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Performance analysis of an experimental plant factory

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Abstract : Plant factory has drawn attention in many countries in the world due to capability of environmental control not only for better yield and quality, but also for increase in functional and medicinal components of the products. In this paper, an experimental plant factory was constructed for various tests under different environmental conditions, and the operations were evaluated. A production room was constructed with adiabatic materials with dimensions of 6,900 × 3,000 × 2,500 mm (L×W×H). Four sets of 2,890 × 600 × 2,320 mm (L×W×H) production frame unit, each with 9 light-installed beds and an aeroponic fertigation system, resulting in 36 beds, were prepared. Accuracy and response were evaluated for each environmental control component with and without crops. Air temperature, humidity, CO_2 concentration, light intensity, frequency, and duty ratio, fertigation rate and scheduling were controllable from a main control computer through wireless communication devices. When the plant factory was operated without crop condition, the response times were 8 minutes for change in temperature from 20 to 15°C and 20 minutes from 15 to 20°C; 7 minutes for change in humidity from 40 to 65%; and 4 minutes for change in CO_2 concentration from 450 to 1000 ppm. When operated for 24 hours with crop cultivation; average, maximum, and minimum values of temperatures were 20.06, 20.8, and 18.8°C; humidity were 66.72, 69.37, and 63.73%; CO_2 concentrations were 1017, 1168, and 911 ppm, respectively. Photosynthetic Photon Flux Density was increased as the distance from the light source decreased, but variability was greater at shorter distances. Results of the study would provide useful information for efficient application of the plant factory and to investigate the optimum environment for crop growth through various experiments.

Key words **:** Plant factory, Environment control, Performance evaluation, Response time

I. Introduction

Plant factory may provide environments suitable for crop growth. In a plant factory, crops might be produced continuously in optimum conditions of environmental factors such as light, temperature, humidity, CO_2 concentration, water content, and nutrient. Plant factory has been constructed and tested in many countries. Plant factory is mainly classified into two types: full-control type with artificial light and partial-control type with sun light. Ikeda et al. (1992) controlled environmental factors, monitored and managed a full-control type plant factory. Son et al. (2002) developed and controlled an urban-type plant factory. Kim et al. (2006) controlled environmental factors in a plant factory using programmable logic controller (PLC).

Light is an important factor affecting crop growth through photosynthesis. Light sources frequently used in plant factory are fluorescent lamp, Cold Cathode Fluorescent Lamp (CCFL), External Electrode Fluorescent Lamp (EEFL), Light-Emitting Diode (LED), and Ultraviolet (UV) Lamp. LED is relatively expensive, but could be supplied with selected wave-lengths. Some LEDs are known to increase functional components of crops, producing high value products (Nishimura et al., 2006). Kwon and Lim (2011) suggested optimum light sources for crop growth. CO_2 concentration is a factor affecting crop growth through photo-synthesis. Jin et al. (2000) reported that lettuce in

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the middle of growing stage grow fast at CO_2 concentration of 1000 to 2000 ppm.

Temperature affects crop growth, and abnormal condition may cause physiological disorder. Optimal temperatures are different for different crops and growth stages. Choi et al. (2011) investigated germination rate of bokchoi and lettuce according to no light and 25 ℃ temperature conditions. Choi et al. (2003) investigated the effect of temperature on early, middle, and night growth at 22~26, 20~24, and 15 °C, respectively, with lettuce. If humidity is too high, mold disease may be formed in the crops. Growing-room should be maintained a constant humidity for favorable crop growth (Jin et al., 2000).

Nutrient is also very important factor that needs to be maintained at an optimum level. Lee et al. (2002) investigated suitable electrical conductivity (EC) and pH in a plant factory for roses. Hydroponic methods include Deep Flow Technique (DFT), Nutrient Film technique (NFT), and aeroponic systems. Aeroponic system can be advantageous in oxygen supply on the roots, resulting favorable conditions for leaf and root growth. Ritter et al. (2001) reported that potato production and weight in an aeroponic system were improved by 70% and 2.5 times, respectively. In addition, maintaining a constant temperature in root part is favorable with an aeroponic system (Lee et al., 2002). Morimoto et al. (1995) proposed a control algorithm for high yield and good quality. Ioslovich and Gutman (2000) suggested model-equations for transplanting interval for several crops.

