A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

Analysis of Growth Factors and Profitability for Quinoa Production as a Leafy Vegetable in a Closed–type Plant Factory System

완전제어형 식물공장 시스템에서 잎채소로서의 Quinoa 생육 요인 및 수익성 분석

BY

JIRAPA AUSTIN

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DEPARTMENT OF HORTICULTURAL SCIENCE

GRADUATE SCHOOL

JEJU NATIONAL UNIVERSITY

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(Supervised by Professor **Young-Yeol Cho**, PhD)

Submitted in partial fulfillment of the requirements

for the degree of Master of Science in Agriculture

August, 2015

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ABSTRACT

Quinoa (*Chenopodium quinoa* Willd.) is a native food plant in Andean region. It is a grain crop, loaded with high antioxidant, anticancer activities, and nutritional values. Until now, most of the attention to this crop has, however, been focused on the seed. It is plausible that the leaves may provide an additional source of food and nutrition. This study was carried out to obtain the optimum electrical conductivity (EC), photoperiod, light intensity, and planting density to develop the model, and to get the basic data to practically design for growth and yield of quinoa (*Chenopodium quinoa* Willd.) for a leafy vegetable in a closed-type plant factory system.

The experiments of the optimum EC, light intensity and photoperiod were conducted with three EC levels (1.0, 2.0, and 3.0 $dS{\cdot}m^{-1}$), two light intensity levels (120 and 143 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$), and three different photoperiod levels (8/16 h, 14/10 h, and 16/8 h, day/night). The shoot fresh weight, shoot dry weight, plant height, leaf area and light use efficiency of plants were higher grown in the EC at 2.0 $dS{\cdot}m^{-1}$ with PPFD of 143 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ under 14/10 h photoperiod than in the other culture conditions. The plants grown under a 16/8 h photoperiod did not flower. Quinoa was a short-day plant in this study. According to the results, the optimum EC at 2.0 $dS{\cdot}m^{-1}$ with PPFD of 143 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ under 16/8 h (day/night) photoperiod could be recommended for growth productivity of quinoa for a leafy vegetable in a closed-type plant

factory system.

The optimum planting density was determined. The plants were arranged to four plant spacing 10, 15, 20 and 25 cm between plants and 15 cm between rows. The planting densities were 27, 33, 44, and 67 plants/m^2. Shoot fresh weight and shoot dry weight per plant were the highest at the planting density of 33 plants/m^2 (15x20 cm). However, shoot fresh weight and shoot dry weight per area were the highest at the planting density of 67 plants/m^2 (15x10 cm).

The models of plant height, CO_2 curve, net photosynthesis rate, and plant growth of quinoa were developed to the linear, quadratic, non-rectangular hyperbola, and expolinear equations. A linear relationship was obtained between plant heights and days after transplanting (DAT). Plant height model was $5.4+0.58 \cdot DAT^{-1}$ (R^2=0.932***). The light compensation point, light saturation point, and respiration rate were 29 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 813 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and 3.4 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. CO_2 saturation point of leaves was 400 $\mu mol \cdot mol^{-1}$ (R^2=0.826***). The crop growth rate and relative growth rate were 22.9 $g \cdot m^{-2} \cdot d^{-1}$ and 0.28 $g \cdot g^{-1} \cdot d^{-1}$, respectively. It is concluded that these models can accurately estimate the plant height, net photosynthesis rate, CO_2 curve, shoot fresh weight, and shoot dry weight of quinoa.

The basic data to practically design an artificial light-used plant factory system for quinoa cultivation were collected and profitability was evaluated. When the yield was 1,000 plants per day, the planting density and light intensity were 0.015 m^2/plant (15×10 cm) and 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. The total number of the plants, cultivated area, and electric consumption were estimated as 25,000 plants, 375 m^2, and 93,750 $\mu mol \cdot s^{-1}$, respectively. The white fluorescent lamps power was 20.4 kW with 1,857 fluorescent lamps (FL, 55 W) and the electricity charge was 2.19 million won per month. If the daily harvest plant was 1,000 plants per day in a closed-type plant factory, the light installation cost, total installation cost, and total production cost were 18.57, 55.70, and 66.85 million won, respectively. The production cost per plant including labor cost was calculated as 320 won, providing that the cultivation period was 25 days and marketable ratio was 80%. Considering the annual total expenses, incomes, and depreciation cost, the selling price per plant could be estimated around 670 won or a little bit higher. From the results, the economic feasibility for quinoa cultivation based on fluorescent lamps in a closed-type plant factory system was estimated. If the selling price per plant was 670 won, the total revenue was 174.4 million won or 0.47 million won/m^2. Excluding the various costs which are estimated to 174.2 million won, the profit was 0.2 million won. In particular, in the case of the product improvement at 90%, the total revenue was 196.0 million won. The profit was 21.6 million won or 57,600 won/m^2.

The results demonstrated that we can provide the optimum environment conditions for quinoa cultivation. We developed models for predicting the growth of quinoa for a leafy vegetable in a closed-type plant factory system.

Furthermore, the economic feasibility was analyzed based on the fluorescent lamp for producing quinoa. We demonstrated the optimum selling price per plant of quinoa for a leafy vegetable in a closed-type plant factory system.

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INTRODUCTION

A plant factory is the technology of protected horticulture which is a new facility to grow plants under a controlled environment that enable high yield and quality production all year around. The operating cost of plant factories is usually high due to intensive energy consumption. It is crucial to choose appropriate crops or cultivars for cultivation at proper time for revenue maximization (Hari et al., 2012; Hu et al., 2014; Morimoto et al., 1995; Tian et al., 2014).

Quinoa (*Chenopodium quinoa* Willd.) is a native food plant in Andean region. It is a grain crop, loaded with high nutritional values. Its leaves and sprouts can also be consumed as in raw or cooked which provide amounts of nutritive values, high antioxidant and anticancer activities (Gawlik-Dzik et al., 2013; Paśko et al., 2009; Schlick and Bubenheim, 1996).

However, until now most of the attention to this crop has focused on the seed. It is plausible that the leaves may provide an additional source of food and nutrition. Moreover, the effects of the electrical conductivity (EC), photoperiod, light intensity and planting density on growth and yield of quinoa (*Chenopodium quinoa* Willd.) for a leafy vegetable in a closed-type plant factory system have not been reported yet.

The objectives of this study were established to evaluate the optimum nutrient solution electrical conductivity (EC), photoperiod, light intensity, and planting density to attain the best quality on yield and plant growth. The study was also carried out to get the basic data which were used for predicting potential effects of a plant factory system on the development rates and the economic feasibility for producing quinoa for a leafy vegetable in a closed-type plant factory system. This thesis consists of four experiments:

Experiment I. Effects of photoperiod, light intensity, and electrical conductivity on the growth and yield of quinoa (*Chenopodium quinoa* Willd.) for a leafy vegetable in a closed-type plant factory system.

Experiment II. Growth response of quinoa (*Chenopodium quinoa* Willd.) to various planting density levels in a closed-type plant factory system.

Experiment III. Development of models for estimating growth and yield of quinoa (*Chenopodium quinoa* Willd.) for a leafy vegetable in a closed-type plant factory system.

Experiment IV. Practical design of an artificial light-used plant factory for quinoa (*Chenopodium quinoa* Willd.) for a leafy vegetable.

Chapter I. Effects of Photoperiod, Light Intensity, and Electrical Conductivity on the Growth and Yield of Quinoa (*Chenopodium quinoa* Willd.) for a Leafy Vegetable in a Closed-type Plant Factory System

Abstract

Quinoa (*Chenopodium quinoa* Willd.) is a native food plant of high nutritional value grown in Andean region. The objectives of this study were determined the optimum photoperiod, light intensity, and electrical conductivity (EC) of nutrient solution on growth and yield of quinoa in a closed-type plant factory system. The experiment on optimum photoperiod was conducted with three different photoperiod levels (8/16 h, 14/10 h, and 16/8 h, day/night) in a growth chamber. The optimum EC of nutrient solution was conducted with three different EC levels (1.0, 2.0, and 3.0 $dS \cdot m^{-1}$) and two different light intensity levels (120 and 143 $\mu mol \cdot m^{-2} \cdot s^{-1}$) under 12/12 h (day/night) and 14/10 h (day/night) photoperiods in a closed-type plant factory. The plants grown under a 16/8 h photoperiod did not flower. The long-day photoperiod delayed the flowering more. Quinoa was a short-day plant in this study. The shoot fresh weight and dry weight per plant of plants grown in the EC at 2.0

dS·m^{-1} under PPFD of 120 μmol·m^{-2}·s^{-1} and 12/12 h photoperiod were the highest than the other culture conditions but all treatments made flowering. The shoot fresh weights, shoot dry weights, plant heights, leaf areas and light use efficiencies of plants were higher grown in the EC at 2.0 dS·m^{-1} with PPFD of 143 μmol·m^{-2}·s^{-1} under 14/10 h photoperiod than the other culture conditions. According to the results, the optimum EC at 2.0 dS·m^{-1} with PPFD of 143 μmol·m^{-2}·s^{-1} under 16/8 h (day/night) photoperiod could be recommended for growth productivity of quinoa for a leafy vegetable in a closed–type plant factory system.

Additional key words: flowering, light use efficiency, nutrient solution, photosynthetic photon flux density

Introduction

A closed-type plant factory system is a controlled environmental facility for plant production. In closed-type plant factory systems, plants are consistently grown all year around with high productivity and less water, nutrition, pesticides and labors are consumed for plant cultivation. Hence, plant factories are sustainable and artificially controlled environment systems which are able to stably produce high quality vegetables. In plant factory, an optimal control for obtaining higher yield and better quality of plants is essential (Hu et al., 2014; Morimoto et al., 1995).

Quinoa (*Chenopodium quinoa* Willd.) is a native food plant in Andean region. Its seed can be a potential raw material for oil extraction. The highest percentage of fatty acids presented in these oils is Omega 6 (linoleic acid), around 50%. The high content of dietary fibers has many positive health effects. The seeds of quinoa are considered to be the edible form of the plant while the leaves have generally been overlooked. The leaves and sprouts can be consumed as in raw or cooked and provide a substantial amount of nutritive values and high antioxidant and anticancer activities (Gawlik-Dzik et al., 2013; Paśko et al., 2009; Schlick and Bubenheim, 1996). The biomass production and allocation of quinoa were affected by photoperiod (12 and 16 h) and irradiance (1,800 $\mu mol \cdot m^{-2} \cdot s^{-1}$) (Schlick, 2000).

The electrical conductivity (EC) values for hydroponic systems range from

1.5 to 2.5 $dS \cdot m^{-1}$. The higher EC hinders nutrient uptake by increasing osmotic pressure, whereas lower EC may severely affect plant health and yield. Some crops can grow with high levels of EC, and even a proper management of EC of the nutrient solution can provide an effective tool to improve vegetable quality. The higher or the lower EC will regard to outer quality (yield and firmness) and inner quality characterized by taste (total soluble solids and acids), nutritional values, antioxidative capacity and aroma volatiles (Auerward et al., 1999; Carrasco et al., 2007; Caruso et al., 2011; Cliff et al., 2012; Feltrin et al., 2012; Krauss et al., 2006; Liopa-Tsakalidi et al., 2010; Rouphael et al., 2006; Sarooshi and Cresswell, 1994; Wu and Kubota, 2008).

Until now, most of the attention to this crop has focused on the seed. It is plausible that the leaves may provide an additional source of food and nutrition, and the effects of the photoperiod, light intensity and EC of nutrient solution on growth and yield of quinoa for a leafy vegetable in a closed-type plant factory system have not been reported yet.

The objectives of this study were established to evaluate the optimum photoperiod, light intensity and EC of nutrient solution to produce quinoa for a leafy vegetable in a closed-type plant factory system.

Materials and Methods

Plant Material

The experiments were conducted from March to August, 2014 in a growth chamber (Multi-room chamber HB-302 S-4H., HANBAEK Co. Ltd., Korea) and a closed-type plant factory (700x500x300 cm, L x W x H) at Jeju National University, Jeju, Republic of Korea. The quinoa seeds sown into 288 cells of a polyurethane sponge (2.5x2.5x2.5 cm) in a plastic tray filled with distilled water.

Experimental Set-up

Three photoperiod conditions, 8/16 h, 14/10 h, and 16/8 h (day/night), were investigated for flowering of quinoa in a growth chamber. The first trial was conducted from March 7, 2014 to April 8, 2014 with three different EC levels (1.0, 2.0, and 3.0 $dS{\cdot}m^{-1}$) under 12/12 h (day/night) photoperiod in a closed-type plant factory. The second trial was done from July 14, 2014 to August 26, 2014 with three different EC levels (1.0, 2.0, and 3.0 $dS{\cdot}m^{-1}$) under 14/10 h (day/night) photoperiod in a closed-type plant factory. Light intensities were 120 and 143 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$.

Closed-type Plant Factory System

Three-band radiation type fluorescent lamps (55 W, Philips Co. Ltd., Amsterdam, the Netherlands) were used (Fig. 1-1). Light intensity (photosynthetic photon flux density, PPFD) was measured with a quantum sensor (LI-190, Li-cor Inc., Lincoln, NE, USA). The temperature and relative humidity were 25°C and 60% in the growth chambers, respectively. The temperature was maintained at 23-25°C in a plant factory system. The relative humidity and CO_2 concentration were not controlled in a plant factory system. The plants were transplanted into the troughs (each trough 250x5x4 cm, L x W x H) at the fourth true leaf stage in a closed-type plant factory. Ten plants were spaced 10 cm apart within each trough and each trough was spaced 10 cm apart (100 plants/m^2). The nutrient film technique (NFT) system with two layers and each layer with six troughs were used for the plant growth system. Total volume of the nutrient solution in the tank was 90 L and the dissolved oxygen concentration was maintained. The nutrient solution was composed of 15 NO_3-N, 1 NH_4-N, 1 P, 7 K, 4 Ca, 2 Mg, 2 SO_4-S $mM{\cdot}L^{-1}$ (Table 1-1).

