Image processing algorithm to estimate ice-plant leaf area from RGB images under different light conditions

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Abstract. The productivity of horticultural crops in an artificial light condition are highly influenced by the structure of plant and the area coverage. Accurate measurement of leaf area is very important for predicting plant water demand and optimal growth. In this paper, we proposed an image processing algorithm to estimate the ice-plant leaf area from the RGB images under the artificial light condition. The images were taken using a digital camera and the RGB images were transformed to grayscale images. A binary masking was applied from a grayscale image by classifying each pixel belonging to the region of interest from the background. Then the masked images were segmented and the leaf region was filled using region filling technique. Finally, the leaf area was calculated from the number of pixel and using known object area. The experiment was carried out in three different light conditions with same plant variety (Ice-plant, Mesembryanthemum crystallinum). The results showed that the correlation between the actual and measured leaf area was found over 0.97 (R²:0.973) by our proposed method. Different light condition also showed significant impact on plant growth. Our results inspired further research and development of algorithms for the specific applications.

1. Introduction
A plant factory is an indoor crop cultivation system where plant growth and ambient environmental variables can be monitored and controlled very intensively [1]. Besides, the application of Hydroponic (soil-free crop cultivation) method in plant factories is increasing gradually due to the sustainable amount of water and nutrient saving, diseases free cultivation, and high crop quality and quantity [2]. Moreover, the variety of light sources, e.g., fluorescent lamps, high-pressure sodium lights, light-emitting diode (LED), and mixed lighting sources are often used in the plant factories, and have significant effects on plant and vegetables production [3,4].

Leaf is an essential component of a plant and leaf area (LA) plays a significant role in the study of plant development, biomass, and yield through photosynthesis [5, 6]. Moreover, the leaf area is also used in the calculation of functional and structural parameters such as rates of photosynthesis, light-interception, use of water and nutrients, and crop growth and a core parameters of plant's growth phase [7, 8]. Consequently, several researches were conducted precisely to calculate the leaf areas, by direct and indirect methods [9]. Direct techniques include leaf area meter, scanner, or blue printing, which...
leads to a disruptive plant sampling. Therefore, the direct approach is often laborious [10]. The indirect approaches are focused on the implementation of regression models between the leaf surface and leaf dimensions. The methods can be repeatable and economically efficient, but it is still laborious and can often lead to major errors due to the measuring mechanism of various leaf dimensions [10,11].

Therefore, the precise estimation and monitoring of the growth of plants required an effective approach for leaf area estimate. Digital image based automatic systems are being used in recent years in the agriculture industry, given its possibility of precision, rapidity and cost-effectiveness of measurements [12]. Several researchers applied imaging methods to quickly and accurately quantify the area of the leaf area [13]. For leaf region segmentation some researchers employ contour extraction techniques [14, 15], others employ threshold-based segmentation [16]. Image processing methods were also presented to classify and characterize plant leaves [17, 18].

Leaf area measurements may be suitable for convex or plane-type leaves with extremely good circumstances, depending on these various methodologies. Concave shaped and closed to stem or shoot leaves gave an extremely poor estimate of the area of the leaves using those image processing method already available. In addition, the leaf size is commonly indicated as the total number of pixels in the longest row of the binary image during measurement using digital image processing technologies [10]. Moreover, these methods were used for single or several leaves with extremely good condition or in a laboratory scenario. In a plant factory with diverse light circumstances and a controlled environment, no such study has been done to estimate the leaf area.

Leaf development is significantly affected by the light conditions and electrical conductivity (EC) of nutrient solution. Besides, the direct estimation of leaf area is a destructive method and also disturbs the continuous growth monitoring of any targeted plant. An image-based leaf area characterization can be a relevant solution for accurate estimation and monitoring of plant leaf area. To date, very few studies have applied the image-based leaf area estimation technique for ice-plant, especially when grown in plant factories under different light and EC conditions. In this work, an adequate approach to measure the leaf area was established given the restrictions described above. The approach developed was based on the precise estimation of the edge of the leaves with extremely various light circumstances and the efficient removal of distortions and tilt.

Therefore, the objective of this study was to measure the leaf area of ice-plant (Mesembryanthemum crystallinum) grown in a plant factory under different LED and EC conditions using image processing techniques.

2. Materials and methods

2.1. Ice-plant cultivation

The plant factory used in this experiment was located in the Department of Agricultural Machinery Engineering, Chungnam National University, Daejeon, Korea. All experiments were performed utilizing a recirculating hydroponic system under controlled conditions. A recycling type automated nutrient management system based on Nutrient Film Technique (NFT) was used to grow ice-plant in the plant factory. To monitor the growth of the ice-plant, we implemented three different types of red-blue LED light combinations, and three different levels of EC. Total nine treatments were applied and the effects of lights along with the EC levels were evaluated for growth monitoring of ice plants. The ambient environment parameters, i.e. temperature, humidity, CO₂, and airflow were maintained precisely during the experiment. The ambient environment parameters and nutrient condition were summarized in Table 1.