The objective of the research was to build an experimental plant factory for testing crop growth and the components in various environmental conditions and to evaluate the control performance.

II. Materials and methods

1. Concept and construction of the plant factory

The plant factory was constructed to investigate the environmental factors on yield, quality, and functional components of plants. Major environmental factors including light, nutrient, temperature, humidity, and CO_2 concentrations were fully and continuously monitored and controlled. Fig. 1 shows dimensions, major components of the experimental plant factory. The plant factory was composed of a cultivation room (6,900 (L) × 3,000 (W) × 2,500 (H) mm) and a monitoring and control room (2,000 (L) × 3,000 (W) × 2,500 (H) mm). In the cultivation room, 12 three-bed cultivation columns were located, resulting in total of 36 beds. Each bed was covered

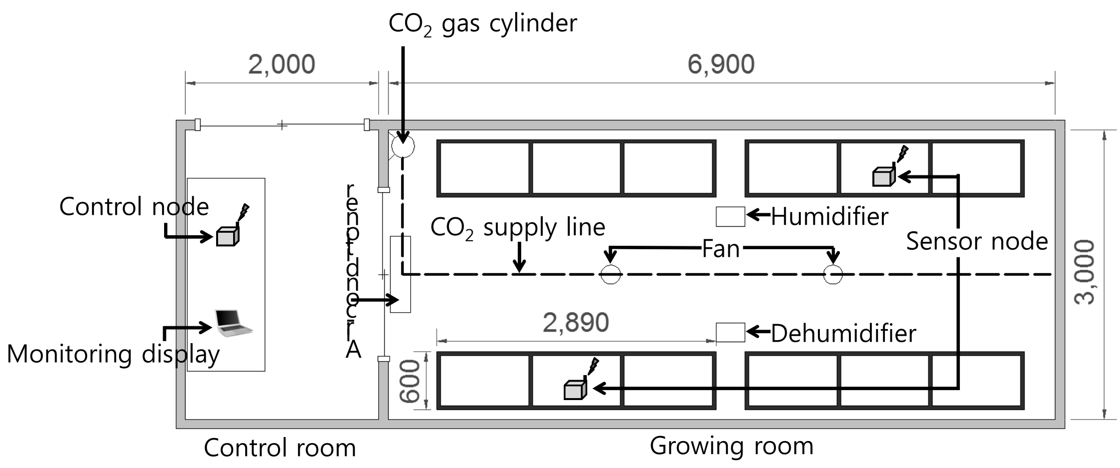

Fig. 1. Layout of the experimental plant factory (unit: mm).

with a growing tray with dimensions of 900 × 600 mm (L × W) and 15 holes designated for planting ports.

The plant factory has fully artificial light sources. Each growing bed has a separate and replaceable lighting source. Different light sources would be considered: LED (light emitting diode), fluorescent, or halogen lamps. Lighting interval and intensity was controlled electronically for LEDs, and with a timer for other light sources. Mixed LED array of 11:4:3 (R:B:W) was selected, and the wavelengths were blue (440 nm), red (mixture of 640 and 660 nm), and white (mixture of 460 and 550 nm). Maximum Photosynthetic Photon Flux Density (PPFD) was 220 $\mu mol \cdot m^{-2}s^{-1}$ at a 400-mm distance from the light source, the intensity was maintained at 160 $\mu mol \cdot m^{-2}s^{-1}$ during crop cultivation. Lighting duty ratio was set a 16:8 (day:night) combination.