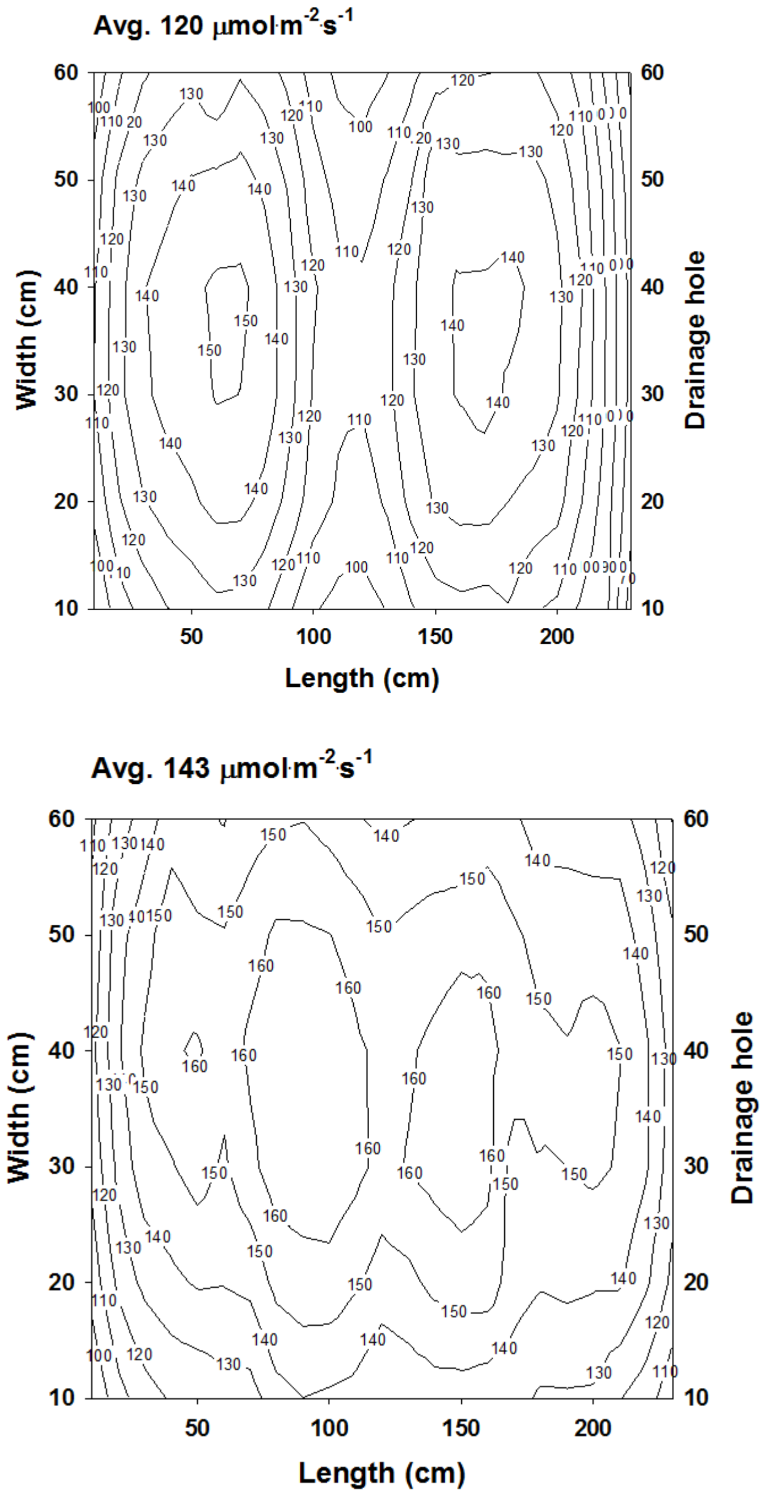

Fig. 1-1. Distribution of light intensities below 3-band radiation type fluorescent lamps.

Table 1-1. The 100 times strength ‘Quinoa’ nutrient stock solution contains the following amounts of various fertilizers.

Component	g stock solution/10L
$Ca(NO_3)_2{\cdot}4H_2O$ (Calcium nitrate)	944
KNO_3 (Potassium nitrate)	708
$NH_4H_2PO_4$ (Ammonium dihydrogen phosphate)	115
$MgSO_4{\cdot}7H_2O$ (Magnesium sulfate)	492
Fe-EDTA (Iron chelate)	38.4
$CuSO_4{\cdot}5H2O$ (Copper sulfate)	0.20
H_3BO_3 (Boric acid)	2.57
$MnSO_4{\cdot}5H_2O$ (Manganese sulfate)	1.27
$ZnSO_4{\cdot}7H_2O$ (Zinc sulfate)	1.32
$Na_2MoO_4{\cdot}2H_2O$ (Sodium molybdate)	0.13

The pH and EC of nutrient solutions were measured daily for each treatment in the nutrient solution tanks. The measurements were pursued with a pH meter (HI 98106, Hanna Instruments Ltd, Bedfordshire, Leighton Buzzard, UK) and a portable conductivity meter (COM-100, HM Digital Inc., Culver City, CA, USA). The pH was adjusted to the range of 5.5-6.5 with potassium hydroxide (KOH) or phosphoric acid (H_3PO_4), and EC was adjusted by the nutrient solution or tap water when needed. The volume of nutrient solution in each tank was constantly monitored. The nutrient solutions were controlled with every 10 minutes pump-on and every 10 minutes pump-off during the period from transplantation to harvest. They were not renewed throughout the entire experimental period.

Measurements

The plant growth was measured at 5 days intervals of culture after transplanting on 4 plants from each treatment. Growth analysis was done based on destructive measurements of plant height, shoot fresh weight, shoot dry weight, number of leaves and leaf area of quinoa. The shoot dry weight was measured after drying for 72 hours at 70°C in hot air oven (VS-1202D2N, Alphatech KOREA, Seoul, Korea). Leaf area was measured using an area meter (Li-3100, Li-cor Inc., Lincoln, NE, USA). Light use efficiency (LUE) ($g \cdot mole^{-1}$) may then be calculated.

Statistical Analysis

Completely randomized design was used as the experimental design. Statistical analyses were carried out using the SAS system (Release 9.01, SAS institute Inc., Cary, NC, USA) and Sigmaplot (Version 9.01, Sistat Software Inc. San Jose, CA, USA). Experimental results were subjected to variance analysis (AVOVA). When significant differences occurred, the means were separated by Duncan’s multiple range test (DMRT) at 5% level.

Results and Discussion

The different photoperiods affecting on the flowering of quinoa in the growth chamber were shown that the flowering decreased with increasing photoperiod (Fig. 1-2). The plants grown under a 16/8 h photoperiod did not flower and under a 14/10 h and 8/16 h photoperiods they flowered 19.3% and 92.8%, respectively. The long-day photoperiod delayed the flowering more. Quinoa was a short-day plant in this study. A linear relationship was assumed between flowering rate and different photoperiods. The estimated slope was negative, and the flowering rate was 11.8% (R^2=0.998*). This means that the flowering rate decreased or increased about 12% per hour.

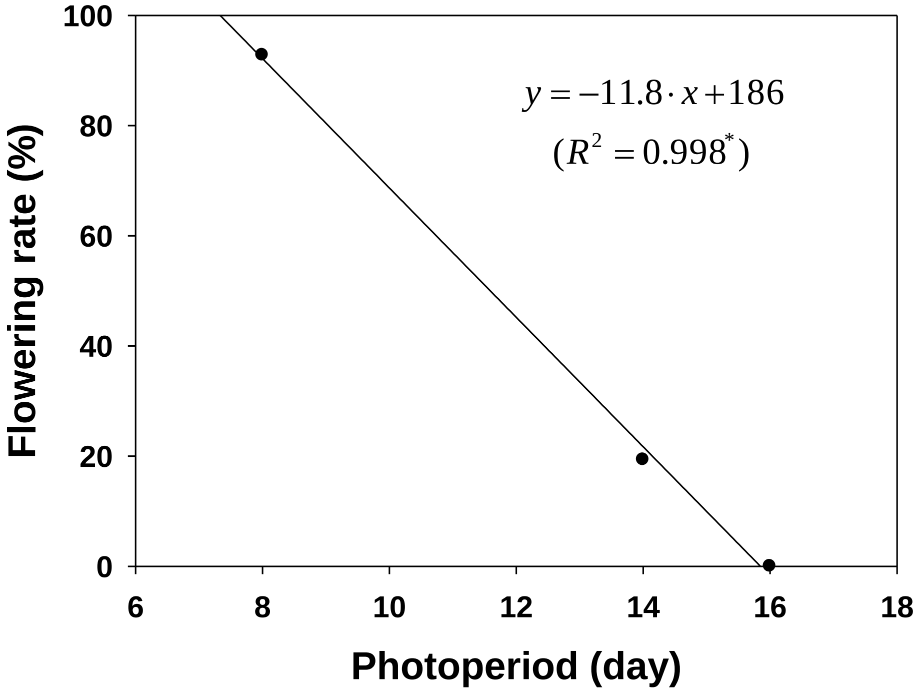

Fig. 1-2. Flowering response of quinoa under different photoperiods.

Photoperiod is a major factor affecting development in many plants (Kitaya et al., 1998). The time of flowering is strongly influenced by photoperiod (Jarillo et al., 2008). The photoperiod responses differed markedly among cultivars of quinoa with different conditions (Bertero, 2001; Bertero et al., 1999a, 1999b; Gesinski, 2008; Hirich et al., 2014; Ruiz and Bertero, 2008). Photoperiod had strong effects on all stages of quinoa plant reproduction and often acted indirectly, as shown by delayed responses expressed in later phases of development (Bertero et al., 1999b). According to the results, it is suggested that a 16/8 h photoperiod should be used to prevent the flowering and a 7/17 h photoperiod should be used to induct 100% of flowering rate of quinoa in a closed-type plant factory system.

The shoot fresh weight and shoot dry weight per plant grown in the EC at 2.0 $dS{\cdot}m^{-1}$ under PPFD of 120 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ were higher than the other treatments (Fig. 1-3). They were decreased with increasing of the EC from 2.0 to 3.0 $dS{\cdot}m^{-1}$ and increasing of PPFD from 120 to 143 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$. The shoot fresh weight and shoot dry weight per plant grown in the EC at 3.0 $dS{\cdot}m^{-1}$ with PPFD of 143 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ treatment were significantly different. However, the shoot fresh weight and shoot dry weight per plant were lower than those grown in the EC at 2.0 $dS{\cdot}m^{-1}$ under PPFD of 120 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ treatment. From the results, the shoot fresh weight and shoot dry weight of plants grown in the EC at 2.0 $dS{\cdot}m^{-1}$ with PPFD of 120 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ were the highest.

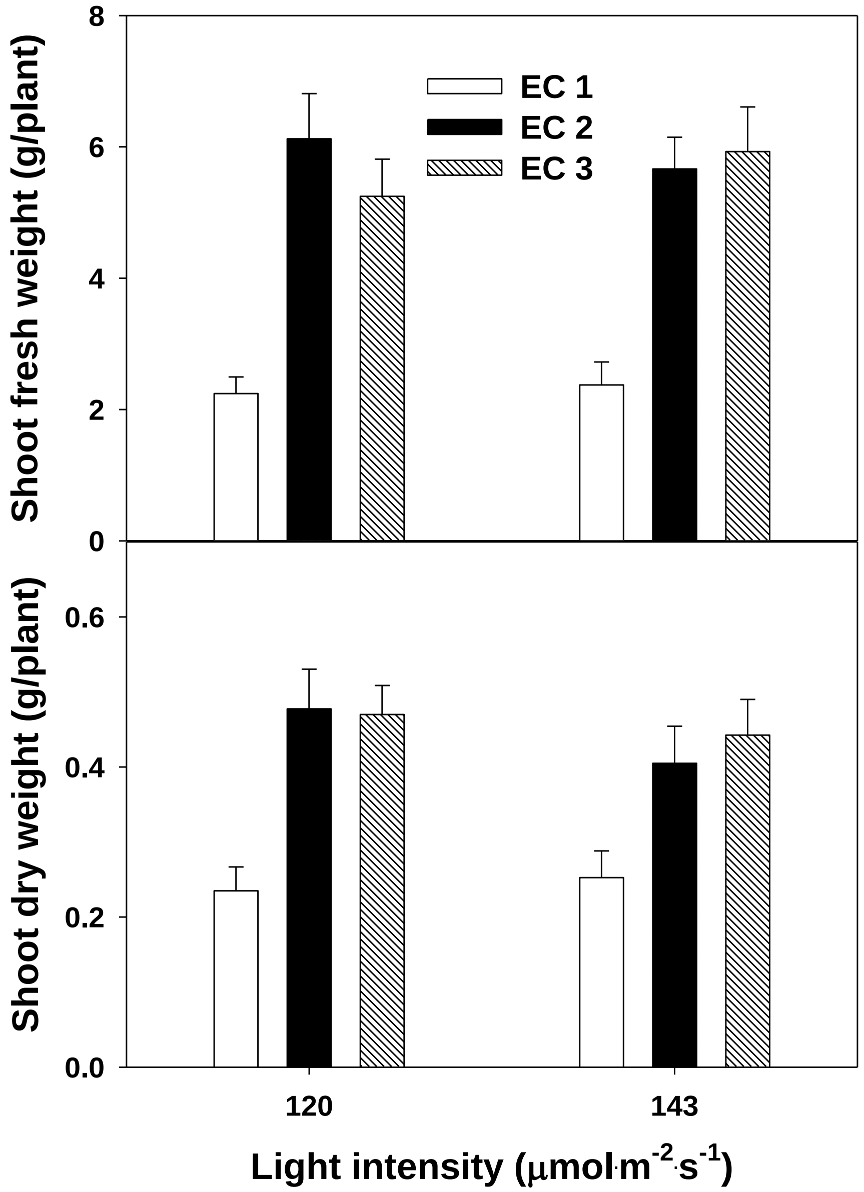

Fig. 1-3. Shoot fresh and dry weights of quinoa grown under different levels of light intensity and electrical conductivity (EC) of nutrient solution in a closed-type plant factory system. The vertical bars represent the standard errors (n=4).

