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Growth Modeling of *Perilla frutescens* (L.) Britt. Using Expolinear Function in a Closed-type Plant Factory System

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Abstract. Growth modeling in plant factories can not only control stable production and yield, but also control environmental conditions by considering the relationship between environmental factors and plant growth rate. In this study, using the expolinear function, we modeled perilla [*Perilla frutescens* (L.) Britt.] cultivated in a plant factory. Perilla growth was investigated 12 times until flower bud differentiation occurred after planting under light intensity, photoperiod, and the ratio of mixed light conditions of 130 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 12/12 h, red:green:blue (7:1:2), respectively. Additionally, modeling was performed to predict dry and fresh weights using the expolinear function. Fresh and dry weights were strongly positively correlated (r = 0.996). Except for dry weight, fresh weight showed a high positive correlation with leaf area, followed by plant height, number of leaves, number of nodes, leaf length, and leaf width. When the number of days after transplanting, leaf area, and plant height were used as independent variables for growth prediction, leaf area was found to be an appropriate independent variable for growth prediction. However, additional destructive or non-destructive methods for predicting growth should be considered. In this study, we created a growth model formula to predict perilla growth in plant factories.

Additional key words: growth prediction, Korean perilla, leaf area, plant height, shoot dry weight, shoot fresh weight

Introduction

Several methods have been investigated to predict plant growth during cultivation. Growth has been modeled using expolinear or sigmoidal functional equations (Kim et al., 2018; Lee et al., 2003). Methods using growth characteristics, such as leaf length, leaf width, and petiole length (Cho et al., 2007; Jung et al., 2016) have been used along with non-destructive prediction analysis methods using video or images (Tackenberg, 2007). Recently, artificial neural networks have been used to predict plant fresh weight (Moon et al., 2020). Additionally, fresh weight has been studied by measuring real-time changes in the weight at each growth stage during crop cultivation in a plant factory (Kim et al., 2016). Plant factories have an advantage in predicting growth because environmental factors, such as light, air temperature, and relative humidity, carbon dioxide concentration, culture medium, suitable for cultivation can be manually set and precise controlled. Predicting the crop growth is necessary for planned cultivation and quality control of crops in plant factories.

Perilla [*Perilla frutescens* (L.) Britt.] is an annual herbaceous plant belonging to the family Lamiaceae. It required an eco-friendly cultivation method because its leaves are mainly used as a “Ssam” (wrapped) vegetable (Ann et al., 2020; Sul et al., 2022). Plant factories, which artificially control the plant growth environment, create optimal conditions for plant growth and represent an optimal nutritional system that is free from pests and diseases. Therefore, stable and eco-friendly cultivation of perilla is possible in plant factories. Particularly, research on growth models is essential because a closed-type plant factory system can promote crop production throughout the year. However, such studies are still limited.

Therefore, this study aimed to find an appropriate independent variable for growth prediction and perform growth modeling using an expolinear function to predict the growth of perilla in a closed-type plant factory.

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Materials and Methods

1. Experimental materials and environmental conditions

Hydroponic system using a nutrient film technique (2.4 × 0.6 × 2.0 m, length × width × height) was applied in a closed-type plant factory at Jeju National University. Perilla seeds (*Perilla frutescens* (L.) Britt; baby perilla, Danong, Korea) were sown on a urethane sponge (2.5 × 2.5 × 2.5 cm), and plant with four true leaves were planted in a cultivation bed at a planting density of 44.4 plants/m^2 (15 × 15 cm). A tube-type light-emitting diode (LED, HT204, ESLEDs, Korea) was used as the artificial light source in the experiment. Photosynthetic photon flux density was measured using a quantum sensor (LI-190R, LI-COR, Lincoln, NE, USA). The light source was set at a height of 35 cm. The light intensity was set 130 μmol·m^{-2}·s^{-1}, and the light quality was fixed at a ratio of 7:1:2 (red:green:blue). The day/night photoperiod was fixed at 12/12 h.

Hoagland's solution was used as the culture medium, with the pH adjusted in the rage of 5.5 – 6.5, and the electrical conductivity adjusted to 1.0 dS·m^{-1} every 1 – 2 d. Temperature and relative humidity of the cultivation environment were maintained at 19 – 21°C and 55 – 65%, respectively, using a temperature and humidity sensor (HMP60, Vaisala, Finland). Carbon dioxide concentration was measured using a carbon dioxide concentration sensor (GMP252, Vaisala) are the concentration change was maintained in the range of 600 – 700 μmol·mol^{-1}.

