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Embedded System for Spatial Mapping of Lettuce Fresh Weight in Plant Factory

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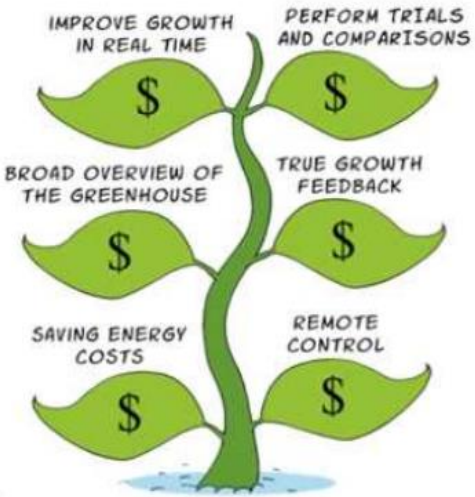
Plant Factory

✓ **Advantages of plant factory**

- Plant quality can be effectively managed under better optimized conditions for plant growth.
- Plants can be easily monitored using various engineering systems.

✓ **Why we need plant monitoring?**

- To observe how well plants grow
- To determine how to control environmental factors for maximizing plant productivity
- To determine the optimum time for harvesting

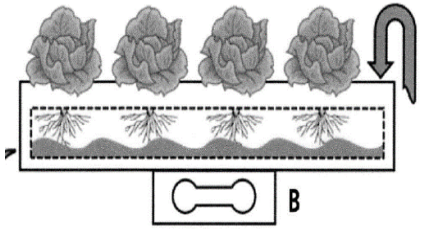


Plant Growth Measurement

✓ **Conventional methods**

- Pick up plants and measure them with electronic balances
- Destructive, laborious, and time consuming

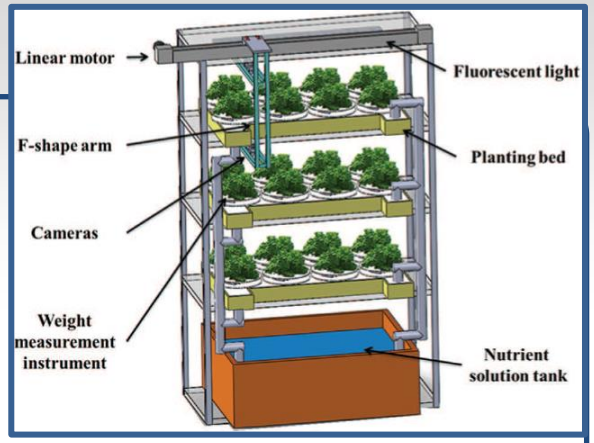
✓ **Load cell based system**



- It is possible to measure the weight of plants in real time
- Costly
- It is difficult to obtain weight information on individual plants

Examples of load cell based weight measurement instrument (PRIVA GroScale; Kim et al., 2016)

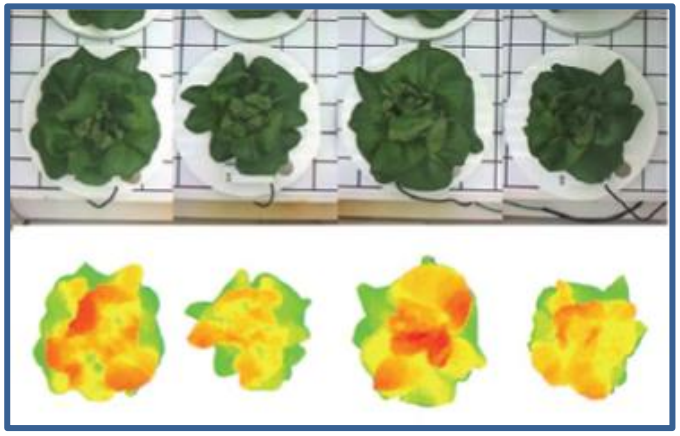
Non-destructive Fresh Weight Evaluation



(Chen et al., 2016)

✓ **Use of Camera (Morphology)**

- High-throughput data acquisition
- Pixel based weight estimation method
- Post image processing was needed
- It was not applicable to growing systems with overlapped plants



(Chen et al., 2016)

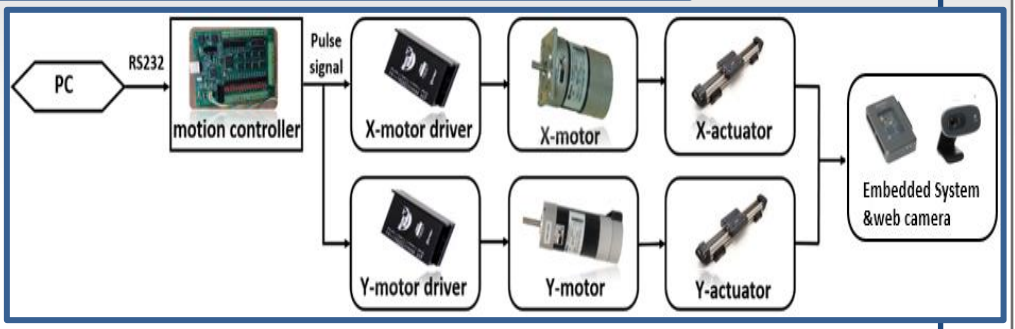
(Jung et al., 2015)

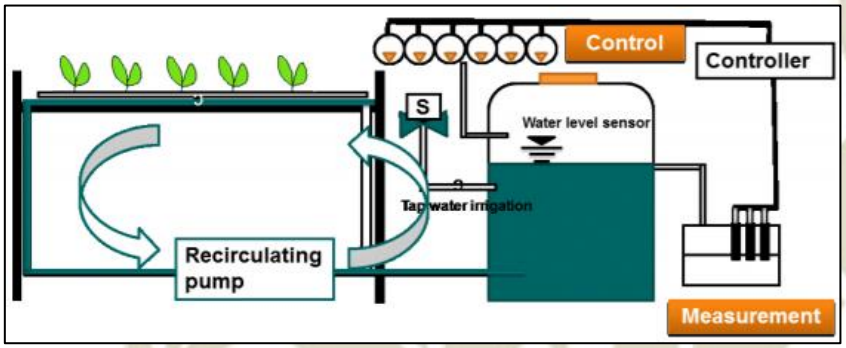
Objectives

- **To develop an embedded system for spatial mapping of lettuce fresh weight in plant factory**

  - **To develop an on-the-go image processing system for estimating the fresh weights of individual plants in real-time**
  - **To design image processing algorithms for segmenting the images of individual plants in the presence of overlapped leaves**

