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Development of Growth Model for Grafted Hot Pepper Seedlings as Affected by Air Temperature and Light Intensity

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Abstract: The objective of this study was to develop a growth model for grafted hot pepper seedlings as affected by air temperature and light intensity. After grafted union formation, the hot pepper seedlings were cultivated in various environmental factors in terms of four levels, mean daily air temperature (17, 22, 27, and 32 °C) and 3 levels of light intensity (150, 350, and 550 $\mu mol \cdot m^{-2} \cdot s^{-1}$). The growth traits were measured 0, 7, 14, 21, and 28 days after grafted union formation (DAGU). The plant height was improved, and development of leaves enhanced by higher air temperature. The number of leaves was greatest under the combination of the high temperature and high light intensity, resulting in 39.0/plant at 28 DAGU. The leaf area and dry weight showed 491.9 cm^2/plant and 2.68 g/plant, respectively, at 28 DAGU under 32 °C air temperature and 550 $\mu mol \cdot m^{-2} \cdot s^{-1}$ light intensity. The changes of dry weight were rapidly increased under the higher air temperature and light intensity as followed by analysis of the growth curve. The beta distribution model was developed, and the relative growth rate (RGR) was simulated by the model, the maximum RGR was predicted at 0.116 $g \cdot g \cdot d^{-1}$. The RGR showed 0.113, 0.127, and 0.109 $g \cdot g \cdot d^{-1}$ at 10, 20, and 30 °C air temperature, respectively, and RGR was improved by 12% by increasing the air temperature by 10 °C, without going over 25 °C ADT. Results indicated that the developed growth model might be applied to optimal environmental control for maximized RGR of production of grafted hot pepper seedlings.

Keywords: grafting; environmental control; beta distribution model; seedling; scion; rootstock

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1. Introduction

The development of protected horticulture has allowed producing horticultural crops with high quality all year round, and it is necessary for commercial nurseries to produce high quality seedlings through the year [1]. Use of grafted seedlings in fruit vegetables has been increased for soil-borne disease resistance, unfavorable environment tolerance, fruit yield, and quality [2–4]. In Korea, hot pepper is one of the major fruit vegetables for grafted seedling use, and the number of grafted seedlings required was approximately 96 million for hot pepper in 2018 [5].

Korea has four distinct seasons with hot summers and cold winters, and it is unfavorable to produce uniform seedlings and fix production scheduling throughout the year. Additionally, the number and duration of extreme weather (extreme high or low temperature, low irradiation during rainy season, etc.) has increased due to climate change in recent years [6]. Grafted seedlings are cultivated in a greenhouse, and the cultivation conditions are largely affected by outside weather. Therefore, commercial nurseries try to control environmental conditions more properly and precisely for the uniform production of seedlings with high quality.

Modeling of crop growth can be used to better understand the physiological response to changes in environmental conditions and allow strategies to be applied [7]. The environment control in a greenhouse must be determined based on the desired crop performance; therefore, a crop growth model is important to manipulate the environment conditions to achieve optimal plant growth and development [8,9]. Modeling of crop growth can be a good support tool to help the optimization of plant growth with lower costs and can assist decision-making at the right time [10].

In many crop growth models, environmental factors play an important role, because plant growth and development are dependent on the environment conditions surrounding the plant [10,11]. Response to environmental conditions differ among plant species, and each species has a specific optimum range [12]. Among various environmental factors, temperature and light are primary factors affecting plant growth and development. Temperature and light conditions are not independent; therefore, growth response is affected by the interaction of temperature and light [13]. Accordingly, an optimal environment condition for grafted seedling production in a greenhouse should be controlled considering the interaction of multiple environmental factors.

