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Precision Nutrient Management System based on Ion and Crop Growth Sensing

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Abstract. *Automated sensing and variable-rate supply of nutrients in hydroponic solutions according to the status of crop growth would allow more efficient nutrient management for crop growth in closed systems. The Structure from Motion (SfM) method has risen as a new image sensing method to obtain 3D images of plants that can be used to estimate their growth, such as leaf cover area (LCA), plant height, and fresh weight. In this sense, sensor fusion technology combining ion-selective electrodes (ISEs) and a machine vision technique would be useful in measuring and managing the concentrations of nutrients based on the biomass estimation of crops grown in a plant factory. In this study, a computer-based nutrient management system was developed to effectively manage concentrations of* NO_3*, K, and Ca ions using an array of ISEs and fertilizer pumps to grow lettuce in a closed hydroponic system. Images of lettuce grown were obtained with a RGB camera and an image processing algorithm based on Excess Green (ExG) and RGB indexes was developed to estimate biophysical parameters related to lettuce growth, such as LCA and fresh weight. The growth parameters estimated with the developed image algorithm were validated by a comparison to the actual values. In a validation test, the fresh weights of lettuce plants estimated with the developed image processing algorithm were almost comparable to actual values, exhibiting slopes of 1.26 and with* R^2 *of 0.89. In addition, a Gompertz growth model fitted changes in the estimated fresh weight over time well (*$R^2 > 0.99$*). There were no significant correlations between individual ion absorption rate and the parameters of lettuce growth, but* NO_3 *ion absorption showed a potential (*$P<0.1$*) as a* *nutrient for managing plant growth. The results of this research provided a potential of using an automated nutrient control system and an image processing method for efficient management of lettuce plants grown in a plant factory. Further studies include variable nutrient management of lettuce based on automated sensing of lettuce growth status using an on-the-go image acquisition system that can automatically take lettuce images while moving along a predefined path.*

Keywords. *Greenhouse, Nutrient Management, Crop growth, Image Processing, Biomass*

Introduction

In recent years, concerns about environmental pollution resulting from the excessive use of fertilizers and agricultural chemicals have been increased, and workforce becomes a major issue as the rural communities are aging. To address these issues, plant factories can be regarded as an effective cultivation platform because they can allow the efficient use of nutrients in growing plants under automatically-controlled conditions. In this regard, hydroponics, known as a soilless farming, has been widely considered an effective cultivation technique, because it can allow the efficient use of water, energy, space, and cost for plant cultivation in plant factories (Rius-Ruiz, Andrade, Riu, & Rius, 2014). However, conventional electrical conductivity (EC) based management has a difficulty in managing the concentration of individual ions in the solution that feeds plants, which results in a high increase in total concentration of most of the nutrients and an imbalance of the nutrient salts. For the accurate, fast, and continuous measurement of the individual nutrients in the solution, ion-selective electrode (ISE) technology was employed by several studies (Bamsey, Berinstain, & Dixon. 2014; Gutierrez et al. 2007, 2008; Jung et al. 2015a; Kim et al. 2013; Rius-Ruiz et al. 2014). However, signal drift and biofilm accumulation can be a major concern with an in-line management system that includes continuous immersion of ISEs in hydroponic solution (Cloutier et al., 1997). The use of a computer-based measurement system including automatic solution sampling and electrode calibration would improve accuracy and precision in the determination of nutrient concentrations. In our previous study, a PC -based nutrient management system with an ISE array was developed while employing a two-point normalization method to minimize such signal drifts and matrix effects (Jung et al. 2015a). The use of an embedded system technique based on micro-computers is advantageous, as compared to a PC-based system because of the capability to reduce the size and production cost of the system while maintaining its reliability and performance. Cho et al. (2015) reported that an embedded system for automated nutrient solution management could effectively manage the nutrients based on real-time measurement of ion concentrations, pH, and EC using ISEs.

Estimations of crop growth parameters such as leaf cover area (LCA), biomass, and height, could be achieved using an image-based measurement method due to its nondestructive and effective way to determine external plant features, and it is appropriate for monitoring and modelling plant growth (Yeh et al., 2014). In practical, such image-based sensing techniques were successfully used to estimate the fresh weight and reconstruct 3D geometrical features (Jung et al. 2015b; Lati, Filin, & Eizenberg, 2013).

The overall goal of the research was to develop a precision nutrient management system for growing plants in closed hydroponic systems by variably supplying the nutrients according to the status of plant growth. Toward that goal, the specific objectives of this study were (1) to develop an embedded nutrient management system that could automatically monitor and control the concentrations of individual ions and (2) to develop an automated plant image acquisition system that could measure the biomass of the plants. A lettuce growing test was performed based on the ebb-and-flow method with the automated nutrient management system. During the period of lettuce growth, changes of NO_3-K-Ca ion concentrations in hydroponic solution were monitored using an array of ISEs previously developed. Multi-temporal images were obtained using a low-cost RGB camera (Powershot S110, Canon, Japan) mounted on the frame of an image acquisition system. Acquired images were initially geo-located based on the visual markers in background and then mosaicked using a SfM (Structure from Motion) image mosaicking program (Agisoft Photoscan, Agisoft, Russia). Image processing algorithms based on Excess Green (ExG) and RGB indexes were used to estimate two parameters related to crop growth, i.e., LCA and crop fresh weight. The biophysical parameters estimated with the developed image processing algorithm were validated by comparing with the real values measured using direct methods. A multivariate analysis was conducted to investigate the correlation between ion concentrations and the estimated growth parameters.

Materials and methods

Development of an embedded system

Based on a PC-based system developed in our previous studies (Jung et al. 2015a; Kim et al. 2013), an embedded system for precision nutrient management including automatic measurement of the ISE voltages and individual replenishment control of water and nutrients was designed to effectively grow lettuce in a closed system by maintaining the ion concentrations within a certain range. As shown in Fig.1, the system included three main subsystems: (i) a nutrient reservoir part that holds the nutrient solution dispensed with six concentrated stock solutions, (ii) a mixing tank part that mixes the nutrient solution with injected stock solutions to be fed into a growing bed, and (iii) a measurement-control part that senses nutrient concentrations and controls six fertilizer injectors independently. The embedded system was finally connected to a plant cultivation system with the growing bed and fluorescent lamps.