On-the-go image acquisition system

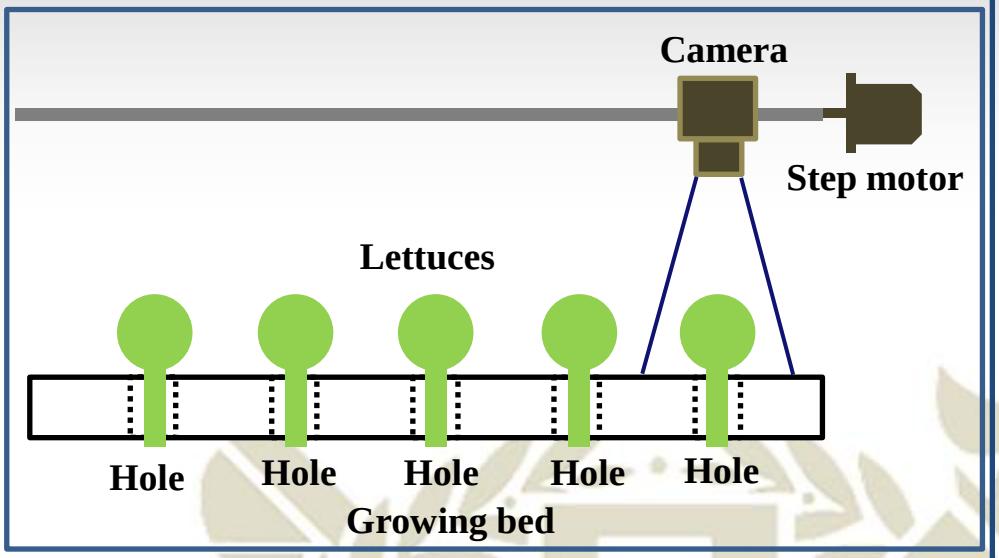




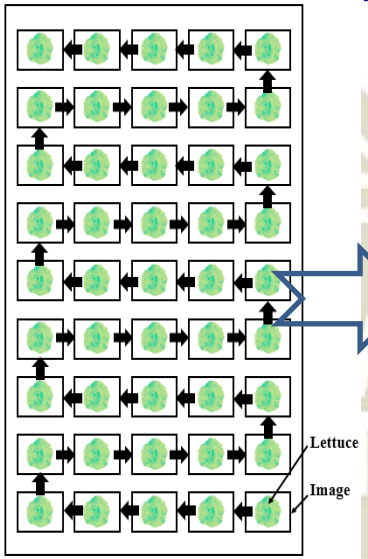
- **Lighting time :** 9:00 AM to 11:00 PM
- **Temperature :** 18 to 22°C
- **Plant :** lettuce
- **Date :** Feb 10 to March 1 2018

- **Growing bed:** $0.94\ m \times 1.7\ m$
- **Plant Spacing :** 200 cm
- **Irrigation interval:** every 2 hr

On-the-go Image Acquisition System

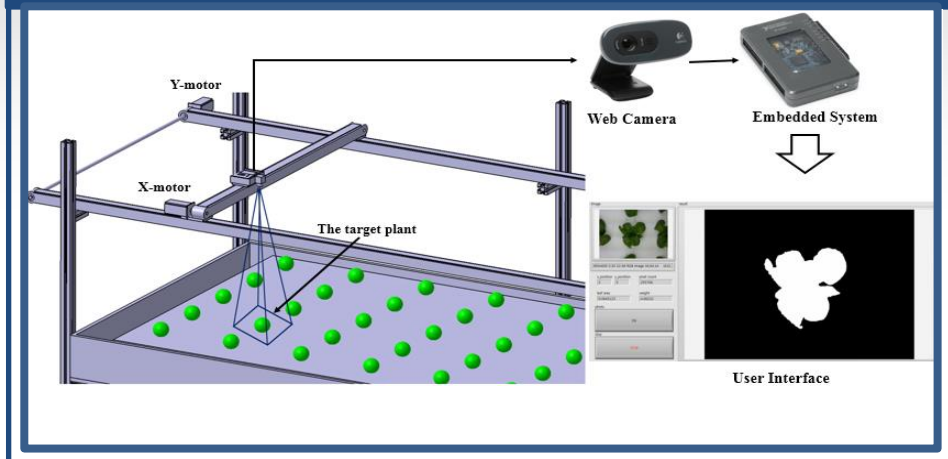


- The RGB camera was moved to locate on top of lettuces at each stop.
- The camera coordinates were recorded.



Camera path

On-the-go image acquisition system



- **Camera**: web camera (C270, Logitech, Switzerland)
- **Embedded controller**: MyRio (NI, USA)
- **Data storage:** USB, PC(wireless)
- **Programming language:** Labview (NI, USA)

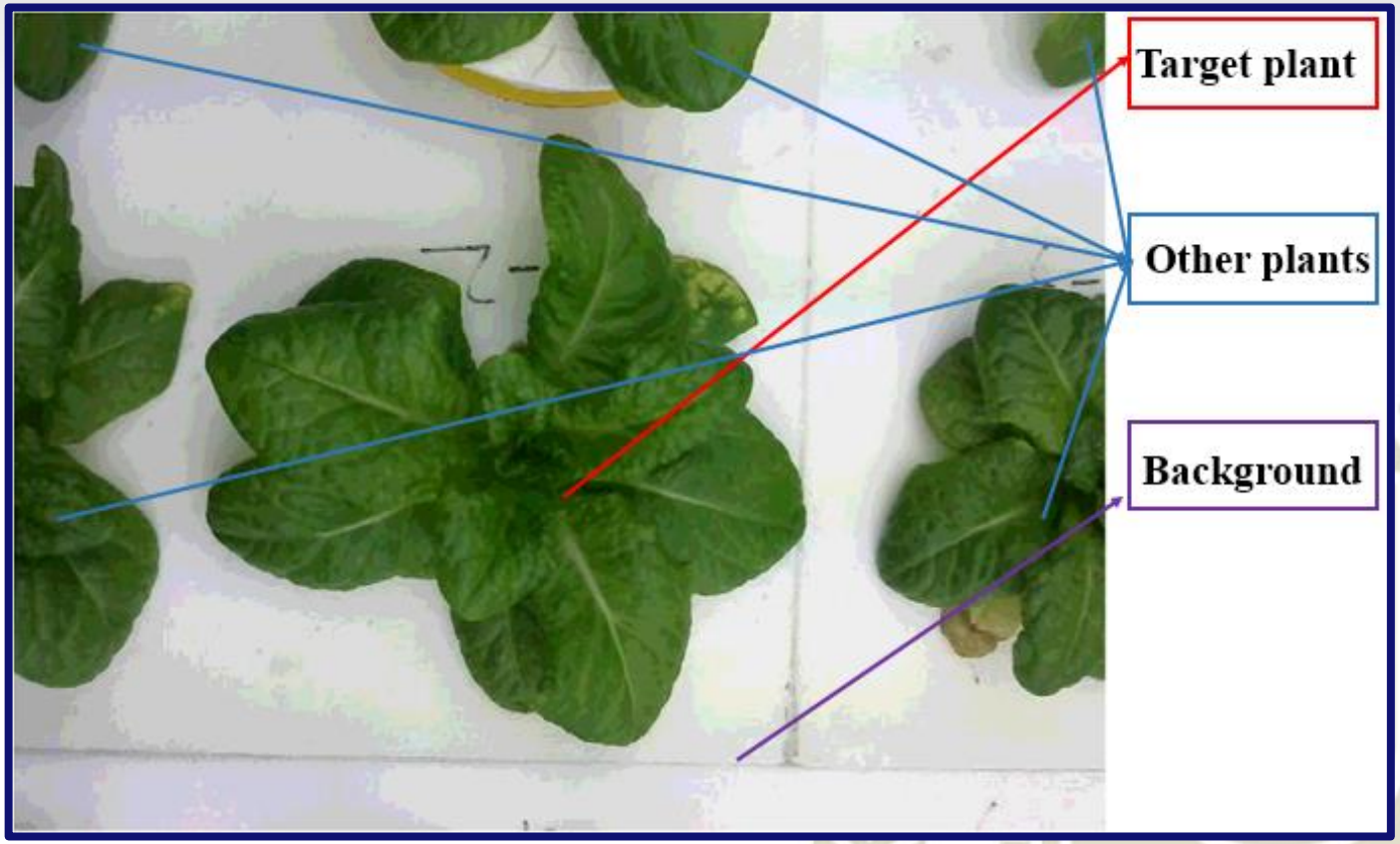
Processing time

The average processing time (RMSE = 110.3 (ms))

	Processing time (ms)	Percentage (%)
Image acquisition	1500	41.8
Image segmentation	645	18.3
Target plant extraction	63	1.76
Fresh weight calculation	35	0.98
Camera movement	1333	37.16
Total	3585	100

- The image acquisition and camera movement accounted for about 79 percent of the total time.

Image processing for plant weight estimation



< An example of captured images>

It was necessary to extract the images of single plants for estimating the weight of each lettuce.

