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A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

Modeling of Whole Canopy Photosynthesis of Romaine Lettuce Using Controlled Growth Chamber

제어형 생육 챔버를 사용한 로메인 상추의 군락 광합성 모델링

BY

TAE YOUNG KIM

FEBRUARY, 2017

MAJOR IN HORTICULTURAL SCIENCE AND BIOTECHNOLOGY
DEPARTMENT OF PLANT SCIENCE
GRADUATE SCHOOL
COLLEGE OF AGRICULTURE AND LIFE SCIENCES
SEOUL NATIONAL UNIVERSITY

Modeling of Whole Canopy Photosynthesis of Romaine Lettuce Using Controlled Growth Chamber

UNDER THE DIRECTION OF DR. JUNG EEK SON

SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL OF

SEOUL NATIO NAL UNIVERSITY

BY

TAE YOUNG KIM

DEPARTMENT OF PLANT SCIENCE

COLLEGE AGRICULTURE AND LIFE SCIENCES

SEOUL NATIONAL UNIVERSITY

FEBRUARY, 2017

APPROVED AS A QUALIFIED THESIS OF TAE YOUNG KIM

FOR THE DEGREE OF MASTER OF SCIENCE

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Modeling of Whole Canopy Photosynthesis of Romaine Lettuce Using Controlled Growth Chamber

Tae Young Kim

Department of Plant Science, Graduate School of Seoul National University

ABSTRACT

The objective of this study was to develop a canopy photosynthesis model of Romaine lettuce that can be applied to plant factories using three parameters of CO_2 concentration, light intensity and growth stage. The plants were grown in plant factory modules and photosynthesis rates were measured in sealed growth chambers made of acrylic. First of all, in combining CO_2 concentration and light intensity conditions, it was analyzed whether it is efficient to fix a certain factor and control (change) the other one. The time constant when controlling the CO_2 concentrations with a fixed light intensity was 3.2 times higher and the deviation was larger than when changing the light intensity. Based on these results, canopy photosynthetic rates of the plants were measured at five CO_2 concentrations (600 to 2200 μmol · mol^{-1}), 5 light conditions (60 to 340 μmol · m^{-2} · s^{-1}), and four growth stages (5, 10, 15 and 20 days after transplanting). The parameterization and regression analysis were used to develop the canopy photosynthesis model according to the growth stage. The canopy photosynthetic rates estimated using

the developed model showed good agreement with the measured ones (R^2 = 0.87). It is expected that the developed model will help to determine the optimum CO_2 concentration and light intensity conditions with growth stage required for the efficient production in plant factories.

Additional key words: CO_2 concentration, growth stage, light intensity, photosynthetic rate, plant factory

Student number: 2011-21184

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GENERAL INTRODUCTION

Photosynthetic rate is an important index to be able to predict and determine the plant growth among many methods (Farquhar et al., 2001). There are two types of measuring the photosynthetic rate; measuring single leaf and canopy. An assumption in using single leaf is that a leaf photosynthetic rate represent the whole crop photosynthetic rate. Due to its simplicity this method has been applied for long times (Chang etal., 2009; Flexas et al., 2007; Kaipianinen and Pelkonen, 2007; Shin et al., 2011; Shipp et al., 1998), but also it has limitations in accuracy and reliability (Elmore, 1980; Evans, 1996). Takahashi et al. (2008) suggested measuring canopy photosynthetic rates for practical purpose. In general, photosynthetic rates are affected by environmental factors such as light, carbon dioxide, and temperature. In addition, the response of the plants differs with growth stage (Perez-Peña and Tarara, 2015) because the light use efficiency decreases as leaf area increases (Green, 1987; Leadly et al; Jung et al., 2016). Therefore, parameters of photosynthetic models should be described with time. In order to perform efficient environmental management in plant factories, photosynthetic models that consider various environmental factors and growth stages are required. For this purpose, it is necessary to measure photosynthesis at combined conditions of various environmental factors and to obtain an effective

application method considering the responses of plants and the system responses to changes in environmental factors. The objectives of this study were to find an effective measurement method to combine the conditions of CO_2 concentration and light intensity when measuring the canopy photosynthesis rate in a sealed growth chamber and to develop a canopy photosynthesis model of Romaine lettuce that can be applied to plant factories using three parameters of CO_2 concentration, light intensity and growth stage.

LITERATURE REVIEW

Canopy Photosynthesis Model

The first canopy photosynthesis model for light interception and photosynthesis rate was developed by Monsi and Saeki (1953). They described the distribution of light exponentially. The slope (extinction coefficient, k) is similar to the Beer-Lambert's law and is mainly dependent on the angle of the leaf. A rectangular hyperbolic curve was used to represent light-response curves of photosynthesis, and the canopy photosynthetic rate was calculated as the sum of leaf photosynthesis rates (Acock et al., 1971; Thornley 1976; Charles-Edwards, 1981; Goudriaan et al., 1985). This model successfully included the essential part of the canopy photosynthesis in a mathematical way. Many photosynthesis studies showed an equation that presumes the leaf photosynthesis of whole crops, assuming that the distribution and capacity are the same for individual chloroplasts (Boote et al., 1997; Farquhar, 1989; Norman, 1993). This led to the next generation big-leaf models. Big-leaf models (BLMs) is a model dealing with a canopy in one large layer. Recent crop models has expanded from single leaf to canopy for an accurate prediction of canopy photosynthetic rates.

Dynamic Environment Control using Growth Chamber

Chamber experiments capable of controlling growth were mainly focused on the reaction of plants to the changes in light, temperature, and CO_2 (Caporn and Wood, 1990; Frantz et al., 2004; Monje and Bugbee 1998). In addition, the response of plants was monitored whether the plant tended to adapt to various environments in short- or long-term (Li et al., 2012; Mun et al., 2011; Wheeler et al., 1994). According to the previous literatures, there is a time lag when measuring the photosynthetic rate using the chamber. Because this delay time directly affects the total CO_2 emissions, it must be excluded (Davidson et al., 2002; Perez-Priego et al., 2015; Pihlatie et al., 2013). In this way, it is necessary to understand and analyze the response of the plants according to environmental conditions when measuring photosynthesis using the chamber, and to collect reliable data (Langensiepen 2012).

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CHAPTER I

Effective Measurement of Canopy CO_2 Exchange of Romaine Lettuce (*Lactuca sativa* L.) Using Controlled Growth Chamber

Abstract

The objective of this study is to find out an effective measurement method in combining CO_2 concentration and light intensity conditions when measuring canopy photosynthetic rates with closed growth chamber. The plants were grown in plant factory modules and photosynthesis rates were measured in sealed growth chambers made of acrylic (1000 x 800 x 500 mm). In the first experiment, the response of the plants was measured by changing the light intensity at a fixed CO_2 concentration while measured by changing the light intensity at a fixed CO_2 concentration. Then the reaction time of the plants was compared using the time constant. In the second experiment, based on the average time constant obtained from the first experiment, the photosynthetic rates were measured by changing light intensities at the CO_2 concentration of 1000 μmol · mol^{-1} were compared

with those measured by changing CO_2 concentration at the light intensity of 200 μmol · m^{-2} · s^{-1}. As a result, the time constant when controlling the CO_2 concentrations with a fixed light intensity was 3.2 times higher and the deviation in photosynthesis estimates was larger than when changing the light intensity. Therefore, it is more efficient to control the light intensity than to control the CO_2 concentration in various environment combinations with short-term measurement.