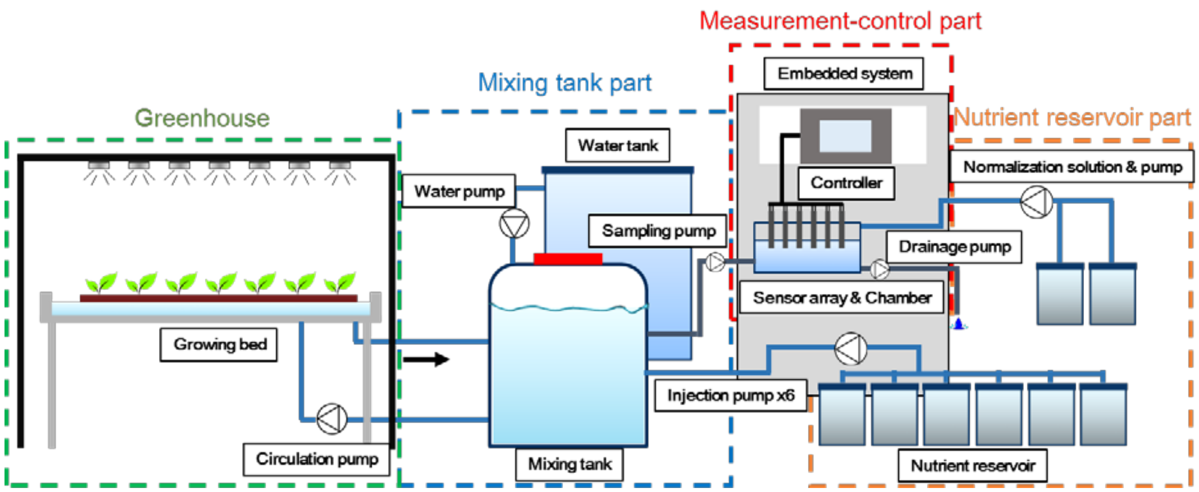

Fig 1. Schematic diagram of the embedded system for automated nutrient management.

The automatic nutrient management system allowed sensor normalization, ion measurement, and solution replenishment sequentially based on timer settings. Fig. 2 shows a flowchart of the nutrient solution management algorithm developed in the study. That is, when the time is up according to the timer setting, prior to the ion measurement, the system triggered the two-point normalization for compensating for changes in sensor signals that might result from the sensor drift and matrix effects. Then, the electrodes were rinsed with the sample solution. After the drainage of the 1st sample solution, re-sampling was conducted and a sample measurement was then made. When the measured values were over target values, the sample solution was released and conditioning solution containing 0.01M NO_3, K, and Ca ions was injected to condition the ISEs. The solution level of the mixing tank was monitored using a 3-pole water level sensor. When the water level dropped, tap water was automatically pumped into the mixing tank to return to the original total volume. Then, the concentrations of NO_3, K, and Ca ions contained in the hydroponic solution were monitored using the ISE array in conjunction with the nutrient dosing algorithm to determine the amounts of the three nutrients to be replenished to the target concentrations. Finally, using a UI (user interface) program developed into the embedded system, the injection times of individual pumps were variably controlled to supply the three nutrients contained in six individual stock solution tanks to the mixing tank (Cho et al., 2015).