Image processing steps

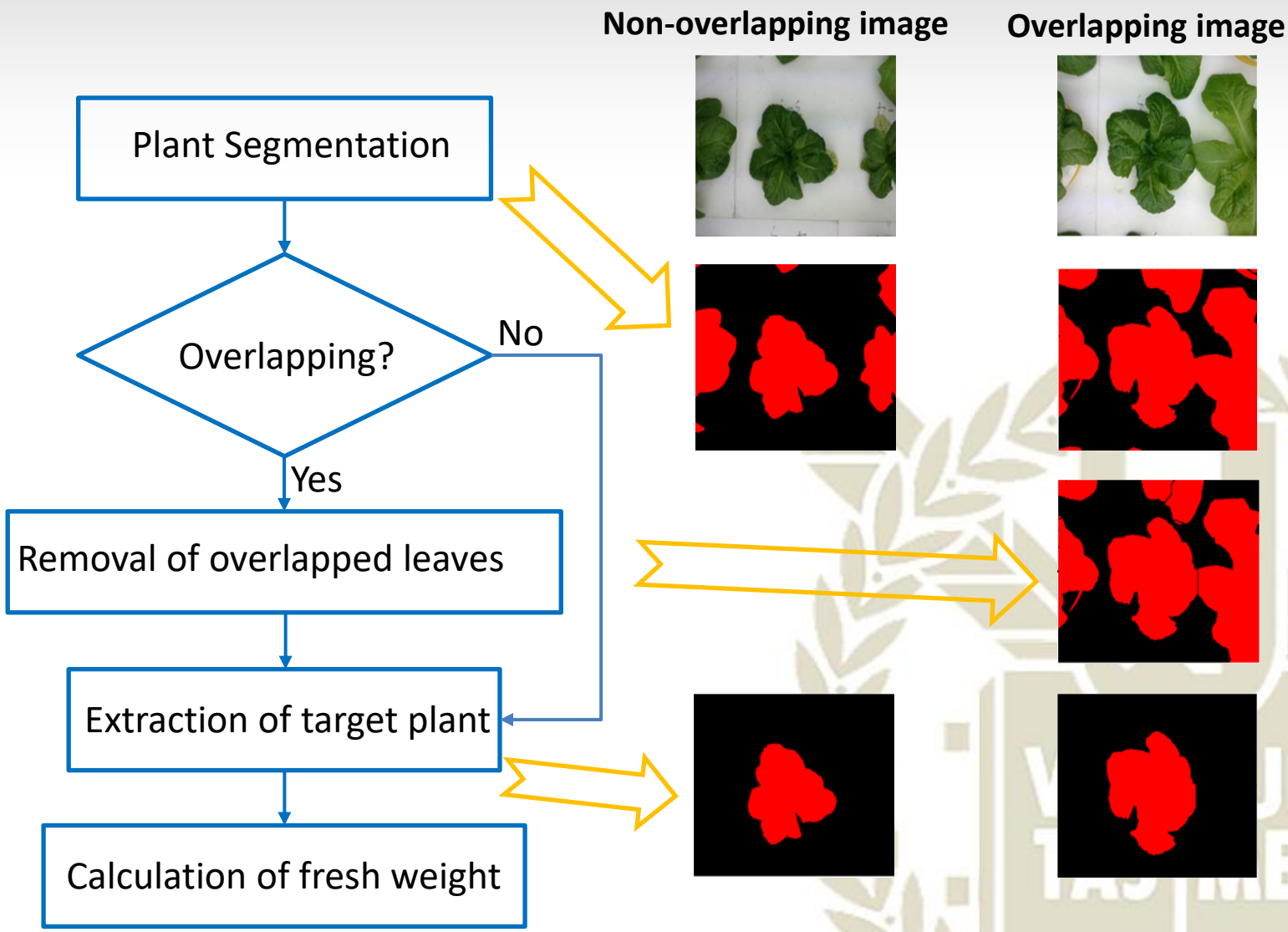
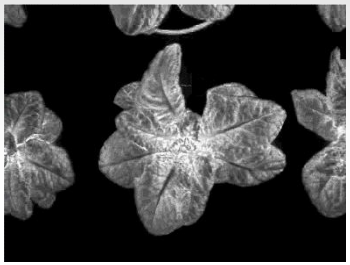
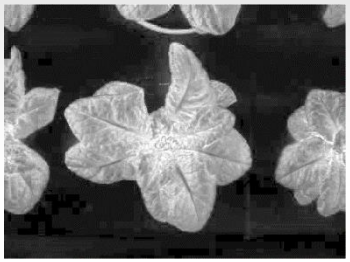
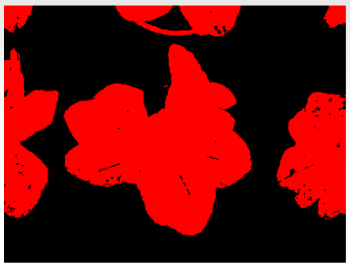


Image processing – plant segmentation


RGB image


Grayscale image


Enhanced image


Binary image


Result image

1. S channel of the HSV color space

(*grayscale image).*

2. A square root function(Gordon et al., 1984)

(Enhanced image)

3. Otsu's threshold method(*Otsu, 1979*)

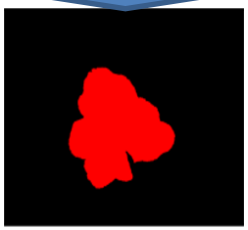
(*binary image*)

4. Remove noise and fill holes (*removal error*)

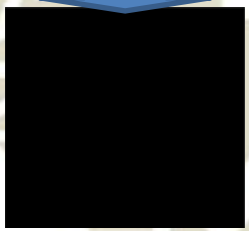
Image processing – Overlapping Decision

❖ **Overlapping diagnosis**

Exclude plants in contact with the boundary (*IMAQ Border filter*)



No-overlapping image (No. of plant = 1)



Overlapping image (No. of plant = 0)

Border filter ❱ $No.\,of\ plant \geq 1?$
- Yes: No-overlapping
- No: Overlapping

Image processing – Extraction of single lettuce

✓ **Separation of overlapped leaves** *(IMAQ_separation) (ROBERT et al., 1987)*

1. **Repeat 'Erosion' tool till the separation of overlapped leaves (1 to 8)**
2. **Extract individual lettuces based on the target position (9)**