Salinity often affects the timing of development. Yield components and growth parameters also show different responses to salinity stress. At low salinities root growth is often less affected or sometimes even stimulated by salinity, as compared to shoot growth (Shannon and Grieve, 1999). Quinoa is regarded as a highly salt tolerant halophyte crop of great potential for cultivation on saline areas around the world. Responses to salinity differed greatly among the varieties (Shabala et al., 2013). The EC of 2.8 and 3.8 $dS \cdot m^{-1}$ were not affected the plant height and slightly influenced the yield of rocket (D'Anna et al., 2003). The EC at 8 $dS \cdot m^{-1}$ did not drop the fresh matter of endive (Kowalczyk et al., 2012). The optimum EC varies with growing season, growth stage (Cho, 2004; Choi et al., 2011) cultivar and crops. In basil (Carrasco et al., 2007) and chicory (Park et al., 1995), the optimum EC was 1.5 $dS \cdot m^{-1}$, dill and thyme (Udagawa, 1995) was 2.4 $dS \cdot m^{-1}$. The optimum EC for lettuce (*Lactuca sativa* L.) range from 1.0 to 2.5 $dS \cdot m^{-1}$ depending on environmental conditions (Carlo et al., 2009; Cometti et al., 2008, 2013; Costa et al., 2001; Samarakoon et al., 2006), pak-choi, range from 1.5 to 2.0 $dS \cdot m^{-1}$ (Cho, 2004) and sowthistle, range from 1.5 to 2.0 $dS \cdot m^{-1}$ (Cho et al., 2012). According to the results, the optimum EC at 2.0 $dS \cdot m^{-1}$ could be recommended for growth productivity of quinoa for a leafy vegetable in a closed-type plant factory system.

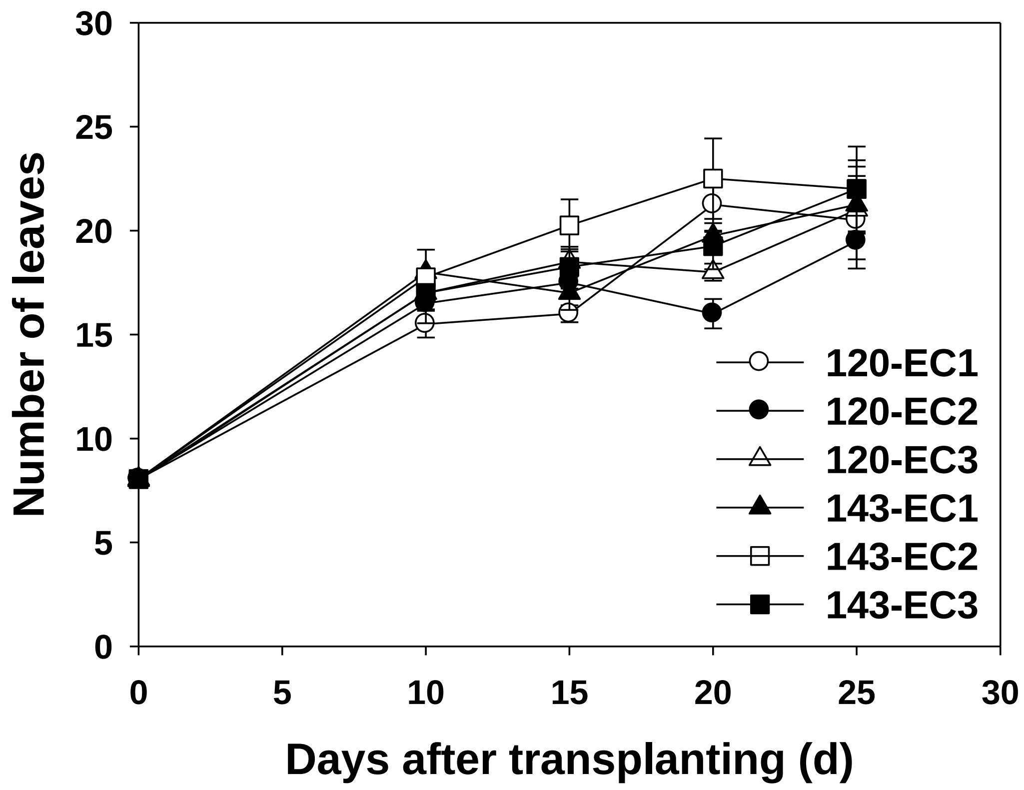

Fig. 1-4. Number of leaves of quinoa grown under different levels of light intensity and electrical conductivity (EC) of nutrient solution in a closed-type plant factory system. The vertical bars represent the standard errors (n=4).

The plants grown in the EC at 2.0 $dS{\cdot}m^{-1}$ with PPFD of 143 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ were significantly greater than the other culture conditions. The number of leaves was found significant between both EC and PPFD treatments (Fig. 1-4). Under the EC at 2.0 $dS{\cdot}m^{-1}$ they increased as PPFD increased. The number of leaves was the highest under the EC at 2.0 dS·m^{-1} with PPFD of 143 μmol·m^{-2}·s^{-1} at 20 days after transplanting.

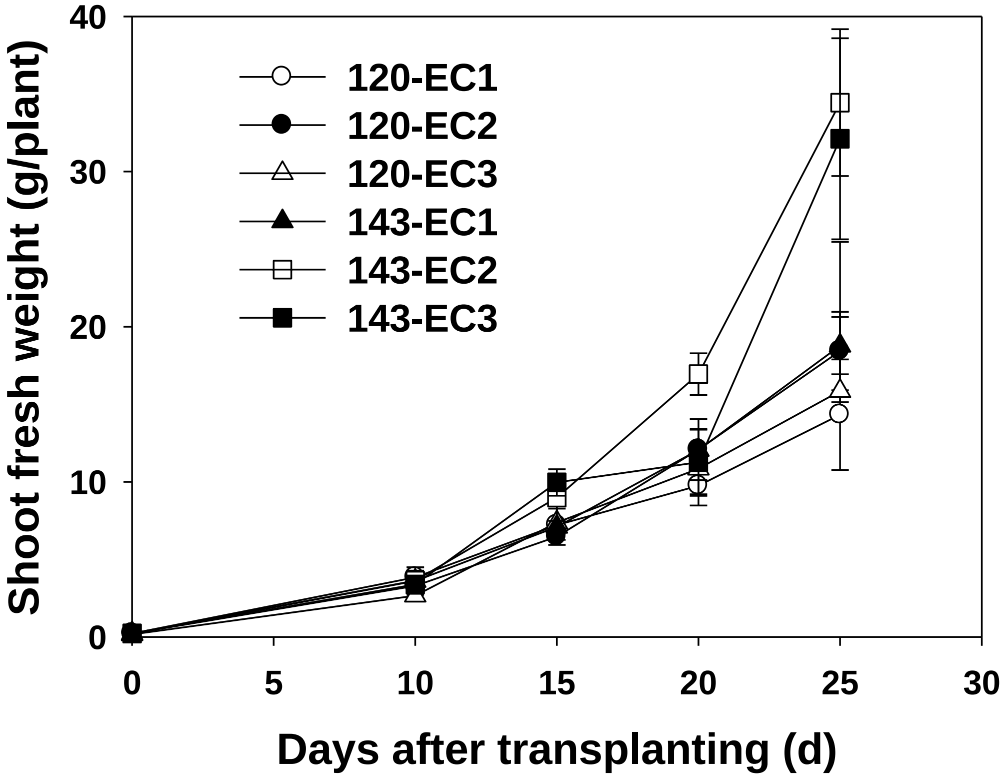

Fig. 1-5. Fresh weights of quinoa grown under different levels of light intensity and electrical conductivity (EC) of nutrient solution in a closed-type plant factory system. The vertical bars represent the standard errors (n=4).

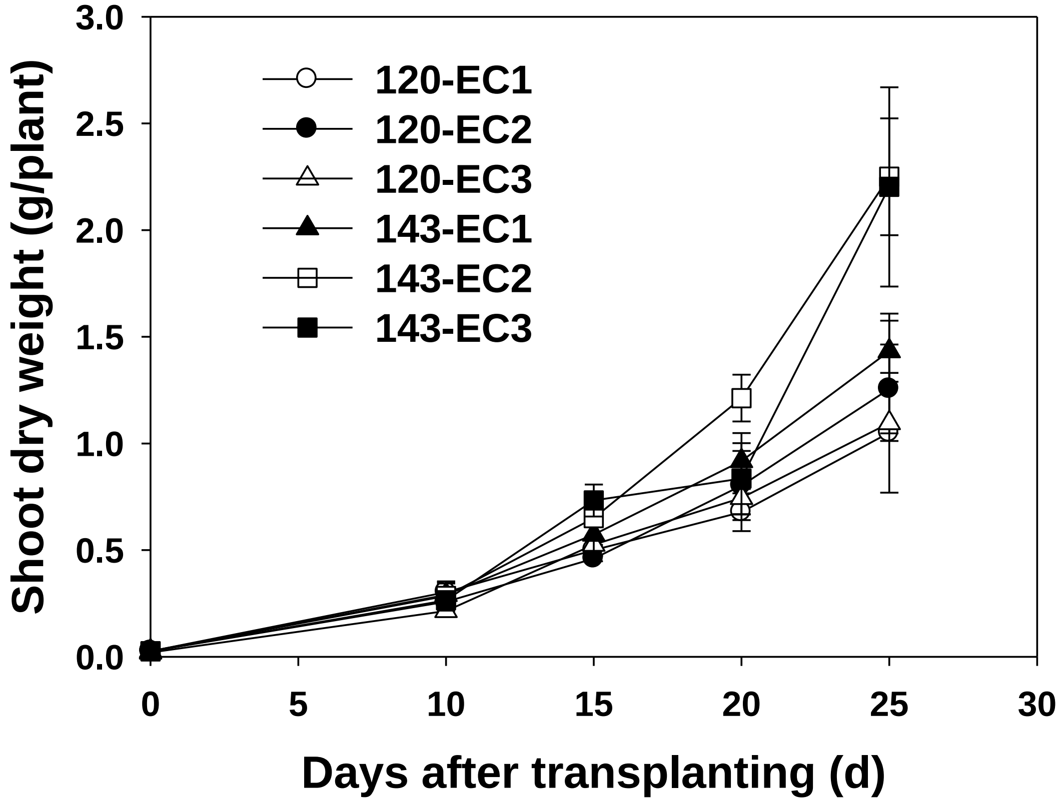

Fig. 1-6. Dry weights of quinoa grown under different levels of light intensity and electrical conductivity (EC) of nutrient solution in a closed-type plant factory system. The vertical bars represent the standard errors (n=4).

The shoot fresh weight per plant (Fig. 1-5) and the shoot dry weight per plant (Fig. 1-6) were found significant between both EC and PPFD treatments and increased linearly under each EC and PPFD treatment. And under the EC at 2.0 and 3.0 $dS{\cdot}m^{-1}$ they increased faster after 20 days after transplanting. The shoot fresh weight and shoot dry weight per plant were the highest under the EC at 2.0 dS·m^{-1} with PPFD of 143 μmol·m^{-2}·s^{-1} at 25 days after transplanting.

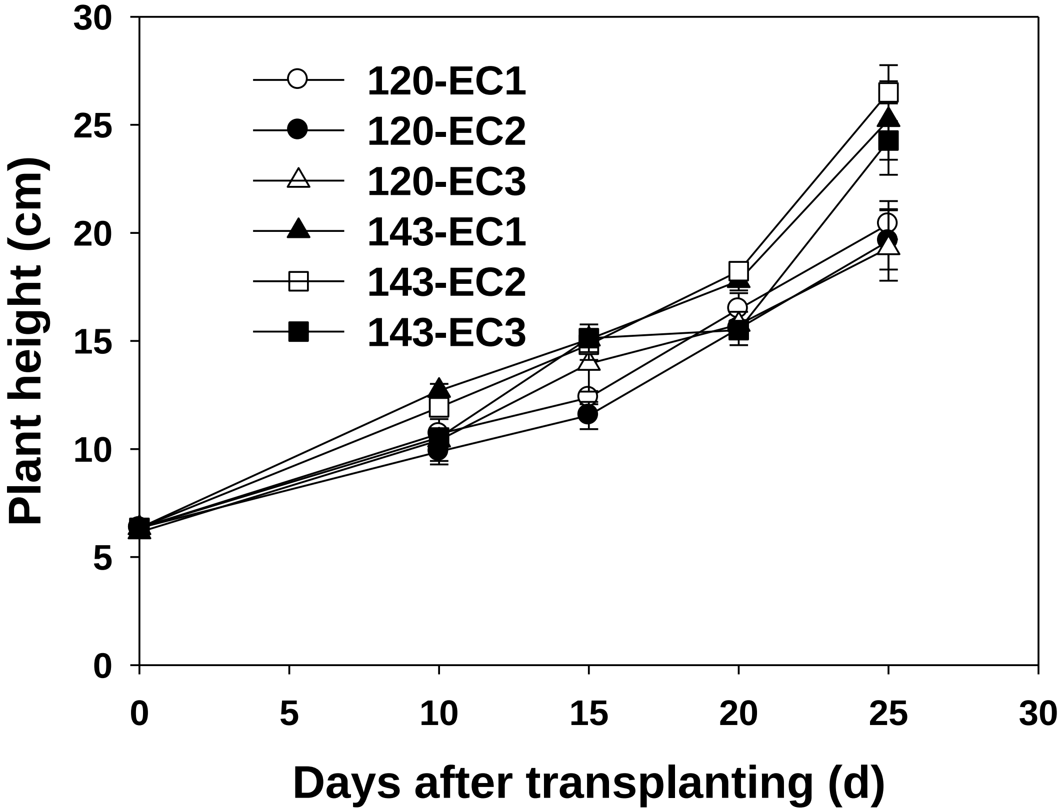

Fig. 1-7. Plant heights of quinoa grown under different levels of light intensity and electrical conductivity (EC) of nutrient solution in a closed-type plant factory system. The vertical bars represent the standard errors (n=4).

The plant heights were found significant between both EC and PPFD treatments (Fig. 1-7). Under each EC treatments they increased linearly as PPFD increased from 120 to 143 μmol·m^{-2}·s^{-1}. With all EC treatments with

PPFD of 143 μmol·m^{-2}·s^{-1}, the plant heights were greater than those of all EC treatments with PPFD of 120 μmol·m^{-2}·s^{-1}. The plant height was the highest under the EC at 2.0 dS·m^{-1} with PPFD of 143 μmol·m^{-2}·s^{-1} at 25 days after transplanting.