Nutrient was supplied by using an aeroponic-type hydroponic device, composed of growing tray, water tank, water pump and nozzle. UV lamp and filter were also used to remove impurities into roots. The water tank level was maintained at 40 L during crop cultivation. Each tray was equipped with five nozzles, whose capacity was up to 2 L/min. Nutrient supply columns, consisted of three growing beds, were controlled independently.

Temperature was controlled by using an air conditioner (CSV-Q115N, Carrier, USA). Humidity was also controlled by using a humidifier (NH-4, Hwajeun Engineering, Republic of Korea) and a dehumidifier (LD-106D, LG, Republic of Korea). CO_2 was supplied with a CO_2 gas cylinder and controlled by using a solenoid valve. Air agitation in the plant factory was controlled by using fans (TWP-20P, Innotech, Republic of Korea). Table 1 shows specifications of the equipment in the growing room. The growing room was monitored with a web-camera in the control room. The environmental factors (temperature, humidity, CO_2 concentration), were controlled from the control room with a wireless controller and measured by sensors. Those data also were saved for subsequence later analyses.

2. Operation tests

Operations of the plant factory were evaluated in the various temperatures, humidities, light intensities, and CO_2 concentrations, with and without crop cultivation. First, the tests were conducted without crop cultivation. Response times of the environmental variables were evaluated to identify the suitability of the equipments for adjusting the environments to the target levels. Response time was measured for various conditions; temperature from 15 to 20°C and 20 to 15°C, simulating heating and cooling, respectively, humidity from 45 to 65%, and CO_2 concentration from 400 to 1,000 ppm, the values selected considering practical deviations between measured and target levels.

Accuracy of temperature and humidity control at constant levels was also evaluated. Experiments were conducted using the simple ON/OFF control algorithm where the actuators would be operated when there was deviation between the measured and target levels. In addition, variability of these factors at different locations in the growing room was evaluated. Effects of agitation on the temperature variation were tested. PPFD of LED was collected at 100 to 400 mm distances from the light source at a 50-mm interval with a quantum flux sensor (MQ-200, Apogee, USA). Also, pH and EC were measured by using pH and EC meters for 24 hours at an 1-h interval.

In crop cultivation experiments, Chinese cabbage and kale were chosen. The environmental factors were maintained at optimum levels; 20 ± 1°C for temperature, 65 ± 5% for humidity, 1000 ± 100 ppm for CO_2, and 160 $\mu mol \cdot m^{-2}s^{-1}$ for illumination intensity. Fig. 2 shows locations of environmental sensors for both experiments with and without crop culitication. Sensor was located innermost and outermost envir-

Table 1. Specifications of the equipments in the experimental plant factory.

Item	Specifications
Air-conditioning equipment	
Company	Carrier, USA
Model	CSV-Q115N
Cooling area (m^2)	37
Heating area (m^2)	28
Cooling capacity (kW)	4.50
Heating capacity (kW)	5.50
Control range	17～30℃
Humidifier	
Company	Hwajeun engineering, Republic of Korea
Model	NH-4
Humidification capacity (mL/h)	3000
Control range (RH)	15～85%
Dehumidifier	
Company	LG, Republic of Korea
Model	LD-106DR
Dehumidification capacity (L/day)	10
Watts (W)	290
Control range	30～70%
Solenoid valve	
Company	Hyo shin electric, Republic of Korea
Model	HAD 032 L-2
Fluid temperature	0～60℃
Ambient temperature	50℃ (MAX)
Fan	
Company	Innotech, Republic of Korea
Model	TWP-20P
Air volume (m^3/h)	540
Nutrient Sytems	
Manufacturing company	Parus, Republic of Korea
Water tank capacity	61.25 L
Growing bed dimension (D*W*H)	600*900*150 mm
Number of nozzle in growing bed	5 ea
Water nozzle capacity	2 L/min
Water pump capacity, company	5.5 L/min, Multi Engineering, Australia
LED	
Company	Parus, Republic of Korea
Wavelength	Blue(440 nm), Red(640, 660 nm) and White (460, 550 nm)
PPFD	220 $\mu mol \cdot m^{-2}s^{-1}$
Web-camera	
Company	Microsoft, USA
Model	HD-5000
Resolution	720p HD video, up to 30fps