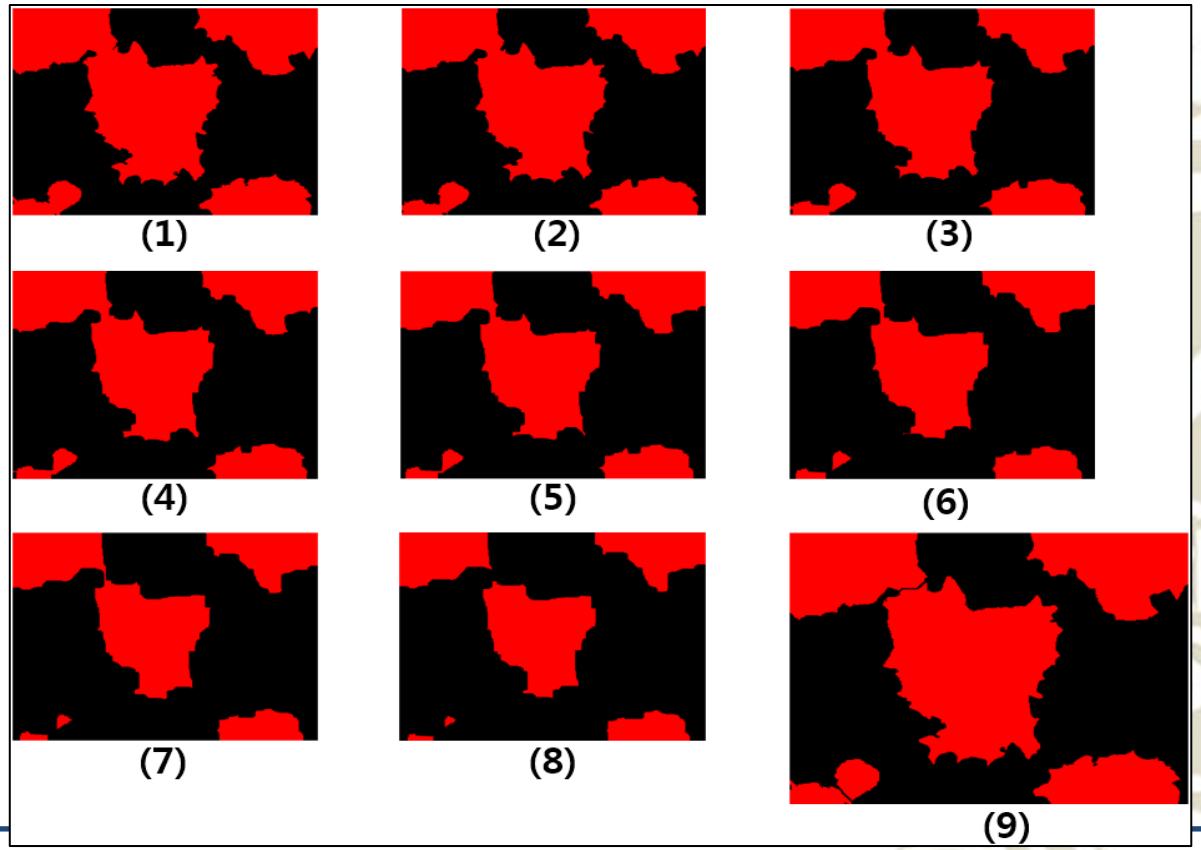


Image processing – Extraction from the overlapped area

✓ **Minimum Bounding box (MBB) algorithm (Bergen, 1997)**

- Generate a box for the separated image
- Calculate the distances between the box and the image border
- If the distance of one side was zero, the distance of the opposite side would be applied to cut the separated image (Top-Bottom)
- If the distances of the opposite sides were not zero, the minimum distance would be applied to cut the separated image (Left-Right)

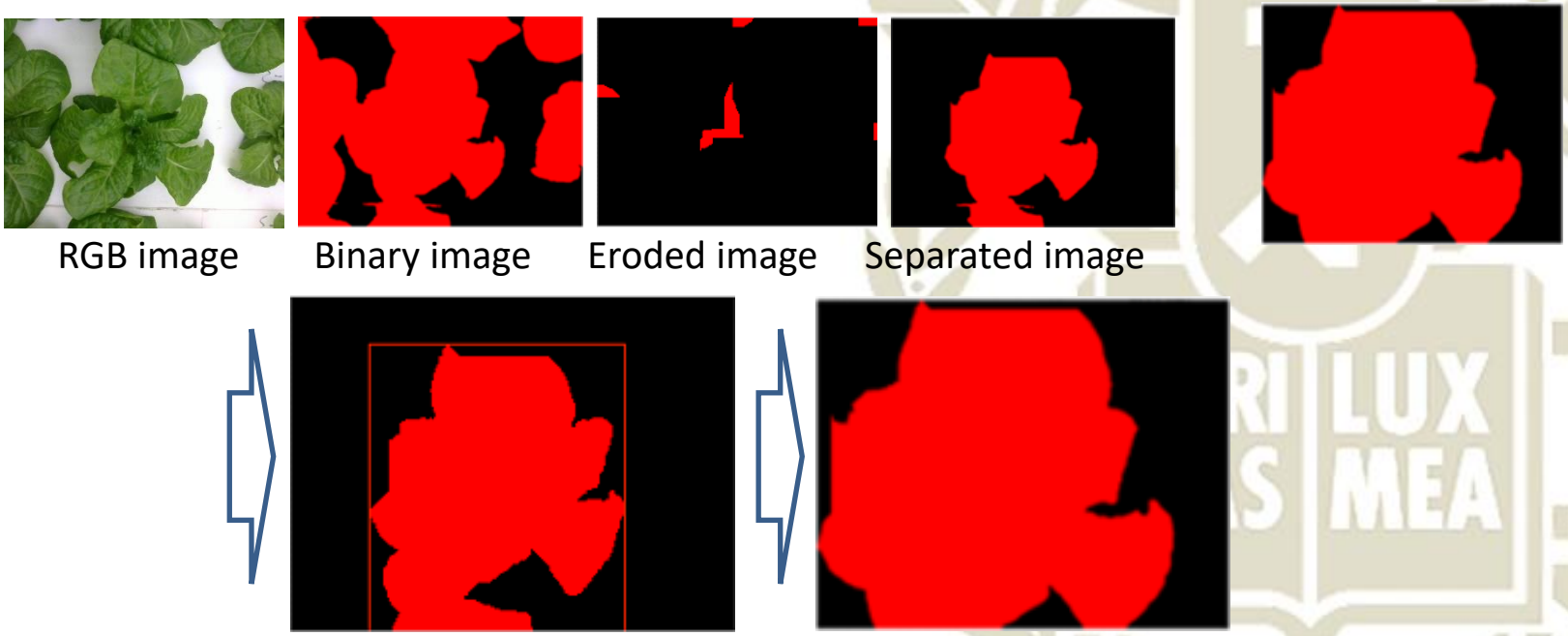


Image processing – Plant weight estimation

Pixel count

Target plant fresh weight

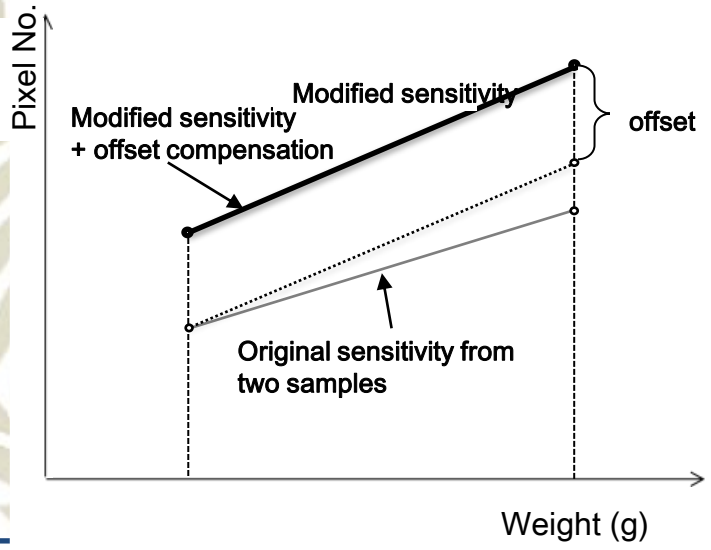
- The lettuce fresh weight was calculated using the following equation:

$$Fresh\ weight(g) = 9.4332 \times 10^{-12}X^2 + 1.5821 \times 10^{-5}X$$ ***(Jung et al., 2015)***

X=the pixel number of the plant

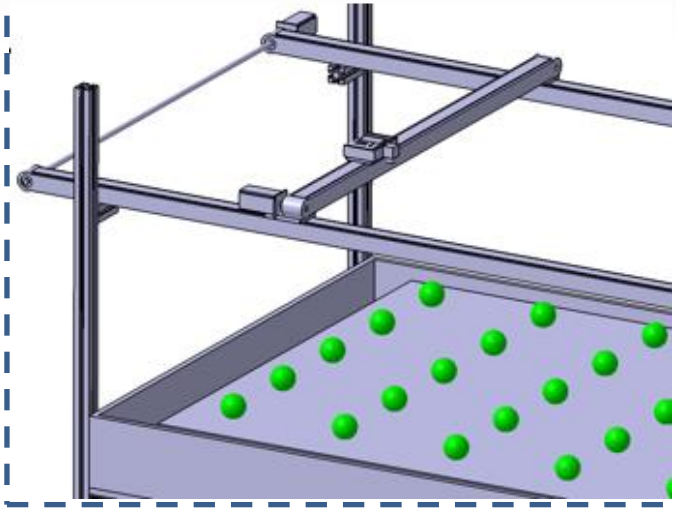
- ➢ Variability in canopy among crop species
- ➢ Different camera (resolution)
- ➢ Different object distance

➔ **The two-point normalization**



Application of two-point normalization

- **Two real samples** were taken prior to weight measurement and the ratio and offset were applied to the weights estimated using the original calibration.