***Additional key words*:** closed chamber, CO_2 concentration, light intensity, photosynthetic rate, time constant

Introduction

Efficient environmental control by understanding crop growth rates under various environmental conditions is an important key for planned crop production in plant factories. Photosynthetic rate that directly affected by environmental factors (Pastenes et al., 2003) is known as a common index to predict the crop growth rate.

In general, photosynthetic rate of a single leaf was used to understand the total photosynthetic rate of the entire plant (Chang et al., 2009; Flexas et al., 2007; Kaipianinen and Pelkonen, 2007; Shin et al., 2011; Shipp et al., 1998). However, the photosynthetic rate of the single leaf is not always representing that of the entire plant (Elmore, 1980; Evans, 1996). To estimate accurate crop growth, more reliable photosynthetic models based on canopy photosynthetic rates should be required.

Since photosynthesis is involved in all the elements that affect the growth of crop, it is very ideal to study the response of crops by setting all the environmental factors as variables and construct them as models. In fact, several environmental factors, such as light intensity and CO_2 concentration, have been studied on photosynthesis (Caporn and Wood 1990; Wangner and Reicosky 1992; Wheeler et al., 1992; Steduto et al., 2002; Song et al 2015).

In order to perform efficient environmental control in plant factories, it is necessary to construct a photosynthesis model considering various environmental factors. For this purpose, it is required to measure photosynthesis for multi-dimensional combinatorial conditions of various environmental factors, and obtain an effective application method of combinatorial conditions considering plant and system reactions to the changes of environmental factors.(Suh et al., 2006; Mcdermitt et al., 1989) In combining CO_2 concentration and light intensity

conditions, it should be analyzed whether it is efficient to fix a certain factor and control (change) the other one.

The objective of this study was to establish an effective way of combining CO_2 concentration and light intensity conditions in measurement of canopy photosynthetic rates considering plant responses and controlled characteristics of growth chamber.

Materials and Methods

Plant Growth Conditions

Romaine lettuces (*Lactuca sativa* L. 'Asia Heuk Romaine' , Asia seed Co., Ltd. Seoul, Korea) were cultivated in a plant factory at a light intensity of 150±20 μmol · m^{-2} · s^{-1}, photoperiod of 16/8 (day/night), light spectrum of red:blue:white=8:1:1, temperature of 21±1℃, CO_2 concentration of 700~1000 μmol · mol^{-1}, and relative humidity of 70 ± 5%.

Controlled Closed-Chamber for CO_2 Measurement

Closed acrylic chambers (1000 x 800 x 500 mm, W x L x H) with adjustable light intensity, temperature, relative humidity, and wind velocity were installed

for crop growth and CO_2 measurement (Fig. I-1). Red, blue, and white LEDs (FGL-B1200, FC Poibe Co., Ltd., Yeongdeungpo, Korea) with a ratio of 8:1:1 were used. For environmental condition control, sensors for CO_2 concentration, temperature and relative humidity was installed (S-VT200B, Soha Tech. Nowon, Korea) was installed. Indoor temperature and wind velocity were as maintained at 21±1.5℃ and 0.3m s^{-1}, respectively. In order to absorb the moistures from due to the transpiration, slica-gels were used to maintain the relative humidity at 70±5%. CO_2 concentrations in the chamber were measured for 90 min with and without plants crops each at a CO_2 concentration of 1000 μmol • mol-1 by using a CO_2 analyzer (LI-820, LICOR, Lincoln, NE, USA). Every measured data Micro-climate factors were stored in a data logger (CR1000, Campbell Scientific, Logan, UT, USA).

Exp 1: Comparison of plant response to the change in light intensity or CO_2 concentration

The experiment was conducted to compare the light intensity and CO_2 concentration changes. Treatment 1 consists of CO_2 concentration of 1000 μmol · mol^{-1} with different light intensities of 340, 270, 200, and 130 μmol · mol^{-2} · $s^{-1}$and treatment 2 was held under light intensity of 200 μmol · m^{-2} · s^{-1} with CO_2 concentrations 600, 1000, 1400, and 1000 μmol · mol^{-1}. Different

environmental conditions for each growth stages are controlled in temperature 21±2.0℃ and relative humidity 72±18%.

CO_2 concentration consumption was measured in 1 second interval and saved every in 5 seconds intervals. A time constant indicating the response of the system is estimated using a time constant measured as the time it takes to reach 63.2% of the target value is sought in the following equation.

$$Y = A(1 - e^{\left(-\frac{t}{T}\right)} \quad \text{(Eq. I-1)}$$

A: target value, t: time, T: time constant

Exp 2: Comparison of photosynthetic rates at varying light intensity or CO_2 concentration

Whole canopy photosynthetic rates of Treatments 1 and 2 were compared. Treatment 1 in Exp 2 had the same environmental conditions as Treatment 1 in Exp 1 (2200 μmol · mol^{-1}) but added 60 μmol · m^{-2} · s^{-1} light intensity condition. Treatment 2 in Exp 2 held the same as Treatment 2 in Exp 1 but 2200 μmol · mol^{-1} CO_2 level was added as another condition (temperature 21±1.5℃ and relative humidity 72±15%). Canopy photosynthetic rate was calculated by measuring CO_2 decrement for all other windows excluding the time lag identified in Exp 1. The experiment was repeated three times.

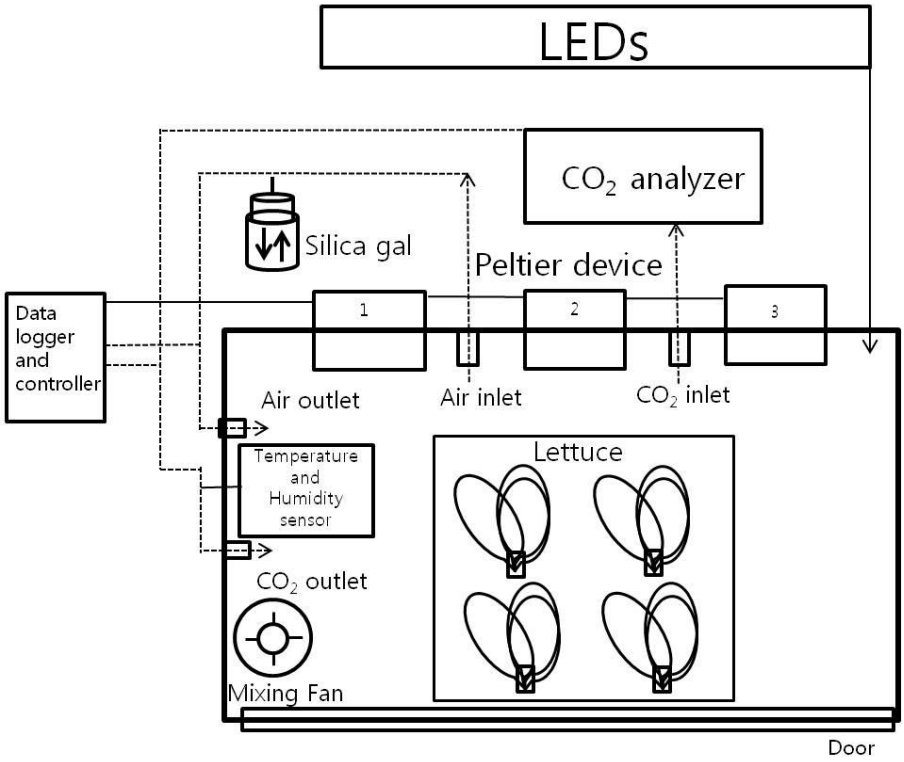


Fig. Ⅰ-1. Schematic diagram of a controlled growth chamber using light-emitting diodes.