In this study, we set 12 treatments combined with 4 different mean daily air temperatures (17, 22, 27, and 32 °C) and 3 different light intensities (150, 350, and 550 μmol m^{-2} s^{-1}). The combined treatments of air temperature and light intensity were controlled with natural dynamic pattern in a growth chamber. Additionally, we investigated the effect of air temperature and light intensity conditions on the growth traits and developed the beta distribution model for the simulation of RGR in grafted hot pepper seedlings.

2. Materials and Methods

2.1. Plant Materials, Environments Treatment, and Growth Data Collections

The scion ("Shinhong") and rootstock ("Tantan") of hot pepper were sowed in 50-cell plug trays filled with commercial topsoil (Bio media, Hungnong Seed Co., Seoul, Korea) and grown in a glasshouse for seedling production. The graft was commenced at 21 days after sowing and the grafting was performed with splicing methods. The grafted seedlings of hot pepper were moved to a room with 28 °C air temperature, 95% relative humidity, and 50 $\mu mol \cdot m^{-2} \cdot s^{-1}$ photosynthetic photon flux (PPF) for 7 days for grafted union formation. They were grown in four different extreme weather growth chambers (EWGC; Modified CEEWS model, EGC, Chagrin Falls, OH, USA) applied with 17, 22, 27, and 32 °C average daily air temperature, respectively, and three PPF levels (150, 350, and 550 $\mu mol \cdot m^{-2} \cdot s^{-1}$). The set air temperature and PPF were calculated by Thornely's model (Equations (1)–(4)) and then the values were applied in the growth chamber with hour intervals.

$$T_{air} = T_{mean} - T_{var} \times \sin\left[2\pi \frac{\left[t_{dec} + 1 - \frac{1}{2}(1 + t_{dawn} + 0.625)\right]}{2(1 + t_{dawn} - 0.625)}\right] \quad (1)$$

where if $0 \le t_{dec} \le t_{dawn}$, T_{air}: air temperature, T_{mean}: average daily temperature, T_{var}: the difference of maximum temperature between minimum temperature.

$$T_{air} = T_{mean} + T_{var} \times \sin\left[2\pi \frac{\left[t_{dec} - \frac{1}{2}(t_{dawn} + 0.625)\right]}{2(0.625 - t_{dawn})}\right] \quad (2)$$

where if $t_{dawn} \le t_{dec} \le 0.625$, T_{air}: air temperature, T_{mean}: average daily temperature, T_{var}: the difference of maximum temperature between minimum temperature.

$$T_{air} = T_{mean} + T_{var} \times \sin\left[2\pi \frac{\left[t_{dec} - \frac{1}{2}(1 + t_{dawn} + 0.625)\right]}{2(1 + t_{dawn} - 0.625)}\right] \quad (3)$$

where if $0.625 \leq t_{dec} \leq 1$, T_{air}: air temperature, T_{mean}: average daily temperature, T_{var}: the difference of maximum temperature between minimum temperature.

$$if\ t_{dawn} \leq t_{dec} \leq t_{dusk}\ then\ j_{PPF,\ sec}(fullsin) = \frac{j_{PPF,\ day}}{86400\tau_{day}}\left[1 + \cos\left(\frac{2\pi(t_{dec} - 0.5)}{\tau_{day}}\right)\right]\ j_{PPF,\ sec}(step) = 0 \quad (4)$$

where $j_{PPF,sec}$: PPF (μmol·m^{-2}·s^{-1}), t_{dusk}: decimal number when dusk, $j_{PPF,\ day}$: average daily PPF (μmol·m^{-2}·s^{-1}), τ_{day}: photoperiod (hours).

The grafted seedlings were treated by 12 combination environment scenarios in terms of four levels of air temperature × three levels of PPFs for 29 days after grafted union formation (DAGU) in EWGC and the sub-irrigation (EC 1.2 dS·m^{-1} and 6.5 pH nutrient solution) were supplied 1 time per 2 days during experiment periods. There were four collections of growth data at the 7, 14, 21, and 28 DAGU. The growth data of grafted transplants of hot pepper were measured in plant height, number of leaves, leaf area, fresh shoots, and dry weight.