A small sample

A big sample

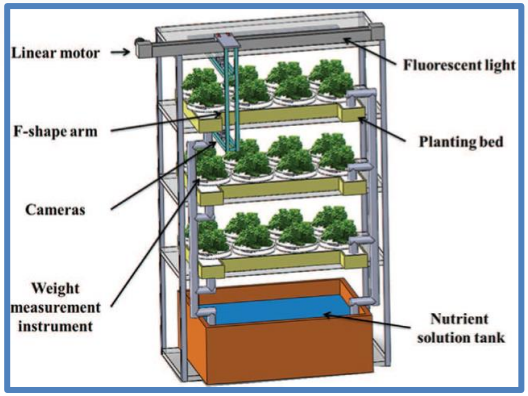
- **Image acquisition and estimation**
- **Actual weight measurement**

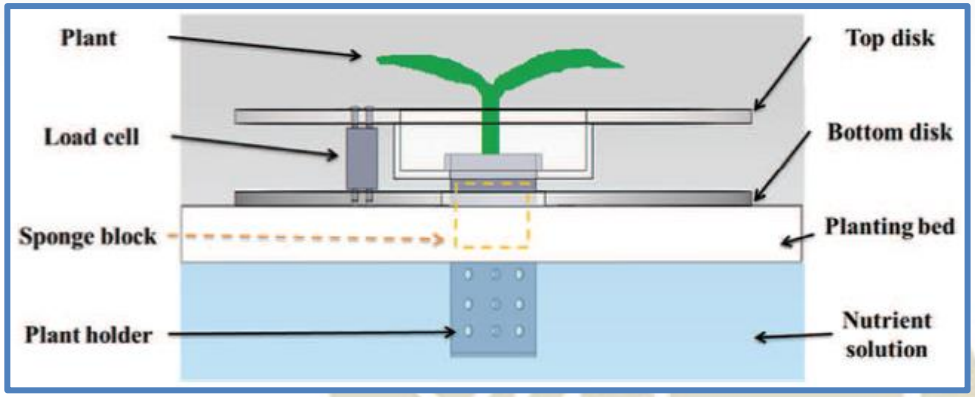
$$W_R = \frac{y_2 - y_1}{x_2 - x_1} W_0 + \left(y_1 - \frac{y_2 - y_1}{x_2 - x_1} x_1\right)$$

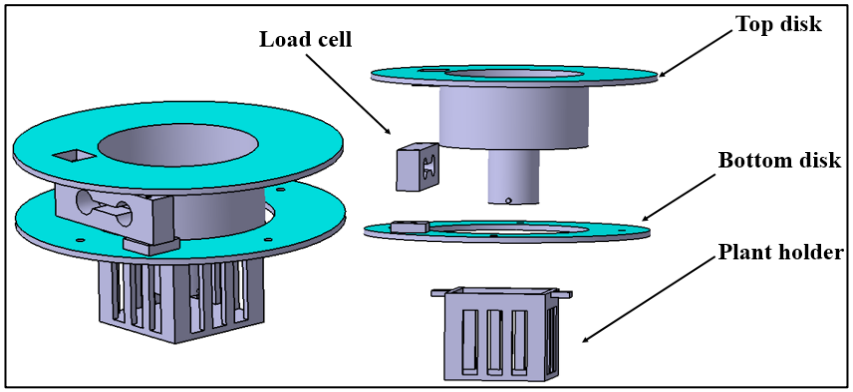
W_R= Lettuce fresh weight corrected based on the two-point normalization method
W_0= Lettuce fresh weight estimated from the original calibration equation
x_1= Fresh weight of sample 1 estimated using the original calibration equation
x_2= Fresh weight of sample 1 estimated using the original calibration equation
y_1= Actual fresh weight of sample 1
y_2= Actual fresh weight of sample 1

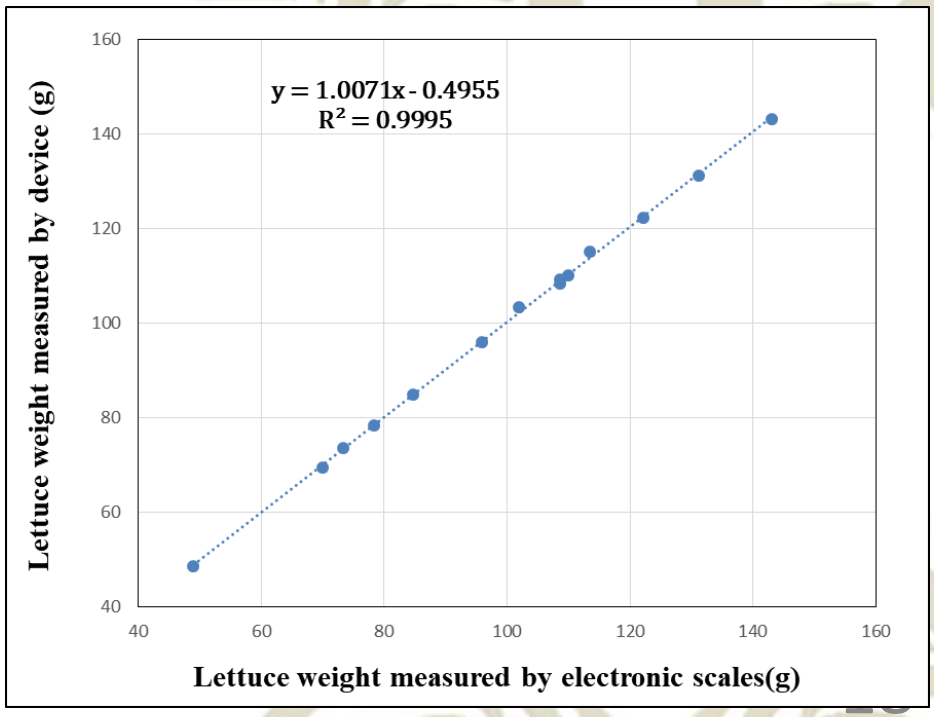
Validation of fresh weight estimation

- A load-cell based plant weight measurement system was fabricated by referring to a previous study (Chen et al., 2016)



