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Growth of Cucumber Scions, Rootstocks, and Grafted Seedlings as Affected by Different Irrigation Regimes during Cultivation of 'Joenbaekdadagi' and 'Heukjong' Seedlings in a Plant Factory with Artificial Lighting

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Abstract: Irrigation scheduling and programming are very effective tools for efficient water use in a plant factory with artificial lighting (PFAL). In order to confirm optimal irrigation schemes for the production of cucumber scions and rootstocks in a PFAL, in this study, four different start points of irrigation were applied by measuring the weight of the plug tray to compare the growth of cucumber scions and rootstocks cultivated in a PFAL. Additionally, the growth characteristics of cucumber seedlings grafted with scions and rootstocks cultivated between in a greenhouse and in a PFAL were investigated. Although the growth of cucumber scions and rootstocks was highest when irrigation was conducted at 70% of water content in a medium, the growth of grafted cucumber seedlings before and after transplanting was not significantly different among the irrigation treatments in a PFAL. However, water use efficiency (WUE) during cucumber scions and rootstock production in a PFAL was higher at 60% than at 70%. Considering seedling growth and the efficiency of irrigation such as WUE and irrigation schedule, the optimal start point of irrigation during the production of cucumber scions and rootstocks in a PFAL was determined as 60% of water content in a medium. When the optimal irrigation regime was applied to the production of cucumber scions and rootstocks in a PFAL, the morphological characteristics of cucumber scions and rootstocks cultivated in a PFAL were more suitable for grafting compared with that of the cucumber scions and rootstocks cultivated conventionally in a greenhouse. The favorable environmental conditions during the cultivation of cucumber scions and rootstocks in a PFAL also positively affected the flowering response of cucumber grafted seedlings after transplanting.

Keywords: evapotranspiration; grafting; sub-irrigation; water content of medium; water use efficiency

1. Introduction

The production of grafted seedlings has been increased continuously to overcome several problems caused by successive and intensive cultivation in vegetables such as heavy infection of soil-borne diseases, stressful environmental conditions for plants, and the lack of well-balanced fertilizer [1,2]. The use of grafted seedlings can alleviate the problems associated with successive cropping and stress tolerance by using proper rootstocks.

Despite the advantages of grafted seedlings, the production of grafted seedlings compared with non-grafted seedlings has more complicated production processes and considerations that require a very high level of specialization [3]. In particular, the uniformity of scions and rootstocks is a primary factor not only for producing good quality grafted seedlings, but also for increasing the efficiency of grafting. Furthermore, the grafting success and speed by grafting workers and machines can be promoted by the use of uniform scions and rootstocks [4]. However, the production of uniform scions and rootstocks by the conventional method in a greenhouse is becoming more difficult due to extreme weather and climate change.

The plant factory with artificial lighting (PFAL) can solve the difficulties in the production of uniform scions and rootstocks. The PFAL is covered with thermally well-insulated walls and artificial lights such as Light emitting diodes (LEDs) are used as the light source for growing plants [5]. The PFAL enables the production of a large quantity of high-quality seedlings because the environment in this system can be easily controlled and maintained without the issue of outside weather [6]. Many researchers have reported that using the PFAL increased not only the quality and efficiency of seedling production, but also the performance after transplanting in horticultural crops [7–9]. Although most research on the production of seedlings in a PFAL have focused on the control of the environment in aerial parts like light, temperature, and CO₂ concentration, there have been a few studies on the control of the environment in subterranean parts such as medium, nutrients, and water [10–14].

In particular, the efficient use of water by irrigation is becoming increasingly important, and irrigation scheduling is considered as one of the key factors to save water in open field and protected agriculture including plant factories [15,16]. In almost all PFALs, a sub-irrigation system is applied and the irrigation scheduling is often controlled by a timer by setting an irrigation interval. Irrigation scheduling and water application programming are very effective tools for efficient water use in a PFAL, and soil or plant sensors are usually used for this purpose. However, it is difficult to use soil sensors in a cell of a plug tray as the volume of medium in a cell is too small and an increased root volume disturbs measuring the accurate water content in a medium. As the number and area of leaves in young seedlings are too small and many seedlings are cultivated densely in a plug tray, plant sensors also have limits to accurately measure the water amount required for the plants. Tateishi and Murase [17] developed a micro precise irrigation device that could precisely control the irrigation in each cell of a 72-cell plug tray and confirmed the irrigation schedule by estimation of the evapotranspiration rate. However, there have been few studies that provide guidelines for irrigation to be applicable to the seedling production in a PFAL.

Therefore, this study aimed to figure out the optimal irrigation schemes for cucumber scions and rootstock production in a PFAL and hypothesized that the growth of cucumber scions, rootstocks, and grafted seedlings could be promoted by setting more favorable environmental conditions including irrigation in a PFAL rather than in a greenhouse. In this study, we set four different start points of irrigation by measuring the weight of the plug tray and investigated the growth of cucumber scions and rootstocks under different irrigation treatments in a PFAL. Furthermore, the growth of cucumber grafted seedlings after transplanting was confirmed when using the scions and rootstocks cultivated in a PFAL and GH.

2. Materials and Methods

2.1. Comparison of Growth in Cucumber Scions, Rootstocks, and Grafted Seedlings by Different Irrigation Treatments in a Plant Factory with Artificial Lighting (PFAL) (Exp. 1)

2.1.1. Plant Materials and Germination

Cucumber scions and rootstocks used in this study were ‘Joenbaekdadagi’ (Farm Hannong Co. Ltd., Seoul, Korea) and ‘Heukjong’ (Farm Hannong Co. Ltd., Seoul, Korea), respectively. These seeds were sown in 162-cell plug trays (W 280 × L 540 × H 48 mm) filled with commercial medium (Hungnong Bio Co. Ltd., Farm Hannong, Seoul, Korea). The plug trays of cucumber scions and rootstocks were

watered and placed in a dark room at constant air temperature (28°C) and relative humidity (100%) for 36 and 60 h, respectively.