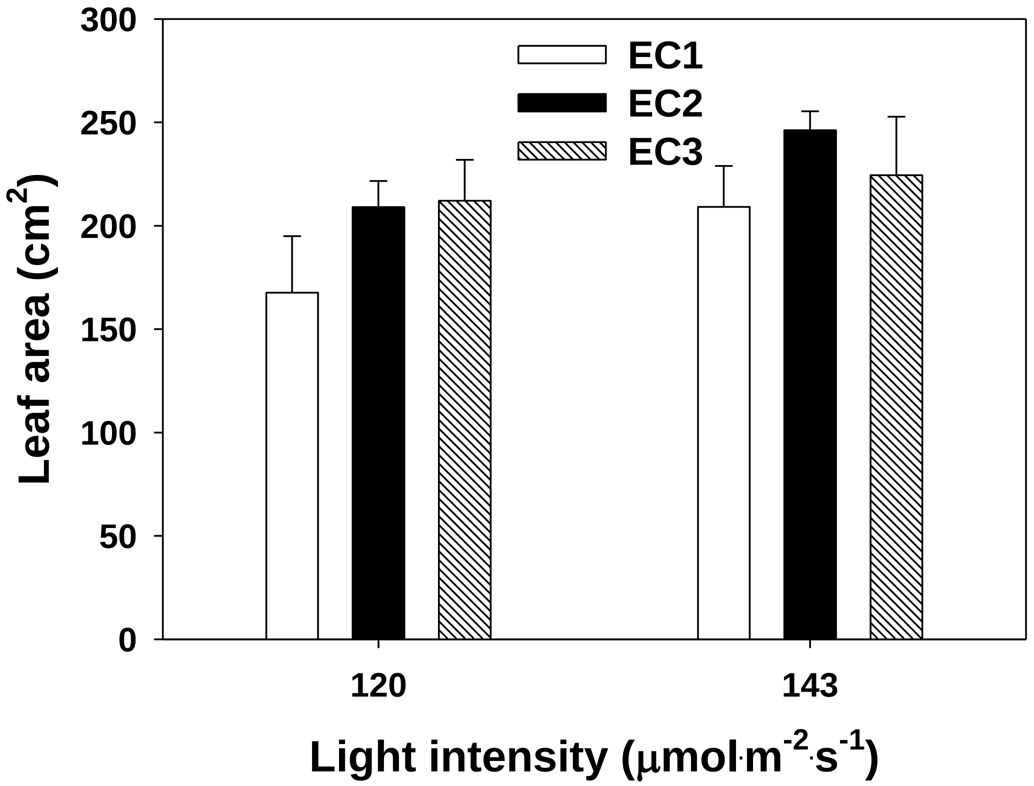

Fig. 1-8. Leaf areas of quinoa grown under different levels of light intensity and electrical conductivity (EC) of nutrient solution in a closed-type plant factory system. The vertical bars represent the standard errors (n=4).

The leaf areas were found significant between both EC and PPFD treatments (Fig. 1-8). Under each EC treatment they increased linearly as PPFD increased from 120 to 143 μmol·m^{-2}·s^{-1}. With all EC treatments with PPFD of 143 μmol·m^{-2}·s^{-1}, the leaf areas were greater than those of all EC treatments with PPFD of 120 μmol·m^{-2}·s^{-1}. The leaf area was the highest under the EC at 2.0 dS·m^{-1} with PPFD of 143 μmol·m^{-2}·s^{-1} at 25 days after transplanting.

The light use efficiencies (LUE) were found significant between both EC and PPFD treatments (Fig. 1-9). Under each EC treatment they increased linearly with PPFD of 120 μmol·m^{-2}·s^{-1}, but under the EC at 3.0 dS·m^{-1} with PPFD of 143 μmol·m^{-2}·s^{-1} they were lower than that of the EC at 2.0 dS·m^{-1} with PPFD of 143 μmol·m^{-2}·s^{-1}. In all EC treatments with PPFD of 143 μmol·m^{-2}·s^{-1}, the light use efficiencies were greater than those of all EC treatments with PPFD of 120 μmol·m^{-2}·s^{-1}. The light use efficiency was the highest under the EC at 2.0 dS·m^{-1} with PPFD of 143 μmol·m^{-2}·s^{-1}.

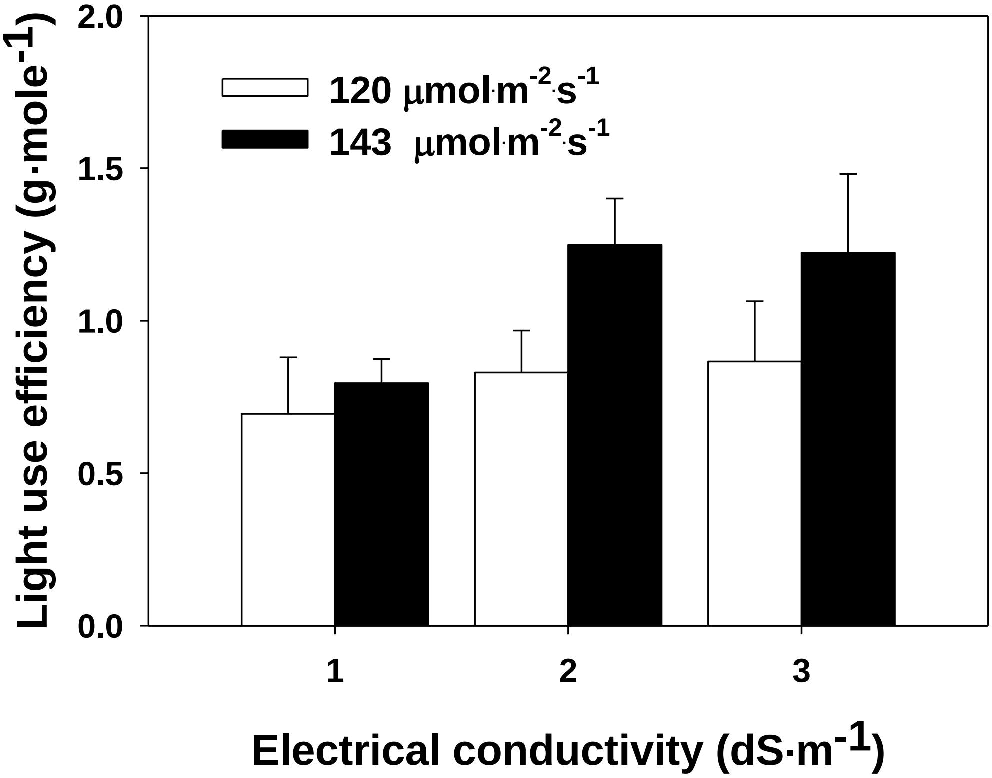

Fig. 1-9. Light use efficiencies of quinoa grown under different levels of light intensity and electrical conductivity (EC) of nutrient solution in a closed-type plant factory system. The vertical bars represent the standard errors (n=4).

The growth of quinoa was optimum in the EC at 2.0 dS·m^{-1} under 12/12 h photoperiod with PPFD of 120 μmol·m^{-2}·s^{-1} and at 2.0 dS·m^{-1} under 14/10 h photoperiod with PPFD of 143 μmol·m^{-2}·s^{-1}. The results are similar to those obtained by Seo et al. (2009) who reported that the leaf area index, number of leaves, plant height, fresh weight per plant, and chlorophyll content of lettuce were the highest in the EC at 2.0 dS·m^{-1}. Cho (2004) reported that the optimum EC for pak-choi was 1.5 to 2.0 dS·m^{-1} on the growth stage 1 (from seedling emergence to transplanting with 3-4 leaves) and 2.0 dS·m^{-1} on the growth stage 2 (from transplanting to harvest with 14-15 leaves or fresh weight $\geq$60g).

Light intensity is the one of the key environmental factors influencing transplant growth and quality. The dry mass, dry mass percentage and leaf number increased linearly with daily light integral (DLI, the product of PPFD and photoperiod) of lettuce (Kitaya et al., 1998). According to Cho et al. (2012), the growth characteristics of sowthistle in plant factory, i.e. the number of leaves, fresh weight and dry weight were the highest in the EC at 2.0 dS·m^{-1} with PPFD of 200 µmol·m^{-2}·s^{-1} by increasing PPFD from 100 to 200 µmol·m^{-2}·s^{-1}. Chlorophyll content (SPAD) and leaf photosynthetic rate increased with increasing PPFD and EC. Qin et al. (2008) reported that elevated PPFD from 100 to 700 µmol·m^{-2}·s^{-1} increased the rate of photosynthesis for sowthistle and lettuces. The elevated light intensity increased the rate of photosynthesis. Therefore, increasing the intensity of an artificial lighting source increases the plant growth rate.

Light use efficiency (LUE) is one of the most useful parameters for estimating crop productivity. LUE relates dry matter (DM) productivity to solar radiation received on the canopy (Akmal and Janssens, 2004). LUE is the relation between intercepted radiation and biomass production (Haxeltine and Prentice, 1996; Lee and Heuvelink, 2003).

The ratio of net primary production (NPP) to absorbed photosynthetically active radiation (APAR) is called the PAR utilization efficiency or light use efficiency which was used to determine the consequence crop productivity. The periodic measurements of shoot dry weights in this study were shown that the shoot dry weight was greater than 2.0 g/plant under the EC at 2.0 $dS\cdot m^{-1}$ with PPFD of 143 $\mu mol\cdot m^{-2}\cdot s^{-1}$ treatment. Biomass production of quinoa could be improved if periods of interception below 50% of incoming PAR were reduced to ensure high radiation use efficiency (Ruiz and Bertero, 2008).

Based on the results, the optimum EC at 2.0 $dS\cdot m^{-1}$ with PPFD of 143 $\mu mol\cdot m^{-2}\cdot s^{-1}$ under a 16/8 h photoperiod could be recommended for growth productivity of quinoa for a leafy vegetable in a closed-type plant factory system.

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Chapter II. Growth Response of Quinoa (*Chenopodium quinoa* Willd.) to Various Planting Density Levels in a Closed-type Plant Factory System

Abstract

Planting density is an important factor to determine crop productivity and yield in vegetable production systems. The objective of this study was to determine the optimum plant density to produce quinoa in a closed-type plant factory system. The plants were arranged to four plant spacing 10, 15, 20 and 25 cm between plants and 15 cm between rows. The planting densities were 27, 33, 44, and 67 plants/m^2, respectively. The highest growth characteristics were recorded at the planting density of 33 plants/m^2. Planting densities did not significantly affect the leaf number, lateral shoot number, lateral shoot leaf number and total leaf number. However, the shoot fresh weight, shoot dry weight, leaf area, lateral shoot leaf area, total leaf area and stem diameter were significantly higher in the planting density of 33 plants/m^2. The leaf area was greater, resulting in greater total biomass (shoot dry weight) at this planting density. The yields per unit area increased as planting density increased. The highest shoot fresh weight, shoot dry weight and total leaf area were obtained from planting transplants at the spacing of 15x10 cm or

the planting density of 67 plants/m^2.

Additional key words: biomass, leaf area, shoot dry weight, shoot fresh weight

Introduction

Planting density is an important factor to determine crop productivity and spacing efficiency in vegetable production systems (Cho and Son, 2005). The ideal plant population can lead to optimum yields, whereas too high or too low planting densities can result in relatively lower yields and qualities (Abu-Rayyan et al., 2004; Antonietta et al., 2014; Ibrahim, 2012; Jovicich et al., 2014; Khazaie et al., 2008; Laczi et al., 2013; Yaseen et al., 2013; Mulayim et al., 2002; Papadopoulos and Pararajasingham, 1997; Perez de Camacaro et al., 2004; Qiu et al., 2013; Rekowska and Jurga-Szlempo, 2011; Rodriguez et al., 2007; Sarooshi and Cresswell, 1994; Scuderi et al., 2013).

Quinoa is planted in rows (row spacing range 40-80 cm) where mechanized agriculture practices are used. The sowing density may vary according to the region. It has been recommended that a density for seed production of 1.2 $g{\cdot}m^{-2}$ (Jancurova et al., 2009) and planting density of 327-220 plants/m^2 in Denmark (Jacobsen et al., 1994). The variety ‘Baer’ was sown in rows 0.2 m apart at 20 kg $seed{\cdot}ha^{-1}$. The highest grain yield was 6.96 $ton{\cdot}ha^{-1}$ at ‘Cambridge’ and ‘England’ of varieties (Risi and Galwey, 1991). In a greenhouse using hydroponics system, planting density of 140 plants/m^2 appears to be optimal for seed production (Schlick, 2000). Until now, the effects of the planting density on growth and yield of quinoa for a leafy vegetable in a closed-type plant factory system have not been reported yet.

The objective of this study was to determine the optimum planting density for producing quinoa for a leafy vegetable grown in a closed-type plant factory system.

Materials and Methods

Plant Material

The experiment was conducted from December 2, 2014 to January 14, 2015 in a closed-type plant factory (700x500x300 cm, L x W x H) at Jeju National University, Jeju, Republic of Korea. The quinoa seeds sown into 288 cells of a polyurethane sponge (2.5x2.5x2.5 cm) in a plastic tray (30x23x6 cm) were sub-irrigated once a day with tap water.

Experimental Set-up

The experiments were assigned to four plant spacing 10, 15, 20 and 25 cm between plants and 15 cm between rows. The planting densities were 27, 33, 44, and 67 plants/m^2. The pH of nutrient solutions and temperature were 6.0 and 20°C under 16/8 h (day/night) photoperiod, respectively. Emerged seedlings with fully developed cotyledons were sub-irrigated once a day with the electrical conductivity (EC) of nutrient solution of the 0.5 $dS \cdot m^{-1}$ and 1.0 $dS \cdot m^{-1}$ for a week before transplanting. The plants were transplanted into the troughs (each trough 250x5x4 cm, L x W x H) at the fourth true leaf stage. The seedlings were supported by plastic plug places in holes in the cover of the trough.