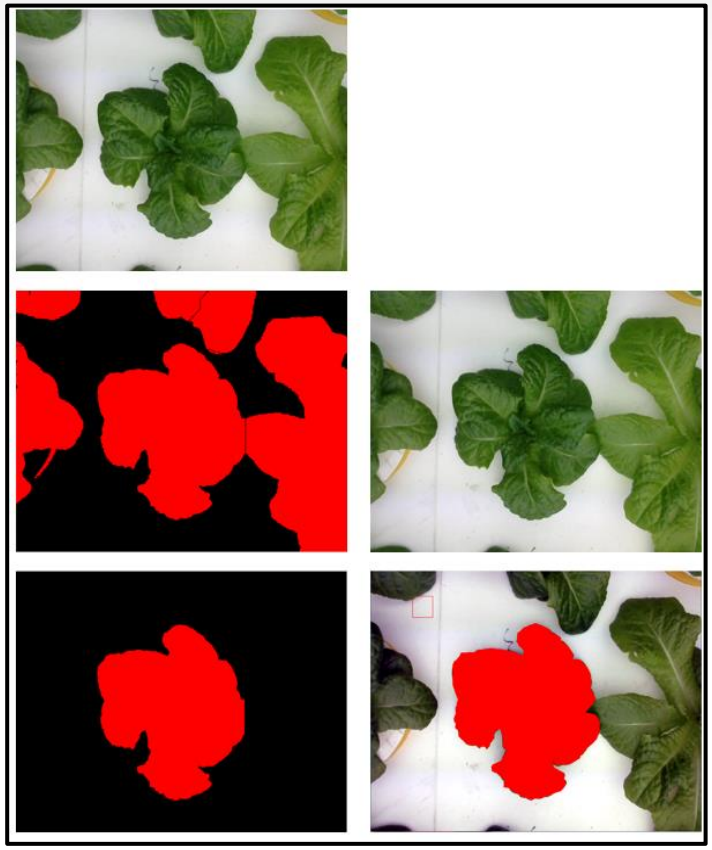






Validation of individual plant extraction algorithm

✓ **To investigate if it can extract the images of individual plants**

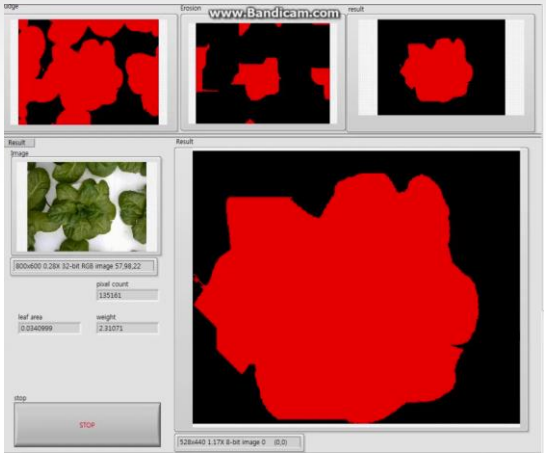


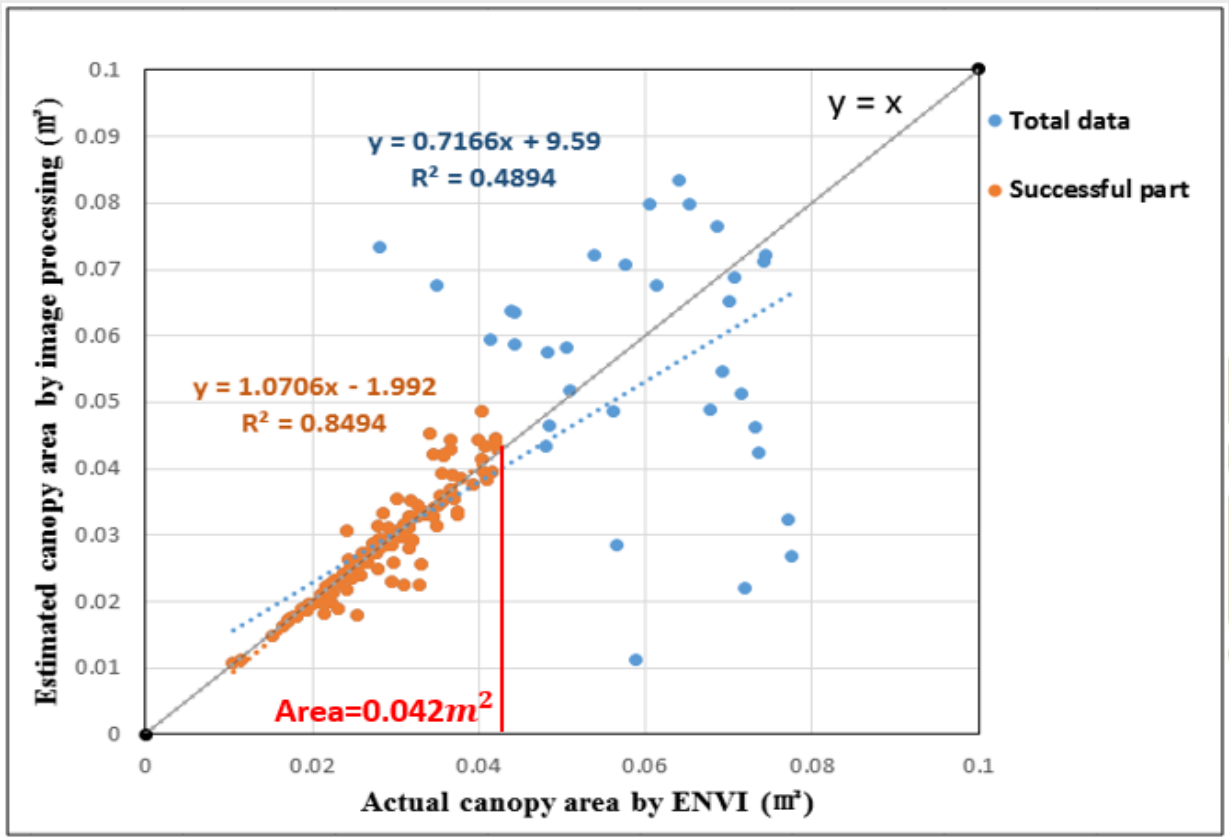
algorithm **manual**

- Numbers of pixels were compared.
- The manual separation was done using a commercial image processing program, ENVI (actual leaf surface)
- Linear regression analysis was conducted by comparing the actual and estimated results.

Comparison between estimated area and actual area

Validation test results





- The leaf area estimation was satisfactory when the leaf area was under 0.042 m²
- However, the leaf area estimation was deviated when the plant growth was saturated

Investigation of images by growth stage

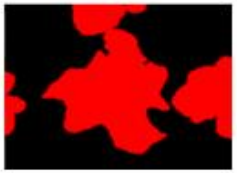
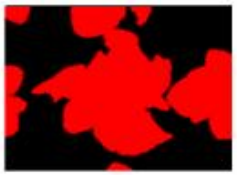
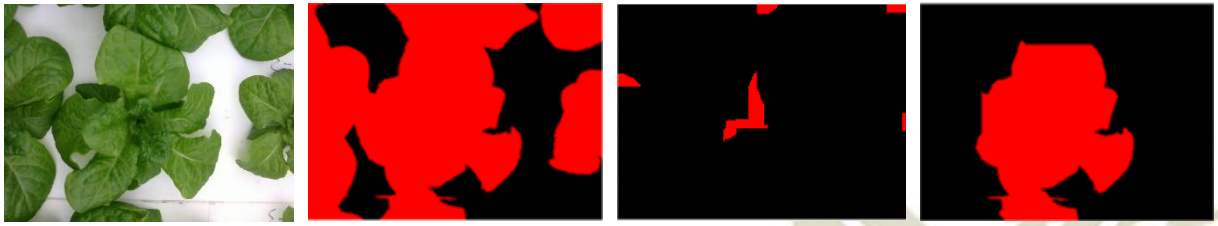
Canopy Area (m^2)	RGB Image	Binary Image	Separated Image	Cropped Image
0.026				
0.030				
0.035				
0.042				
Saturation 0.048				

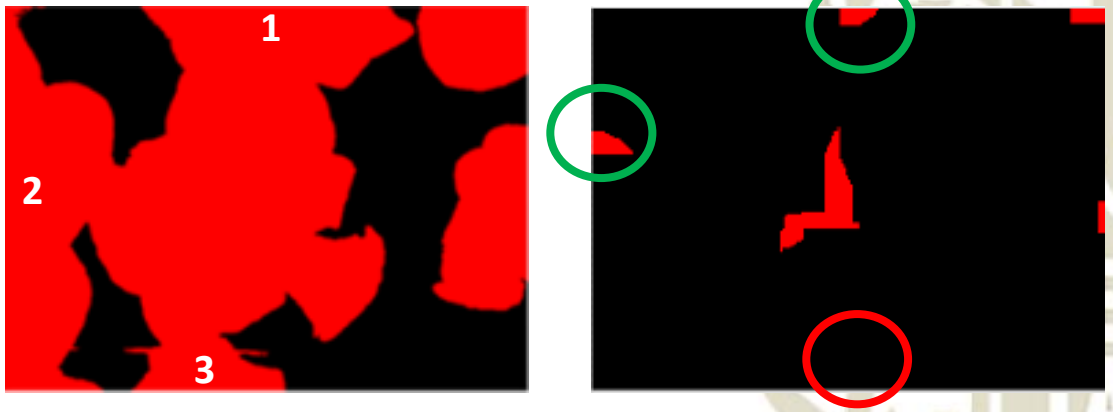
Image processing – Extraction from the overlapped area

✓ **Limitation of** *IMAQ_separation*

- If the overlapped area is too much, the separation was not achieved successfully



