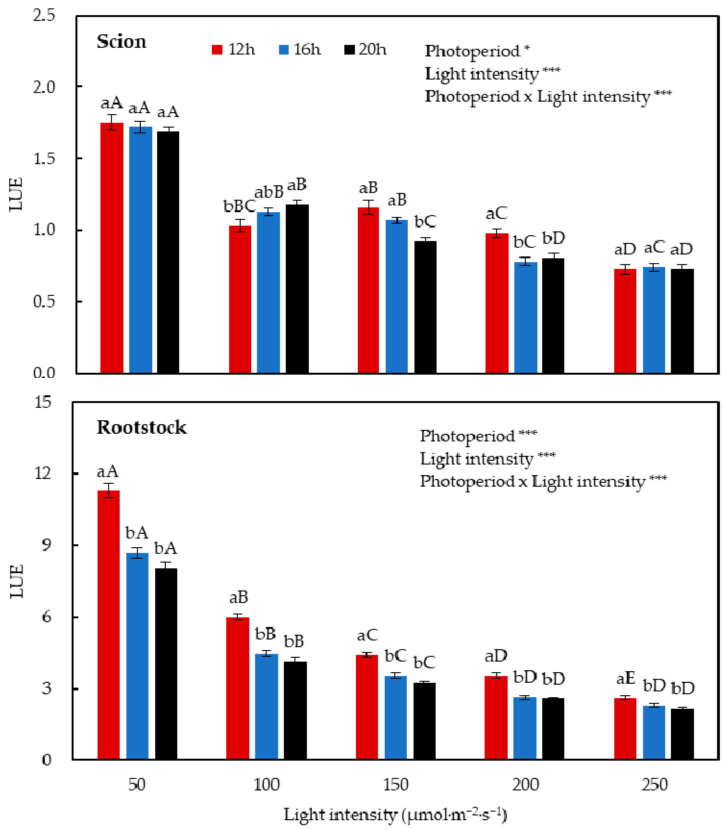

Figure 11. Light use efficiency (LUE) of cucumber scions and rootstocks as affected by the different photoperiod and light intensity treatments in a PFAL. The error bar indicates the standard error of the mean for 3 replicates with 7 samples. * and *** indicate significant differences at $p < 0.05$ and 0.001, respectively. Values with different letters differ significantly at the 95% level according to Tukey's HSD test. Lowercase letters compares photoperiod treatments for each light intensity treatment. Uppercase letters compare light intensity treatments for each photoperiod treatment.

4. Discussion

4.1. Growth of Cucumber Scions and Rootstocks as Affected by Air Temperature, Light Intensity and Photoperiod in a PFAL

Hypocotyl length, stem diameter, leaf area, dry matter, compactness, LAI and LAR have been considered to compare vegetable seedling growth and quality [14–16]. A seedling with proper hypocotyl length and high compactness is considered as a high-quality seedling [17,18]. LAI is used to characterize canopy light condition and photosynthetic rate [19] and LAR indicates overall leafiness [9], and it is helpful to identify the factors affecting plant growth.

In the results of experiment 1, increasing the difference between day and night temperature (DIF) could not increase the hypocotyl length of cucumber scions and rootstocks.

Many researchers reported that the increased DIF promotes the stem elongation [20–24] and the stem elongation response to DIF increased by increasing the irradiation intensity [25]. Grimstad and Frimanslund [20] reported that internode length of cucumber increased with increasing average temperature and DIF, and Berghage [26] presented that cucumber is strongly responded to DIF. On the contrary to previous research, our study showed the negative relationship between the DIF and the hypocotyl length. Increasing the light intensity reduced the hypocotyl length of cucumber scions and rootstocks, however, it did not increase the hypocotyl elongation response to the DIF. The leaf area and shoot dry weight tend to increase with increasing the light intensity, however, the relationship between the DIF and the leaf area or the shoot dry weight was not significantly shown. In previous studies, it was reported that the DIF affects the leaf expansion and carbon partitioning [25]. Our results suggest that the control of light intensity is more effective to control the hypocotyl elongation rather than the control of DIF during the production of cucumber scions and rootstocks in a PFAL.

Much research on the effect of the DIF on the growth and morphological characteristics in plants was conducted, however, the most of studies showed the plant response when the negative and positive DIF conditions were applied. Carvalho et al. [27] reported that the response of internode length is strongly related to DIF in chrysanthemum, however, this response is simply the outcome of independent and opposite effects of day and night temperatures. In addition, the relationship between internode length and DIF was more significantly positive when the period of DIF treatment was longer. In this study, we set three positive DIF treatments (5, 8 and 11 °C) and the period of DIF treatment was short (6 days after germination), therefore, the response of hypocotyl length to DIF was not shown clearly.

Generally, it is recommended that air temperature during daytime increases by optimum temperature in order to promote photosynthesis and carbon accumulation. In addition, air temperature during night time decreases by minimum temperature within effective temperature range for the reduction of respiration. The optimum temperature ranges during day and nighttime for cucumber growth was 22~28 °C and 15~18 °C, respectively [28]. The air temperature during photo- and dark-period in the highest DIF treatment (27/16 °C) was included in the optimum temperature ranges for cucumber growth, however, the growth of cucumber scions and rootstocks was lower than the other DIF treatments. As the day and night temperatures were controlled in a greenhouse, the change of temperature between day and night was occurred slowly and gradually. However, the change of temperature between photo- and dark-period was occurred rapidly within less than an hour in the PFAL used in this experiment. The rapid change of temperature between day and night can cause stress to plants and the lager DIF affects more negatively the plant growth in our study. Kozai [29] suggested that it would be better to keep small DIF in order to promote the growth of plants cultivated in a PFAL.