Results and Discussion

Chamber Leakage

For testing chamber leakage, CO_2 concentration decrement was measured with and without plants while maintaining similar environmental conditions (i.e. 1010 $\mu mol \cdot m^{-1}$ CO_2 concentration, temperature, and humidity at the same condition and similar light spectrum). CO_2 concentration after one and a half hour without the presence of the plants was measured to be 1010 $\mu mol \cdot m^{-1}$ (Fig. I-2).

According to Wheeler (1992), leakage rate increases as chamber size increases. Due to reasons stated above closed system chambers in the past have been manufactured in small sizes; 0.19 m^3 (Dutton et al., 1988), 0.3 m^3 (Knight et al., 1988), and 0.2 m^3 (Schwartzkopf and Stofan, 1981). Proving 0.4 m^3 sized chamber to be reliable. But when measuring CO_2 consumption for a long period, CO_2 leakage before and after the experiment must be measured and calibrated into the calculations. Because chamber leakage directly affects to the photosynthetic rate.

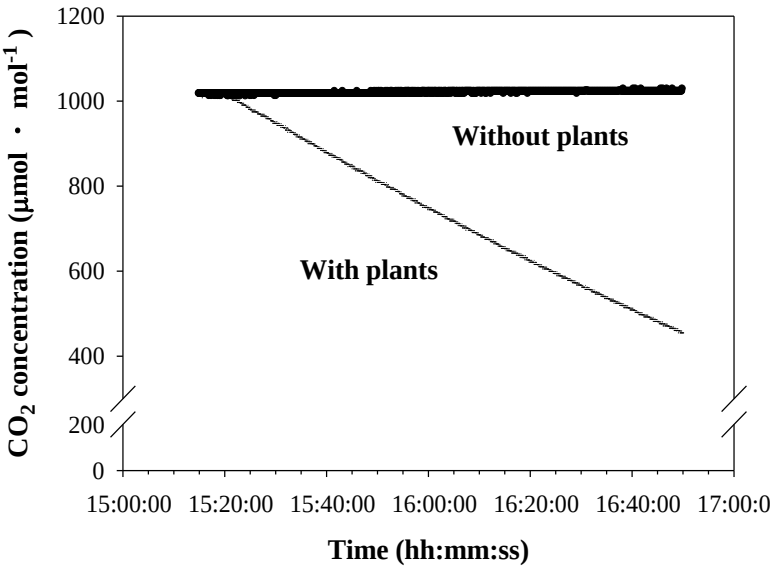


Fig. Ⅰ－2. Changes in CO_2 concentrations in the growth chamber with and without plants, respectively.

Measurement of Crop CO_2 Consumption and Time Constant

Fig. I-3 and I-3-1 shows the results of Exp 1. CO_2 consumption decreased rapidly as light intensity increased in Treatment 1 and CO_2 consumption also decreased rapidly as CO_2 concentration increased. As shown in Fig. I-4, the time constant for A (200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ light intensity with fixed 1000 $\mu mol \cdot mol^{-1}$ CO_2 concentration) was 30 seconds and 300 seconds. The time constant for different environmental conditions varied but when the average was taken and compared, the time constant in Treatment 1(at fixed CO_2 concentration with varied light intensity) was 3.24 times shorter than that in Treatment 2. This can be interpreted as lettuce being more sensitive to change in light intensity than change in CO_2 concentration. Time formula in Fig. I-4 (B) is as follows.

$$Y = 2.5E - 5(1 - e^{-t/60}) \qquad \text{(Eq. I-2)}$$

Langensiepen (2012) stated that the response time for plant adjustment will be different for each condition when environments are artificially controlled. Bazot (2008) indicated that CO_2 concentration changes in the atmosphere bring about a complex response to the plant's physiology. 500-600 $\mu mol \cdot mol^{-1}$ CO_2 concentration was injected within 5 minutes for all treatments in Treatment 2. The sharp change in CO_2 concentration in the chamber within a short period of

time (10 minutes) needs to be followed by sufficient response time for the plants to adapt to its circumstances. Sestak (1971) argued that it would take over an hour for plant stoma to fully adjust to change in CO_2 concentration. In order to obtain a various CO_2 responses depending on the concentration, sufficient measurement time is required.

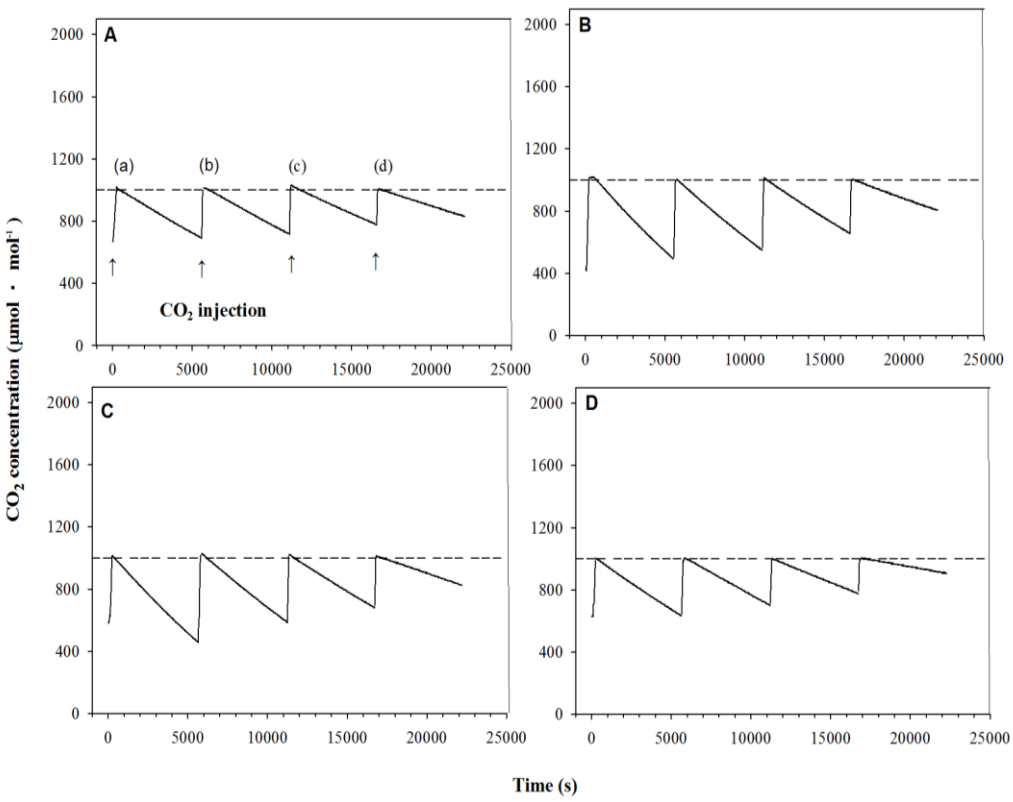


Fig. Ⅰ-3. Decrement of CO_2 concentration in response to the light intensities of 340 (a), 270 b), 200 (c), and 130 (d) μmol · mol^{-2} · s^{-1} at a CO_2 concentration of 1000 μmol · mol^{-1}. A, B, C, and D indicate 5, 10, 15, and 20 days after transplanting, respectively.