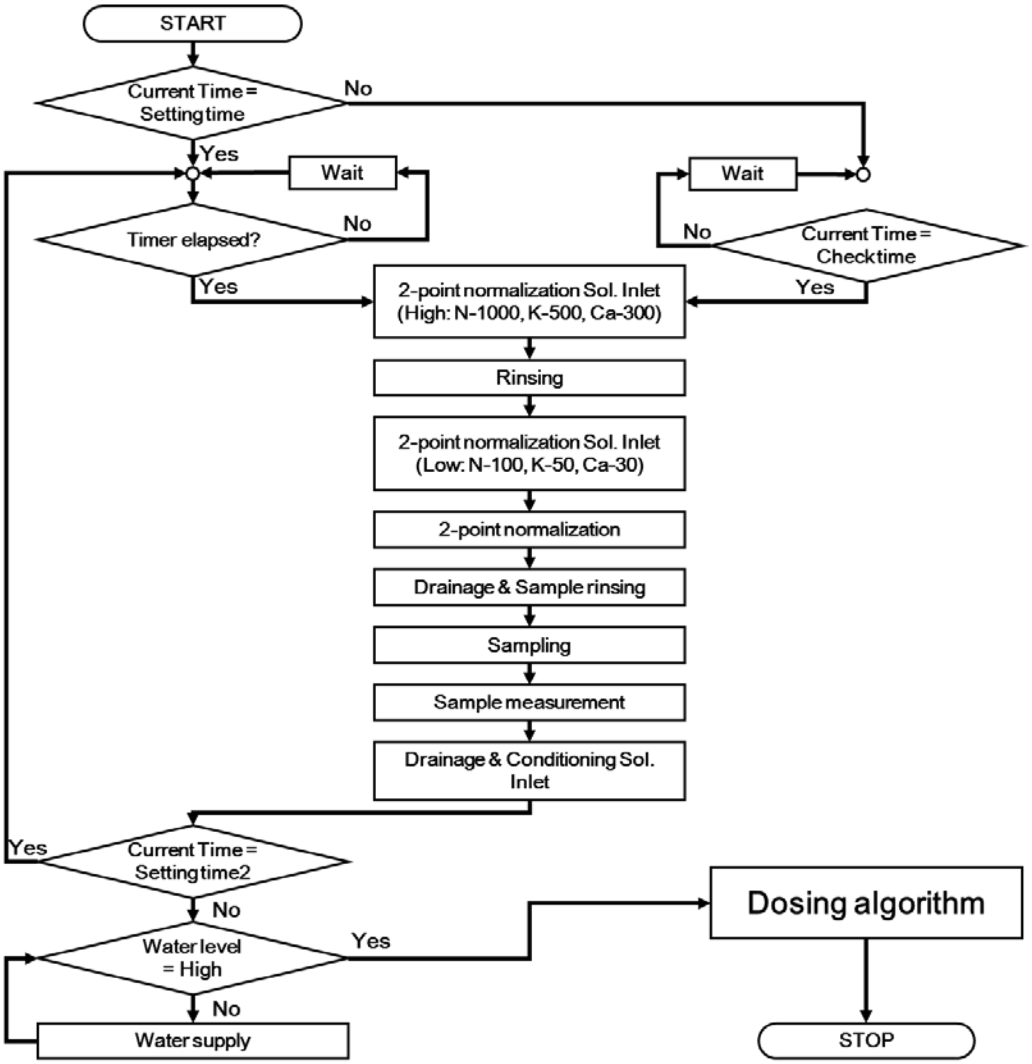

Fig 2. Nutrient solution management algorithm built in the developed embedded system.

Replenishment of the three macronutrients in hydroponic solution was conducted using highly-concentrated nutrient stock solutions for the maintenance of target nutrient concentrations in the hydroponic solution. To reduce the coupled ion replenishment problem in the previous study (Jung et al. 2015a), the developed dosing algorithm was designed which could automatically calculate the required amounts of target ions using six nutrient salts, i.e., $Ca(NO_3)_2 \cdot 4H_2O$, KNO_3, K_2SO_4, $NH_4H_2PO_4$, $MgSO_4 \cdot 7H_2O$, and $Mg(NO_3)_2 \cdot 6H_2O$. The amounts of $H_2PO_4^-$ ions and Mg^{2+} ions to be supplied were calculated using two different linear equations relating to NO_3 and Ca ions, respectively, reported by Choi et al. (2015). Fig. 3 shows a flowchart that shows the steps for nutrient replenishment using six different nutrient salts.

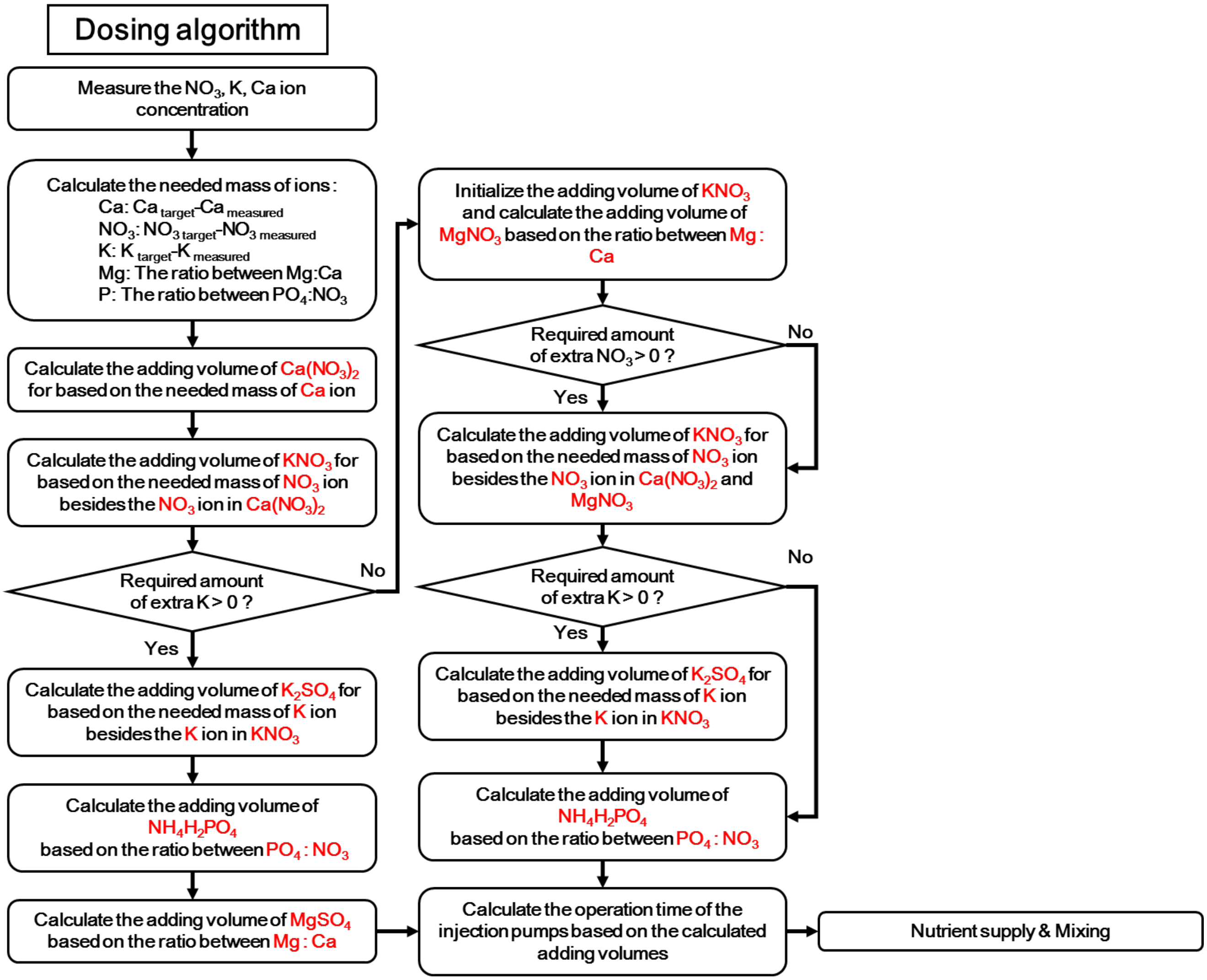

Fig 3. Nutrient solution dosing algorithm built in the developed embedded system.