2.2. Growth Analysis and Development of Growth Models

The growth curve presented is based on biomass (dry weight of grafted transplants), the formula adapted in the exponential curve (Equation (5)), and the relative growth rate calculated by Equation (6).

$$\text{Growth curve}_{DAGU} = a \times exp^{b \times DAGU} \quad (5)$$

where a: potential of maximum dry weight and b: constant of crop growth efficacy.

$$Relative\ growth\ rate = \left(ln^{W_2} - ln^{W_1}\right) \div (t_2 - t_1) \quad (6)$$

where ln: natural logarithm, W_1, W_2: dry weight at time one or two, t_1, t_2: days after grafted union formation at time one or two.

The growth model was developed by beta distribution models (Equation (7)) depending on average daily temperature (ADT). There were two methods applied for developing those models, parameterization by relative growth rate (RGR) data and then the three primary air temperatures in terms of base, ceiling, and optimal temperature were estimated by regression analysis (Equations (8) and (9)). The other methods were applied by reference data (reference) for three primary air temperatures (12.0, 35.0, and 27.5 °C).

$$RGR_{ADT} = R_{max}\left(\frac{T_{max} - T_{ADT}}{T_{max} - T_{opt}}\right) \times \left(\frac{T_{ADT}}{T_{opt}}\right)^{\frac{T_{opt}}{T_{max} - T_{min}}} \quad (7)$$

where R_{max}: maximum RGR estimated using the Gauss–Newton algorithm, T_{max}: ceiling temperature, T_{min}: base temperature, and T_{opt}: optimal temperature.

$$\text{RGR} = \text{c} + \text{b} \times \text{T} + \text{a} \times T^2 \quad (8)$$

$$T_{opt} = \frac{-b}{2a}, T_{max} = \frac{-b - \sqrt{b^2 - 4ac}}{2a},\ T_{base} = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (9)$$

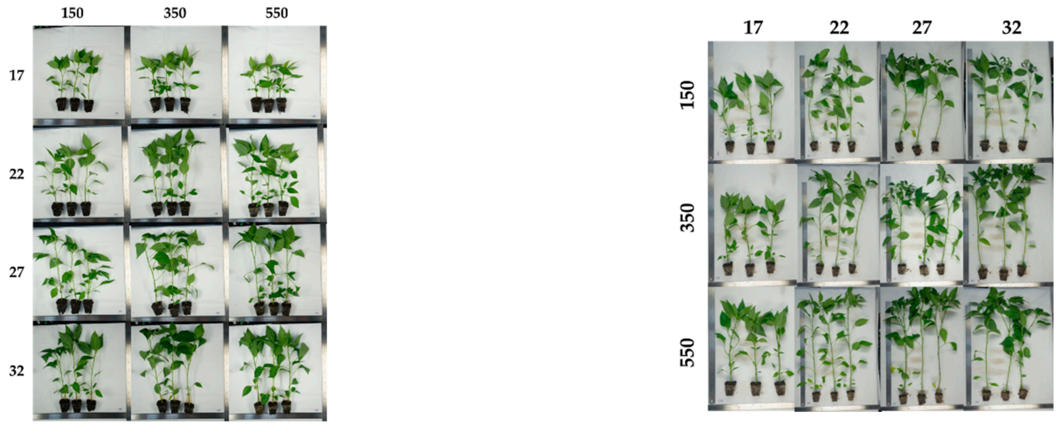
where, a, b, and c were the intercept, first, and second order regression coefficients, respectively.

2.3. Experiment Design and Statistical Analysis

The grafted seedlings of hot pepper were placed in each EWGC treatment condition. Each EWGC condition was an independent treatment and was part of a randomized block design and three replications using a cell tray. The nine samples for growth analysis were selected randomly. The two-way factorial ANOVA was performed for growth parameters using SAS (SAS 9.4, SAS Institute Inc., Cary, NC, USA).