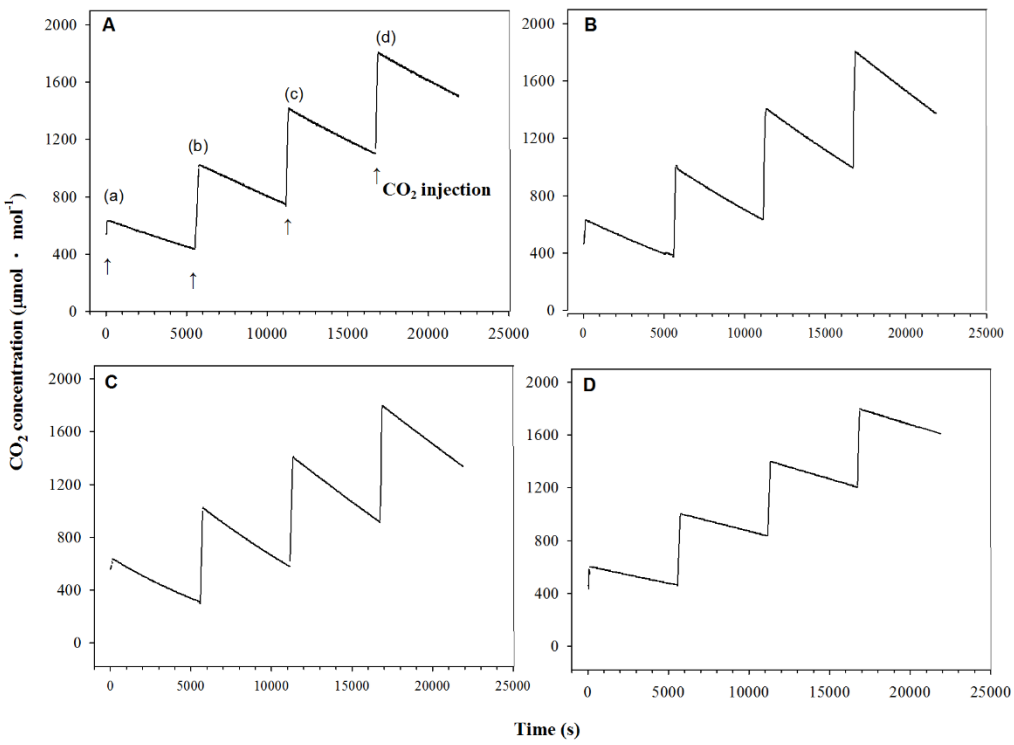


Fig. Ⅰ－3-1. Decrement of CO_2 in response to the CO_2 concentrations of 600 (a), 1000 (b), 1400 (c), and 1000 (d) μmol · mol^{-1} at a light intensity of 200 μmol · mol^{-2} · s^{-1}. A, B, C, and D indicate 5, 10, 15, and 20 days after transplanting, respectively.

Comparison of Canopy Photosynthetic Rates at the Same Environmental Conditions

Fig. I-5 shows the result of Exp 2. The photosynthetic rates measured at 1 minute and 6 minutes of time lags were compared. The photosynthetic rates in Treatments 1 and 2 increased with increasing light intensity and CO_2 concentration, respectively. The deviation in Treatment 2 was larger than that in Treatment 1.

According to Gros and Chabot (1978) research, there was a time lag of several seconds that the light changed according to the change in light intensity when measuring photosynthetic rates. In other words, the environmental factor that makes it possible to know the response of crops for a few seconds is light. According to Creese et al., (2014), it is clear that the response to stimulation by stomatal conductance is clear from light when compared with the response of CO_2 concentration. When CO_2 is a control element, it is considered that it is difficult to analyze the response by mechanical measurement within a certain short-period of time. Therefore, in order to obtain reliable data, experiments must be performed after appropriate measurement time is executed for each environmental control element.

In conclusion, holding light intensity constant with varying CO_2 concentration in a short-term (under 1 hour) lead to inappropriate measurement

in controlled closed-chamber system. Holding CO_2 constant with varying light intensity led to efficient and reliable canopy photosynthetic rate. It was possible to identify a reliable and accurate canopy photosynthesis measurement method using closed growth during short-term by combining various environmental factors. The method proposed in this paper could be applied to the establishment of specific canopy photosynthesis models in the future.

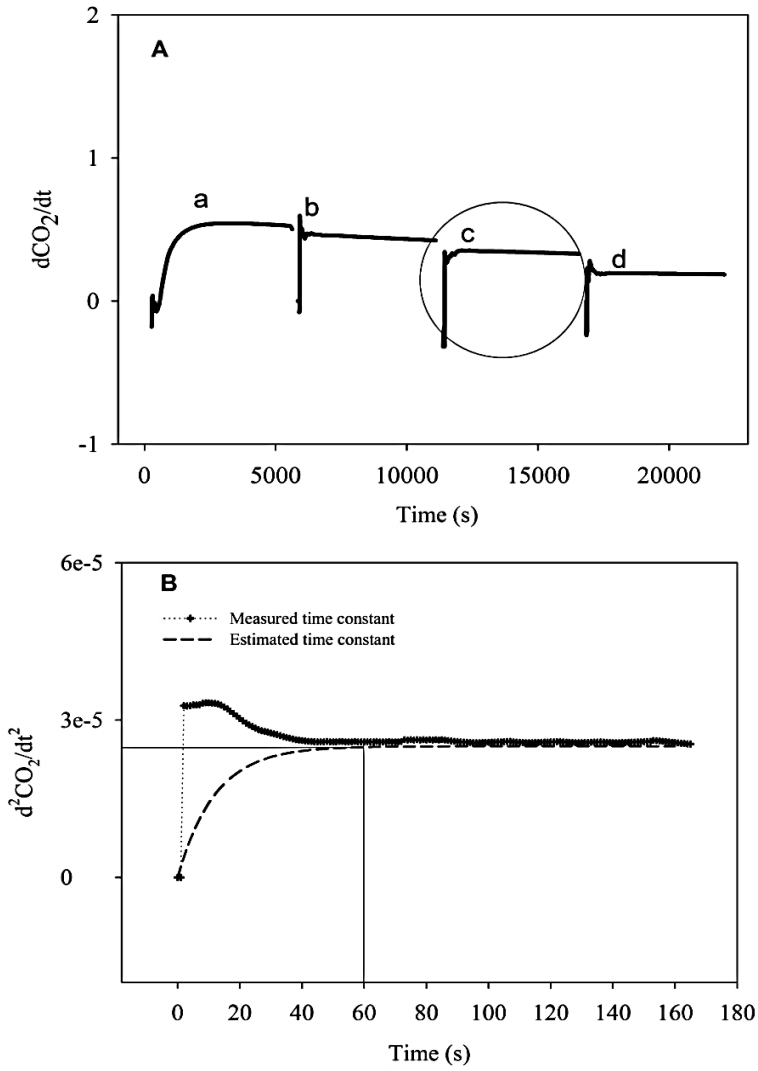


Fig. Ⅰ-4. Slopes of CO_2 changes in treatment 1 (CO_2 1000 μmol · mol^{-1} under varying light intensities of 340 (a), 270 (b), 200 (c), and 130 (d) μmol · mol^{-2} · s^{-1}). B indicates the second derivative of A (in case of light intensity 200 μmol · mol^{-2} · s^{-1} and CO_2 1000 μmol · mol^{-1} at DAT 10)