2.1.2. Cultivation Conditions in a Plant Factory with Artificial Lighting

After germination, cucumber scions and rootstocks were cultivated for six days in a PFAL (Figure 1). White LEDs for plants cultivation (Future Green Co. Ltd., Hwaseong, Korea) were used as a light source (Figure 2), and the light intensity of the photosynthetic photon flux (PPF) and photo/dark period were $147.1 \pm 5.7 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and 16/8h, respectively. In the PFAL, the air temperature and relative humidity were controlled at $25 \pm 0.4/20 \pm 0.4^{\circ}\text{C}$ and $70 \pm 2/85 \pm 2\%$, respectively (Figure 3).



Figure 1. Plant factory with artificial lighting (PFAL) for seedling production (A) and cucumber scions and rootstocks on load-cells installed in PFAL (B).

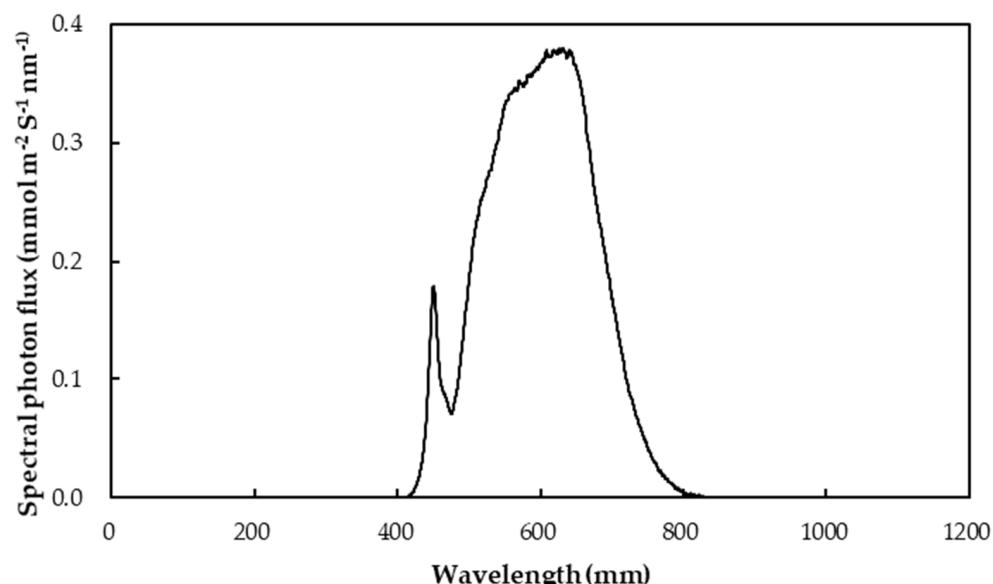


Figure 2. The spectral distribution of white LEDs used in this experiment. Light spectral scan was measured at center of the tray in photosynthetic photon flux (PPF) $150 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

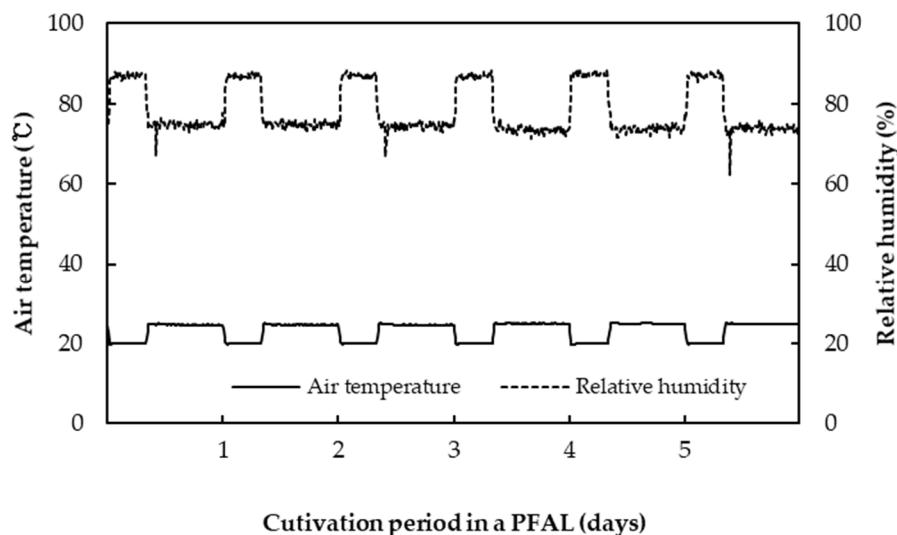


Figure 3. Air temperature and relative humidity conditions at 16 h·d⁻¹ in this experiment.

2.1.3. Irrigation Treatments

Load-cells were installed to continuously measure the weight of the plug trays with plants and medium after irrigation (Figure 1). The moisture content of the medium (%) was calculated based on the weight of the plug tray, and the weight of the plug tray with maximum water holding capacity immediately after irrigation was set as 100%. To determine the irrigation start points, the first wilting point of cucumber seedlings in a PFAL was determined as cucumber seedlings start to wilt at 40% of the moisture content of medium (data not shown). However, plants could already be under drought stress when the visual symptom of wilting is observed. In this study, three irrigation start points at 50, 60, and 70% of the moisture content in a medium were applied to avoid water stress for cucumber seedlings. Additionally, no irrigation treatment was considered because the moisture content in a medium decreased by 40% at six days in a PFAL. The cucumber scions and rootstocks were sub-irrigated for 10 min using the nutrition solution recommended by the National Institute of Horticultural and Herbal Sciences in Korea for cucumber cultivation. The elemental composition of the nutrient solution was NO₃-N 12, NH₄-N 0.7, P 2, K 7, Ca 5, Mg 2, and SO₄-S 2 me L⁻¹. The pH and EC (electrical conductivity) of the nutrition solution were 5.5 and 1.4 dS/m, respectively.