For the sensor array, which could measure the NO_3, K, and Ca concentrations, three ISEs for nitrate, three ISEs for potassium, one ISE for calcium, one reference electrode, one probe for pH, and one probe for EC were employed. PVC-based ion-selective membranes were used for ISEs and the chemical compositions followed the methods used in previous studies (Cho et al. 2015; Jung et al. 2015a; Kim et al. 2013). And a double junction glass electrode (900200, Orion, USA) was used as the reference electrode. For the Ca ions, a commercially available Ca ISE (9720BN, Orion, USA) was used and a pH electrode (8157BNUMD, Orion, USA) and an EC sensor (Conductivity probe, Vernier, USA) were employed to check the pH and EC of the hydroponic solution. All chemicals were purchased from Sigma Aldrich, USA.

Setup of the image acquisition system

For measuring the status of crop growth using a RGB camera, an automatic image acquisition system with a moving camera unit was built. The moving camera unit consisted of the two-axis conveyor belt system with two stepping motors (MW-57BL36D180-A1000, Ntrex, Republic of Korea) and servo drivers (Moon Walker iSERVO SBL2420U-B, Ntrex, Republic of Korea). A RGB camera (Powershot S110, Canon, Japan) was mounted on the camera unit toward the plant to obtain visible images of lettuce plants on a spatial resolution of 1920×1080 pixels. A flowchart of the image acquisition algorithm is shown in Fig. 4 (a). The camera was moved by a zigzag form, as shown in Fig. 4 (b). The distance between the camera and the growing bed was 50 cm, and an entire image of the lettuce plants could be obtained by stitching images individually collected based on the use of known overlapped markers. A flowchart of the image acquisition algorithm is shown in Fig. 4 (a). However, in this study, images of the lettuce crop were obtained manually, because building the automatic image acquisition system was not finalized due to a delay in purchasing a servo motor to automatically move the camera mount at that time.

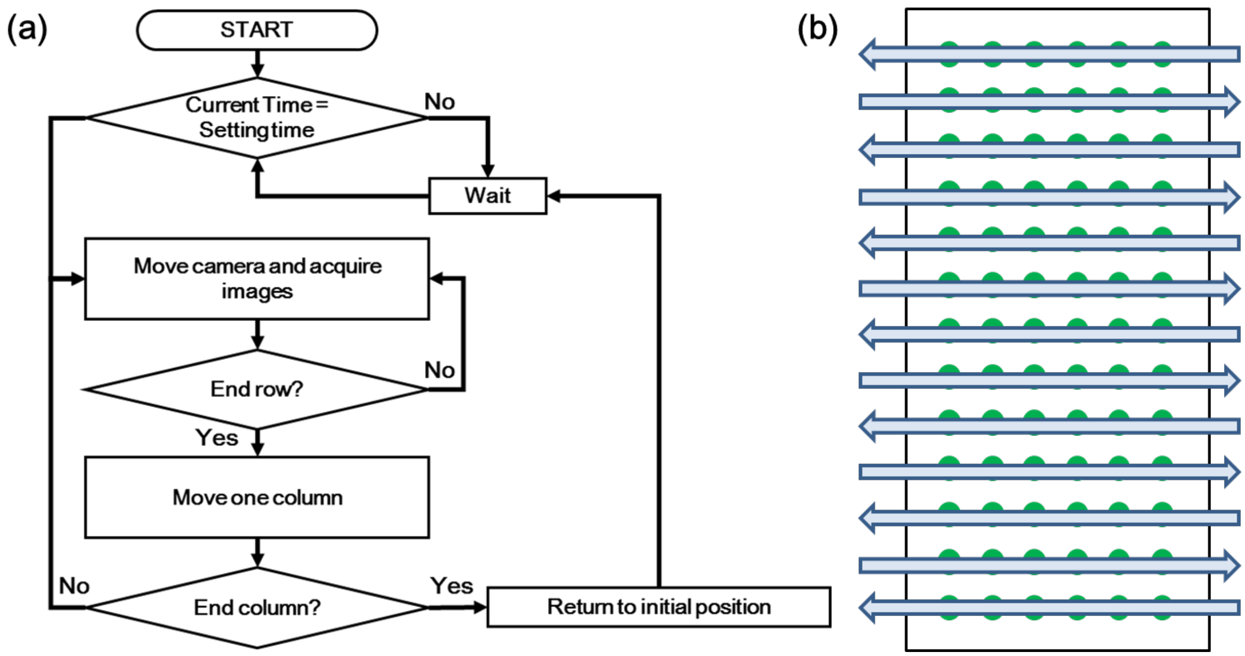

Fig 4. The operating algorithm (a) and movement path (b) of the automatic image acquisition system.

Lettuce cultivation test

Lettuce cultivation tests were conducted to investigate the feasibility of using the developed automated nutrient control and crop growth monitoring system for lettuce cultivation. Seventy-eight lettuce seedlings about two weeks old were transplanted into the growing bed (Jung et al. 2015a). A recirculating pump supplied a nutrient solution into the growing bed for 5 min. The solution in the growing bed was then drained back into the mixing tank due to gravity for 40 min. The solution supply and drainage were repeated every 1 hr. The level of water and the concentrations of the three nutrients in the mixing tank were repeatedly monitored on a 3-hr-interval using the sensor array. The water and concentrated nutrient solution replenishments were set to be done at 10 p.m. The replenishment procedure started the water level check first. When the water level measured was lower than the target level (i.e., 80 L), tap water was automatically pumped into the tank to restore the target water level. Then, the concentrations of NO_3, K, and Ca ions contained in the hydroponic solution were measured using the sensor array and the deficient amounts of the individual ions were calculated based on the dosing algorithm developed in the previous study (Cho et al., 2015). Finally, injection pumps were activated to supply the highly concentrated stock solutions with the adequate volumes for the replenishment of the nutrients. Target ion concentrations were set as NO_3 - 436 mg/L, K - 117 mg/L, Ca - 80 mg/L, respectively. Image acquisition of lettuce was carried out in every 2-3 days. About 100 images were captured in each day.