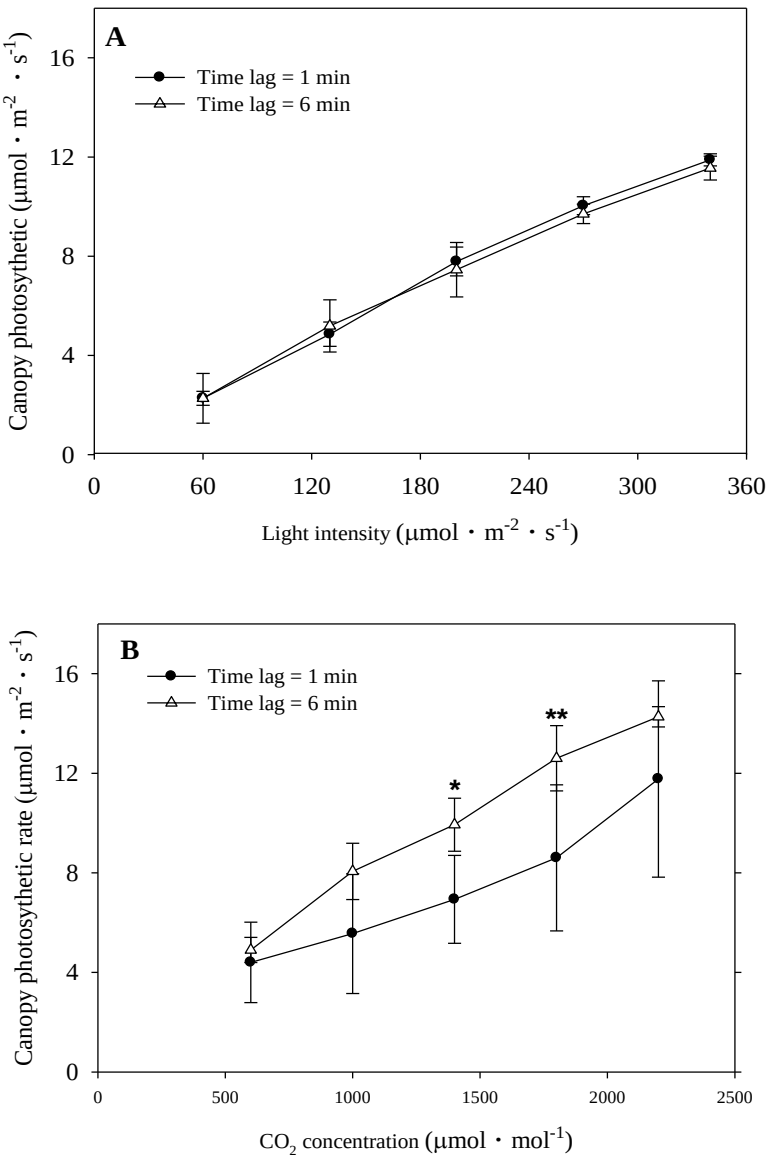


Fig. Ⅰ－5. Comparison of canopy photosynthetic rate under the same environmental conditions. A is changing light intensities at a CO_2 concentration of 1000 μmol · mol^{-2}. B is changing CO_2 concentrations at a light intensity of 200 μmol · m^{-2} · s^{-1}. NS, *, **, *** Nonsignificant or significant at $P < 0.05$, 0.01 or 0.001, respectively.

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CHAPTER II

Modeling of Canopy Photosynthetic Rate using Light Intensity, CO_2 Concentration, and Growth Stages in LED Plant Factory

Abstract

The objective of this study was to develop a canopy photosynthesis model of Romaine lettuce, which can be applied to plant factories, using three variables of CO_2 concentration, light intensity and growth stage. Canopy photosynthetic rates of the plants were measured at 5 CO_2 concentrations (600 to 2200 μmol · mol^{-1}), five light conditions (60 to 340 μmol · m^{-2} · s^{-1}), and four growth stages (5, 10, 15 and 20 days after transplanting) by using four sealed-acrylic chambers (1000 x 800 x 500 mm). The following photosynthetic model was statistically analyzed for the response of the plants to the growth stage: $p = \alpha (I / I + \beta) * (c / c + \gamma)$. As a result, α, β, γ parameter values were obtained according to the growth stage. A canopy photosynthesis model of the plant was developed through regression analysis. The canopy photosynthetic rates estimated using the developed model showed good agreement with the measured ones (R^2 = 0.87). It was concluded

that the model developed in this study will contribute to the determination of optimal CO_2 concentration and light intensity with growth stage in plant factories.

Additional key words: photosynthesis model, plant factory, Romain lettuce, three-variable model, growth stage

Introduction

Plant factory using artificial light are highly energy-intensive production systems (Mills 2012). These production systems require efficient production management (Li et al., 2016). The photosynthetic rate is an indicator of the growth state and growth rate of crops and is an important factor in constructing an efficient production system.

Existing photosynthesis models are built on the photosynthesis model with CO_2 as an explicit variable. The model based on light intensity and CO_2 change has been studied as rectangular hyperbolae (Acock et al., 1971; Acock and Allen 1985; Goudriaan et al., 1985; Thornley 1976). Recently, there have been recent studies on harmonizing the canopy level from the leaf photosynthesis level in the recent crop modeling (Hikosaks et al., 2016). However, the photosynthetic

measurement value of single leaf is a limit to represent the entire crop. Whole-canopy photosynthetic measurements indicate that crop growth prediction is more closely related to crop yield than single leaf measurement value. Therefore, photosynthesis measurement in the construction of photosynthesis model requires whole canopy photosynthesis measurement.

Existing photosynthesis models have estimated photosynthesis by light and CO_2, but have not been applied to photosynthesis models with time. The response of the crops to different growth stages is different (Perea pena and Tarara, 2015), and the efficiency of light utilization decreases as the leaf area increases (Green, 1987; Leadly et al; Jung et al., 2016). Niinemets (2016), who photo-plasticity and photosynthesis capacity differed according to the leaf age. Therefore, factors for photosynthetic reaction over time should be applied to the model.

The objectives of this study were to analyze canopy photosynthetic rates at varying combinations of CO_2 concentration, light intensity, and growth stage and develop a canopy photosynthetic model using the three variables by modifying the photosynthesis model for plant factory.

Materials and Methods

Plant Cultivation Conditions

Romain lettuce (*Lactuca sativa* L. 'Asia Heuk Romaine' Asia seed Co., Ltd., Seoul, Korea) was hydroponically grown with deep flow technics (DFT) systems under red:blue:white=8:1:1 light spectrum, 150±20μmol·m^{-2}·s^{-1} light intensity, 16 hours light frequency, 21±1℃ temperature, 1000 μmol · mol^{-1} CO_2 concentration level, and 70±5% relative humidity (RH) conditions.

Measurement of CO_2 Concentration

Acrylic chambers (1.0 x 0.8 x 0.5 m) were used for measuring canopy photosynthetic rate (Fig. II-1). Sensors for temperature, CO_2, and RH (S-VT200B, Soha Tech, Seoul, Korea) were installed inside the chamber. The temperature was controlled by peltier-devices. Red, blue, and white light-emitting diodes (FGL-B1200, FC Poibe Co., Ltd., Seoul , Korea) were used as light sources. Increase in relative humidity due to transpiration was controlled by a silica gel installed in the chamber. Wind speeds around plants were maintained as 0.3-0.5 m · s^{-1}. CO_2 concentration was measured by a CO_2 analyzer (LI-820, LI-COR, Lincoln, NE, USA) every five seconds. The measured data of CO_2 concentration, temperature, and RH were stored into a data logger (Campbell Scientific, Inc., Logan, UT, USA) every 5 seconds.