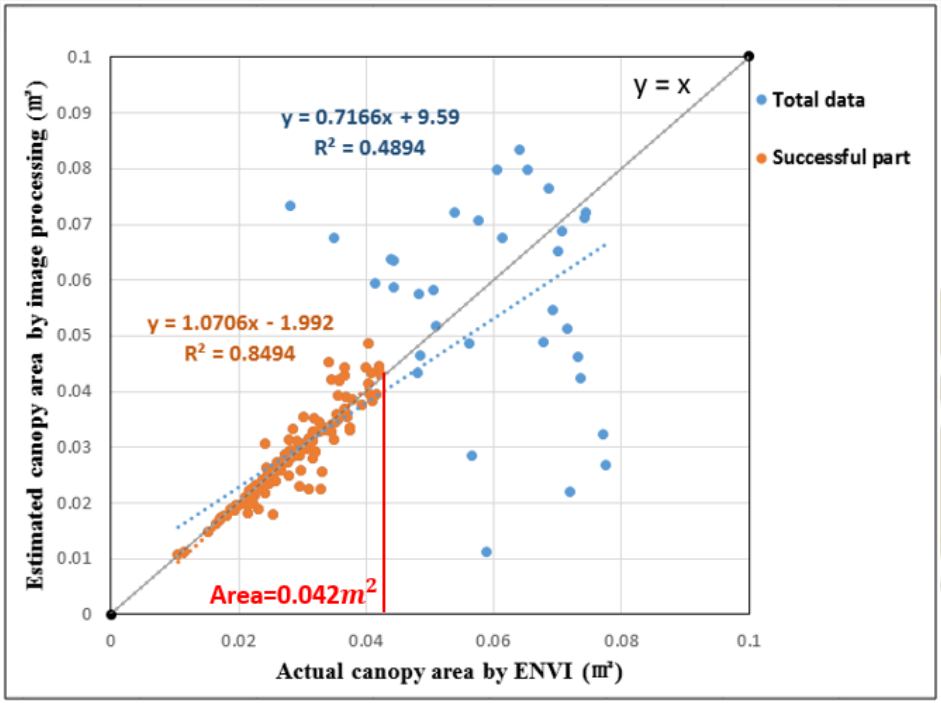
RGB image Binary image Eroded image Separated image



The small overlapped area (3) was overlooked during the erosion of other large overlapped areas (1, 2)

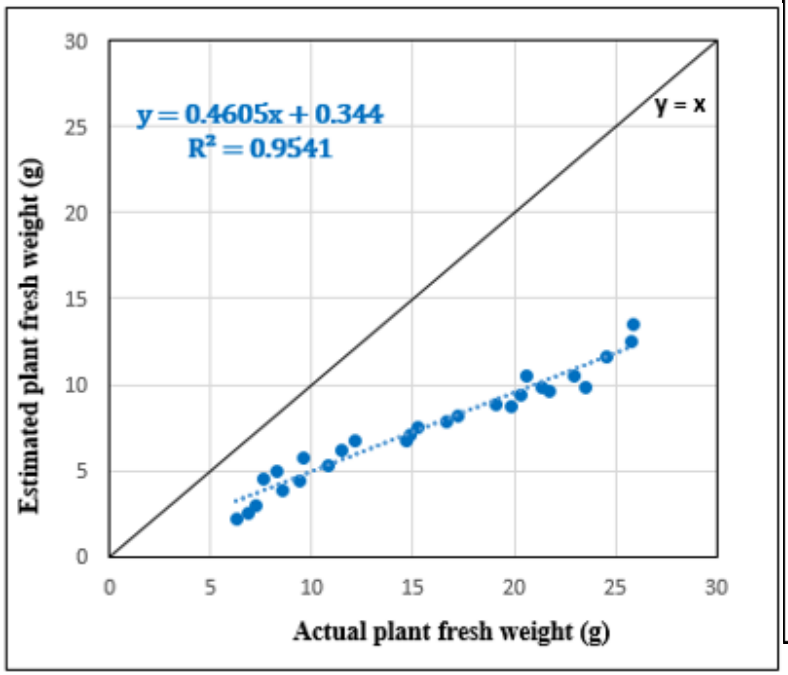
Comparison of the target plant extraction

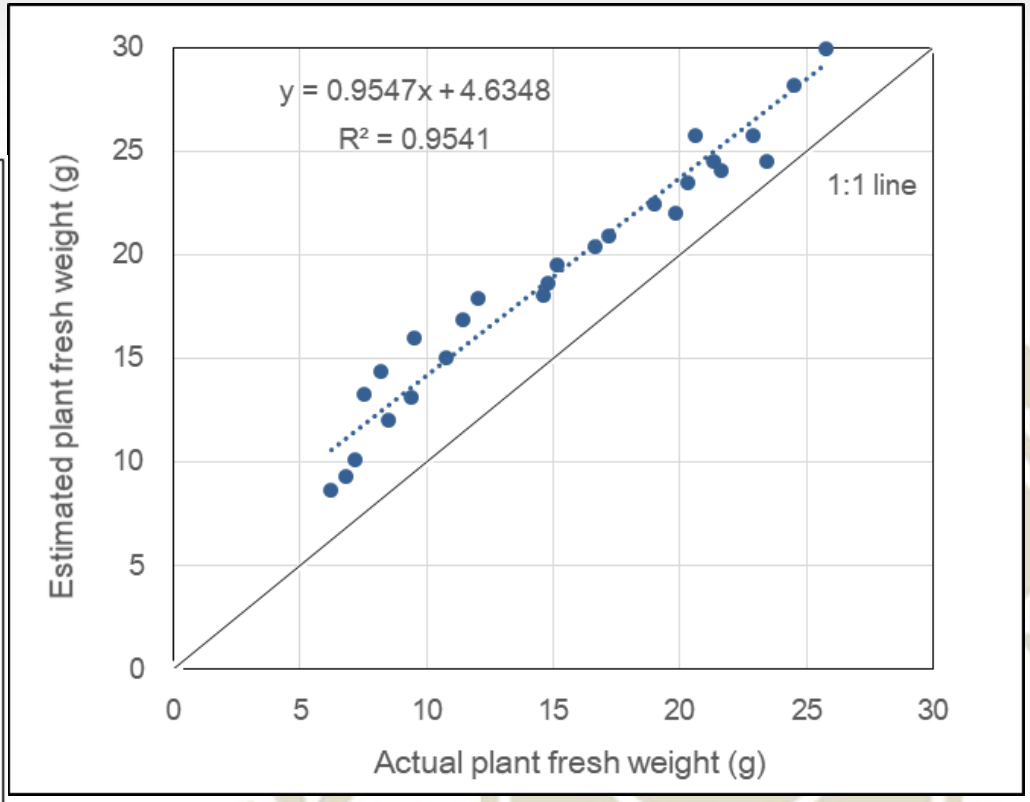
<0.042m^2 lettuce>



- The average of leaf lengths in harvested lettuces was 12.7 cm.
- The developed image extraction algorithm would be applicable to the embedded system that quantitatively measures the fresh weights of individual lettuces prior to harvesting.