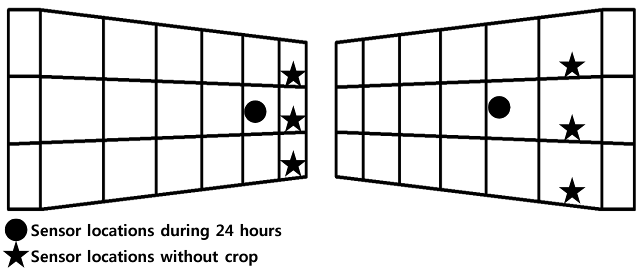

Fig. 2. Sensor locations in the growing room.

onment in order to investigate the average environment conditions in the plant factory.

III. Results and Discussions

Fig. 3 shows the growing-room for this study (left) and monitoring and control display in the control room (right). Fig. 4 shows temperature responses as a function of time at different conditions. Time constants to reach 63.2% of the total change, defined as the response time in the study, were 8 minutes for temperature change from 20 to 15°C and 20 minutes from 15 to 20°C. Maximum and minimum standard deviations of temperature were 0.60, and 0.37 with air-agitator and 2.46, and 0.86 without air-agitator (Fig. 4, bottom). Temperature change was completed

Fig. 3. Growing room in the plant factory (left) and monitoring view (right).

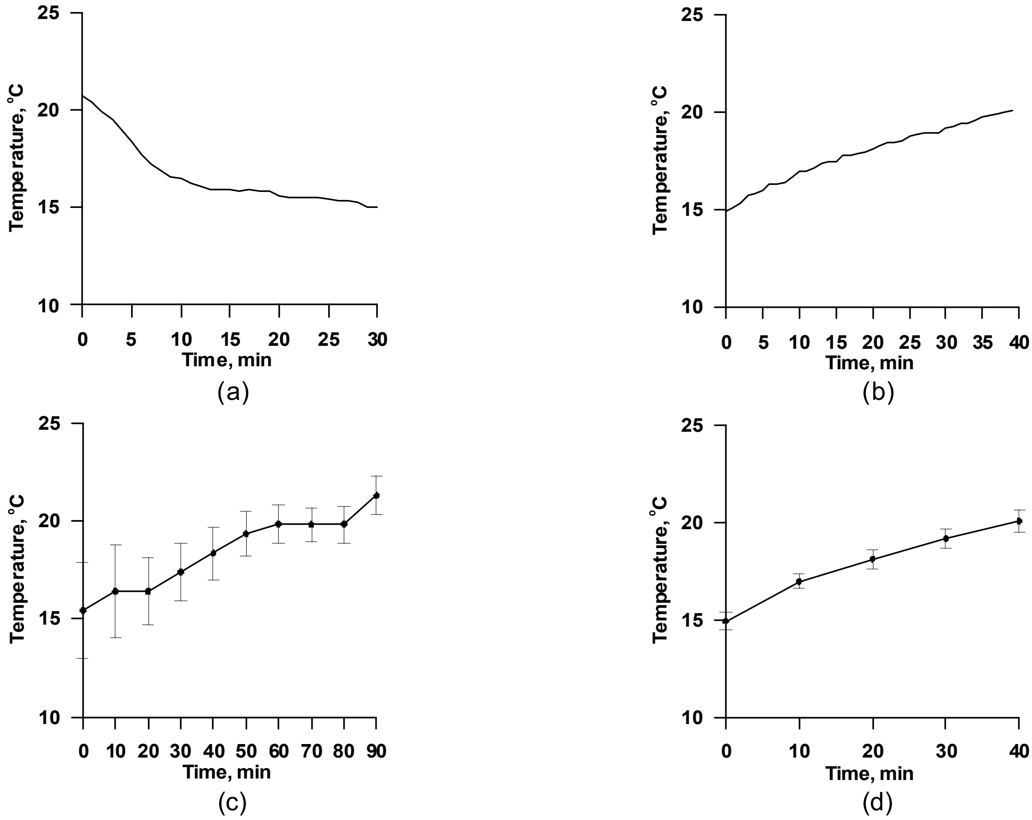

Fig. 4. Response temperature as a function of time; (a) temperature from 20 to 15℃, (b) temperature from 15 to 20℃, (c) with air agitation, (d) without air agitation.