Image Processing and Plant Feature Calculation

The image processing techniques used in the study consisted of three main procedures, i.e., image mosaicking, plant extraction, and LCA calculation. The image mosaicking was performed using a SfM software (Agisoft Photoscan, Agisoft, Russia), which could recognize the difference among the obtained images and the overlapped regions. Based on the overlapped regions, each image was mosaicked to be integrated as one image. Then, the Otsu's threshold method was used to extract the plant region from the mosaicked image (Otsu, 1979). ExG values were calculated using Eq. 1.

$$\mathrm{ExG} = 2\mathrm{g} - \mathrm{r} - \mathrm{b} \tag{1}$$

where $\mathrm{r} = \frac{\boldsymbol{R}^*}{\boldsymbol{R}^*+\boldsymbol{G}^*+\boldsymbol{B}^*}, g = \frac{\boldsymbol{G}^*}{\boldsymbol{R}^*+\boldsymbol{G}^*+\boldsymbol{B}^*}, b = \frac{\boldsymbol{B}^*}{\boldsymbol{R}^*+\boldsymbol{G}^*+\boldsymbol{B}^*}$ and $\boldsymbol{R}^* = \frac{\boldsymbol{R}}{\boldsymbol{R_m}},\ \boldsymbol{G}^* = \frac{\boldsymbol{G}}{\boldsymbol{G_m}},\ \boldsymbol{B}^* = \frac{\boldsymbol{B}}{\boldsymbol{B_m}}$

The histogram of ExG values determined a threshold value for the criteria for binary imaging. If a point was beyond the threshold value, the point would be regarded as black. Otherwise, the point would be regarded as white. The function *graythresh* in MATLAB (v2015b, Mathworks, USA) was used to convert original images to binary images based on the threshold value. Then, an additional process for filling image regions and holes was carried out to reduce the errors of estimated leaf areas. To calculate plant features individually, the binary image was cropped in grid. Finally, the number of pixels in plant region in each grid was multiplied by the pixel size (0.0002 m^2) to measure LCA. Fresh weights of the lettuce were estimated using a regression equation (Eq. 2) for lettuce plants relating fresh weight and LCA, which were modified from the developed equation in the previous study (Jung et al. 2015b).

$$\text{Fresh weight(g)} = 4672.4\,A^2 + 367.51A - 0.2474 \ (R^2 = 0.89) \tag{2}$$

where $\mathrm{A} = \text{Leaf area}(m^2)$

Regression and correlation analysis

The modified Gompertz curve, one of the growth curves, was used for determining a temporal variability in greenness of lettuce plants (Eq. 3) (Kataoka, Kaneko, & Okamoto, 2003). The least-squares method with bisquare robust and Levenberg-Marquardt algorithm was applied to obtain the coefficients of A and B as shown in Eq. 3.

$$\frac{dy}{dx} = \boldsymbol{A}(\boldsymbol{B} - \mathbf{y})\mathbf{y} \tag{3}$$

where x = Time (day), y = LCA (g), A and B = Coefficients of the Gompertz model

Changes in LCAs of lettuce plants over time were fitted with the modified Gompertz curve. The amounts of NO_3-K-Ca ions supplied using nutrient solutions during the period of lettuce growth were calculated based on the ISE-measured values in every day and the amounts of ions supplied were assumed to be the absorbed rate of the ions by lettuce. A correlation study relating LCA to individual ion uptake was conducted by means of multivariate analysis using SAS (v9.4, SAS Institute, USA).

Results and discussion

Development of an automated system for nutrient management and image acquisition

Fig. 5 shows the view of the automated nutrient management system developed in the study, which was constructed with an exterior enclosure made of steel for the robust operation in the greenhouse including an WinCE-based embedded controller, a sensor array chamber, multiple pumps for introducing highly concentrated nutrient stock solutions, two-point normalization solutions, and tap water. A touch screen-based Graphic User Interface (GUI) program in the form of a pull down menu was programed in the main controller to enable the information regarding each channel of the electrodes used to be configured and to enable a calibration method to be selected prior to testing. The specifications of main parts used in the embedded system are shown in Table 1. The automated image acquisition system was built using a two-axis motor controller and a set of aluminum conveyer profiles to enable the camera to move along the predefined paths (Fig 6).

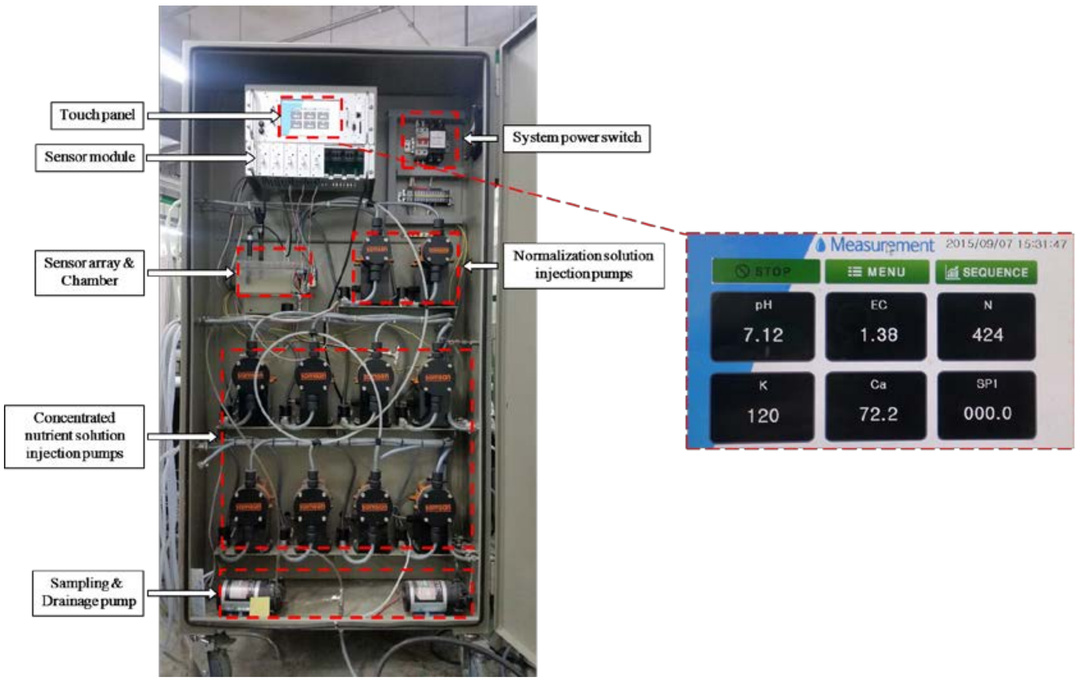

Fig 5. View of the developed embedded system

Table 1. The specifications of the embedded system.