Closed-type Plant Factory System

Three-band radiation type fluorescent lamps (55 W, Philips Co. Ltd., Amsterdam, the Netherlands) were used. Light intensity (photosynthetic photon flux density, PPFD) was measured with a quantum sensor (LI-190, Li-cor Inc., Lincoln, NE, USA). The temperature and relative humidity were maintained at 23-25°C and 60%, respectively. The plants were transplanted into the troughs at the fourth true leaf stage. The nutrient film technique (NFT) system with three layers and each layer with four troughs were used for the plant growth system. Total volume of the nutrient solution in the tank was 90 L and the dissolved oxygen concentration was maintained. The nutrient solution was composed of 15 NO_3-N, 1 NH_4-N, 1 P, 7 K, 4 Ca, 2 Mg, 2 SO_4-S $mM \cdot L^{-1}$. The EC of nutrient solutions at 2.0 $dS \cdot m^{-1}$ was adjusted mixing with tap water and supplied to each treatment. The pH and EC of nutrient solutions were measured daily for each treatment in the nutrient solution tanks. The measurements were done with a pH meter (HI 98106, Hanna Instruments Ltd, Bedfordshire, Leighton Buzzard, UK) and a portable conductivity meter (COM-100, HM Digital Inc., Culver City, CA, USA). The pH was adjusted to the range of 5.5-6.5 with potassium hydroxide (KOH) or phosphoric acid (H_3PO_4), and electrical conductivity was adjusted by the nutrient solution or tap water when needed. The volume of nutrient solution in each tank was constantly monitored. The nutrient solutions were controlled with every 10 minutes pump-on and every 10 minutes pump-off during the period from transplantation to harvest. They were not renewed throughout the entire experimental period.

Measurements

The plant growth was measured at 5 days intervals of culture after transplanting on 12 plants from each treatment. Growth analysis was based on destructive measurements of plant heights, shoot fresh weights, shoot dry weights, number of lateral shoots, number of leaves and leaf areas. The shoot dry weight was measured after drying for 72 hours at 70°C in hot air oven (VS-1202D2N, Alphatech KOREA, Seoul, Korea). Leaf area was measured using an area meter (Li-3100, Li-cor Inc., Lincoln, NE, USA).

Statistical Analysis

Completely randomized design was used as the experimental design. Statistical analyses were carried out using the SAS system (Release 9.01, SAS institute Inc., Cary, NC, USA) and Sigmaplot (Version 9.01, Sistat Software Inc., San Jose, CA, USA). Experimental results were subjected to variance analysis (AVOVA). When significant differences occurred, the means were separated by Duncan’s multiple range test (DMRT) at 5% level.

Results and Discussion

The planting density affected the growth characteristics of quinoa (Table 2-1). The highest growth characteristics were recorded at the planting density of 33 plants/m^2 (15x20 cm). Planting densities did not significantly affected on the leaf number, lateral shoot number, lateral shoot leaf number and total leaf number. However, the shoot fresh weight, shoot dry weight, leaf area, lateral shoot leaf area, total leaf area and stem diameter except plant height were significantly higher in the planting density of 33 plants/m^2. Leaf area was greater, resulting in greater total biomass (shoot dry weight) at this planting density.

According to Cho and Son (2005) who reported that the growth and yield of hydroponically grown pak-choi, number of leaf and top fresh weight per plant decreased with increasing planting densities, while yield per area was increased reaching the maximum value at 133 plants/m^2. The maximum crop growth rate, light use efficiency, yield and yield index, which are closely related with planting density, were the highest at 67 plants/m^2. Maboko and Du Plooy (2009) reported that plant population significantly affected plant height, fresh and dry leaf masses, leaf area and leaf number per square meter and indicated that an increase in plant population results in a significant increase in yield and yield components of leafy lettuce. In broccoli, planting density affected the intercepted and accumulated PAR. There were no effects on the length of the vegetative and reproductive periods, the total and final number of leaves, and the spear diameter and fresh weight (Francescangeli et al., 2006). In faba bean, planting density can affect canopy development, radiation interception, dry matter production, evaporation of water from soil under the crop, weed competition, the development of fungal and viral diseases, plant and first pod height, seed yield and ultimately the economic productivity of a crop in the farming system. The primary branch raceme and pod numbers per unit area significantly increased with the increase in planting density (Lopez-Bellido et al., 2005). In greenhouse grown sweet pepper, the stem length and the number of nodes per stem increased linearly with the decrease in plant spacing (Jovicich et al., 2014).

Table 2-1. Effects of planting density on the growth characteristics of hydroponically grown quinoa in a closed-type plant factory at 30 days after transplanting.

Planting density (plant/m^2)	Plant height (cm)	Stem diameter (cm)	Fresh weight (g)	Dry weight (g)	Leaf number	Lateral shoot number	Lateral shoot leaf number	Total leaf number	Leaf area (cm^2)	Lateral shoot area (cm^2)	Total leaf area (cm^2)
27	23.8 b[z]	5.4 ab	24.1 c	3.9 b	22.0	18.3	90.7	112.7	262.7 c	232.0 c	494.7 b
33	27.3 a	6.1 a	42.2 a	5.2 a	20.0	19.7	125.7	145.7	402.8 a	438.4 a	841.2 a
44	26.3 a	5.6 a	30.4 b	3.7 b	20.7	18.7	95.0	115.7	316.3 b	313.5 b	629.8 b
67	27.3 a	4.9 b	25.2 bc	3.7 b	22.3	21.7	95.3	117.7	315.4 b	240.3 b	555.8 b

[z]Means within column followed by the same letters are not significantly different as determined by Duncan's multiple range test at $P<0.05$.

The yields per square meter increased as planting density increased. The significantly higher yield of quinoa of the highest shoot fresh weight, shoot dry weight and total leaf area was obtained from planting transplants at the spacing of 15x10 cm or the planting density of 67 plants/m^2 (Table 2-2). According to Schlick and Bubenheim (1996) who reported that quinoa grown in controlled environments at higher planting densities resulted in improved light interception and increased yields. For the yield per unit area, harvest index, and biomass accumulation data, a planting density of 140 plants/m^2 appears to be optimal for quinoa seed production grown hydroponically in controlled environment production. In basil, the yield increased as planting density increased (D'Anna et al., 2003). Raimondi et al. (2006) reported that the highest planting density increased the total yield without affecting the fresh produce quality with the exception of a slightly lower TSS content.

Table 2-2. Effects of planting densities on the shoot fresh weight, shoot dry weight and total leaf area of hydroponically grown quinoa in a closed-type plant factory at 30 days after transplanting.

Planting density (plant/m^2)	Fresh weight (kg/m^2)	Dry weight (g/m^2)	Total leaf area (m^2/m^2)
27	0.65 c[z]	104.22 c	1.34 c
33	1.40 b	172.59 b	2.77 b
44	1.34 b	162.21 b	2.77 b
67	1.69 a	246.11 a	3.72 a

[z]Means within column followed by the same letters are not significantly different as determined by Duncan's multiple range test at $P<0.05$.

Based on the results, the optimum planting density of 67 plants/m^2 (15x10 cm) could be recommended for growth productivity of quinoa for a leafy vegetable in a closed-type plant factory system.

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Chapter III. Development of Models for Estimating Growth and Yield of Quinoa (*Chenopodium quinoa* Willd.) for a Leafy Vegetable in a Closed-type Plant Factory System

Abstract

Models for predicting plant height, net photosynthesis rate, CO_2 curve, plant growth of quinoa (*Chenopodium quinoa* Willd.) for a leafy vegetable in a closed-type plant factory system were developed using the model equations which were linear, non-rectangular hyperbola, linear or quadratic, and expolinear. The plant growth and yield were measured at 5 days intervals after transplanting. The photosynthesis and growth curve models were calculated. A linear relationship was obtained between plant heights and days after transplanting (DAT). Plant height model was 5.4+0.58·DAT^{-1} (R^2=0.932***). The non-rectangular hyperbola model was chosen as the response function of net photosynthesis. A non-linear regression was carried out to describe the increasing of the shoot dry weight of quinoa as a function of time using an expolinear equation. The CO_2 saturation point of leaves was 400 μmol·mol^{-1} (R^2=0.826***). The photosynthesis rate was the highest at

PPFD of 400 μmol·m^{-2}·s^{-1}. The light compensation point, light saturation point, and respiration rate were 29 μmol·m^{-2}·s^{-1}, 813 μmol·m^{-2}·s^{-1} and 3.4 μmol·m^{-2}·s^{-1}, respectively. The shoot fresh weight was a linear relationship with the shoot dry weight. The crop growth rate and relative growth rate were 22.9 g·m^{-2}·d^{-1} and 0.28 g·g^{-1}·d^{-1}, respectively. The regression coefficient of shoot dry weight was 0.75 (R^2=0.921***). It is concluded that these models can accurately estimate the plant height, net photosynthesis rate, CO_2 curve, shoot fresh weight, and shoot dry weight of quinoa.

Additional key words: crop growth rate, expolinear equation, photosynthesis rate, plant height

Introduction

A crop model is a simple representation of crop. In general, it is used to study crop growth and to calculate growth. There are many crop growth models that simulate the physiological development, and growth and yield of a crop on the basis of the interaction between environmental variables and plant physiological processes (Miglietta and Bindi, 1993; Mo et al., 2005). Recently, a crop growth model is used to investigate the optimal control problem associated with plant factory operation (Ioslovich and Gutman, 2000). Last year, crop growth models have become an essential tool to support field research and to improve agriculture productivity. Simulation model results, in contrast with the usual field observations, can be extrapolated to different conditions, other cultivars or other cropping schemes. Crop growth models can be used in research and application such as yield predictions, agricultural planning, farm management climatology and agrometeorology (Miglietta and Bindi, 1993).

Quinoa (*Chenopodium quinoa* Willd.) seed provides high nutritional values. The leaves and sprouts can also provide high nutritive values and high antioxidant and anticancer activities, too. (Gawlik-Dzik et al. 2013; Paśko et al. 2009; Schlick and Bubenheim, 1996).

This experiment was carried out to get the basic data which could be used for predicting potential effects of a plant factory system on the development rates of quinoa for a leafy vegetable in a closed-type plant factory system.

Materials and Methods

Plant Material

The experiment was conducted between August and October, 2014 in a closed-type plant factory (700x500x300 cm, L x W x H) at Jeju National University, Jeju, Republic of Korea. The quinoa seeds sown into 288 cells of a polyurethane sponge (2.5x2.5x2.5 cm) in a plastic tray (30x23x6 cm) were sub-irrigated once a day with tap water. Emerged seedlings with fully developed cotyledons were sub-irrigated once a day with the electrical conductivity of nutrient solution of the 0.5 $dS{\cdot}m^{-1}$ and 1.0 $dS{\cdot}m^{-1}$ for a week before transplanting. The plants were transplanted into troughs at the fourth true leaf stage. The seedlings were supported by plastic plugs in holes in the cover of the trough. The plants were spaced 10 cm apart within each trough and each trough was spaced 15 cm apart (67 plants/m^2). The plant was grown in the EC at 2.0 $dS{\cdot}m^{-1}$ under 16/8 h (day/night) photoperiod.

Closed-type Plant Factory System

Three-band radiation type fluorescent lamps (55 W, Philips Co., Ltd., Amsterdam, the Netherlands) were used. Light intensity (photosynthetic photon flux density, PPFD) was measured with a quantum sensor (LI-190, Li-cor Inc., Lincoln, Nebraska, USA). The temperature was maintained at 23-

25°C and the light intensity was 143 μmol·m^{-2}·s^{-1}. The relative humidity and CO_2 concentration were 50-70% and 400-600 μmol·mol^{-1}, respectively. The nutrient film technique (NFT) system with three layers and each layer with four troughs was used for the plant growth system. Total volume of the nutrient solution in the tank was 90 L and the dissolved oxygen concentration was maintained. The nutrient solution was composed of 15 NO_3-N, 1 NH_4-N, 1 P, 7 K, 4 Ca, 2 Mg, 2 SO_4-S mM·L^{-1}. The EC of nutrient solutions at 2.0 dS·m^{-1} was adjusted mixing with tap water and supplied to each treatment. The pH and EC of nutrient solutions were measured daily for each treatment in the nutrient solution tanks. The measurements were done with a pH meter (HI 98106, Hanna Instruments Ltd, Bedfordshire, Leighton Buzzard, UK) and a portable conductivity meter (COM-100, HM Digital Inc., Culver City, CA, USA). The pH was adjusted to the range of 5.5-6.5 with potassium hydroxide (KOH) or phosphoric acid (H_3PO_4), and electrical conductivity was adjusted by the nutrient solution or tap water when needed. The volume of nutrient solution in each tank was constantly monitored. The nutrient solutions were controlled with every 10 minutes pump-on and every 10 minutes pump-off during the period from transplantation to harvest. They were not renewed throughout the entire experimental period.

Measurements

The plant growth was measured at 5 days intervals of culture after transplanting on 12 plants. Growth analysis was based on destructive measurements of plant height, shoot fresh weight and shoot dry weight. The shoot dry weight was measured after drying for 72 hours at 70°C in hot air oven (VS-1202D2N, Alphatech KOREA, Seoul, Korea). Net photosynthetic rate was generated using a portable photosynthetic system (Li-6400, Li-cor Inc., Lincoln, NE, USA). Photosynthetic rate was measured at 22 days after transplanting. Plants were randomly selected with 10 replications, and measurements were taken on the fully expanded leaves.

Model Construction and Validation

The plant height is defined following the linear equation:

$$H=a \cdot X + b \quad (1)$$

where H is the plant height (cm), X is days after transplanting (days, DAT), a and b are the constants.

Net photosynthetic rate [PAR, (P_n)] is defined following the non-rectangular hyperbola equation and was calculated according to Goudriaan and Van Laar (1994):

$$P_n=P_{max}x\{1-exp(-\alpha xPAR/P_{max})\}-R \quad (2)$$

where P_n is the photosynthesis rate ($\mu mol\cdot CO_2\cdot m^{-2}\cdot s^{-1}$), P_{max} is the potential photosynthesis rate ($\mu mol\cdot CO_2\cdot m^{-2}\cdot s^{-1}$), α is the start gradient to straight line ($\mu mol\cdot CO_2\cdot m^{-2}\cdot s^{-1}$), PAR is the photosynthetic active radiation ($\mu mol\cdot m^{-2}\cdot s^{-1}$), and R is the photosynthesis rate ($\mu mol\cdot CO_2\cdot m^{-2}\cdot s^{-1}$) at PAR 0.