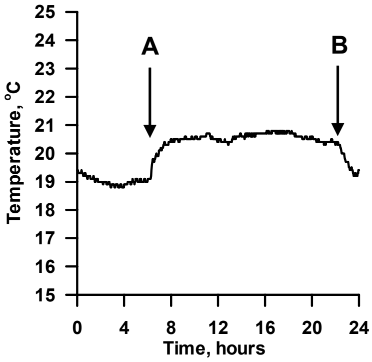

Fig. 5. Temperature variation in the plant factory with crop cultivation for 24 hours.

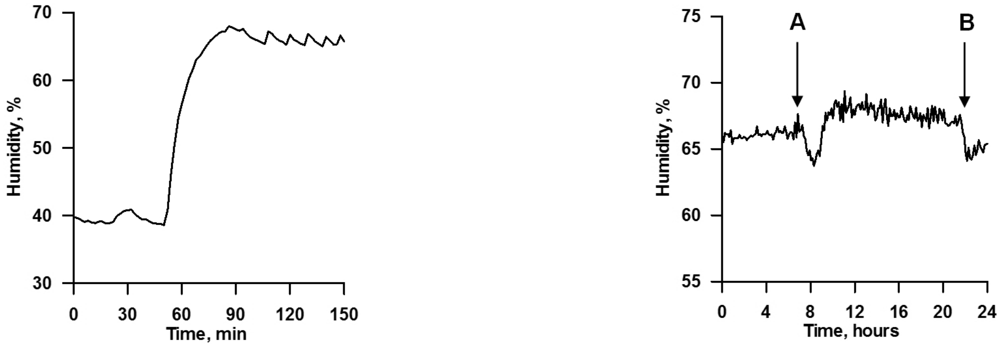

Fig. 6. Response of humidity change from 40 to 65% (left) and performance of humidity control for 24 hours with crop (right).

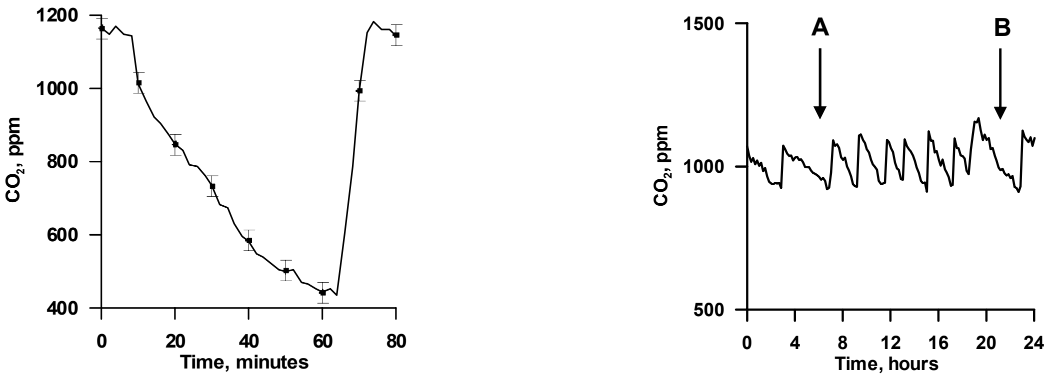

Fig. 7. Performance of CO_2 change (left) and constant control for 24 hours with crop (right).

50 minutes faster with agitation than without agitation.