2.1.4. Growth of Cucumber Scions and Rootstocks

After six days of cultivation in a PFAL, the hypocotyl length, stem diameter, number of leaves, and leaf area were investigated. In Korea, cucumber rootstocks are cut just above the root zone and then grafted by the single cotyledon splice grafting method. Therefore, only shoot parts in cucumber scions and rootstocks were measured as the fresh and dry weights. The percentage of dry matter, compactness [8], leaf area index (LAI) [18], leaf area ratio (LAR) [19], and water use efficiency (WUE) [20] were calculated with the following equations:

$$\text{Percentage of dry matter} = \frac{\text{shoot dry weight (g)}}{\text{shoot fresh weight (g)}} \times 100$$

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

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

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

$$\text{WUE} = \frac{\text{shoot dry weight (mg)}}{\text{evapotranspiration rate (g)}}$$

2.1.5. Morphological Characteristics of Cucumber Seedlings after Grafting

Cucumber scions and rootstocks cultivated in a PFAL were grafted by the single cotyledon splice grafting method. The grafted cucumber seedlings were planted in 50-cell plug trays filled with commercial medium (Hungnong Bio, Farm Hannong Co. Ltd., Seoul, Korea) and acclimated for six days in a controlled chamber maintained at air temperature 26 ± 0.5 °C and relative humidity above 90% with LED (Red:Blue = 2:1; T & I Co. Ltd., Gwangju, Korea) lighting. The LEDs were turned on constantly at PPF $20 \pm 5 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. After acclimation, the survival rate of grafted cucumber seedlings was investigated. The grafted cucumber seedlings were cultivated in a greenhouse at the National Institute of Horticultural and Herbal Sciences, Wanju, Korea. After the cultivation for 15 days in a greenhouse, the plant height, stem diameter, and number of leaves were measured.

2.1.6. Growth of Grafted Cucumber Seedlings after Transplanting

The grafted cucumber seedlings were transplanted in plastic pots ($\varnothing = 15$ cm) filled with commercial medium (Hungnong Bio, Farm Hannong Co. Ltd., Seoul, Korea) and cultivated for 21 days in a greenhouse at the National Institute of Horticultural and Herbal Sciences, Wanju, Korea (35°50' N, 127°01' E). After 21 days after transplanting (DAT), the plant height, stem diameter, number of leaves, and flowers (female and male) were investigated.

2.2. Comparison of Growth in Cucumber Scions, Rootstocks, and Grafted Seedlings after Transplanting by Production of Scions and Rootstocks in a PFAL and Greenhouse (GH) (Exp. 2)

2.2.1. Growth of Cucumber Scions and Rootstocks in a PFAL and GH

To compare the growth of cucumber grafted seedlings using scions and rootstocks in a plant factory with artificial lighting (PFAL) and greenhouse (GH), 'Joenbaekdadagi' scions and 'Heukjong' rootstocks were cultivated in a PFAL and GH for eight and six days after sowing, respectively. In a GH, cucumber scions and rootstocks were cultivated conventionally on summer season (3–8 June 2020) in Korea. The air temperature and relative humidity in a GH were $33.0 \pm 5.7/24.1 \pm 1.8$ °C (day/night) and $46.5 \pm 14.6/70.4 \pm 7.2\%$ (day/night), respectively. The average irradiation during day time was 209 W m^{-2} and the maximum value of irradiation was 782 W m^{-2} in a GH. The conditions for germination and cultivation in PFAL was similar to that above-mentioned, and the irrigation start point was set at 60% of the moisture content in a medium. The hypocotyl length, stem diameter, number of leaves, leaf area, fresh and dry weight of shoot, dry matter, compactness, leaf area index (LAI) and leaf area ratio (LAR) in cucumber scions and rootstocks cultivated in a PFAL and GH were investigated.

2.2.2. Growth of Grafted Cucumber Seedlings after Transplanting

The cucumber scions and rootstocks were grafted and acclimated by a similar method as above-mentioned, and the grafted cucumber seedlings using scions and rootstocks cultivated in a PFAL and GH were cultivated in a greenhouse for nine and 10 days after acclimation. After that, the grafted cucumber seedlings using scions and rootstocks cultivated in a PFAL and GH were transplanted and cultivated for 18 and 19 days in a greenhouse, respectively. The plant height, stem diameter, number of leaves, leaf area, fresh and dry weight, and number of flowers (female and male) were investigated.

2.3. Statistical Analysis

The experiments were conducted in a randomized block design with three replications. All experimental data for each treatment were analyzed by ANOVA, and Duncan's multiple range tests ($p < 0.05$) were performed to determine any significant difference between various treatments using SAS (Enterprise Guide 7.1, SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Comparison of Growth in Cucumber Scions, Rootstocks, and Grafted Seedlings by Different Irrigation Treatments in a PFAL (Exp. 1)

3.1.1. Growth of Scions and Rootstocks in Different Irrigation Treatments

In 'Joenbaekdadagi' scions, the hypocotyl length, stem diameter, leaf area, and shoot fresh weight were highest when the irrigation started at 70% of water content in medium (Figure 4 and Table 1). The cucumber scions in the treatment of no irrigation showed the lowest growth. The 'Heukjong' rootstocks also showed the highest hypocotyl length, stem diameter, leaf area, and shoot fresh weight in 70% irrigation treatment. The growth of rootstocks was reduced by decreasing the water content in the medium at the start point of irrigation. However, the shoot dry weight of rootstocks was not affected by the water content in the medium at the start point of irrigation. The percentage of dry matter in cucumber scions and rootstocks was increased by decreasing the water content in a medium at the start point of irrigation, and decreasing the water content in the medium at the start point of irrigation reduced the LAI and LAR of cucumber scions and rootstocks (Table 2). Decreasing the water content in the medium at the start point of irrigation increased the compactness of the cucumber scions and rootstocks, however, the compactness of the cucumber scions was lowest in 40% (no irrigation) treatment due to the low value of the shoot dry weight.