Calculation of Canopy Photosynthetic Rate

For measuring canopy photosynthetic rate, changes in CO_2 concentration in the chamber were measured at different growth stages for given CO_2 concentrations with varying light intensities: 5 growth stages (5, 10, 15, and 20 days after transplanting) x 5 CO_2 concentrations (600, 1000, 1400, 1800, and 2200 $\mu mol \cdot mol^{-1}$) x 5 light intensities (60, 130, 200, 270, and 340 $\mu mol \cdot m^{-2} \cdot s^{-1}$). In order to obtain photosynthetic rate, the CO_2 consumption amount during the measuring period excluding time lag were multiplied by chamber volume and divided by leaf areas (Takahashi et al., 2008). CO_2 loss due to the leakage of the chamber was considered (ventilation rate was 0.09 m^2/h^{-1}) when calculating the photosynthetic rate. CO_2 emission due to root respiration was around 0.69% of the total CO_2 consumption and was considered negligible.

Development of Canopy Photosynthetic Rate Model

From the basic formula of the photosynthesis model (Farquhar and Caemmerer, 1982), a modified photosynthetic model using time variables were developed as follow:

$$P = \alpha(t)\frac{I}{I+\beta(t)} \times \frac{C}{C+\gamma(t)} \quad \text{(Eq. II-1)}$$

where, *I*, *C*, and *t* are light intensity (μmol · m^{-2} · s^{-1}), CO_2 concentration (μmol · mol^{-1}), and days after transplanting (DAT), respectively. The values of *α(t), β(t),* and *γ(t)* were obtained through regression analysis with photosynthetic rates under various combinations of light intensity, CO_2 concentration, and growth stage. All regression analyses of simple modified models were conducted using the statistical program SPSS (IBM, New York, NY, USA).

Validation of the Whole Canopy Photosynthesis Model

The simple multiplication model was validated by linear regression analysis comparing measured canopy photosynthesis rates with estimated canopy photosynthesis rates. The model was validated using the plant at the same growth stage as used for model development.

Results

Classification of Growth Stages

Both leaf area and fresh weight increased over time but showed drastic increase at the end stage (Fig. II-2). Analytical result showed a correlation coefficient of 0.99 between days after transplant and fresh weight and 0.98 between days after transplant and leaf area. Thus growth stage was classified according to days after transplant. Since leaf area and fresh weight did not show much increase from Day after transplant to 5 days after transplant, stage one was classified as 5 days from transplant. Significant growth was recorded from day 6 to the last day of observation (day 20) and stage 2, 3, 4 were classified in 5 day intervals.

Canopy Photosynthetic Rate with Growth Stage

At each constant CO_2 concentration, the rate of photosynthesis increased as the light intensity increased. As the growth progressed, the rate of photosynthesis tended to decrease (Fig. II-2).

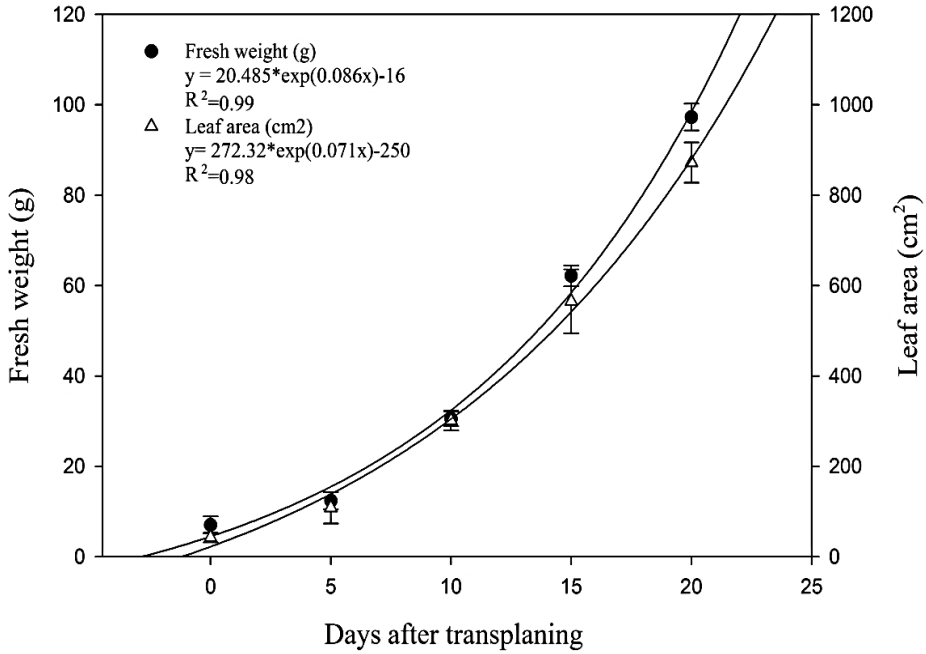


Fig. Ⅱ- 1. Quantitative analyses of fresh weight (circle) and leaf area (open triangle) of lettuce with days after planting.

Estimation of Parameter Values of Canopy Photosynthesis Model Using Growth Stage

The results of estimating the values of *α(t), β(t),* and *γ(t)* are shown in each DAT (Eq.II-1). The values were obtained as; 55.076, 477.595, 231.028 at DAT 5; 138.842, 1968.326, 126.259 at DAT 10; 107.809, 1707.068, 159.003 at DAT 15; and 43.964, 69.256, and 221.398 at DAT 20. The values of R^2 were estimated to be 0.95, 0.96, 0.94, and 0.87 at DAT 5, 10, 15, and 20, respectively.

$$f = ut^2 + vt + w \qquad \text{(Eq. II-2)}$$

Each growth stage parameter was regression analyzed again and derived as follows: Eq. II-2 of each vales of $q, g,$ and k was estimated (Table II-1). Photosynthetic rates were measured at combined CO_2 concentration and light intensity conditions at each growth stage (Fig. II-2). Based on these results, the model was expressed as Eq. II-3. Compared with measured photosynthesis, the model performed with slight overestimated according to light intensity (Fig. II-4).

$$P = (-1.47T^2 + 36.61T - 81.99) \times \frac{I}{I - 25.07T^2 + 634.42T - 2017.80} \times \frac{C}{C + 1672T^2 - 41.71T + 392.41} \qquad \text{(Eq. II-3)}$$

Validation of the Canopy Photosynthesis Model

Estimated canopy photosynthetic rates using light intensity, CO_2 concentration, and growth stage (DAT) showed a good agreement with measured ones having $R^2 = 0.87$ over growth stage (Fig. II-5).

Table Ⅱ-1. Equations of α, β, and γ with days after transplanting (t, DAT).

Parameter	Coefficient			R^2
	u	v	w	
α	-1.476	35.615	-81.999	0.94
β	-25.075	-634.42	-2017.8	0.97
γ	1.672	-41.714	392.414	0.92