The daily light integral (DLI) is the product of PPF and photoperiod and it affects biomass accumulation and leaf pigmentation in plants [30]. In many horticultural crops, increasing the total sum of irradiation is effective to increase biomass accumulation and harvestable yield [31–33]. From the results of experiment 2, increasing the DLI promoted the growth of cucumber scions and rootstocks. At the same DLI, the specific combination of light intensity and photoperiod differently affected the seedling growth. When the DLI was same, the growth of seedlings in a relatively low light intensity and long photoperiod condition promoted compared with that in a higher light intensity and shorter photoperiod. Kelly et al. [31] reported that at the same DLI (15.6 $\mathrm{mol \cdot m^{-2} \cdot d^{-1}}$), the growth of lettuce under PPF 180 $\mathrm{\mu mol \cdot m^{-2} \cdot s^{-1}}$ and photoperiod 24 $\mathrm{h \cdot d^{-1}}$ condition was higher than that under PPF 216 $\mathrm{\mu mol \cdot m^{-2} \cdot s^{-1}}$ and photo-period 20 $\mathrm{h \cdot d^{-1}}$ condition or PPF 270 $\mathrm{\mu mol \cdot m^{-2} \cdot s^{-1}}$ and photo-period 16 $\mathrm{h \cdot d^{-1}}$ condition. Hwang et al. [34], also, confirmed a similar result in tomato and red pepper seedlings and these results might account for photosynthesis efficiency.

4.2. Quality of Cucumber Scions and Rootstocks as Affected by Air Temperature, Light Intensity and Photoperiod in a PFAL

In the experiment of air temperature and light intensity, the shoot dry weight and compactness increase with increasing the light intensity, however, the effects of air temperature on the shoot dry weight and compactness were small. Grimstad and Frimanslund [20] reported that the dry weight in cucumber increased with increasing the average day temperature (ADT) in regardless of the DIF. In this experiment, the ADT in three different DIF treatments was same (23.3 °C), therefore, the different air temperature regimes affected slightly the dry weight of cucumber scions and rootstocks.

In the experiment of light intensity and photoperiod, the increase in the shoot dry weight lagged with increasing the light intensity. The relationship between the compactness and the light intensity in all photoperiod treatments was strongly positive due to the increased dry weight and the reduced hypocotyl length by high PPF. Cucumber scions showed the logarithmic relationship between dry weight and light intensity; however, the dry weight of rootstocks was linearly related to light intensity. It was supposed that gourd rootstock has higher light saturation point than cucumber scions.

The effects of air temperature, light intensity and photoperiod on the LAR were not shown significantly in rootstocks. In cucumber scions, the LAR tend to decrease with increasing the light intensity, and the similar relationship was observed in Impatiens plug seedlings [35]. The LAR was calculated based on the shoot dry weight rather than the leaf dry weight in our study, and it is complicated to elucidate the LAR as indicators of leaf thickness. However, if we take no account of this factor, our results showed that the cucumber scions had thin and succulent leaves under the low PPF conditions. Low LAR and long hypocotyl of seedlings are often considered as poor seedling quality in terms of handling and grafting works.

4.3. LUEs of Cucumber Scions and Rootstocks as Affected by Air Temperature, Light Intensity and Photoperiod in a PFAL

From the results of experiment 1 and 2, the LUEs were mainly affected by the light intensity. In a PFAL, the electricity energy consumed by artificial lighting accounts for more than 80% of the total electric energy consumed in all production process [36]. Therefore, it is necessary to consider not only the plant growth but also LUE for the cost-effective production of seedlings in a PFAL. Increasing the light intensity and the photoperiod promoted the growth of cucumber scions and rootstocks, however, the LUE was lowest in the highest PPF and the longest photoperiod condition.

From the results in the experiment 1, the growth of cucumber scions and rootstocks was highest in the PPF 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ at 25/20 °C. In the experiment 2, the growth of cucumber scions was highest in the treatment of the photoperiod 20 $h \cdot d^{-1}$ and the PPF 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$; and the rootstocks showed the high growth in the photoperiod 20 $h \cdot d^{-1}$ treatments. The cucumber scions showed the second highest growth in the treatment of the photoperiod 16 $h \cdot d^{-1}$ and the PPF 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$. In the treatment of the photoperiod 20 $h \cdot d^{-1}$ and the PPF 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$, the LUE was lowest and hypocotyl length was too short. The appropriate range of hypocotyl length for grafting work was 7–8 cm in cucumber scions [37]. Therefore, the light conditions with the photoperiod 16 $h \cdot d^{-1}$ and the PPF 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ is more favorable for the energy efficiency and quality of seedlings. As all results from experiment 1 and 2 were considered, the appropriate temperature and light conditions for the effective production of cucumber scions and rootstocks in a PFAL were air temperature 25/20 °C, PPF 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$, photoperiod 16 $h \cdot d^{-1}$.

5. Conclusions

The growth of cucumber scions and rootstocks was affected more strongly by the control of light intensity and photoperiod than by the control of air temperature. Increasing the DIF in a PFAL did not increase the hypocotyl length and affected negatively on the growth of cucumber scions and rootstocks. Increasing the light intensity and the photoperiod increased the growth of seedlings and compactness, however, reduced the LUE. In addition, it was found that, at the same DLI, the growth of seedlings was promoted by decreasing the light intensity and extending the photoperiod. In this study, we suggest that the appropriate temperature and light conditions for the effective production of cucumber scions and rootstocks in a PFAL were air temperature 25/20 °C, PPF 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$, photoperiod 16 $h \cdot d^{-1}$ considering the plant growth and energy efficiency.

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