Component	Specification
MCU	Atmel ATMEGA8
CPU (WinCE system)	32Bit RISC ARM1179JZF - 667MH
Cache	32KB
RAM	256MB(mDDR)
Data slot	SD/SDHC card
Display	Touch/7-inch LCD display
OS	WinCE 6.0
Sampling chamber	Sensor array installment
Sampling & drainage pump	Flow rate: 1 L/min (DX-8000-0350, KOTEC, Korea)
Concentrated nutrient solution injection pump	0.6 L/min (ST-600, Samsan, Korea)
Calibration solution pump	0.3 L/min (ST-300, Samsan, Korea)
Mixing tank	80 L nutrient solution reservoir
Mixing pump	32 L/min (MD-30RM-220N, IWAKI pumps, Japan)
Water reservoir	200 L water reservoir
Water replenishment pump	0.3 L/min (ST-300, Samsan, Korea)
Circulation pump	70 L/min (PE-350MA, WILO, Germany)
Water level sensor	3-pole electrode holder (PS-3S, KUNWOO Tech., Korea)

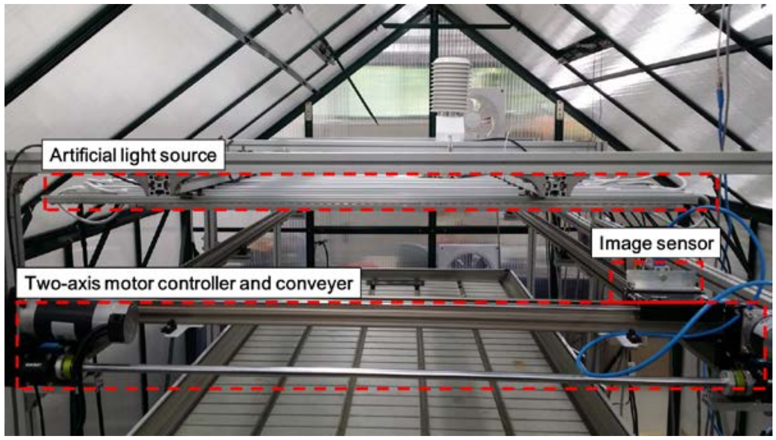

Fig 6. View of the developed image acquisition system

Concentration control and ion absorption in lettuce cultivation

Changes in NO_3, K, and Ca ion concentrations in hydroponic solution measured with the sensor array and the amounts of the three ions supplied into the growing bed during the period of lettuce growth are shown in Fig 7. Overall, when using the developed nutrient management system, the concentrations of the three ions in hydroponic solutions were automatically controlled to reach the levels of target concentrations with an acceptable level of error except for a problem with K data outliers that occurred due to a broken K ISE from 7 to 14 days after the test. In addition, sometimes, ion concentrations were not increased although corresponding nutrient injection pumps were properly operated (Fig. 7(bottom)), which might be related to an error in the calculation method programmed in the system. That is, since the dosing algorithm calculates the amount of injection volume for the corresponding nutrient assuming that total volume of the mixing tank is constant, the addition of small amount of highly concentrated nutrient stock solution might affect a change in total volume of the mixing tank, thereby resulting in a decrease in the target concentration. During the period of lettuce cultivation, the NO_3, K, and Ca ions were managed with errors in concentrations of -14.8±18, -5.4±12, and -9.12±5 mg/L as compared to target ion concentrations, i.e., 436, 117, and 80 mg/L, respectively, when data obtained with a broken K ISE were excluded.