Figure 4. Cucumber scions and rootstocks as affected by different irrigation regimens during the cultivation in a PFAL.

Table 1. Hypocotyl length, stem diameter, number of leaves, leaf area, shoot fresh and dry weight of cucumber scions and rootstocks as affected by different irrigation regimens during cultivation in a PFAL ($n = 7$, $R = 3$).

	Irrigation Treatments	Hypocotyl Length (cm)	Stem Diameter (mm)		No. of Leaves (/plant)		Leaf Area (cm ²)	Shoot Fresh Weight (g)	Shoot Dry Weight (g)
Scion	No irrigation	6.0 ± 0.1	c ^z	1.70 ± 0.03	b	2.0 ± 0.0	a	12.9 ± 0.3	d
	50%	6.4 ± 0.1	b	1.78 ± 0.03	b	2.0 ± 0.0	a	18.6 ± 0.3	c
	60%	7.6 ± 0.1	a	1.93 ± 0.03	a	2.0 ± 0.0	a	20.4 ± 0.3	b
	70%	7.7 ± 0.1	a	1.92 ± 0.02	a	2.0 ± 0.0	a	21.6 ± 0.4	a
	Significance	***		***		NS		***	***
Rootstock	No irrigation	4.9 ± 0.1	d	2.33 ± 0.03	c	2.9 ± 0.1	a	21.2 ± 0.5	d
	50%	7.0 ± 0.1	c	2.83 ± 0.04	b	3.0 ± 0.0	a	37.8 ± 0.6	c
	60%	7.8 ± 0.1	b	2.79 ± 0.06	b	3.0 ± 0.0	a	42.8 ± 1.1	b
	70%	9.8 ± 0.1	a	2.96 ± 0.04	a	3.0 ± 0.0	a	46.6 ± 1.3	a
	Significance	***		***		NS		***	NS

^z Means and standard errors within each column followed by the same letters are not significantly different according to Duncan's multiple range test at $p < 0.05$. NS: non-significant, *** = significant at $p < 0.001$.

Table 2. The percentage of dry matter, compactness, leaf area index (LAI), leaf area ratio (LAR) and water use efficiency (WUE) of cucumber scion and rootstock as affected by different irrigation regimes during the cultivation in a PFAL ($n = 7$, $R = 3$).

	Irrigation Treatments	% of Dry Matter (%)	Compactness (mg/cm)		LAI	LAR	WUE
Scion	No irrigation	5.8 ± 0.1	a ^z	5.3 ± 0.1	c	1.4 ± 0.0	d
	50%	5.6 ± 0.1	b	7.0 ± 0.1	a	2.0 ± 0.0	c
	60%	4.9 ± 0.1	c	6.0 ± 0.2	b	2.2 ± 0.0	b
	70%	4.7 ± 0.1	c	5.9 ± 0.2	b	2.3 ± 0.0	a
	Significance	***		***		***	***
Rootstock	No irrigation	10.0 ± 0.2	a	32.4 ± 1.4	a	2.3 ± 0.1	d
	50%	6.5 ± 0.1	b	22.9 ± 0.5	b	4.0 ± 0.1	c
	60%	6.0 ± 0.2	c	21.6 ± 0.8	b	4.6 ± 0.1	b
	70%	5.0 ± 0.1	d	16.8 ± 0.7	c	5.0 ± 0.1	a
	Significance	***		***		***	***

^z Means and standard errors within each column followed by the same letters are not significantly different according to Duncan's multiple range test at $p < 0.05$. NS: non-significant, *** = significant at $p < 0.001$.

3.1.2. Evapotranspiration Rate and Irrigation Schedule of Scions and Rootstocks in Different Irrigation Treatments

The integrated evapotranspiration rates of 'Joenbaekdadagi' scions for six days in a PFAL were 1.39, 1.51, 1.59, and 1.70 kg/tray in 40 (no irrigation), 50, 60, and 70% irrigation treatments, respectively. The integrated evapotranspiration rates per cucumber scion were 8.48, 9.23, 9.70, and 10.38 g/plant in 40 (no irrigation), 50, 60, and 70% irrigation treatments, respectively. The schedules of irrigation in the 50 and 60% irrigation treatments were conducted once at five and four days after the cultivation of cucumber scions in a PFAL, respectively. In 70% irrigation treatment, the irrigation took place twice at three and five days after the cultivation of cucumber scions in a PFAL. In 'Heukjong' rootstocks, the integrated evapotranspiration rates for six days in a PFAL were 1.44, 1.64, 2.19, and 2.32 kg/tray in 40 (no irrigation), 50, 60, and 70% irrigation treatments, respectively. The integrated evapotranspiration rates per rootstock were 8.75, 9.98, 13.33, and 14.17 g/plant in 40 (no irrigation), 50, 60, and 70% irrigation treatments, respectively. The irrigation schedules of rootstocks in each treatment were similar to those of the cucumber scions.