3. Results

Figure 1 shows the growth of grafted hot pepper seedlings according to temperature and light intensity at 14 and 28 DAGU. The morphology of the grafted hot pepper seedlings was different according to the influence of air temperature and light intensity.



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

Figure 1. The growth and morphology of grafted hot pepper seedlings at (**a**) 14 DAGU and those shown at (**b**) 28 DAGU.

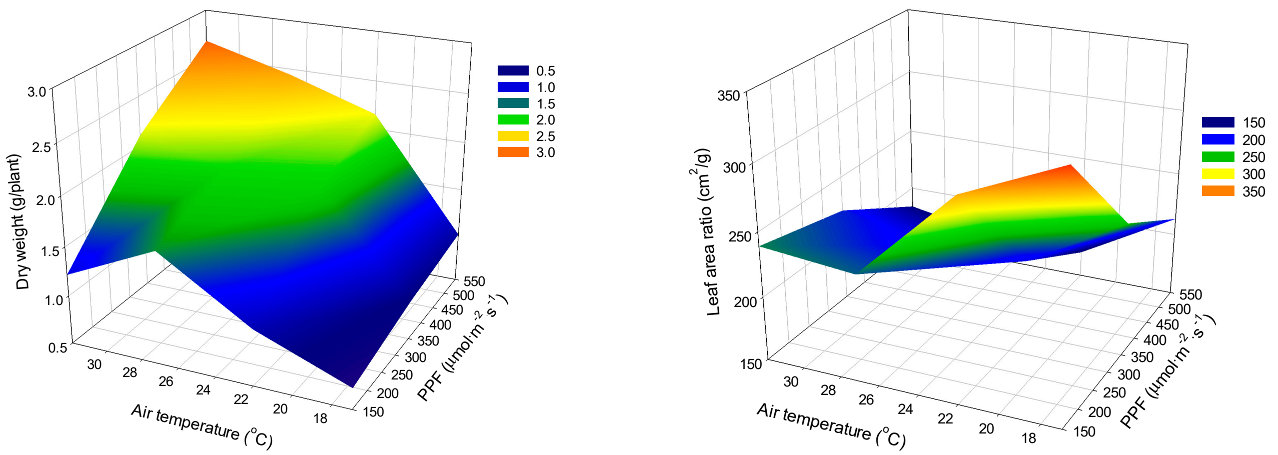
Table 1 shows the growth of grafted hot pepper seedlings according to air temperature and light intensity at 28 DAGU. As the air temperature increased, the plant height of the grafted hot pepper seedlings increased. Under the high-temperature condition (32 °C), the plant height was 47.2–58.6 cm/plant, and the leaf development was faster as the temperature increased. Under the condition of high temperature and high light intensity (32 °C and 550 μmol·m^{-2}·s^{-1}), the leaf area and dry weight of grafted hot pepper seedlings were the largest at 491.9 cm^2/plant and 2.68 g/plant, respectively. The higher air temperature and light intensity induced a higher dry weight in the grafted hot pepper seedlings. At the high light intensity (550 μmol·m^{-2}·s^{-1}), the change in the dry matter production according to the temperature was the greatest.

Table 1. The growth of grafted hot pepper seedlings as affected by different air temperature and light intensity conditions at 28 DAGU.