The LED lights were placed on the top of the plant growth bed as a light source for 18 hours of daytime and night time for 6 hours. Temperature and relative humidity in the plant factory were monitored at 25°C and about 65%, respectively. We used a measuring scale to quantify the length and width of the leaf region and calculated the area of the leaf to verify the estimation of the precision of our image processing method, without taking it from the bed at every two days interval. The cultivation was performed from October 28 to November 18, 2020 (20 days) with a total of forty ice-
plants were planted. The spacing between plants was 0.14 m and six ice-plant were planted on a bed of 0.10x0.85 m. Figure 1 shows the plant bed and light conditions inside the controlled plant factory.

**Table 1.** Ambient environment parameters, light type and EC in the Plant factory with the sensors specifications.

| Parameter                    | Set value | Sensor used        | Specification                                      |
|------------------------------|-----------|--------------------|---------------------------------------------------|
| Temperature (°C)             | 25±1      | DHT22, China       | Temperature range: -40~80 °C                      |
|                              |           |                    | Humidity range: 0-100%                            |
|                              |           |                    | Temperature accuracy: ± 0.5                       |
|                              |           |                    | Humidity accuracy ± 2%                            |
|                              |           |                    | Compatible: 3.0~5V                                |
|                              |           |                    | Measurement range: 0 to 2,000 ppm                 |
| Humidity (%)                 | 65±5      |                    |                                                  |
| CO₂ (ppm)                    | 600~1000  | Sense Air S8, Sweden| Accuracy: ± 70 ppm                                |
|                              |           |                    | Compatible: 4.5~5.25V                             |
| Air flow                     | Static    |                    |                                                  |
| Light type (Red: Blue)       | R90:B10; R70:B30; R50:B50 | - | Range: 1 – 65535 lx                               |
| Light intensity (µmol m²s⁻¹) | 150       | GY 30, China       | Accuracy: ± 20%                                   |
| Photoperiod (hr)             | 18/6      |                    | Compatible: 3.3 and 5V                            |
| Cultivation system           | Nutrient Film-technique (NFT) | - | Range: 2-2000 dS·m⁻¹                              |
| EC (dS·m⁻¹)                  | 1.5, 3, 4.5 | EC-BTA, Vernier, OR, USA | Temperature range: 0-80 °C                       |
| pH                           | 6.5~7     | pH-BTA, Vernier, OR, USA | Range: 0-14                                       |
|                              |           |                    | Temperature range: 5-80 °C                        |

![Figure 1](image-url)
2.2. Image acquisition and image processing for leaf area characterization

An Intel real sense D435i (Intel Corporation, CA, USA) camera was used for a plant bed to capture the plant leaves images. The camera was connected with a Raspberry pi 4B board with a Raspberry pi monitor. The system has the capability to monitor and acquire image remotely. To perform the remote access we used VNC (Virtual Network Computing) viewer with the Raspberry Pi 4. To ensure automatic start of the viewer, it enables the device to operate remotely with pi’s GUI (Graphical User Interface) display. Plants were grown in a controlled environment in the plant factory. For image acquisition, the camera was placed top of the plant and the camera angle was nadir to the plant. A squared size (5.1cm × 5.1cm) white paper sheet was used during the image acquisition process as a reference object as shown in Figure2c. We captured plant images remotely from the top every two days interval using Intel real sense SDK (Software Development Kit). The captured image dimension was 1280 × 780 pixels. All the image data were stored as a PNG format on a micro SD memory card connected to the Pi board.

Figure 2. Image acquisition system in the plant factory: Intel real sense D435i camera setup with Raspberry pi4B board (a), remote acquisition and monitoring with VNC viewer with Raspberry pi 4B (b), and plant images with the reference object in the plant factory (c).

Figure 3 shows the flowchart of the steps involved in the leaf area measurement. First, the RGB images of plant leaf were acquired from the camera. To minimize the noise, these images were color transformed from RGB image to grayscale images. The conversion of the grayscale image was achieved by eliminating the hue and saturation while keeping the image luminance. This conversion turns RGB values into gray values by the formation of a weighted total of the components R, G and B as in Equation (1) [19, 20]:

$$G_{gray} = 0.3R + 0.59G + 0.11$$

Then, histogram equalization was applied for the images to boost the contrast of the region of interest (ROI) by changing the intensity distribution of the histogram. A binary masking was applied then from a grayscale image by classifying each pixel as the belonging to the region of interest from the background. The binary mask can be expressed as Equation (2) [21]:

...
\[ i_{\max}(x, y) = \begin{cases} 1 & \text{if } f_w^{\text{gray}}(x, y) > T \\ 0 & \text{if } f_w^{\text{gray}}(x, y) \leq T \end{cases} \]  

Where, \( T \) is the threshold value and \( x, y \) are the value point coordinates. All gray levels greater than \( T \) are labelled as white and less than or equal to \( T \) are black. Then the masked images were segmented and the leaf region was filled using region filling technique. The number of pixel in a leaf area was calculated and finally, the leaf area was calculated based on the pixel size, calculated from the reference object area. The MATLAB R2020B (The MathWorks, Inc., USA), a commercial software was used to program the image processing system.