The CO_2 curve is defined following the linear and quadratic equation:

$$P=a\cdot X^2 + b\cdot X + c \quad (3)$$

where P is the photosynthetic rate, X is the CO_2 concentration ($\mu mol\cdot mol^{-1}$), a, b and c are the constants.

The mathematical function used for expressing shoot dry weight by time is called expolinear equation (Goudriaan and Monteith, 1990):

$$W=C_m/R_m x1n\ [1+exp\{R_m x(t-t_b)\}] \quad (4)$$

where W is biomass (shoot dry weight, $g\cdot m^{-2}$) at t days from transplanting, C_m is the maximum crop growth rate ($g\cdot m^{-2}\cdot d^{-1}$), R_m is the maximum relative growth rate ($g\cdot g^{-1}\cdot d^{-1}$) in the exponential growth phase, t is the time after transplanting (day), and t_b is the time at which the crop effectively reaches a linear phase of growth (lost time, d).

Statistical Analysis

Completely randomized design was used as the experimental design. Statistical analyses were carried out using the SAS system (Release 9.01, SAS institute Inc., Cary, NC, USA) and Sigmaplot (Version 9.01, Sistat Software Inc. San Jose, CA, USA). The variables were estimated using the Gauss-Newton algorithm, a nonlinear least squares technique. The slopes, intercepts and regression coefficients of the models were compared using the SAS REG procedure. The correlation coefficients were calculated between the measured and estimated data.

Results and Discussion

A linear relationship was observed between the plant heights and days after transplantation (Fig. 3-1). Plant height model of quinoa was $5.4+0.58 \cdot DAT^{-1}$ (R^2=0.932***). The change of plant height was 0.58 cm per day. Plant height is one of the most important biomass yield components. Increasing plant height is the most obvious and direct way to impact biomass yield (Salas Fernandez et al., 2009). The potential growth, the potential increase in total biomass, is adjusted daily according to the growth constraints. The adjusted daily total biomass production is accumulated through the growing season (Arnold et al., 1995).

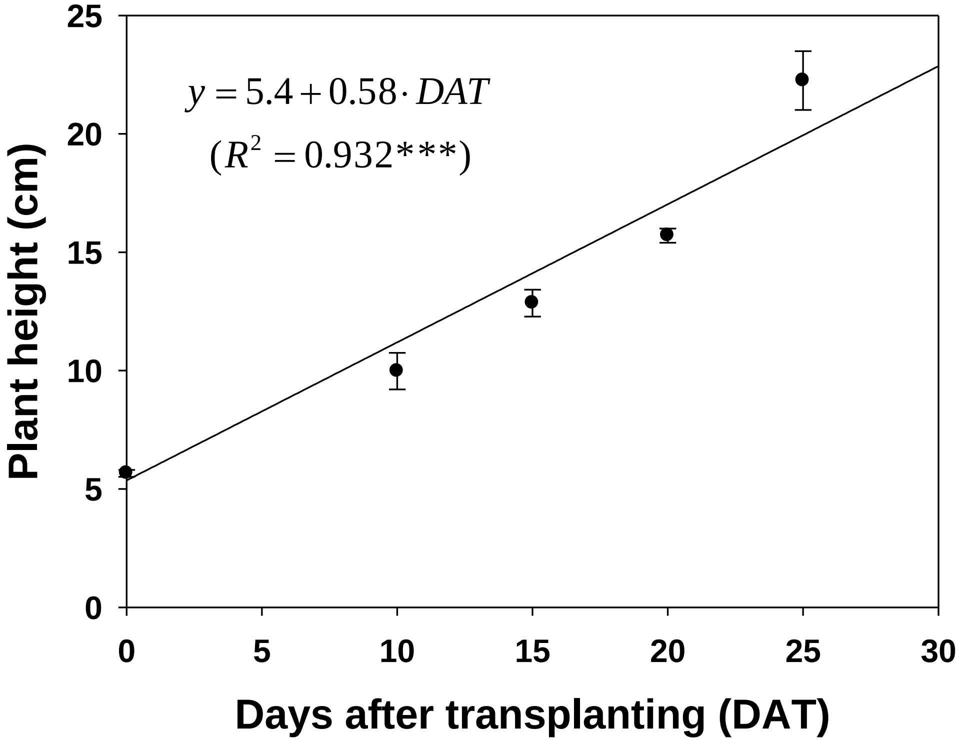

Fig. 3-1. Plant heights (cm) of quinoa with days after transplanting (DAT). Vertical bars indicated SE of the means of 4 replications.

The response of net photosynthesis rate (P_n) of quinoa plants to carbon dioxide concentration was measured and modeled (Fig. 3-2). The quadratic equation was chosen as the response function of net photosynthesis. The CO_2 saturation point of leaves was 400 μmol·mol^{-1} (R^2=0.826***). The photosynthesis rate was the highest at PPFD of 400 μmol·m^{-2}·s^{-1}. For the modelling of photosynthesis, the most important factor is light intensity (Nauha and Alopaeus, 2013). In the crop growth model for potential production, the response of leaf CO_2 assimilation to light intensity is characterized by its slope at low intensity and its maximum rate at light saturation. The maximum CO_2 assimilation capacity of leaves varies with crop species and cultivar (Van Laar et al., 1997).

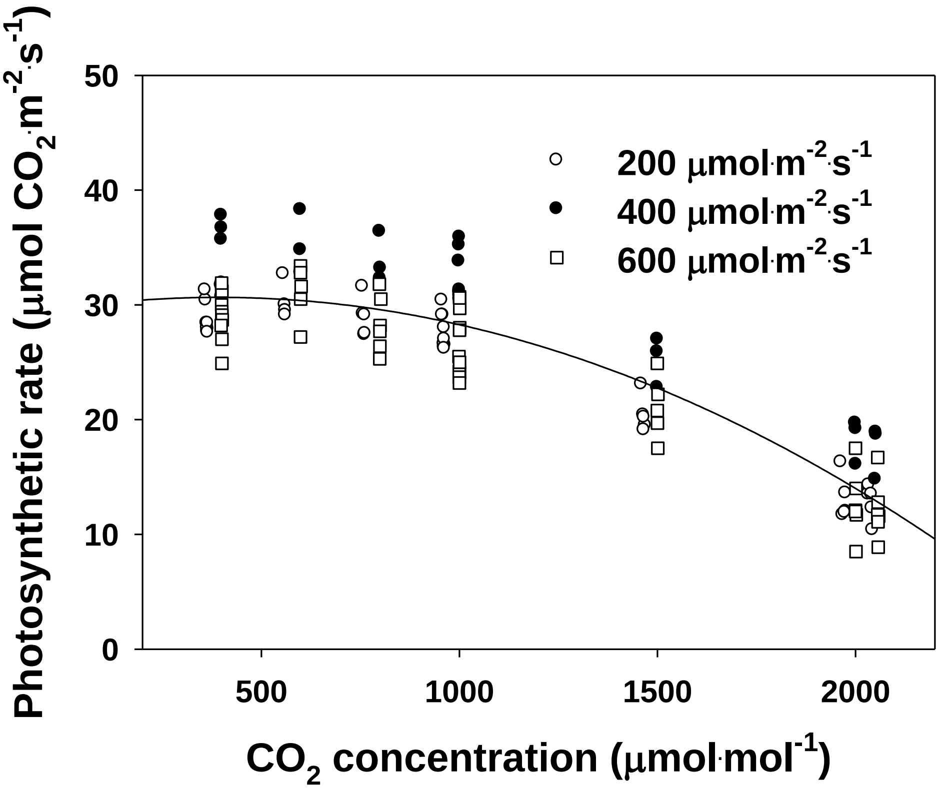

Fig. 3-2. Photosynthetic curves of quinoa at 200, 400 and 600 μmol·$m^{-2}s^{-1}$ of light intensity, 50-60% of relative humidity, and 25.0°C of leaf temperature. ($y=29.7+0.005\cdot x-0.0000006\cdot x^2$ ($R^2=0.826^{***}$)).

The response of net photosynthesis rate (P_n) of quinoa plants to photosynthetic photon flux density (PPFD) or photosynthetic active radiation (PAR) was measured and modeled (Fig. 3-3). The non-rectangular hyperbola model was chosen as the response function of net photosynthesis. From the results, the light compensation point at 29 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and the light saturation point at 813 $\mu mol \cdot m^{-2} \cdot s^{-1}$ were required to quinoa cultivation based on fluorescent lamps and the respiration rate at 3.4 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The potential photosynthesis rate (P_{max}) was 25.3 $\mu mol \cdot CO_2 \cdot m^{-2} \cdot s^{-1}$, the start gradient to straight line (α) was 0.14 $\mu mol \cdot CO_2 \cdot m^{-2} \cdot s^{-1}$, the photosynthesis rate at PAR 0 was 3.4 $\mu mol \cdot CO_2 \cdot m^{-2} \cdot s^{-1}$, and the photosynthesis rate (P_n) was 21.61 $\mu mol \cdot CO_2 \cdot m^{-2} \cdot s^{-1}$. The equation of the non-rectangular hyperbola has been frequently used to describe observed leaf photosynthetic responses to environmental variables (Calama et al., 2013; Cannell and Thornley, 1998; Kim et al., 2004; Lieth and Pasian, 1990; Thornley, 2002). A non-rectangular hyperbola was a suitable mathematical description of the PAR response of rose leaves (Lieth and Pasian, 1990).

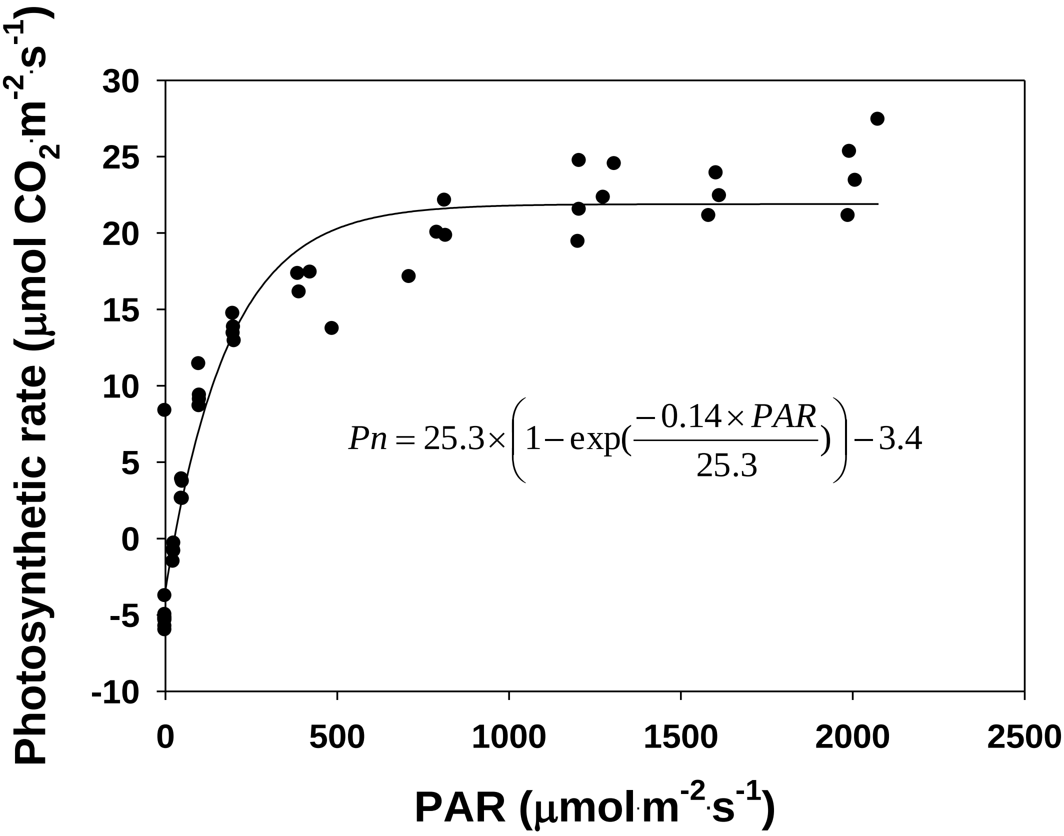

Fig. 3-3. Photosynthetic curves of quinoa at 1,000 μmol·mol^{-1} of CO_2 concentration, 50-60% of relative humidity, and 25.0°C of leaf temperature.

The shoot fresh weight (SFW, g/plant) was closely related to shoot dry weight (SDW, g/plant). The SFW was a linear relationship with the SDW (Fig. 3-4). From the model, the SFW was calculated as 15 multiplied by the SDW. The measured and estimated SFWs were shown in a reasonably good fit with this function. Most researches on crop productivity have usually concentrated on dry matter. The fresh weight is an economic interest in the sector of commercial vegetable production (Cho and Son, 2009).

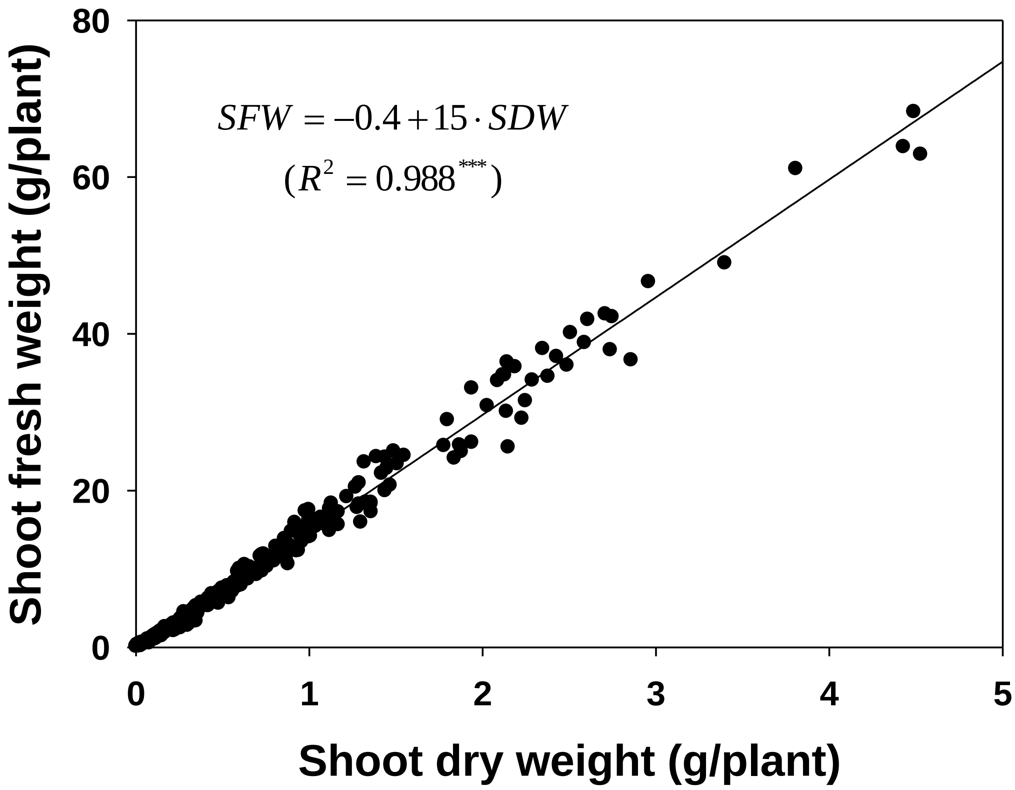

Fig. 3-4. Relationship between shoot dry weight and shoot fresh weight of quinoa (n=333).