Air Temp (A) (°C)	PPF (B) (μmol·m^{-2}·s^{-1})	Plant Height (cm/Plant)	No. of Leaves (/Plant)	Leaf Area (cm^2/Plant)	Fresh Weight (g/Plant)	Dry Weight (g/Plant)
17	150	31.8 d [z]	12.8 f	240.2 e	8.7 f	0.71 f
	350	32.2 d	13.8 fe	225.4 e	9.4 ef	0.89 ef
	550	30.1 d	13.3 fe	215.1 e	9.8 def	1.01 ef
22	150	49.5 c	17.8 de	326.0 cd	12.0 de	1.07 ef
	350	56.9 b	22.2 cd	393.6 bc	18.2 bc	1.87 cd
	550	60.0 b	23.4 c	366.9 cd	17.9 bc	2.15 bc
27	150	57.0 b	31.2 b	382.9 bc	17.1 c	1.64 d
	350	59.0 b	33.6 b	406.3 abc	19.0 abc	1.94 cd
	550	64.7 a	34.1 b	416.6 abc	21.2 a	2.44 ab
32	150	47.2 c	30.0 b	291.1 de	12.3 d	1.22 e
	350	58.6 b	34.3 b	469.8 ab	20.6 ab	2.11 bc
	550	58.8 b	39.0 a	491.9 a	20.6 ab	2.68 a
Significance [y]						
A		***	***	***	***	***
B		***	**	**	***	***
A × B		***	NS	**	**	**

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

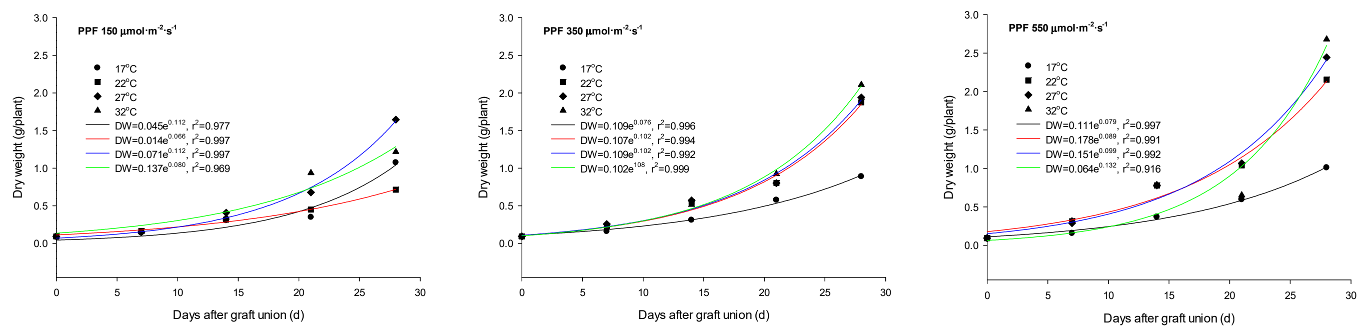
Figure 2 shows the changes of dry weight and leaf area ratio according to the experimental ranges of air temperature (17–32 °C) and light intensity (150–550 μmol·m^{-2}·s^{-1}). At the highest air temperature and light intensity, the dry weight was highest in the grafted hot pepper seedlings. The dry weight of grafted hot pepper seedlings tends to be reduced by decreasing the air temperature and light intensity. Under the lower light intensity conditions, the highest dry weight was shown at approximately 27 °C, and higher air temperatures above 27 °C reduced the dry mass accumulation. Leaf area ratio tends to be decreased by increasing the light intensity in each air temperature regime, except the highest air temperature regime (32 °C).



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

Figure 2. Changes of dry weight (**a**) and leaf area ratio (**b**) of grafted hot pepper seedlings according to the experimental ranges of air temperature and light intensity.