The pixel number statistic was used to compute the area of the leaf. Let \( A_L \) and \( A_S \) indicate the leaf area and area of the reference object, respectively. Let \( P_L \) present the pixel number of leaf in the image. \( P_S \) present the pixel number within the object in the image. Thus, the Equation (3) for calculated area of each leaf is as follows [13]:

\[ A_L = \frac{P_L}{P_S} \times A_S \]  

Where, \( A_L \) is the leaf area in the image, \( A_S \) is the reference object area, \( P_S \) is the counted number of pixel of reference object and \( P_L \) is the counted number of pixel obtained from the leaf area.

2.3. Validation procedure
To quantify the area of the leaf of the individual ice-plant, we used a handheld leaf area meter (LI-3000C, LI-COR Inc., NE, USA). The leaf area meter calculates the area of leaves using a narrow-band LEDs, and the detectors encode the leaf width and the cords encodes the length. Thus it calculates the area of a leaf. We first opened the scan head and closed it on the leaf next to the petiole. Then by
holding the encoding cord, we moved the scanner across the leaf length, so that whole leaf area passed through the scanner. We used the leaf area meter 5 times to each plant leaf and averaged the value. The measurements were taken every two days just before capturing RGB images without taking it from the bed. The calculated leaf area from actual measurement was used to normalize the leaf area calculated by our proposed algorithm. The accuracy of our proposed method was calculated using Equation (4) as follows:

$$\text{Accuracy} = 1 - \left| \frac{x-y}{y} \right| \times 100$$  \hspace{1cm} (4)

Where, $x$ and $y$ are the actual and measured leaf area, respectively.

3. Results and discussion

Figure 4 shows the image processing steps using our proposed algorithm. The RGB images (Figure 4a) were converted into grayscale images and the grayscale images (Figure 4b) were enhanced using histogram enhancement (Figure 4f, and 4g). A binary masking (Figure 4d) was applied from a grayscale image by classifying each pixel as the belonging to the region of interest from the background. Finally, the masked images were segmented and the leaf region are filled using region filling technique (Figure 4e). Then, we calculated all the pixels in the leaf region and calculated the total leaf pixel area. Based on the actual pixel size, estimated from the reference object in the images, we calculated the leaf area of each leaf. Figure 5 shows the application of our proposed image processing algorithm on ice-plant leaves images taken at different growth stages. As the result showed that our method could be used for different growth period and conditions.

![Figure 4. Image processing steps using our proposed algorithm: RGB image (a), grayscale image (b), enhanced grayscale image (c), binary masking of grayscale image (d), background segmentation and region filling (e), histogram of the grayscale image b (f), and equalized histogram of image c (g).](image1)

![Figure 5. Application of our proposed algorithm in different growth stage: one week (a), two weeks (b), three weeks (c), and four weeks (d) aged ice plant images.](image2)
Figure 6 illustrates the validation results for all the samples using the coefficient of determination with $R^2$ for the actual and measured results of leaves area. The value $R^2$ for the ice-plant leaves has a higher coefficient of determinations ($R^2:0.973$), which means that the calculation could reflect the actual measurement of leaves area. Based on several previous studies [14, 16], our proposed method showed higher coefficient of determination for estimating leaf area from the images. The average accuracy of our proposed method was found around 96%. Some studies [13] showed higher accuracy than our proposed method. However, the conditions were more complex in our study than those in other studies. Moreover, in diverse lighting conditions, the performance of our method was likewise quite impressive. Accordingly, the estimated leaf area can be used to predict the effect of different LED light on the plant growth. Figure 7 shows the leaf area with the growing time based on three different light sources. LED light ratio R90:B10 provided the best growth situation for the plant. Figure 8 represents the leaf area with the different light source and EC. In different weeks, the growth status can be forecasted based on the leaf area estimation and monitoring. Different light combination and EC affected the plant growth and its development.

![Figure 6](image6.png)

**Figure 6.** Correlation between actual leaf area and measured leaf area.

![Figure 7](image7.png)

**Figure 7.** Estimated leaf area with different light condition and growth period.

![Figure 8](image8.png)

**Figure 8.** Estimated leaf area with different light condition and EC in different growth period.

4. Conclusion
In this study, an image processing technique was developed to estimate leaf area of ice-plant grown under different light condition and EC levels in a plant factory. The images were taken using a digital camera and the RGB images were transformed into grayscale images. A binary masking and image segmentation was applied to estimate leaf area with a region filling technique. The method showed the ability to measure the leaf area with an acceptable level of accuracy (96%) in different light condition
in the plant factory. The results also showed that the correlation between the actual and measured leaf area was found over 0.97 (R²=0.973) by our proposed method. Light condition of R90:B10 provided the best growth conditions and EC also showed significant impact on plant growth at different growth weeks. Our results inspired further research and development of integrated image acquisition system for measuring and monitoring the condition of plant growth, which can be utilized in computers, and smartphones or tablets. In future, more advanced image processing techniques, deep learning based methods, and 3D plant modelling would be constructed and applied in plant factory to assess different plant parameters.

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