2. Growth survey

Twelve growth surveys were conducted on 7, 14, 18, 21, 25, 28, 32, 35, 39, 42, and 46 DAT (days after transplanting). In each survey, fresh weight, dry weight, leaf number, leaf area, leaf length, leaf width, plant height, and node number of six samples were investigated. The total leaf area was measured using a leaf area meter (LI-3000A, Li-Cor). Dry weight was measured after drying the plant samples at 70°C for 72 h in an oven (VS-1202D2, Vision Scientific, Korea).

3. Applied growth model

The expolinear equation proposed by Goudriaan and Monteith (1990) was used for assessing the changes in growth (Eq. 1).

$$W = C_m / R_m \cdot \ln\left[1 + \exp\{R_m(t - t_b)\}\right] \qquad (1)$$

where W is the dry weight (g·m^{-2}), C_m is the crop growth rate (g·m^{-2}·d^{-1}), R_m is the relative growth rate (g·g^{-1}·d^{-1}), t is the number of days after transplanting, and t_b is the point at which the leaves overlap (lost time, d).

4. Statistical analysis

Statistical analysis was performed using a Statistical Analysis System (SAS Ver9.4, SAS Institute Inc., Cary, NC, USA). Pearson's correlation coefficient was used to analyze the correlation between different growth factors. Significance between mean values was analyzed at the 5% level by Duncan's multiple range test.

Results and Discussion

After transplanting perilla in the plant factory, the changes in the growth rate were measured for 46 DAT before flower bud differentiation (Fig. 1).

Leaf length and width increased linearly with the number of days after transplanting, and the growth rate decreased after approximately 40 DAT. The leaf number gradually increased initially after transplanting but increased rapidly from approximately 15 DAT until flower bud differentiation occurred. Moreover, the number of nodes increased gradually in a linear manner from the initial but increased rapidly from the 20 DAT. Plant height increased linearly until flower bud differentiation occurred. The growth rate of

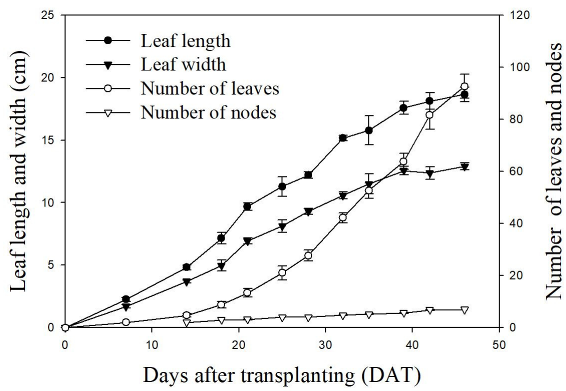

Fig. 1. Leaf length, leaf width, number of leaves and nodes of perilla at different days after transplanting. Vertical bars indicate ±SEs (n = 6).

the leaf area deceased from approximately 40 DAT. Thus, an overall sigmoid growth pattern was observed (Fig. 2).

Pearson's correlation coefficient (Table 1) was determined to assess the linear correlation among the growth characteristics of fresh weight, dry weight, leaf number, leaf area, leaf length, leaf width, plant height, and node number. The correlation between fresh and dry weight was the highest (r = 0.996). Further, fresh weight showed a high positive correlation with leaf area (r = 0.988), followed by plant height (r = 0.949), number of leaves (r = 0.911), number of nodes (r = 0.887), leaf length (r = 0.705), and leaf width (r = 0.722). Leaf area showed a high positive correlation with plant height (r = 0.981). Moreover, because the plant length considers all node lengths, a high positive correlation was observed with the number of nodes (r = 0.978).

The change in dry and fresh weights of perilla according to the number of days after transplanting gradually increased initially, but an expolinear function was observed that increased rapidly after 25－30 d. The modeling coefficients of dry and fresh weights were calculated using Equation (1) (Fig. 3).