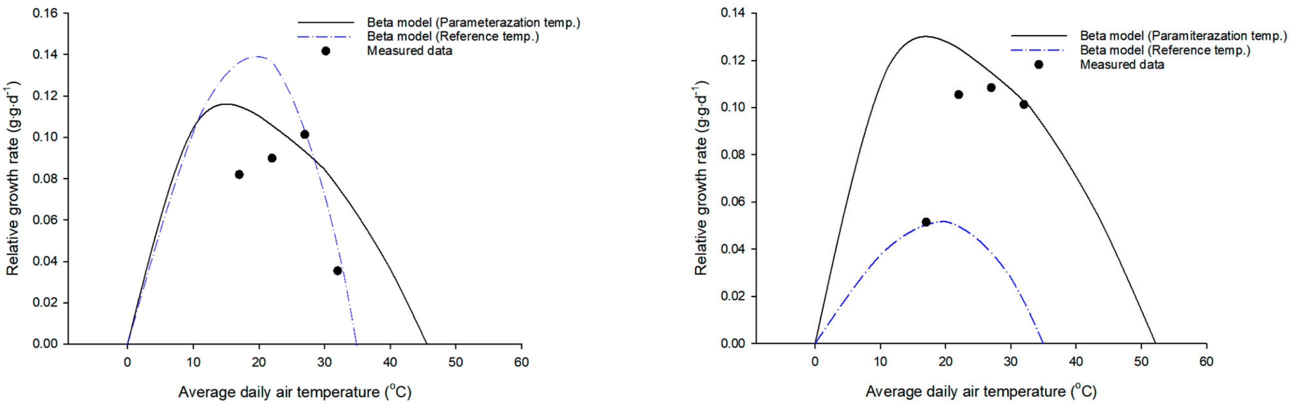
The dry weight of grafted hot pepper seedlings increased exponentially by the cultivation period after graft union in the air temperature and light intensity treatments (Figure 3). As the light intensity increased, the dry mass of grafted hot pepper seedlings accumulated rapidly during the cultivation period after graft union. Under PPF 350 and 550 μmol·m^{-2}·s^{-1} conditions, the dry weight of grafted hot pepper seedlings increased most slowly at 17 °C, and the high-temperature condition promoted the dry mass accumulation.



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

Figure 3. Changes of dry weight in grafted hot pepper seedlings by different air temperature conditions at PPF 150 (**a**), 350 (**b**), and 550 (**c**) μmol·m^{-2}·s^{-1} during cultivation period of hot pepper seedlings after graft union.

Beta function models of RGR of grafted hot pepper seedlings according to ADT were developed under 150 and 350 PPF conditions, respectively (Figure 4). In the PPF 150 μmol·m^{-2}·s^{-1} condition, the maximum RGR was determined to be 0.1031 g·g·d^{-1} by the Gauze–Newton regression equation. Additionally, constant values of a, b, and c (−0.0007, 0.0336, and −0.28, respectively) were obtained by the quadratic regression of RGR by ADT. The ceiling, base, and optimal temperature values were substituted in Equation (9) and those showed 45.98, 2.2, and 24.0 °C, and were applied to the beta distribution model (Equation (7)). The beta distribution model presented $0.1031 \times (45.8 - \text{ADT})/21.8 \times (\text{ADT}/24.0)^{0.550}$, and the beta distribution model applying the main temperature (value suggested in the references) of hot pepper was $0.1031 \times (35 - \text{ADT})/7.5 \times (\text{ADT}/27.5)^{1.196}$. Additionally, in the 350 PPF condition, the ceiling, base, and optimal temperature values were applied to Equation (9) to obtain 52.4, 2.6, and 27.5 °C, respectively. The beta distribution model was $0.1160 \times (52.4 - \text{ADT})/24.9 \times (\text{ADT}/27.5)^{0.553}$. The simulated RGRs of grafted hot pepper seedlings at 10, 20, and 30 °C ADT were 0.113, 0.127, and 0.109 $g{\cdot}g{\cdot}d^{-1}$, respectively.



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

Figure 4. Beta function models of relative growth rate of grafted hot pepper seedlings according to ADT under PPF 150 (**a**) and 350 (**b**) $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ conditions.