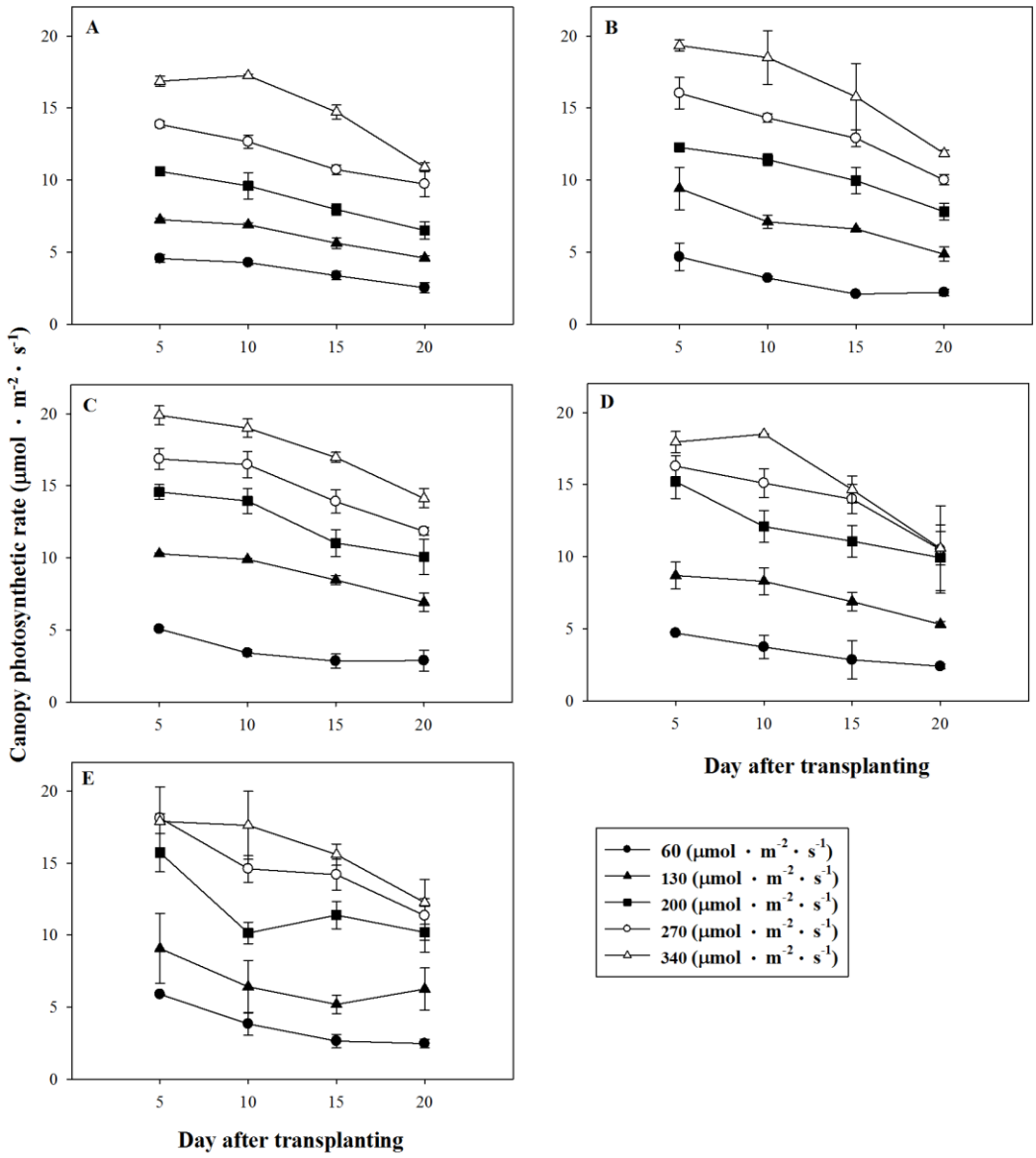


Fig. Ⅱ-2. Changes in canopy photosynthetic rate of lettuce with growth stage and light intensity. A, B, C, D, and E indicate CO_2 concentrations of 600, 1000, 1400, 1800, and 2200 μmol · mol^{-1}, respectively.

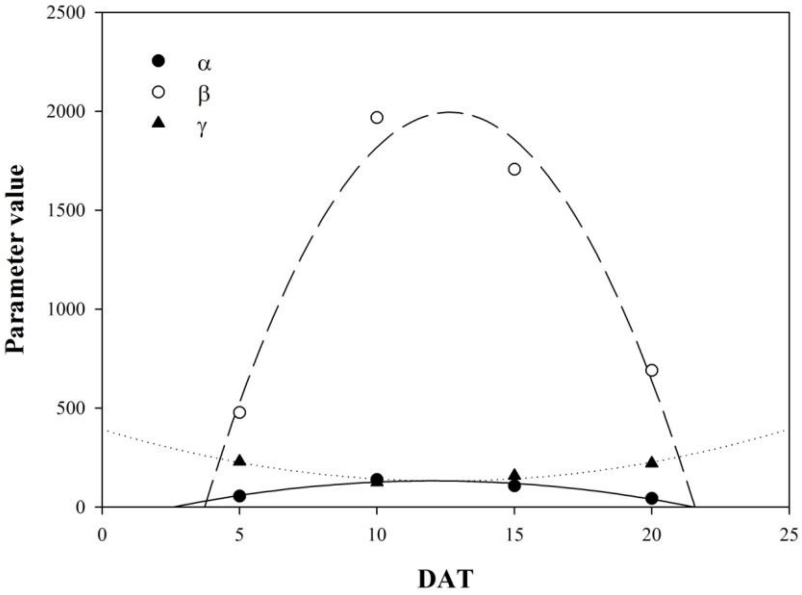


Fig. Ⅱ-3. Parameter values of α, β, and γ with days after transplanting (DAT).

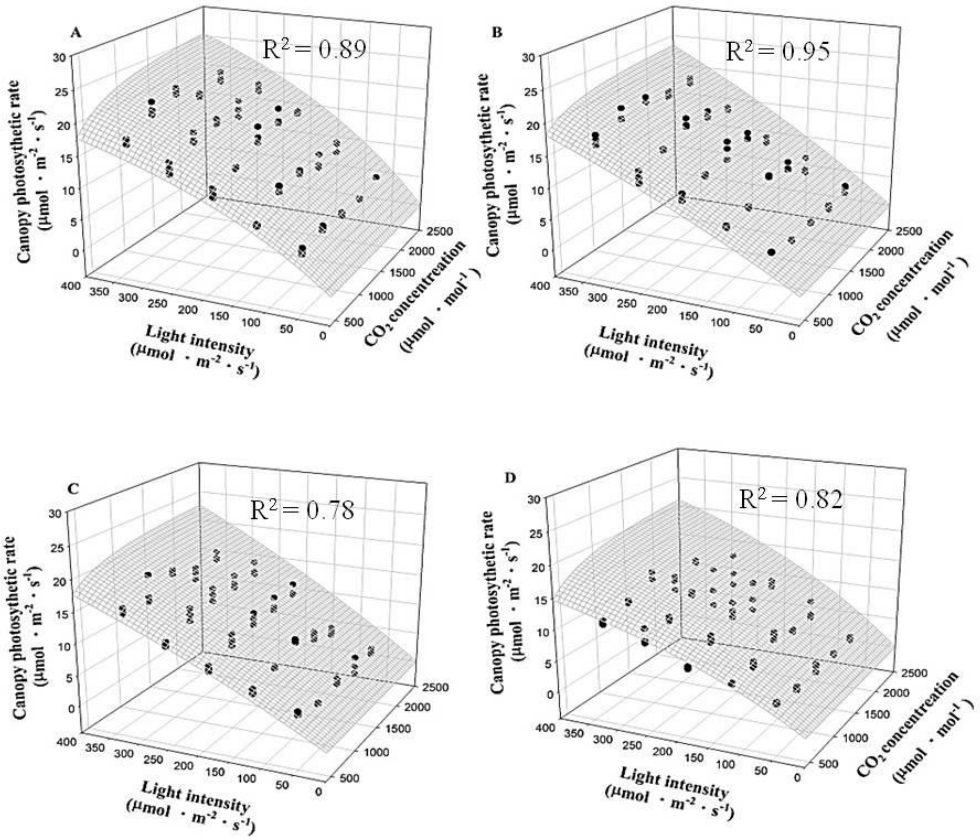


Fig. Ⅱ-4. Comparison of measured (symbols) and estimated values (mesh) for Canopy photosynthetic rate under combined conditions of light intensity and CO_2 concentration with day after transplanting (DAT). A, B, C, and D indicate DAT 5, 10, 15, and D, respectively.