A non-linear regression was carried out to describe the increasing of the shoot dry weight of quinoa as a function of time using an expolinear equation. The maximum crop growth rate was 22.9 $g \cdot m^{-2} \cdot d^{-1}$, the maximum relative growth rate was 0.28 g·g^{-1}·d^{-1} in the exponential growth phase, and the time at which the crop effectively reaches a linear phase of growth was 13 days (Fig.3-5). The curve of the function indicated a pattern of expolinear growth as suggested by Goudriaan and Monteith (1990). Basically, the growth of crop is exponential with a maximum relative growth rate and later becomes linear with a maximum crop growth rate. The expolinear growth model as a type of crop growth model has been applied to many crops and has the potential to predict crop growth and yield.

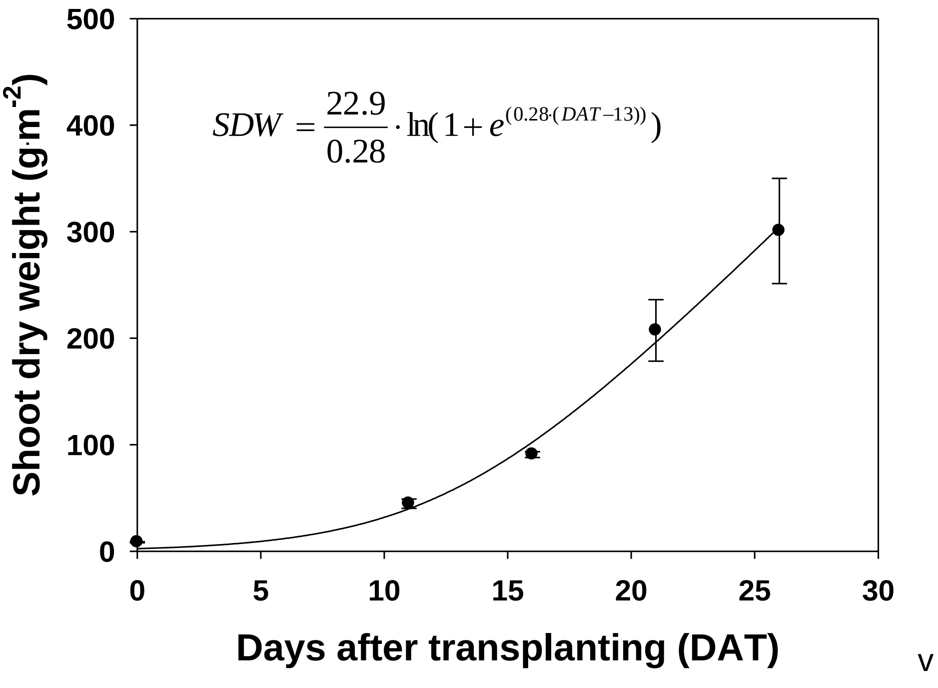

Fig. 3-5. Shoot dry weights (g·m^{-2}) of quinoa with days after transplanting. The vertical bars represent the standard errors (n=4).

The measured and estimated shoot dry weights were compared (Fig. 3-6). The regression coefficient was 0.75 (R^2=0.921***). The measured and estimated SDWs were shown in a reasonably good fit with this function. The crop yield is calculated as the total dry matter multiplied by the harvest index (Mo, et al., 2005).

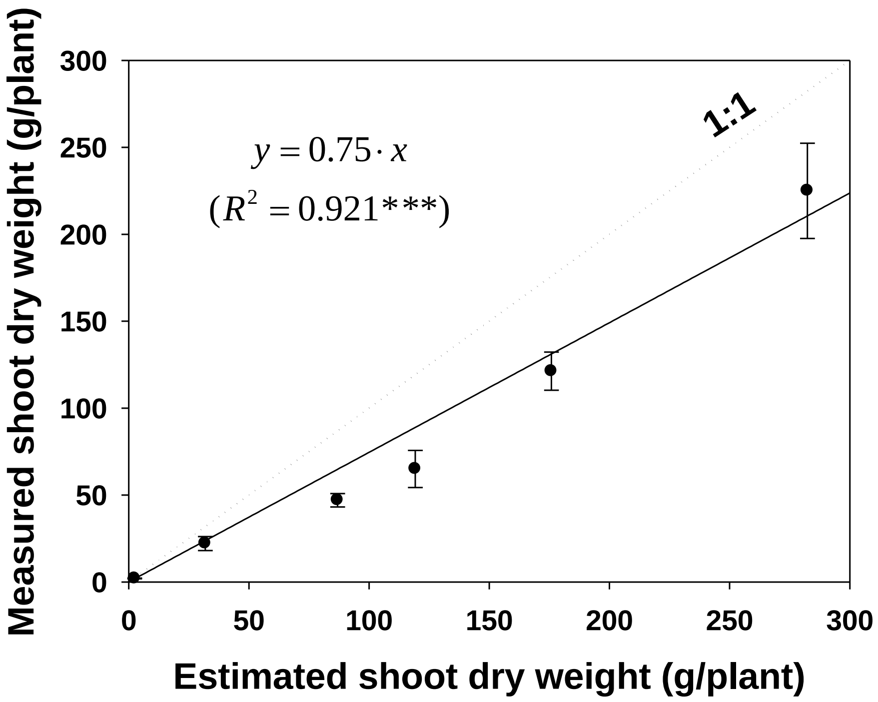

Fig. 3-6. Relationship between the estimated and measured shoot dry weights of quinoa. The vertical bars represent the standard errors (n=4).

It is concluded from this study that the modelling growth and yield of quinoa in a closed-type plant factory system response to photosynthetic photon flux density (PPFD) or photosynthetic active radiation (PAR). The non-rectangular hyperbola model was chosen as the response function of net photosynthesis. The modelling growth and yield responses to environmental variables are very useful to predict attainable quinoa yield and to identify the constraints to crop production and management strategies. The results of the present study evidenced the importance of continuous research on the economic feasibility for producing quinoa for a leafy vegetable grown in a closed-type plant factory system.

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Chapter IV. Practical Design of an Artificial Light-used Plant Factory for Quinoa (*Chenopodium quinoa* Willd.) for a Leafy Vegetable

Abstract

Quinoa (*Chenopodium quinoa* Willd.) is a grain crop. It is loaded with high nutritional values. Its leaves and sprouts can also be consumed as in raw or cooked which provide amount of nutritive values and high antioxidant and anticancer activities. This study was carried out to get the basic data to practically design an artificial light-used plant factory for quinoa cultivation for a leafy vegetable. The energy content and electrical energy required of the produced quinoa were estimated. The results were shown that when the yield was 1,000 plants per day. The planting density and light intensity were 0.015 m^2 (15×10 cm) and 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, respectively. The total number of the plants, cultivated area, and electric consumption were estimated as 25,000 plants, 375 m^2, and 93,750 $\mu mol \cdot s^{-1}$, respectively. The white fluorescent lamps power was 20.4 kW with 1,857 fluorescent lamps (FL, 55 W) and the electricity charge was 2.19 million won per month. If the daily harvest plant was 1,000 plants per day in closed-type plant factory, the light installation cost, total installation cost, and total production cost were 18.57, 55.70, and 66.85

million won, respectively. The production cost per plant including labor cost was calculated as 320 won, providing that the cultivation period was 25 days and marketable ratio was 80%. Considering the annual total expenses, incomes, and depreciation cost, the selling price per plant could be estimated around 670 won or a little bit higher.

***Additional key words*:** light intensity, light installation cost, selling price per plant, total production cost

Introduction

A plant factory is a controlled environment for plant production systems with artificial environments and cultivation solution. In plant factory systems, plants are grown consistently all year around with high technology systems, and less water, nutrition, pesticides and labors are consumed for plant cultivation. The concept of "Plant factory" could realize the multiple targets of high yield, high quality, high efficiency and security. It had become the trend of agricultural development. In a plant factory, an optimal control for obtaining higher yield and better quality of plants is essential (Hu et al., 2014; Tian et al., 2014). The overall design of an industrial crop production system should optimize the system's global parameters such as required total area, intensity of cultivation and general production schedule. The key element is the optimal intensity of cultivation for the prevailing climatic and economic environments (Seginer and Ioslovich, 1999). The operating cost of plant factories is usually high due to intensive energy consumption. It is crucial to choose appropriate crops or cultivars for cultivation at proper time for revenue maximization (Hari et al., 2012).

Quinoa (*Chenopodium quinoa* Willd.) is a grain crop. It is loaded with high nutritional values. Its leaves and sprouts can also be consumed as in raw or cooked which provide amount of nutritive values and high antioxidant and anticancer activities (Gawlik-Dzik et al., 2013; Paśko et al., 2009; Schlick and

Bubenheim, 1996).

The results of the previous study evidenced the importance of continuous research on the economic feasibility for producing quinoa for a leafy vegetable grown in a closed-type plant factory system. Moreover, the economic feasibility in accordance with the number of days to harvest quantity and administrative costs was analyzed.

Materials and Methods

Models

The mathematical function used for expressing shoot dry weight by time is called expolinear equation (Goudriaan and Monteith, 1990):

$$W=C_m/R_m x 1n\ [1+\exp\{R_m x (t-t_b)\}] \quad (1)$$

where, W is biomass (shoot dry weight, $g{\cdot}m^{-2}$) at t days from transplanting, C_m is the maximum crop growth rate ($g{\cdot}m^{-2}{\cdot}d^{-1}$), R_m is the maximum relative growth rate ($g{\cdot}g^{-1}{\cdot}d^{-1}$) in the exponential growth phase, t is the time after transplanting (day), and t_b is the time at which the crop effectively reaches a linear phase of growth (lost time, d).

The cumulative production of quinoa plants in a plant factory was calculated according to:

$$m=nxt \quad (2)$$

where, m is total number of plants in a plant factory, n is daily harvest plants (plants/day), and t is the harvesting days (days).

Electric Consumption Estimation

The estimated electric consumption by lighting in a plant factory (F, $\mu mol \cdot m^{-2} \cdot s^{-1}$) was calculated with the equation:

$$F = A \times PAR / M / U \quad (3)$$

where, A is the coverage area of the light source (m^2), PAR is the photosynthetic active radiation ($\mu mol \cdot m^{-2} \cdot s^{-1}$), M is a rate of return, and U is the lighting rate, it is assumed as M·U=0.8. The approximate conversion value of white fluorescent lamp is 1 W=4.59 $\mu mol \cdot s^{-1}$.

The white fluorescent lamps power (FP) and electricity used per month (E) were calculated by the equations:

$$FP = F / \omega / \varphi \quad (4)$$

$$E = FP \times h \times d \quad (5)$$

where, ω is the conversion value of white fluorescent (4.59 $W \cdot m^{-2}$), φ is the fluorescent efficiency (assumed as 20%), h is number of usage hours per day (16 hours), and d is the number of usage days per month (30 days).

The electricity charges per month (P) were calculated with electricity price (in won per kWh) charge, 39.2 won using the formulas to estimate usage and cost:

$$PW = E \times 39.2 \quad (6)$$

$$P=PW+(PW\times0.1)+(PW\times0.037) \qquad (7)$$

where, PW is electric rates based on kilowatts used per month. Electric rates are based on the commercial electric rate, and the value added tax system prices (VAT, 10%) and electric power commercial electric rate, calculated as 3.7%.

Production Cost Calculation of Area Configuration

The start gradient to straight line (α) is estimated to be for the triple fluorescent lamp in a plant factory. The average lifetime levelized electricity cost (PF) for the plant using the white fluorescent lamps power is calculated by the equation:

$$PF=3\times\chi \qquad (8)$$

where, χ is lighting equipment cost. The estimated operating life of a fluorescent lamp in a plant factory as 10 years and light installation cost per year (β) of the depreciation as 25% of the production costs (ρ) is the following relationship:

$$\beta=3\times\chi/10 \qquad (9)$$

$$\rho=4\times3\times\chi/10 \qquad (10)$$

Light cost per plant (y) and the production cost per plant (k) were calculated as:

$$y=\chi/m \quad (11)$$

$$\kappa=y/9.6 \quad (12)$$

The production cost (CP) is calculated as:

$$CP=\tau x n x \Omega x dy \quad (13)$$

where, τ is a marketable yield (80%), n is daily harvest plants (1,000 plants/day), Ω is a market price per plant, and dy is the total of harvest day (325 days). The maintenance cost (M) per unit of cultivated area amounts were calculated as (Kim, 2009):

$$M=mxPDx201,760\ won/m^2 \quad (14)$$

where, PD is a planting area (m^2).