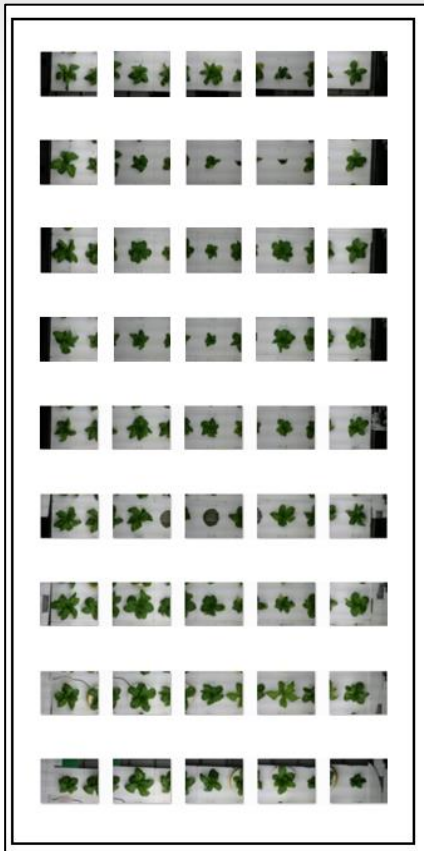
Performance of lettuce fresh weight estimation

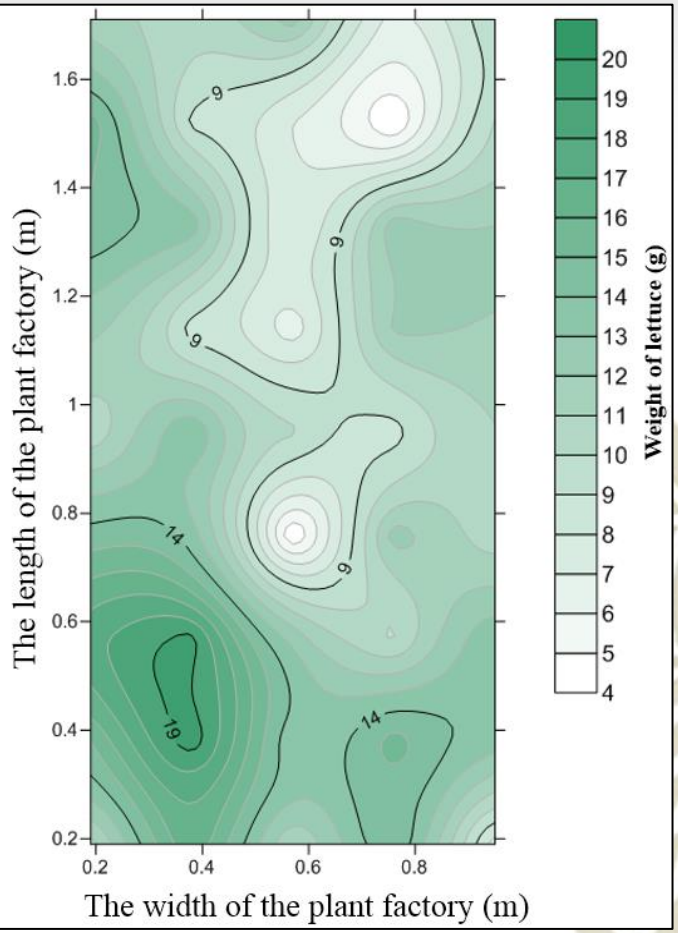


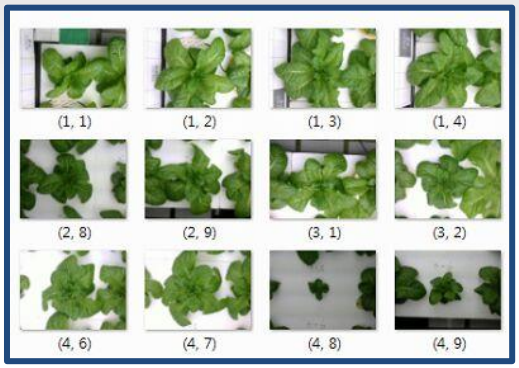


- Although some offset was observed in the estimation, the regression results showed a highly linear relationship with the actual and estimated fresh weights (Slope=0.9547, R^2= 0.9541)

Spatial mapping of fresh weight of lettuces







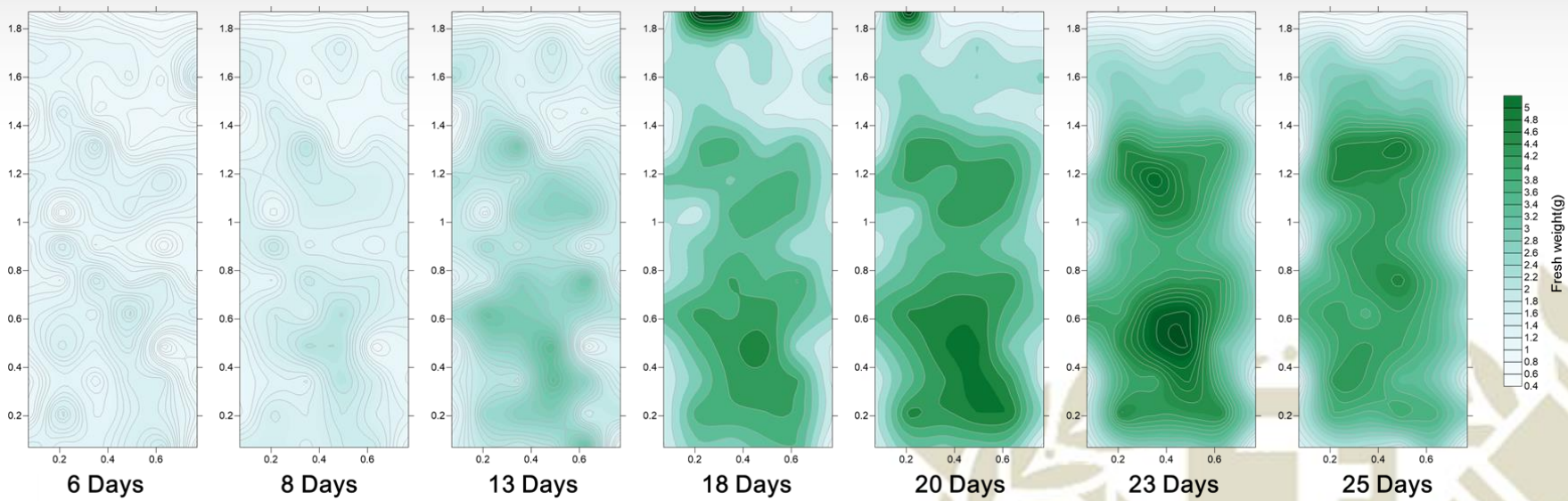
- The locations of each plant were calculated using the XY coordinates recorded.

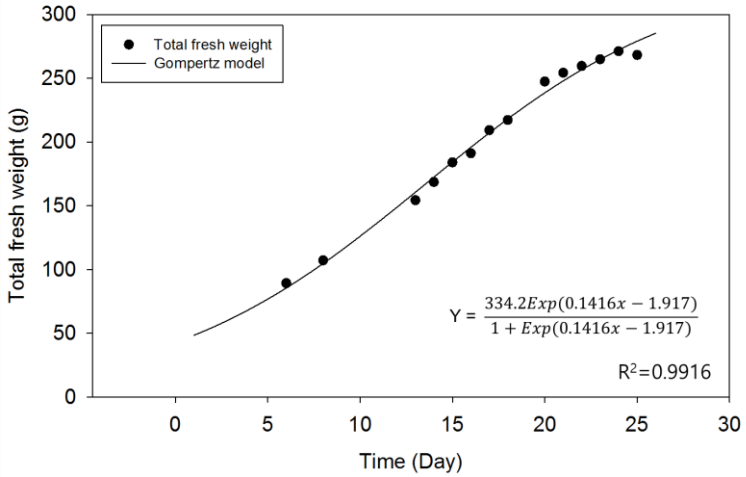
- The spatial maps of lettuce fresh weight were generated using a commercial software (*Surfer®13, Golden Software, USA*)

< An example of generating a lettuce fresh weight spatial map>

Spatial mapping of lettuce by growth stage

Temporal and Spatial maps of growing lettuce





< Gompertz curve for lettuce fresh weight>

- Temporal variability in lettuce fresh weight was observed and a Gompertz growth model for lettuce was built.
- It was apparent to effectively see spatial and temporal variability in fresh weight of lettuce.

Conclusions

- An on-the-go image processing system was developed that could monitor the growth status of lettuces grown in a ebb-and-flow hydronic system, showing the ability to measure the fresh weights of individual lettuces in real-time.

- When using the measured weight and the location of each plant, the spatial map of lettuce fresh weight could be generated, providing a useful tool for growers to determine what plants should be harvested.

- More studies on image processing algorithms to extract individual plants from overlapped plants with an improved level of accuracy were needed. In addition, the estimation of fresh weights based on volume would be needed.

Thank you for your attention！

谢谢