Previous studies have used the expolinear function to predict the output of various crops (Cha et al., 2014; Goudriaan and Monteith, 1990). Although crop growth followed a sigmoid trend, the growth rate could be predicted by the expolinear function because the plant harvest time is advanced in a closed-type plant factory (Cha et al., 2014)

When the weight predicted using the model equation was compared with the measured value to verify the model equation, an error occurred as the weight increased. Thus, values more than the actual value could be predicted. After

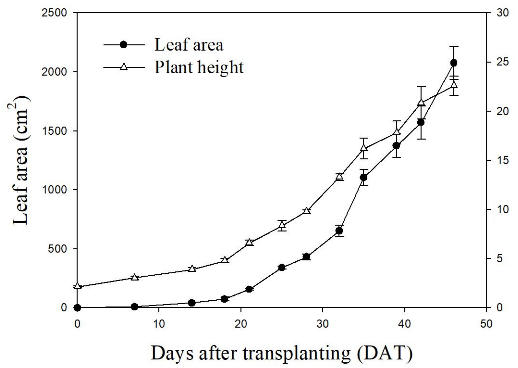

Fig. 2. Leaf area and plant height of perilla at different days after transplanting. Vertical bars indicate ±SEs (n = 6).

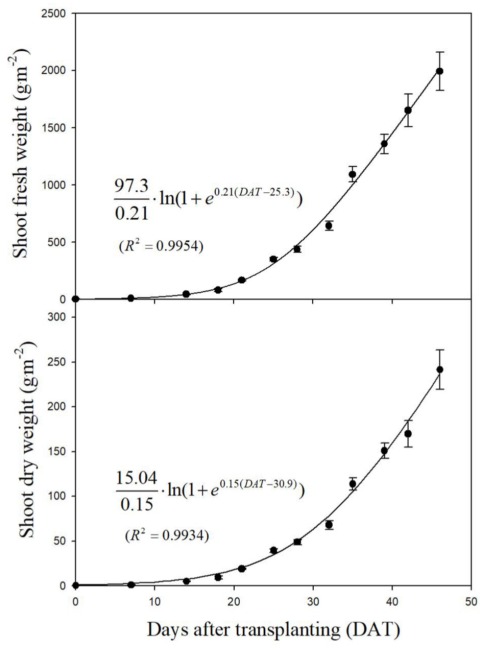

Fig. 3. Shoot fresh weights and dry weights of perilla with days after transplanting. Vertical bars indicate ±SEs (n = 4).

Table 1. Correlation analysis between growth characteristics.

	Dry weight	Number of leaves	Leaf area	Leaf length	Leaf width	Plant height	Number of nodes
Fresh weigh	0.996***	0.911***	0.988***	0.705**	0.722**	0.949***	0.887***
Dry weight		0.875***	0.969***	0.661**	0.679**	0.920***	0.850***
Number of leaves			0.954***	0.900***	0.902***	0.989***	0.979***
Leaf area				0.771***	0.788***	0.981***	0.933***
Leaf length					0.996***	0.874***	0.936***
Leaf width						0.886***	0.942***
Plant height							0.978***
Number of nodes							

, * significant at p < 0.01 or 0.001, respectively.

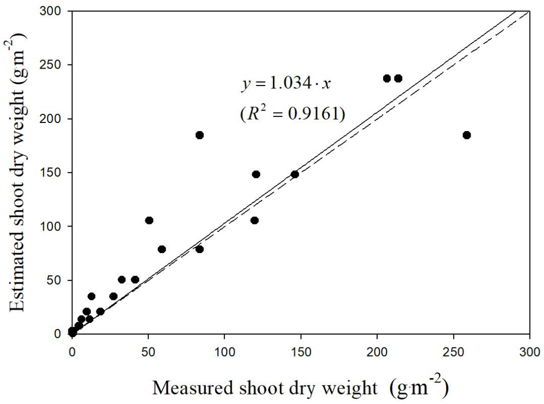

Fig. 4. Validation between the measured and estimated shoot dry weights of perilla.