Results and Discussion

The energy content and electrical energy required of the produced quinoa were estimated. Based on the previous study results, the light saturation point at 813 μmol·m^{-2}·s^{-1}, the photosynthesis rate (P_n) was 21.61 μmol·CO_2·m^{-2}·s^{-1}, and the photosynthetic photon flux density (PPFD) of 200 μmol·m^{-2}·s^{-1} under fluorescent lamps at 25°C was required to quinoa cultivation. Plants use a photon which is in a light for photosynthesis. PPFD is a way of representing a light intensity which is used by plants in this case. In the case of fluorescent light, 1 μmol·m^{-2}·s^{-1} is equivalent to 74 lx (Lee and Kim, 2012). When PPFD was set to 200 μmol·m^{-2}·s^{-1}, the value of illuminance can be calculated as 14,800 lx. Also, when the light supply is 0.2 m above the plant, the area will be 0.04 m^2. The luminous flux is calculated as 1,184 lm. The luminous flux and PPFD of fluorescent lamps are 4,800 lm and 65 μmol·m^{-2}·s^{-1}, respectively. Therefore, when the PPFD of 200 μmol·m^{-2}·s^{-1} is above the 0.2 m of the crop, 2 fluorescent lamps are needed.

The electric consumption was estimated. The total number of the plants was 25,000 plants when the days to harvest quinoa as 25 days after transplanting and the harvest yield per day as 1,000 plants per day. The cultivated area was 375 m^2 when the planting density was 0.015 m^2/plant (15×10 cm). The estimated electric consumption by lighting in a plant factory

(F) was 93,750 μmol·s^{-1} (375 m^2 x 200 μmol·m^{-2}·s^{-1} /0.8). The white fluorescent lamps power (FP) was 20.4 kW with 1,857 fluorescent lamps (FL, 55 W).

The economic feasibility of quinoa plants was analyzed at four different light intensities (Table 4-1). In the case 1, the light intensity of 200 μmol·m^{-2}·s^{-1}, the price of 55 W fluorescent lamp was assumed as 10,000 won per lamp, so that the light installation cost was 18.57 million won. The three levels of fluorescent lamp installed in a plant factory were assumed, then the total installation cost was 55.70 million won. The electricity used per month (E) was 49,020 kWh when the number of usage hours per day was 16 hours and the number of usage days per month was 30 days. When the electricity price (in won per kWh) charge was 39.2 won, the electricity charge per month (P) was 2.19 million won (49,020 kWh×39.2+49,020 kWh×39.2×0.1+49,020 kWh×39.2×0.037) and the electricity charge per year was 26.22 million won. When the lifetime of the fluorescent lamp in a plant factory as 10 years and light installation cost per year of the depreciation as 25% of the production costs (the depreciation rates are determined as four times for production costs) were assumed, the production cost was 1.2 times of the total installation cost (55.70 million won), so the production cost was 66.85 million won.

When n is daily harvest plants, the cultivation period was 25 days (the total of harvest day was 325 days per year), and the marketable ratio was 80%. The production cost (CP) was calculated as 0.8×n×325=260n. If the daily harvest plant was 1,000 plants per day, the total number of plant was 25,000 plants, the light cost per plant was 743 won (18,568,000 won/25,000 plants). Then, the production cost per plant was 77 won (743/9.6).

Seo et al. (2008) reported that the production cost per plant in a plant factory operation is difficult to determine exactly. It was estimated through the results of lettuce. If the daily harvest plant was 1000 plants per day and the 6 part-time employees (employee earns 5,314 won an hour) worked for 5 hours a day, production cost per plant including labor cost per plant was 320 won (80 won+240 won). If included the electricity cost per year and production cost (labor costs+depreciation costs+production cost), the total production cost was 98.75 million won. The plant sale per year was 83.20 million won (0.8×1,000 plants×320 won×325 days). Assuming the transportation of product and administrative expenses were 18,158 won/900 m^2 (Kim, 2009), the total revenue was 174.4 million won or 0.47 million won/m^2. Considering the annual total expense, income, and depreciation cost, the selling price per plant could be estimated around 670 won or a little bit higher.

From the results, the economic feasibility for quinoa cultivation based on fluorescent lamps in a closed-type plant factory system was estimated. If the selling price per plant was 670 won, the total revenue was 174.4 million won. Excluding the various costs which are estimated to 174.2 million won, the profit was 0.2 million won. In particular, in the case of the product improvement at 90%, the total revenue was 196.0 million won. So the profit was 21.6 million won or 57,600 won/m^2.

Table 4-1. Economic feasibility analyses of fluorescent lamps-used plant factories growing quinoa plants at different light intensities.

Item	Case 1	Case 2	Case 3	Case 4
Light intensity ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	200	250	300	400
Yield (plants/day)	1,000	1,000	1,000	1,000
Harvesting time (day)	25	25	25	25
Planting density (m^2/plant)	0.015	0.015	0.015	0.015
Total installation cost (1,000 won)	55,705	69,630	83,556	111,408
Production cost (1,000 won)	66,845	83,556	100,267	133,690
Light installation cost (1,000 won)	18,568	23,210	27,852	37,136
Electricity cost per year (1,000 won)	26,218	32,772	39,327	52,436
Light cost per plant (won)	743	928	1,114	1,485
Production cost per plant (won)	77	97	116	155
Maintenance cost (1,000 won)	75,660	75,660	75,660	75,660
Selling price per plant (≥ won)	670	770	860	1,050

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CONCLUSIONS

The purpose of this study was to define the optimum nutrient solution electrical conductivity (EC), photoperiod, light intensity and planting density to attain the best quality on yield, plant growth and economic feasibility for producing quinoa (*Chenopodium quinoa* Willd.) for a leafy vegetable grown in a closed-type plant factory system. The models and equations were used for yield prediction, production planning, crop management and economic aspects.

The quinoa (*Chenopodium quinoa* Willd.) was grown at the optimum EC at 2.0 $dS{\cdot}m^{-1}$ with PPFD of 143 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ under 16/8 h (day/night) photoperiod for growth productivity without flowering in a closed-type plant factory. The highest shoot fresh weight, shoot dry weight and total leaf area were obtained from planting transplants at the spacing of 15x10 cm or the planting density of 67 plants/m^2. A linear relationship was observed between the plant heights and days after transplantation. Plant height model was $5.4+0.58{\cdot}DAT^{-1}$ (R^2=0.932***). The change of plant height was 0.58 cm per day. The non-rectangular hyperbola model was chosen as the response function of net photosynthesis. A non-linear regression was carried out to describe the increasing of the shoot dry weight of quinoa as a function of time using an expolinear equation. The CO_2 saturation point of leaves was 400 $\mu mol{\cdot}mol^{-1}$. The photosynthesis rate was the highest at PPFD of 400 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$

(R^2=0.826***). The light compensation point, light saturation point, and respiration rate were 29 μmol·m^{-2}·s^{-1}, 813 μmol·m^{-2}·s^{-1} and 3.4 μmol·m^{-2}·s^{-1}, respectively. The crop growth rate and relative growth rate were 22.9 g·m^{-2}·d^{-1} and 0.28 g·g^{-1}·d^{-1}, respectively. The regression coefficient of shoot dry weight was 0.75 (R^2=0.921***). These models can accurately estimate the plant height, net photosynthesis rate, CO_2 curve, shoot fresh weight, and shoot dry weight of quinoa.

The practical design of an artificial light-used plant factory for quinoa cultivation was shown that if the yield was 1,000 plants per day when the plant density and light intensity were 0.015 m^2/plant (15×10 cm) and 200 μmol·m^{-2}·s^{-1}, respectively. The total number of the plants, cultivated area, and electric consumption were estimated as 25,000 plants, 375 m^2, and 93,750 μmol·s^{-1}, respectively. The white fluorescent lamps power was 20.4 kW with 1,857 fluorescent lamps (FL, 55 W) and the electricity charge was 2.19 million won per month. If the daily harvest plant was 1,000 plants per day, the light installation cost, total installation cost, and total production cost were 18.57, 55.70, and 66.85 million won, respectively. The production cost per plant including labor cost was calculated as 320 won, providing 25 days of the cultivation period and 80% of marketable ratio. Considering the annual total expenses, incomes, and depreciation cost, the selling price per plant could be estimated around 670 won or a little bit higher.

The economic feasibility for quinoa cultivation based on fluorescent lamps in a closed-type plant factory system was demonstrated that if the selling price per plant was 670 won, the total revenue was 174.4 million won or 0.47 million won/m^2. Excluding the various costs which are estimated to 174.2 million won, the profit was 0.2 million won. In particular, in the case of the product improvement at 90%, the total revenue was 196.0 million won. So the profit was 21.6 million won or 57,600 won/m^2.

Therefore, the quinoa can be practically applied for a leafy vegetable in a closed-type plant factory system. This work provides the high benefits with the cultivation unit of 375 m^2. Moreover, the quinoa can be successfully cultivated in plant factories, but the operating cost of plant factories is usually high due to intensive energy consumption. The advantages of utilizing artificial light such as the light emitting diodes (LED) should be studied more in the future for producing quinoa for a leafy vegetable in a closed-type plant factory system for the high profit. Because of, the light emitting diodes have many advantages over the fluorescent lamps.

ABSTRACT IN KOREAN

키노아(Quinoa)는 안데스 지역 원산의 식용 식물이며, 높은 항산화, 항암 작용 및 영양학적 가치가 있는 곡물이다. 키노아의 연구들은 대부분 종자에만 국한되어 있으나, 잎을 채소화할 경우 많은 이점이 있을 것이다. 따라서, 본 연구의 목적은 완전제어형 식물공장에서 키노아의 잎채소 생산을 위해 생육과 수량에 대한 최적의 배양액농도, 광주기, 광도와 재식밀도를 얻고, 생육 모델 개발 및 식물공장 설계를 위한 기초자료를 확보하고자 수행되었다.

배양액의 농도(electrical conductivity, EC)는 1.0, 2.0과 3.0 dS·m^{-1}수준으로, 광도는 120과 143 μmol·m^{-2}·s^{-1}수준, 일장은 12/12 h, 14/10 h과 16/8 h (day/night) 수준으로 처리하였다. 광도 143 μmol·m^{-2}·s^{-1}와 EC 2.0 dS·m^{-1}에서 재배된 식물체에서 다른 환경에서 보다 주당 지상부의 생체중, 건물중, 초장, 엽면적과 광 이용 효율이 모두 높게 나타났다. 16/8 h의 일장 조건에서는 화아분화가 일어나지 않았다. 즉, 본 연구에서 키노아는 단일성 식물이었다. 이러한 결과로, 완전제어형 식물공장에서 키노아의 생산에 추천되

는 적정 환경 조건은 EC 2.0 $dS \cdot m^{-1}$, 광도 143 $\mu mol \cdot m^{-2} \cdot s^{-1}$과 일장 16/8 h (day/night)였다.

적합한 재식밀도를 구명하기 위해, 15 cm 열간에서 10, 15, 20와 25 cm 의네 수준의 간격으로 배치하였고, 재식밀도는 각각 27, 33, 44, 그리고 67 $plants/m^2$였다. 식물체당 생체중과 건물중은 재식밀도 33 $plants/m^2$ (15x20 cm)에서 높게 나타났으나, 단위면적당 생체중과 건물중은 재식밀도 67 $plants/m^2$ (15x10 cm)에서 높게 나타났다.

이후, 완전제어형 식물공장에서의 키노아의 생육(초장, 생체중과 건물중) 모델을 개발 하였다. 초장과 이산화탄소 농도는 선형 모델, 광합성 모델은 non-rectangular hyperbola 모델, 건물중 모델은 expolinear 생육 모델을 이용하여 모델식을 예측하였다. 키노아의 초장과 정식 후 일자 사이에서는 선형 관계가 나타났다. 초장의 모델식은 $5.4+0.58 \cdot DAT^{-1}$ (R^2=0.932***)였다. 광보상점, 광포화점, 호흡율은 각각 29 $\mu mol \cdot m^{-2} \cdot s^{-1}$, 813 $\mu mol \cdot m^{-2} \cdot s^{-1}$과 3.4 $\mu mol \cdot m^{-2} \cdot s^{-1}$였다. 이산화탄소 포화점은 400 $\mu mol \cdot mol^{-1}$ (R^2=0.826***)이었다. 생장 곡선은 expolinear 생육 곡선을 보였으며, 작물 생장율과 상대 생장율

은 각각 22.9 $g{\cdot}m^{-2}{\cdot}d^{-1}$와 0.28 $g{\cdot}g^{-1}{\cdot}d^{-1}$였다. 이러한 생장모델을 이용하여 키노아의 초장, 광합성률, 이산화탄소 곡선, 지상부 생체중과 지상부 건물중을 정밀하게 추정할 수 있었다.

완전제어형 식물공장에서 실용적으로 키노아 재배를 설계하기 위하여 기초 자료에 대한 수익성 분석을 수행하였다. 하루에 1000주의 수량을 얻을 때, 재식밀도와 광도는 각각 0.015 m^2/plant (15×10 cm), 200 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$이다. 총 식물 개체 수, 재배 공간과 광도는 각각 25,000주, 375 m^2, 93,750 $\mu mol{\cdot}s^{-1}$로 예측되었다. 필요한 형광등의 개수(55 W)는 1,857개로, 요구되는 전력은 20.4 kW이며, 전기요금은 월 219만원이 된다. 만약 완전제어형 식물공장에서의 하루 수확량이 1,000주라면, 광 설치비용, 총 설치비용과 총 생산비용은 각각 1,857만원, 5,570만원과 6,685만원이 된다. 식물 한 주당 생산비중 인건비는 320원으로 계산되었고, 재배기간을 25일, 상품화율을 80%로 가정하였다. 연간총비용, 소득 및 감가상각비를 고려할 때, 식물 한 주당 판매 가격은 670원이나 그 이상으로 계산될 수 있었다. 식물 한 주당 판매 가격을 670원으로 할 때, 총 수익은 1억7,440만원 혹은 47만원/m^2으

로 나타났다. 추정된 1억7,440만원에서 다양한 비용을 제외하면 총 수익은 20만원으로 나타났다. 특히, 상품화율을 90% 수준으로 높인다면, 총 수익은 1억960만원이었다. 따라서 이익은 2,160만원 혹은 57,600원/m^2으로 나타났다.

이상의 결과로부터, 완전제어형 식물공장에서 키노아의 최적 생육 조건을 제공해줄 수 있었으며, 생육 예측을 위한 모델을 개발할 수 있었다. 뿐만 아니라, 최적 생육 조건하에서의 여러 가지 모델을 통해 생육 상태를 예측할 수 있었고, 또한 키노아 잎 생산을 위한 완전제어형 식물공장의 경제성 분석을 통해 적절한 판매 가격을 제시하였다.

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