4. Discussion

The morphological and growth characteristics of seedlings were largely affected by environmental conditions [14–16]. The growth of grafted hot pepper seedlings increased with increasing air temperature and light intensity. It has been reported that the stem elongation is reduced by increasing light intensity [17,18], however, the plant height of grafted hot pepper seedlings in this study increased with increasing light intensity. In general, plants grown under low light conditions have greater leaf area, thinner leaves, and longer stems compared with plants grown under high light conditions in order to maximize light use [19]. Commercial nurseries produced seedlings using plug trays with many cells, and the ground area per cell is too small. The greater biomass in the seedlings grown under high light intensity condition was primarily due to increased leaf number and biomass [20]. The number of leaves was increased by increasing light intensity, and it induced the increased leaf area. More leaves overlapped each other within a small area for the production of grafted hot pepper seedlings under high light conditions. Therefore, the stem elongation of seedlings might be promoted under high light conditions to use light more efficiently in a highly restricted space.

It was reported that the optimal temperature for hot pepper seedling is 25–28 °C [21], and the high temperatures above 33 °C reduced the growth and development of hot pepper [22–25]. In this study, the growth of grafted hot pepper seedlings increased when increasing air temperature by 32 °C. The growth of seedlings was largely reduced at 17 °C, and the differences of seedling growth among light intensity treatments were small. Under low air temperature conditions, the light intensity required to saturate photosynthesis was decreased [26,27]. Therefore, the reduction of dry mass accumulation could be a result of the restriction of sucrose synthesis by low temperature and light saturation point [28,29]. In addition, leaf characteristics are closely related to the photosynthesis of plants. Lower leaf area ratio means thicker leaves, and leaf area ratio decreased with daily light integral [30]. Additionally, leaf area ratio was positively affected by temperature [31]. Heuvelink and

Dorais [32] reported that the main effect of temperature on RGR may be its effect on leaf area ratio from growth analysis in tomato seedlings.

From the developed beta distribution model, the ceiling, base, and optimal temperatures were 45.98, 2.2, and 24.0 °C at PPF 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and 52.4, 2.6, and 27.5 °C at PPF 350 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. However, at the highest light intensity condition (PPF 550 $\mu mol \cdot m^{-2} \cdot s^{-1}$), the ceiling temperature was overestimated. Under low light intensity conditions, the growth response according to ADT was defined significantly, however, the effect of ADT on the growth was offset by high light intensity. Three different light intensity conditions were set considering the irradiation conditions in each season. Therefore, our simulation results can be used to manipulate the greenhouse temperature condition appropriately during the seasons.

From the simulation results, the maximum RGR was predicted as 0.116 $g \cdot g \cdot d^{-1}$, and RGRs were improved by 12% by increasing the air temperature by 10 °C, without going over 25 °C ADT. In sweet pepper, the maximum RGR was reported as 0.18 $g \cdot g \cdot d^{-1}$ [30]. Growth models can be powerful tools used for greenhouse environment control, prediction, and planning of production in decision support system [33]. The developed growth model in this study can be applied to optimal environmental control for maximized RGR of production of grafted hot pepper seedlings. The prediction of growing period (from sowing to shipping) is relevant with respect to the planning of seedling production [8]. The developed growth model in this study can also be used as a good support tool for decision-making system in production and schedule management of grafted hot pepper seedlings.

5. Conclusions

Research on the development of growth models for hot pepper is insufficient compared with sweet pepper [30,34–36]. In Korea, hot pepper is an important vegetable crop with grafted seedling use; therefore, it is critical to produce uniform grafted seedlings with high quality throughout the year. To produce year-round high quality grafted seedlings, it is necessary to know how the environmental variables affect the seedling growth to be able to determine the optimum strategy adjusted to the growing seasons. We confirmed the growth responses of grafted hot pepper seedlings to different air temperature and light intensity conditions, and simulated RGR of grafted hot pepper seedlings based on the developed growth model. The developed growth model based on environmental variables in this study can be used to better understand the crop growth process to optimize the crop production in a greenhouse and help to manipulate the environmental conditions appropriately in a greenhouse for the production of grafted hot pepper seedlings during the growing seasons.

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