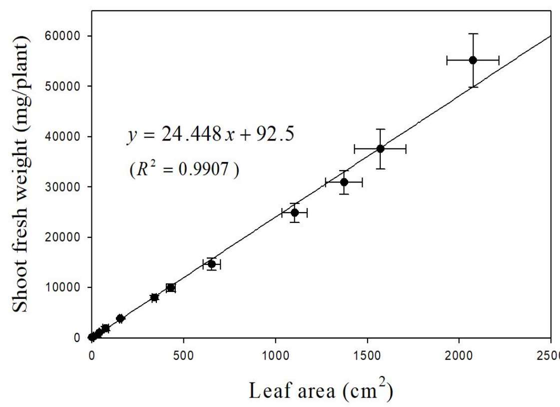

Fig. 6. Relationship between the shoot fresh weight and leaf area. Vertical and horizontal bars indicate ±SEs (n = 4).

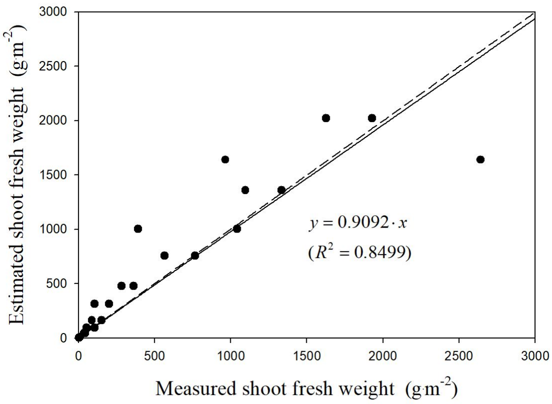

Fig. 5. Validation between the measured and estimated shoot fresh weights of perilla.

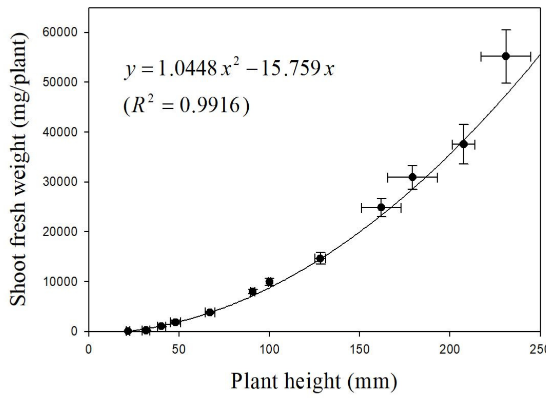

Fig. 7. Relationship between the shoot fresh weight and plant height. Vertical and horizontal bars indicate ±SEs (n = 4).

verifying the model formula, dry weight was predicted to be 3.4% higher than the measured value, and fresh weight was predicted to be 9.1% lower than the measured value. Further, the coefficients of determination of dry and fresh weights were 0.92 and 0.85, respectively (Figs. 4 and 5).

The correlation analysis between growth characteristics indicated a high correlation between the dry weight and fresh weight, followed by leaf area and plant length. Further, the relationship between fresh weight and leaf area could be expressed as a linear regression equation ($y = 24.5\ x + 92.5$) (Fig. 6).

Contrastingly, the relationship between fresh weight and plant length could be expressed as a quadratic regression equation ($y = 1.05x^2 - 15.8x$) (Fig. 7). The error in the value predicted by plant height increased over time compared to the error in the value predicted by leaf area. When the measured and predicted values of fresh weight were compared, the coefficient of determination of the predicted value for leaf area was 0.996 (Fig. 8), and that of the predicted value for plant height was 0.978 (Fig. 9).

Choi et al. (2003) reported the perilla growth increased as the light intensity increased in a range of 90－360 $\mu mol \cdot m^{-2} \cdot s^{-1}$. This was consistent with the results of a previous study, which reported that the perilla growth increased as the light intensity increased in the treatment group in a range of 60－320 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Sul et al., 2022). However, the light intensity in this study was set to 130 $\mu mol \cdot m^{-2} \cdot s^{-1}$, Therefore, changes in the plant growth should be studied according to changes in light intensity. Nguyen and Oh (2021) reported the perilla growth was similar when the blue light ratio was less than 30%. In this study, the blue light ratio was set to 20%. In addition, similar to Park et al. (2013),

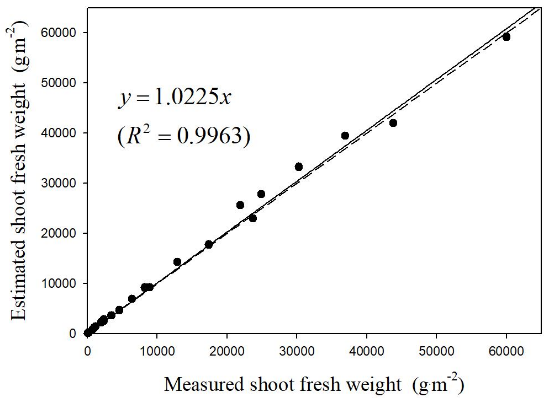

Fig. 8. Validation between the measured and estimated shoot fresh weights of perilla by leaf area.