Fig. 5 shows accuracy of temperature control for 24 hours with crop cultivation. The average, maximum, and minimum temperatures were 20.06, 20.8, and 18.8°C, respectively. Temperature was high when the lights were available which means the duration between A and B in Fig. 5. Fig. 6 shows humidity change from 40 to 65% without crop (left), control at 65% for 24 hours with crop (right). Response time was 7 minutes to reach 63.2% of total change humidity, which was considered to be enough in practical situation without significant changes. Average, maximum, and minimum humidity values were 66.72, 69.37, and 63.73%, respectively. Humidity was relatively unstable for a short period after on and off of the lights. Crop photosynthesize happens under light, but respire in lightless state. Therefore, humidity was unstable when on and off of the light.

Fig. 7 shows performance of CO_2 change (left) and control for 24 hours with a target of 1,000 ppm

Table 2. PPFD about distance of LED (11:4:3) light source (unit : $\mu mol \cdot m^{-2}s^{-1}$).

100 mm					**Max.**	805
655	106	678	110	775	**Min.**	104
740	144	741	124	805	**Avg.**	474.20
690	104	653	107	681	**stdev.**	305.78
150 mm					**Max.**	510
404	243	422	267	451	**Min.**	243
482	305	498	320	510	**Avg.**	384.87
436	268	444	279	444	**stdev.**	93.77
200 mm					**Max.**	380
277	260	318	278	327	**Min.**	260
345	318	380	340	379	**Avg.**	313.40
295	261	318	286	319	**stdev.**	37.79
250 mm					**Max.**	341
238	258	293	261	272	**Min.**	238
277	292	341	314	313	**Avg.**	279.13
245	262	283	270	268	**stdev.**	27.71
300 mm					**Max.**	298
190	230	248	239	230	**Min.**	190
239	274	294	298	267	**Avg.**	246.73
207	238	257	247	243	**stdev.**	28.90
350 mm					**Max.**	272
195	225	240	237	200	**Min.**	192
222	265	272	268	235	**Avg.**	229.13
192	220	234	226	206	**stdev.**	25.30
400 mm					**Max.**	255
176	217	230	224	219	**Min.**	163
199	255	245	238	241	**Avg.**	216.33
163	209	210	220	199	**stdev.**	25.11

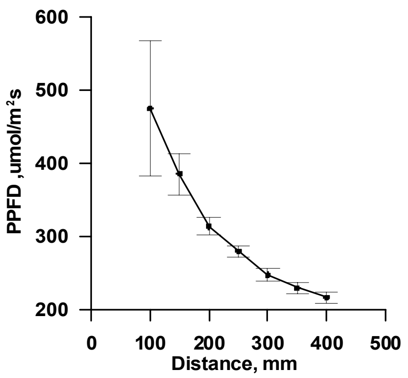

Fig. 8. Average PPFD about distance of LED(11:4:3) light source.

(right). Time constant for CO_2 concentration change from 450 to 1000 ppm was 4 minutes to reach 63.2% of the variation. During constant control, average, maximum, and minimum CO_2 concentrations were 1017, 1168, and 911 ppm, respectively.

Table 2 shows results of measured by a Photo-synthetic Photon Flux Density (PPFD) at different distances from the light source. PPFD was higher when the distance from the light source and the crop was short, but variability was greater at the shorter distances (Fig. 8).

Fig. 9 shows measured changes of EC and pH for 24 hours with and without crops. EC increased from 1.20 dS/m to 1.23 dS/m and pH increased from 6.00 to 6.54 without crops. But, EC decreased from 1.20 dS/m to 1.12 dS/m and pH increased from 6.00 to 6.87 with crops. Because crops absorbed nutrients, EC decreased and pH increased as time goes after the setting of the nutrient conditions.

IV. Conclusions

In this study we evaluated environmental variation and accuracy and responses in an experimental plant factory.