The WUE of cucumber scions and rootstocks was decreased by increasing the water content of the medium at irrigation start point (Table 2). Although the WUE of cucumber scions was lowest in the no irrigation treatment, the rootstocks showed the highest WUE in the no irrigation treatment. For the comparison of WUE between 60% and 70% irrigation treatments, the WUE of scions and rootstocks was higher at 60%.

3.1.3. Growth of Cucumber Grafted Seedlings before and after Transplanting by Different Irrigation Treatments during Cultivation of Scions and Rootstocks

The survival rate of grafted cucumber seedlings after acclimation was 100% in all treatments. At 15 days after grafting, the plant height of the grafted cucumber seedlings was highest when the scions and rootstocks cultivated in the 60% irrigation treatment were used (Figure 5 and Table 3). However, in the grafted cucumber seedlings, the stem diameter and number of leaves were not significantly different due to the different irrigation regimens during the cultivation of scions and rootstocks in the PFAL.



Figure 5. Grafted cucumber seedlings as affected by different irrigation regimens during the cultivation of scions and rootstocks in a PFAL.

Table 3. Growth of grafted cucumber seedlings as affected by different irrigation regimens during the cultivation of scions and rootstocks in a PFAL ($n = 7$).

Irrigation Treatments	Plant Height (cm)		Stem Diameter (mm)		No. of Leaves (per plant)	
No irrigation	15.7 ± 0.7	c ^z	4.62 ± 0.16	a	4.0 ± 0.0	a
50%	17.4 ± 0.6	bc	4.80 ± 0.11	a	4.0 ± 0.0	a
60%	19.9 ± 0.6	a	4.58 ± 0.13	a	4.0 ± 0.0	a
70%	19.1 ± 0.9	ab	4.74 ± 0.10	a	4.0 ± 0.0	a
Significance	**		NS		NS	

^z Means within each column followed by the same letters are not significantly different according to Duncan's multiple range test at $p < 0.05$. NS: non-significant, ** = significant at $p < 0.01$, respectively.

After transplanting, the initial growth and development of grafted cucumber seedlings was not affected by the different irrigation treatments during the cultivation of scions and rootstocks in a PFAL (Figure 6 and Table 4).

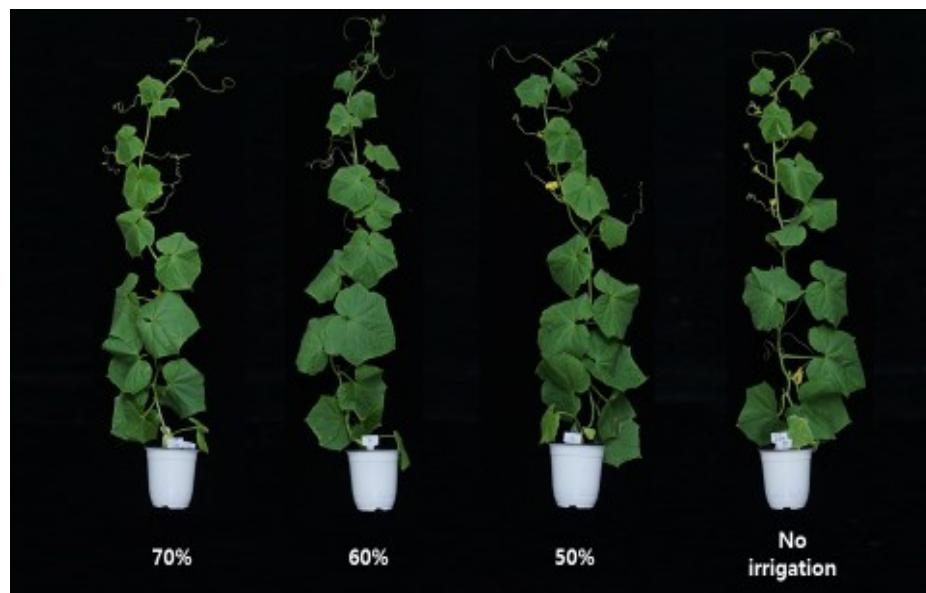


Figure 6. Grafted cucumber seedlings after transplanting as affected by different irrigation regimens during the cultivation of scions and rootstocks in a PFAL.

Table 4. Growth and development of grafted cucumber seedlings after transplanting as affected by different irrigation regimens during the cultivation of scions and rootstocks in a PFAL ($n = 7$).

Irrigation Treatments	Plant Height (cm)	Stem Diameter (mm)	No. of Leaves (per plant)	No. of Female Flowers (per plant)	No. of Male Flowers (per plant)	No. of Flowers (per plant)						
No irrigation	149 ± 2	ab ^z	6.62 ± 0.19	a	19.6 ± 0.2	a	10.2 ± 0.4	a	4.8 ± 0.4	a	15.0 ± 0.0	a
50%	144 ± 2	b	6.76 ± 0.54	a	20.0 ± 0.0	a	12.0 ± 0.5	a	3.0 ± 0.5	a	15.0 ± 0.0	a
60%	154 ± 2	a	6.65 ± 0.13	a	19.6 ± 0.4	a	11.6 ± 0.6	a	3.4 ± 0.6	a	15.0 ± 0.0	a
70%	149 ± 1	ab	6.15 ± 0.15	a	19.2 ± 0.2	a	10.4 ± 0.7	a	4.6 ± 0.7	a	15.0 ± 0.0	a
Significance	*		NS	NS	NS	NS	NS	NS	NS	NS	NS	

^z Means within each column followed by the same letters are not significantly different according to Duncan's multiple range test at $p < 0.05$. NS: non-significant, * = significant at $p < 0.05$.