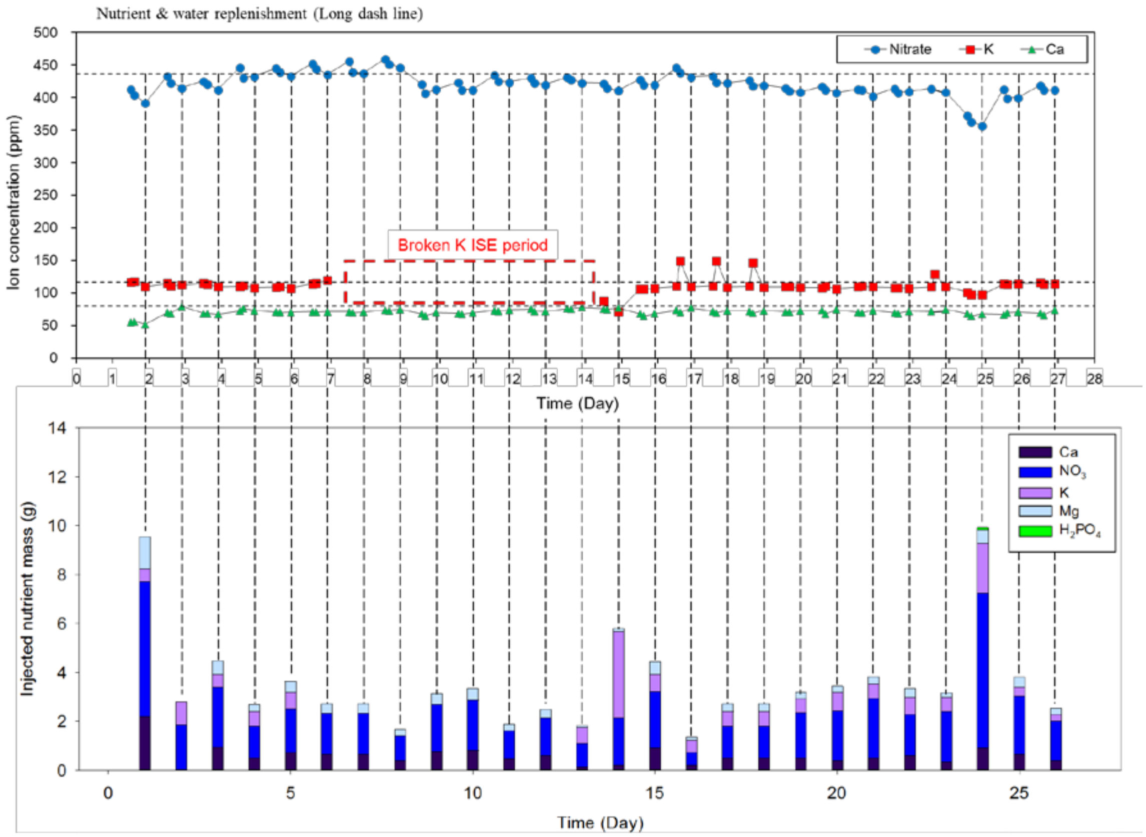

Fig 7. Changes in ion concentrations (top) and the injection mass of the individual nutrient salt (bottom) during the lettuce growing period (Long dash line: Nutrient and water replenishment point, Dash line: Target ion level).

Validation of image- based fresh weight estimation model

The validation result of the LCA-based fresh weight estimation model is shown in Fig 8. High coefficient of determination and almost 1:1 relationship were observed, thereby showing the potential of using the developed image processing method for the measurement of fresh weight related to biomass analysis.

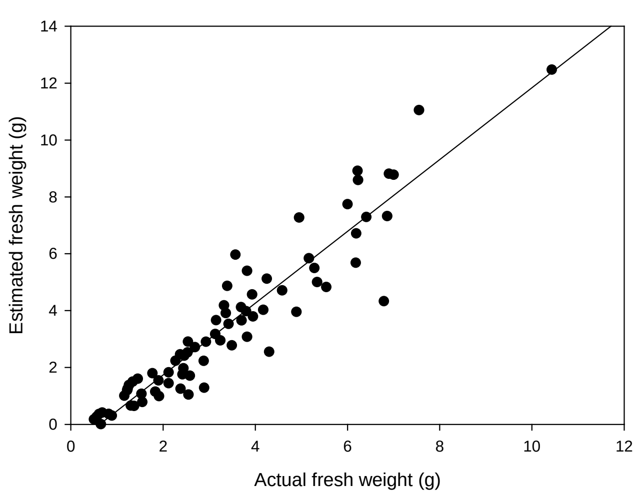

Fig 8. Relationships between the estimated values and actual values for fresh weight.

Temporal variability in lettuce biomass

Examples of the mosaicked lettuce images obtained from the study are shown in Fig 9. The lettuce region was extracted from the mosaicked images based on the Hough transform method and LCAs of the lettuce plants were then calculated by multiplying the corresponding pixel sizes. Using a regression equation relating LCA and fresh weight previously developed by Jung et al. (2013), the modified Gompertz curve in terms of total fresh weight was developed (Fig 10 (a)). As shown in Fig. 10 (a), the Gompertz curve with high coefficient of determination (>0.99) was obtained. And the growth rate curves of total fresh weight showed peak responses between 10 and 20 days (Fig. 10(b)) whereas there was no significant change in ion absorption during the period of high growth (Fig. 11). The maps of fresh weight are shown in Fig. 10 (c), exhibiting a trend that the fresh weights of lettuce became higher in a central region as compared to those measured in a surrounding region over time.

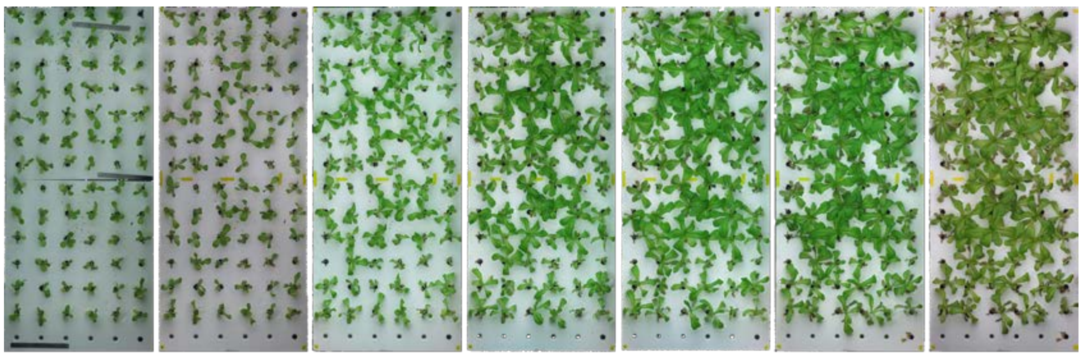

Fig 9. Mosaicked images of lettuce growing bed.