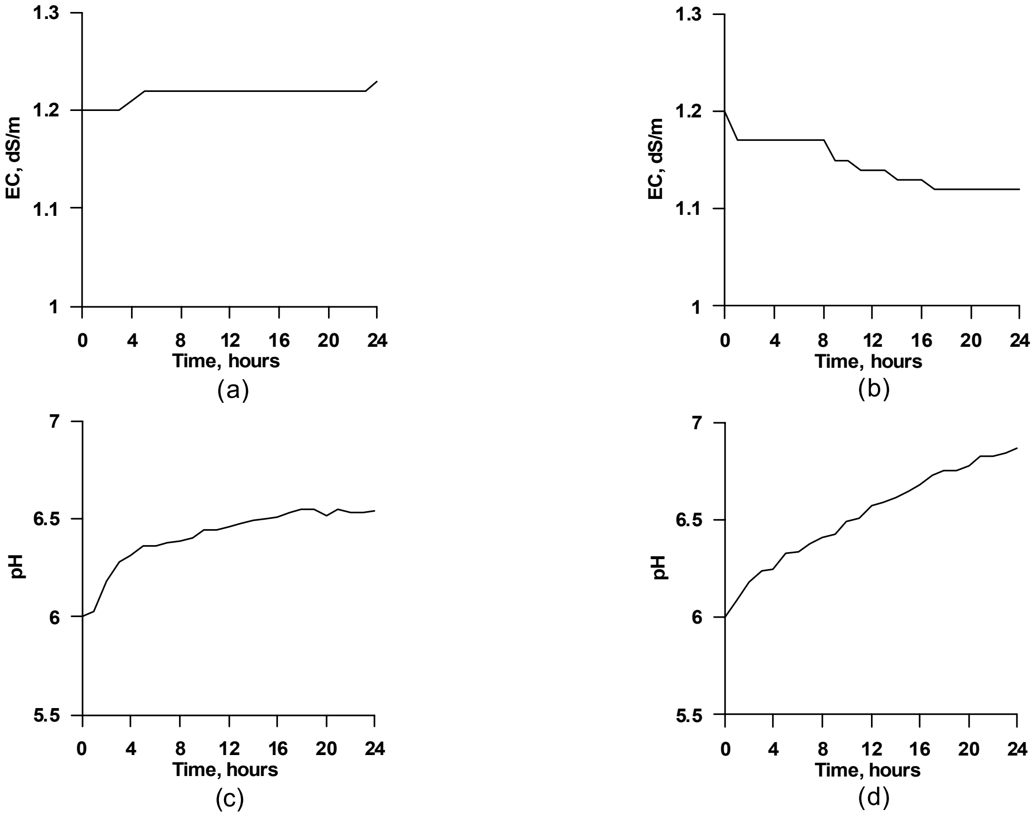

Fig. 9. EC without crop (a) and with crop (b), pH without crop (c) and with crop (d) for 24 hours.

1. The plant factory was designed to have fully artificial light source and controlled environment. Environmental factors such as temperature, humidity, CO_2 concentrations were measured and the data were saved in a computer. Environmental factors were also controlled from the control room with a wireless controller.
2. When the plant factory was operated without crop the response time to time constant was 8 and 20 minutes for temperature change from 20 to 15°C and from 15 to 20°C, respectively; 7 minutes for humidity change from 40 to 65%; and 4 minutes for CO_2 change from 450 to 1000 ppm.
3. When the plant factory was operated with crop; the average, maximum, and minimum values of temperatures were 20.06, 20.8, and 18.8°C; humidity were 66.72, 69.37, and 63.73%; and CO_2 concentrations were 1017, 1168, and 911 ppm, respectively. Temperature, humidity and CO_2 concentration were maintained within the target value. Temperature increased when the lights were on between on and off condition. Whereas, humidity was relatively unstable for a short period after the lights were being turned on and off.
4. PPFD was increased as the distance decreased, but variability was greater at shorter distances. EC and pH values were increased more with crop cultivation than without crop.

Results of this study would provide useful information for efficient application of the plant factory for crop production. Also, plant factory is able to investigate optimum environment for crop growth and functional components through various experiment.

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