3.2. Comparison of Growth in Cucumber Scions, Rootstocks, And Grafted Seedlings after Transplanting by Production of Scions and Rootstocks in a PFAL and GH (Exp. 2)

3.2.1. Growth of Cucumber Scions and Rootstocks Cultivated in a PFAL and GH

The ‘Joenbaekdadagi’ scions cultivated in a PFAL and GH did not show significant differences in the hypocotyl length and number of leaves, however, the stem diameter, shoot fresh weight and dry weight in a PFAL were higher than those in a GH (Figure 7 and Table 5). The ‘Heukjong’ rootstocks cultivated in a GH showed the higher hypocotyl length and stem diameter. In the rootstocks cultivated in a GH, the shoot fresh weight was higher than that in a PFAL, however, the shoot dry weight was lower than that in a PFAL. Although the cucumber scions cultivated in a PFAL showed a higher compactness, LAI, and LAR compared with those in a GH, the percentage of dry matter was higher in a GH (Table 6). In rootstocks, the percentage of dry matter and compactness in a PFAL were higher than those in a GH, and the LAI and LAR were not significantly different between the GH and PFAL.

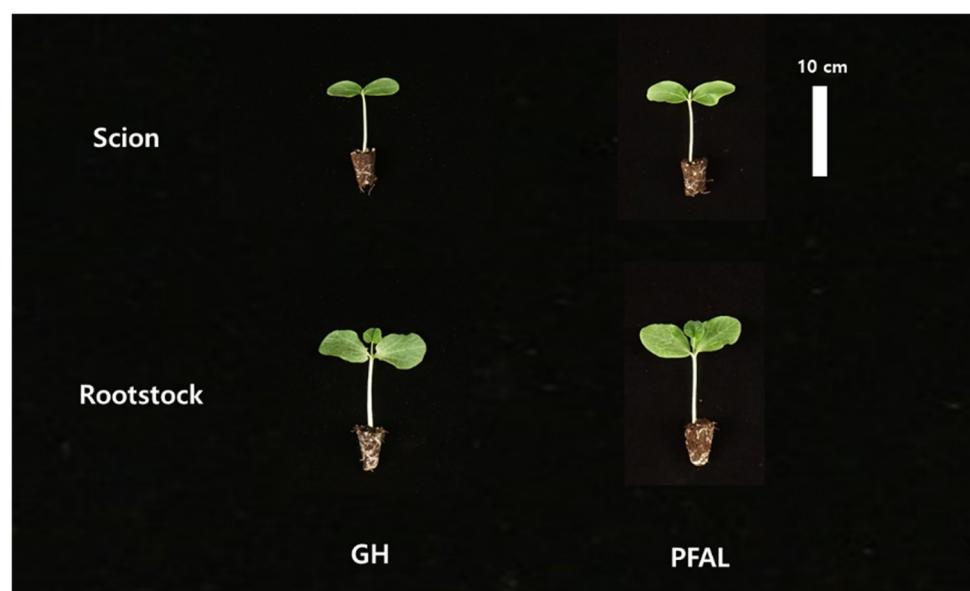


Figure 7. Cucumber scions and rootstocks cultivated in a plant factory with artificial lighting (PFAL) and greenhouse (GH).

Table 5. Hypocotyl length, stem diameter, number of leaves, leaf area, shoot fresh and dry weight of cucumber scion and rootstock cultivated in a PFAL and GH ($n = 7$, $R = 3$).

Treatments		Hypocotyl Length (cm)		Stem Diameter (mm)		No. of Leaves (per plant)		Leaf Area (cm ²)		Shoot Fresh Weight (g)		Shoot Dry Weight (g)	
Scion	GH	6.8 ± 0.1	a ^z	1.75 ± 0.02	b	2.0 ± 0.0	a	14.6 ± 0.2	b	0.681 ± 0.009	b	0.044 ± 0.001	b
	PFAL	6.8 ± 0.1	a	1.86 ± 0.02	a	2.0 ± 0.0	a	18.7 ± 0.4	a	0.841 ± 0.016	a	0.050 ± 0.001	a
	Significance	NS		***		NS		***		***		***	
Rootstock	GH	7.6 ± 0.1	a	2.65 ± 0.04	a	3.0 ± 0.0	a	40.4 ± 1.1	a	2.755 ± 0.116	a	0.167 ± 0.004	b
	PFAL	6.7 ± 0.2	b	2.39 ± 0.04	b	3.0 ± 0.0	a	38.9 ± 0.8	a	2.452 ± 0.074	b	0.171 ± 0.006	a
	Significance	***		***		NS		NS		*		NS	

^z Means within each column followed by the same letters are not significantly different according to Duncan's multiple range test at $p < 0.05$. NS: non-significant, * and *** = significant at $p < 0.05$ and 0.001, respectively.

Table 6. The percentage of dry matter, compactness, leaf area index (LAI) and leaf area ratio (LAR) of cucumber scion and rootstock cultivated in a PFAL and GH ($n = 7$, $R = 3$).

Treatments		% of Dry Matter (%)		Compactness (mg/cm)		LAI		LAR	
Scion	GH	6.4 ± 0.1	a ^z	6.5 ± 0.2	b	1.6 ± 0.0	b	333.6 ± 4.4	b
	PFAL	5.9 ± 0.1	b	7.3 ± 0.2	a	2.0 ± 0.0	a	381.2 ± 7.8	a
	Significance	***		**		***		***	
Rootstock	GH	6.2 ± 0.2	b	22.2 ± 0.7	b	4.3 ± 0.1	a	243.5 ± 6.7	a
	PFAL	7.0 ± 0.2	a	25.9 ± 1.3	a	4.2 ± 0.1	a	232.9 ± 8.1	a
	Significance	**		*		NS		NS	

^z Means within each column followed by the same letters are not significantly different according to Duncan's multiple range test at $p < 0.05$. NS: non-significant, *, **, and *** = significant at $p < 0.05$, 0.01, and 0.001, respectively.