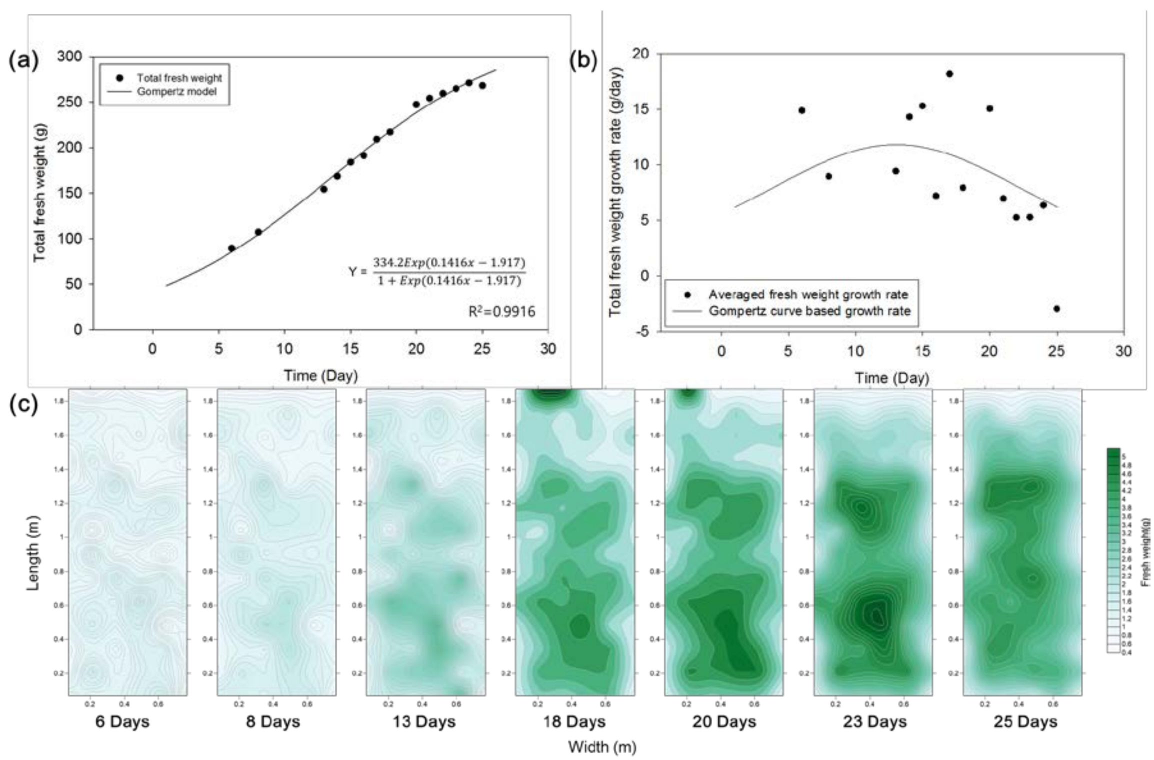

Fig 10. Gompertz curve based on the estimated total fresh weight (a), the growth rate of total fresh weight (b), and maps of fresh weight from the mosaicked images (c) during the lettuce growing period.

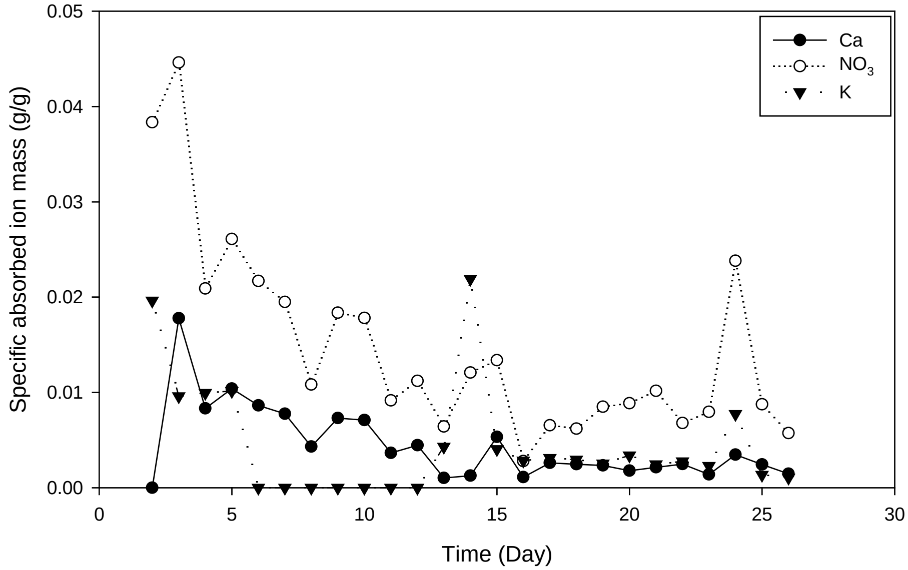

Fig 11. Specific ion absorption mass during the lettuce growing period.

Overall, when the amount of nutrients added to the growing bed was assumed to be the amount of nutrient absorbed by lettuce, the amounts of NO_3, K, and Ca ions absorbed by lettuce didn't show significant correlations with growth parameters in this study (Table 2). However, the amount of NO_3 ion absorbed by lettuce showed a potential ($P<0.1$) as a nutrient for managing plant growth. Additional analysis would be required to improve the feasibility of the nutrient management based on the growth parameters.

Table 2. The significance level (P) in correlation analysis with ion absorption mass

	Day	LCA growth rate (m^2/day)	Fresh weight growth rate (g/day)	Ca (g)	NO_3 (g)	K (g)
Day	-	0.7403	0.9616	0.8714	0.1365	0.3457
LCA growth rate (m^2/day)	0.7403	-	<.0001	0.5745	0.0557	0.9145
Fresh weight growth rate (g/day)	0.9616	<.0001	-	0.59	0.076	0.8728
Ca (g)	0.8714	0.5745	0.59	-	0.0103	0.2979
NO_3 (g)	0.1365	0.0557	0.076	0.0103	-	0.0371
K (g)	0.3457	0.9145	0.8728	0.2979	0.0371	-

Conclusions

In this study, an embedded system for automated nutrient solution management and an automated image acquisition system were developed. Although the automated image acquisition system was not successfully developed in a delay in purchasing a servo motor, various image processing techniques such as mosaicking, extraction of plant region for LCA estimation, and fresh weight estimation from LCA were developed. Especially, when some errors from a broken K ISE were excluded, the ion concentrations of hydroponic solution were managed within errors of with -14.8±18, -5.4±12, and -9.12±5 mg/L for NO_3, K, and Ca ions, respectively, as compared to the target values. And the Gompertz curve for total fresh weight built in the study showed a high coefficient of determination (>0.99). An image-based model to estimate the fresh weights of lettuce predicted the actual values well with almost 1:1 relationships, providing the possibility of using the image-based model in estimating the growth stages or plant phenotyping. Although the estimated growth parameters showed weak correlations with the nutrient absorption, NO_3 ion absorption showed a potential ($P<0.1$) as a nutrient for managing plant growth. The results of this research provided the feasibility of using an automated nutrient control system and an image processing method for efficient management of lettuce plants grown in a plant factory. In further studies, variable nutrient management of lettuce based on automated sensing of lettuce growth status will be implemented using an on-the-go image acquisition system that can automatically take lettuce images while moving along a predefined path.

Acknowledgements

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Nomenclature

ISE: Ion-selective electrode

EC: Electrical conductivity

LCA: Leaf cover area

ExG: Excess green

SfM: Structure from motion

DSM: Digital surface model