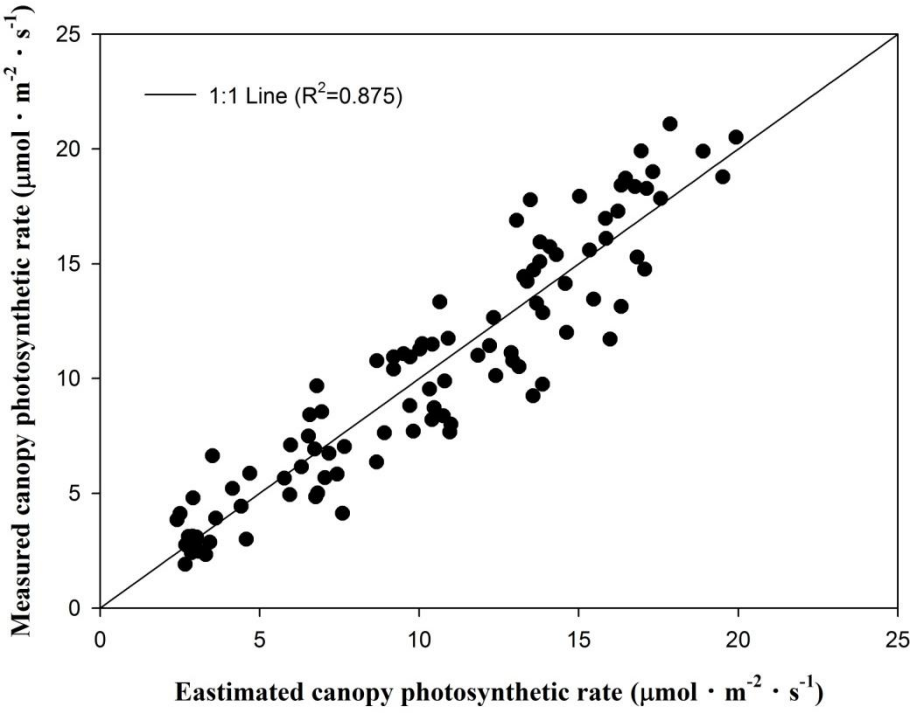


Fig. Ⅱ-5. Validation of measured and estimated canopy photosynthetic rates over growth stage.

Discussion

The growth stage of plants is considered important in constructing practical photosynthetic models because plants have different responses at different stages. Fresh weight was used as an index for classification as germination, vegetation, and reproduction stages (Takatsuji, 2007), while photosynthetic rate used (Kim et al., 2013; Li et al., 2009). Although dividing the growth stage can vary depending on the characteristics of the plant, Li (2001) reported that the fresh weight was the most economic key element in classifying leaf vegetables. Therefore, it is appropriate to separate the growth stage of leaf vegetables with fresh weight.

The R^2 values of canopy photosynthetic rates estimated by the model varied from 0.95 to 0.78 at each stage with slight overestimations (Fig. II-4). It seems to be because the characteristics of the canopy structure was not considered in the photosynthesis model (Monsi et al., 1973). De wit (1965) indicated that the photosynthetic rate has a relation with absorption, reflection, penetration of light in the canopy structure, and therefore light interception by the canopy should be analyzed.

Olessen and Grevesen (1997) also stated that light extinction coefficients differed depending on plant type. Previous researches indicated that fruit vegetables such as tomato, cucumber, and paprika has a light extinction

coefficient of 0.63~0.86 and cauliflower's light extinction coefficient is 0.4~0.65. The light extinction coefficients depend on leaf and canopy conditions, and the difference in the coefficient again contributes to environmental conditions. Especially in a closed plant production system, light interception significantly differs depending on light reflection and light diffusion.

Among various environmental factors, light is the most influential variable in plant growth and development (Inada and Yabumoto, 1989). Due to the characteristics of lettuce, the higher the intensity of light, the more the growth of lettuce grows (Pavlou et al., 2007). The increase in light intensity increases nitrate reductase in lettuce (Gaudreau et al., 1995).

In addition, enrichment of CO_2 concentration promotes the growth of lettuce (Caporn 1989; Campbell et al., 1990). However, the plant growth by setting the light intensity and CO_2 concentration at saturation point is inefficient. Therefore, modelling of photosynthetic rate using light intensity and CO_2 concentration at each growth stage will be helpful in constructing a strategic plant production system. Therefore, it is expected that the developed model will help to determine the optimum CO2 concentration and light intensity conditions with growth stage required for the efficient production in plant factories.

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CONCLUSIONS

It is efficient to control the light intensity at a given CO_2 concentration when measuring the photosynthetic rate by combining CO_2 concentration and light intensity conditions. The time constant was 3.2 times greater and the deviation of the photosynthetic estimates was higher when adjusting CO_2 concentration at a fixed light intensity. Based on the results obtained in Chapter 1, the photosynthetic model was developed including three variables of light intensity, CO_2, and growth stage. The following photosynthetic model was statistically analyzed for the response of the plants to the growth stage: $p = \alpha (I / I + \beta) * (c / c + \gamma)$. As a result, we obtained parameter values of α, β, γ according to the growth stage and developed a canopy photosynthetic model of plants using regression analysis. The canopy photosynthetic rate estimated using the developed model was well agreed with that measured ($R^2 = 0.87$). The canopy photosynthetic rates estimated using the developed model showed good agreement with the measured ones ($R^2 = 0.87$). It is expected that the developed model will help to determine the optimum CO_2 concentration and light intensity conditions with growth stage required for the efficient production in plant factories.

ABSTRACT IN KOREAN

본 연구의 목적은 CO_2 농도, 광도, 생육단계의 3 변수을 이용하여 식물공장에 적용 가능한 로메인 상추의 군락 광합성 모델을 개발하는 것이다. 작물은 식물공장 모듈에서 재배하였으며, 광합성 속도는 아크릴로 제작한 밀폐 챔버로 측정하였다. 먼저, CO_2 농도와 광도를 조합하는 방법에서, 어떤 환경 요소를 고정시키고 어떤 환경 요소를 제어(변화)시키는 것이 효율적인지 비교 분석하였다. 광도를 고정시키고 CO_2 를 제어하면서 측정한 경우의 시상수(time constant)가 광도를 변화시키는 경우보다 3.2 배 더 높았고 편차가 컸다. 이러한 결과를 바탕으로 CO_2 농도를 고정시키고 광도를 제어하는 방식으로, 5 단계 CO_2 농도조건(600-2200 $\mu mol \cdot mol^{-1}$), 5 단계 광도조건(60-340 $\mu mol \cdot m^{-2} \cdot s^{-1}$) 및 4 생육단계(정식 후 5, 10, 15, 20 일)에 대하여 상추의 군락 광합성 속도를 측정하였다. 파라미터 추정과 회귀분석을 통해 생육단계에 따른 작물의 군락광합성 모델을 개발하였고, 검증 결과 예측치와 측정치는 R^2=0.87 수준으로 일치하였다. 본 연구에서 개발된 상추의 군락광합성 모델은 식물공장의 효율적인 생산을 위한 적정 CO_2 농도와 광도 결정에 기여할 것으로 판단된다.

추가 주요어: 광도, 광합성속도, 생육단계, 식물공장, 이산화탄소 농도

학 번: 2011-21184