3.2.2. Growth and Development of Cucumber Seedlings Grafted with Scions and Rootstocks Cultivated in a PFAL and GH after Transplanting

The survival rate of grafted cucumber seedlings after acclimation was 100% when the used scions and rootstocks were cultivated both in a PFAL and GH. The growth of grafted cucumber seedlings after transplanting was not significantly different between the GH and PFAL, however, the grafted cucumber seedlings using the scions and rootstocks cultivated in a PFAL showed better performance in flowering response (Figure 8, Tables 7 and 8). Although there was no significant difference in the number of total flowers between GH and PFAL, the number of female flowers was higher in the grafted cucumber seedlings using the scions and rootstocks cultivated in a PFAL.

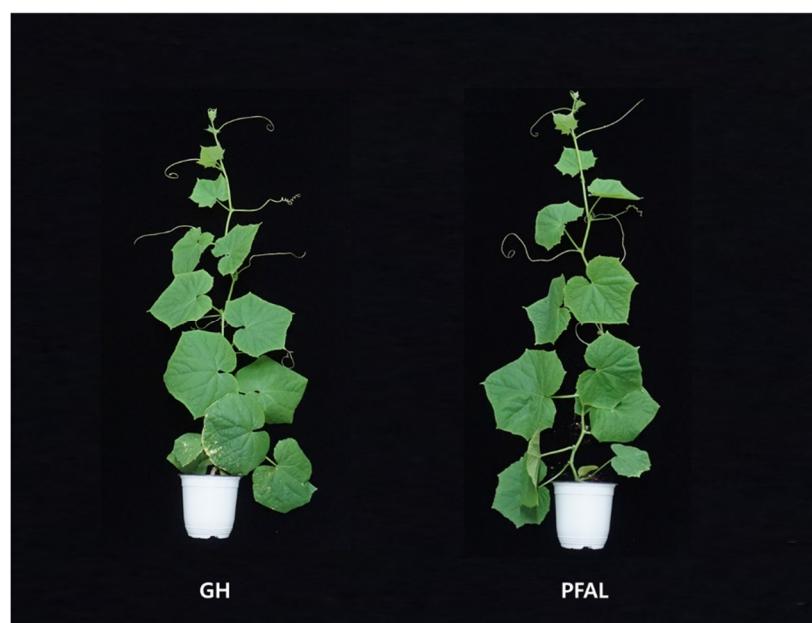


Figure 8. Grafted cucumber seedlings after transplanting as affected by the cultivation of scions and rootstocks in a PFAL and GH.

Table 7. Growth of grafted cucumber seedlings after transplanting as affected by the cultivation of scions and rootstocks in a PFAL and GH ($n = 7$, $R = 3$).

Treatments	Plant Height (cm)	Stem Diameter (mm)	No. of Leaves (per plant)	Leaf Area (cm ²)	Total Fresh Weight (g)	Total Dry Weight (g)						
GH	133.9 ± 1.6	^a ^z	7.53 ± 0.17	a	15.9 ± 0.2	a	2485.2 ± 1.6	a	104.5 ± 0.2	a	9.9 ± 0.3	a
PFAL	135.8 ± 1.5	a	7.90 ± 0.24	a	16.4 ± 0.2	a	2469.4 ± 2.0	a	102.3 ± 0.2	a	9.6 ± 0.4	a
Significance	NS		NS		NS		NS		NS		NS	

^z Means within each column followed by the same letters are not significantly different according to Duncan's multiple range test at $p < 0.05$. NS: non-significant.

Table 8. Development of grafted cucumber seedlings after transplanting as affected by the cultivation of scions and rootstocks in a PFAL and GH ($n = 7$, $R = 3$).

Treatments	No. of Female Flowers (per plant)	No. of Male Flowers (per plant)	No. of Flowers (per plant)			
GH	1.6 ± 0.3	b ^z	8.4 ± 0.3	a	10 ± 0.0	a
PFAL	3.4 ± 0.4	a	6.6 ± 0.4	b	10 ± 0.0	a
Significance	***		***		NS	

^z Means within each column followed by the same letters are not significantly different according to Duncan's multiple range test at $p < 0.05$. NS: non-significant, *** = significant at $p < 0.001$.

4. Discussion

Water status during cultivation usually affects the morphology, physiology, and dry matter partitioning of seedlings [21,22]. Irrigation management can control the growth of seedlings, and is especially critical to produce high quality seedlings with proper morphological characteristics and the ability to survive or grow better after grafting or transplanting under different environmental conditions [22–26].

Hypocotyl length, stem diameter, leaf area, and dry matter are the important factors in seedling quality [11,27,28]. The hypocotyl morphology of the cucumber scion affected the survival rate and growth after grafting [29]. Growth analysis including compactness, LAI, and LAR are used to understand the inherent differences in the response in plants under environmental stress conditions and can be used as important parameters to determine seedling quality [11,27,28]. A seedling with high plant compactness (i.e., high dry weight and short plant height) is considered as a high quality seedling [30,31]. LAI and LAR reflect the size of the photosynthetic apparatus to receive light irradiation [32]. LAR is one of the important factors that determine the growth rate of seedlings [27], and fixing carbon per unit plant weight was reduced by low LAR [33].

In the irrigation study in a PFAL (Exp. 1), the evapotranspiration rates of both ‘Joenbaekdadagi’ scions and ‘Heukjong’ rootstocks were increased by increasing the water content in the medium at the starting point of irrigation. However, the WUE was reduced by increasing the moisture content in the medium at the irrigation start point except that of cucumber scions in the 40% (no irrigation) treatment. The cucumber scions in the 40% irrigation treatment showed the lowest value of WUE because they were already under drought stress conditions and it suppressed photosynthetic carbon assimilation in seedlings. Therefore, the threshold of the irrigation start point for the production of cucumber scions in a PFAL should be set above 40% of water content in a medium.