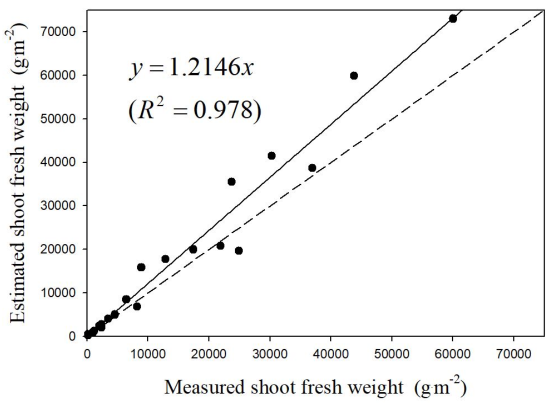

Fig. 9. Validation between the measured and estimated shoot fresh weights of perilla by plant height.

who reported that the Red/Blue/White LED light source was suitable for perilla growth and anthocyanin accumulation, in this study, we supplied a green light ratio of 10%. However, the growth rate differed depending on the type and ratio of the light source. Therefore, further research on the effects of different light ratios should be investigated. Perilla is known as a short-day plant. A previous study (Sul et al., 2022) compared perilla growth by considering treatment groups with 9:15, 12:12, 15:9, and 18:6 LED photoperiod ratios; subsequently, fresh weight, dry weight, leaf area, leaf number and plant height significantly increased. However, electrical energy use efficiency and light use efficiency did not significantly differ in all treatment groups with a day length of more than 12 h (Sul et al., 2022). Therefore, in this study, a 12 h day length was used to model perilla growth.

In conclusion, in this study, growth modeling was performed using an expolinear function to predict perilla growth. The values predicted by modeling and regression were verified by comparison with the measured values. Consequently, the regression equation using leaf area and plant height showed a higher coefficient of determination than the modeling equation using the expolinear function. Measurements of the leaf area or plant height improved the model accuracy because the growth rate in the plant factory could be predicted according to the number of days after transplanting. However, an efficient non-destructive measurement method should be investigated to predict perilla growth.

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완전제어형 식물공장에서 선형지수함수를 이용한 들깨의 생육 모델링

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적 요. 식물공장에서 생육 모델링은 안정적인 생산과 수확량을 조절하는 데 필수적일 뿐만 아니라 환경 데이터와 생육량의 관계를 비교하여 환경 조건을 제어할 수 있는 도구가 되기도 한다. 본 연구는 식물공장에서 재배하는 들깨 [*Perilla frutescens* (L.) Britt.]에 대해 선형지수함수를 이용해 모델링하였다. 광도, 광주기, 혼합광의 비율을 각각 $130\mu mol\cdot m^{-2}\cdot s^{-1}$, 12/12시간, R:G:B(7:1:2)로 설정하여 정식한 후 화아분화가 발생할 때까지 12회 생육 조사하였고, 건물중과 생체중 예측을 위해 선형지수함수를 이용하여 모델링하였다. 생체중과 건물중 간의 상관계수는 가장 높은 양의 상관관계(r = 0.996)를 보였고, 생체중과의 관계에서 건물중을 제외하면 엽면적, 초장, 엽수, 마디수, 엽장, 엽폭의 순으로 높은 양의 상관관계를 나타내었다. 생육 예측을 위한 독립변수로 정식 후 일수, 엽면적과 초장을 사용하였는데, 생육 예측을 위한 적합한 독립변수로는 엽면적이었다. 다만, 생육을 예측하기 위한 파괴적인 방법 또는 비파괴적인 방법에 대해 고려해야 할 것이다. 본 연구에서 식물공장에서 들깨의 생육을 예측하기 위한 생육 모델식을 만들었다.

추가 주제어 : 생육 예측, 들깨, 엽면적, 초장, 지상부 건물중, 지상부 생체중