As a result of the first experiment, 60% of water content in a medium was determined an efficient irrigation regimen and scheduling to produce ‘Joenbaekdadagi’ scions and ‘Heukjong’ rootstocks in a PFAL. The irrigation management was important for plant growth, but also needs to be considered on the side of saving water resources. The growth of cucumber scions and rootstocks was highest in the 70% irrigation treatment, however, the irrigation was conducted twice during the cultivation period in a PFAL. The growth of cucumber scions between 60 and 70% irrigation treatment was not significantly different, and the hypocotyl length of rootstocks in 70% irrigation treatment was too long compared with the proper size (the hypocotyl length 5–7 cm, [34]) for grafting. Considering the growth of seedlings and irrigation efficiency, the proper start point of sub-irrigation was 60% of water content in a medium for the production of cucumber scions and rootstocks in a PFAL and the irrigation can be conducted once during the cultivation period.

The comparable study in the second experiment found that ‘Joenbaekdadagi’ scions and ‘Heukjong’ rootstocks production in a PFAL would be an effective tool to produce a stable and uniform quality of seedling constantly against various adverse weather conditions. In the summer season in Korea, the air temperature and light intensity during day time were very high in a GH and the growth rate of seedlings was fast. Therefore, the period of conventional cultivation in a GH (6 DAS) was shorter than that in a PFAL (8 DAS). In the conventional cultivation in a GH, the cultivation period and growth rate of seedlings were largely affected by weather and season. However, in a PFAL, the growth of seedlings was uniform because the cultivation environment can be maintained constantly regardless of outside weather and season.

Additionally, the results in the second experiment confirmed that seedling quality of ‘Joenbaekdadagi’ scions and ‘Heukjong’ rootstocks cultivated in a PFAL was greater than the conventional seedling production in a GH in terms of dry weight, stem diameter, and flower development. Although this study showed that the cultivation period in a GH was shorter than that in a PFAL, the hypocotyl length of seedlings in a GH was longer compared to the low dry weight of shoot and the compactness was lower than that in a PFAL. Ohyama et al. [35] reported that the plant height of tomato transplants cultivated in a PFAL was lower and the dry weight was higher than that in a GH.

The growth of cucumber scions and rootstocks cultivated in a GH was negatively affected by high air temperature and low irradiation conditions during the summer rainy season. The control of favorable environment conditions for plant growth in a PFAL increased photosynthetic carbon assimilation and reduced excessive stem elongation of seedlings, therefore, more compact and healthy seedlings in a PFAL were produced compared with a conventional cultivation in a GH.

According to Oda et al. [29], the difference of stem diameter between cucumber scions and rootstocks affected the survival rate and growth of grafted seedlings. The reduction of the difference in stem diameter between cucumber scions and rootstocks was effective in promoting the survival rate and growth of grafted seedlings. The difference in stem diameter between scions and rootstocks in a PFAL (0.53 mm) was smaller than that in a GH (0.9 mm). The cultivation of scions and rootstocks in a PFAL could reduce the difference in stem diameter between scions and rootstocks, and it can be advantageous not only to promote the growth of grafted seedlings, but also to increase the efficiency of grafting by workers or machines.

Kwack et al. [9] reported that the number of female flowers increased when the scions and rootstocks cultivated in a PFAL were used for the production of grafted cucumber seedlings. In the tomato seedlings cultivated in a PFAL, the node of first flowering was lower than that in a GH [35]. The environmental control during the cultivation of scions and rootstocks can improve not only the growth of scions and rootstocks before grafting, but also the flowering response of grafted seedlings after transplanting. The differentiation of initial flower primordia was determined at the first leaf stage, and the environmental control at the cotyledonary stage could affect the flowering habit in cucumber [36]. In general, the development of female flowers in cucumber is promoted by low air temperature and short day length conditions [37]. The air temperature in a PFAL was lower than that in a GH, and it could have a positive effect on female flower development in the cucumber seedlings. Although the day length in a PFAL (16 h) was approximately two hours longer than that in a GH, it did not affect the development of female flowers. Fujieda [38] reported that the effect of day length on the development of cucumber female flowers was encouraged by increased the number of true leaves and leaf area of cucumber seedlings. As cucumber scions and rootstocks showed 0–1 true leaves before grafting in this study, the increased photoperiod in a PFAL would improve only the vegetative growth of seedlings without a negative effect on the development of female flowers. The effect of the cultivation of scions and rootstocks in a PFAL on the vegetative growth after the transplanting of grafted cucumber seedlings could be offset, however, the flowering response after transplanting could be promoted by the cultivation of scions and rootstocks under favorable environment conditions in a PFAL.

5. Conclusions

In order to provide a guideline for irrigation scheduling during the cultivation of cucumber scions and rootstocks in a PFAL, four different irrigation regimens were applied in this study. The optimal irrigation start point was 60% of water content in the medium in consideration of the growth of seedlings, irrigation efficiency, and WUE. The threshold of water content in the medium at the irrigation start point was 40% for the production of cucumber scions in a PFAL. As the cucumber scions and rootstocks were cultivated under optimal irrigation conditions in a PFAL, their morphological characteristics were more suitable for grafting compared with the scions and rootstocks cultivated conventionally in a GH. Additionally, the cultivation of cucumber scions and rootstocks under properly controlled environmental conditions (including irrigation scheduling) in a PFAL positively affected the flowering response of grafted cucumber seedlings after transplanting. The production of scions and rootstocks in a PFAL can improve the productivity and uniformity of seedlings, the efficiency of grafting and resource use during the cultivation, and the potential yield of grafted seedlings after transplanting.

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