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Image Processing Methods for Measurement of Lettuce Fresh Weight

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Abstract

Purpose: Machine vision-based image processing methods can be useful for estimating the fresh weight of plants. This study analyzes the ability of two different image processing methods, i.e., morphological and pixel-value analysis methods, to measure the fresh weight of lettuce grown in a closed hydroponic system. **Methods:** Polynomial calibration models are developed to relate the number of pixels in images of leaf areas determined by the image processing methods to actual fresh weights of lettuce measured with a digital scale. The study analyzes the ability of the machine vision- based calibration models to predict the fresh weights of lettuce. **Results:** The coefficients of determination (> 0.93) and standard error of prediction (SEP) values (< 5 g) generated by the two developed models imply that the image processing methods could accurately estimate the fresh weight of each lettuce plant during its growing stage. **Conclusions:** The results demonstrate that the growing status of a lettuce plant can be estimated using leaf images and regression equations. This shows that a machine vision system installed on a plant growing bed can potentially be used to determine optimal harvest timings for efficient plant growth management.

Keywords: Fresh weight, Hydroponics, Image processing, Leaf area, Lettuce

Introduction

Hydroponics, also known as soilless farming, is a method of growing plants using mineral nutrient solutions in water (Kim et al., 2013). In closed hydroponic systems, assessments of plant growth and biomass status provide useful information for crop production and management. Such assessments are usually followed by major decisions such as optimal harvest timing (Bumgarner et al., 2012). Harvesting plants at the optimal time can promote uniform quality production while preserving nutrients and reducing growing time. The optimal harvesting time for each crop can be determined based on the measurement of its fresh weight; this can be estimated using digital images of the crop (Macfarlane et al., 2007; Lati et al., 2011; Son et al., 2014; Easlon and Bloom, 2014). Such a machine vision system is one of the most advantageous sensing techniques for measuring crop-growing status, because it uses real-time sensing and does not cause crop damage. Color crop images offer a substantial amount of information; however, an understanding of the information obtained from the image is required.

Leaf area is an important measurement used to analyze plant growth and predict its yield. In particular, it can be used for evaluating the effects of various crop management practices (Campillo et al., 2008). Grid count and gravimetric methods are generally used for leaf area measurements. To evaluate plant growth and health, a number of methods have been developed for measuring leaf areas. Because they provide greater accuracy, direct measurement procedures that use lamp-based analyzers are commonly employed in the laboratory. However, these methods are laborious, expensive, and time consuming when applied

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to large numbers of leaves (Chaudhary et al., 2012). Sandmann et al. (2013) reported that indirect methods should be developed to measure the leaf areas of various horticultural crops. The morphology of a single plant and its vegetation cover area can affect the accuracy of indirect measurements. However, although such indirect methods have disadvantages related to the clumping model of crop, they are cost-efficient and allow time-repeated measurements for canopy estimation.

Recently, various image processing methods have been reported to be effective in assessing vegetative coverage, nutrient status, and vegetation indices in many agronomic and horticultural plants (Campillo et al., 2008; Li et al., 2010; Stewart et al., 2007). Digital images were obtained with various types of equipment. An inexpensive, consumer-based digital camera captured wide bands of reflected light primarily in the red, green, and blue regions, and various software-based image analysis methods were used. Similar to the cameras, the image analysis software systems included both commercially available and project-specific programs (Bumgarner et al., 2012). Digital images are commonly used in ecology to monitor plant- or landscape-level changes; as a result, the image analysis method has proven useful in describing and identifying green leaves (Ide and Oguma, 2010; Casadesus et al., 2007; Neeser et al., 2009). Image assessment and other remote sensing-based methods have been used in horticultural crop applications, although further investment in techniques and applications were necessary (Lee et al., 2010).

In this study, image-processing methods were developed to estimate the fresh weights of lettuce plants, using two different image analysis methods — morphological and color-value analysis. Regression models were developed to correlate the number of pixels in each lettuce image to the fresh weight of the plant, to estimate fresh weights during the growing stages.

Materials and Methods

Lettuce growing system and image acquisition

In this study, lettuce was grown using a recirculating hydroponic system based on ebb and flow, which is commonly known as the flood drain method. An automated nutrient management system, consisting of a nutrient reservoir system and a measurement-control system, was used to cultivate the lettuce, as shown in Figure 1. The recirculating system temporarily flooded the growing bed with a nutrient solution, and subsequently drained the solution back into a mixing tank. An array of white fluorescent tube lamps was installed on the plant bed as a light source for daytime lighting from 9 AM to 9 PM. The average photosynthetic photon flux density of the light source at the growing bed was 133.45 μmol $S^{-1}m^{-2}$. In addition, temperature was maintained at 21±2°C during the 18-day growing period.

Images of 82 lettuce samples were captured individually using a digital camera (TG-1, Olympus Imaging Corp., Japan). Of these, 52 samples were prepared as a calibration set and 30 samples were used as a validation set. The camera was equipped with an f/2.0 lens (to produce bright images) and an autofocus feature; it was installed at a height of 65 cm from each lettuce canopy. Images with pixel dimensions of 3,968 x 2,976 were analyzed using vision tools provided by both LabVIEW CVI (ver. 12.0, National Instruments, Austin, TX, USA) and MATLAB R2014a (MathWorks, Natick, MA, USA) to calculate the number of pixels in the leaf area of each lettuce plant.

Image processing methods and regression analysis

Gray-scale images were used for the morphological analysis of leaf areas using the LabVIEW program. A binary image process was conducted using a gray value

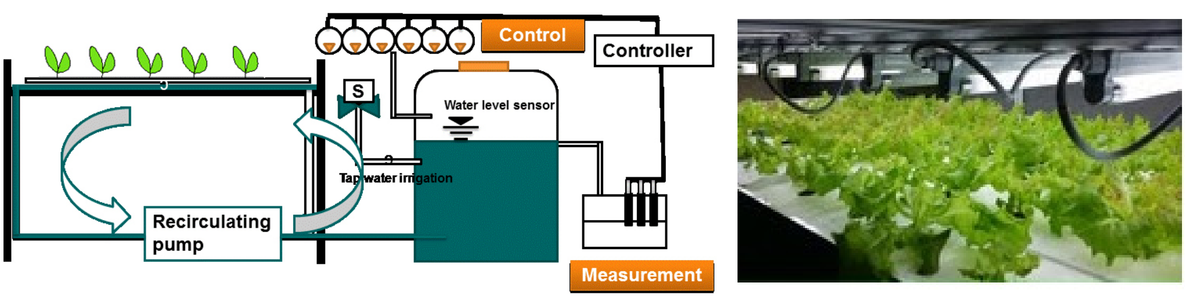

Figure 1. Schematic diagram of an ebb-and-flow-based hydroponic growing system (left) and photo view of lettuce plants growing in the hydroponic system (right).

range of 30~125, which represented the multiple thresholds for identifying the ROI (region of interest). A hole filling process and Heywood circularity factor (H, Eq. 1) were applied to remove non-ROI background areas. H was defined as the ratio of the particle perimeter to the perimeter of a circle having the same area. A perfect circle would have an H of 1 (Karn et al., 2014), while a lettuce area would have a circularity factor between 2 and 5, based on a preliminary investigation of 50 lettuce plants.

$$H = \frac{p}{2\sqrt{\pi A}} \quad (1)$$

where, H = Heywood circularity factor
P = Perimeter of a unit
A = Area of a unit

For pixel-value analysis, the original color images were normalized prior to the detection of leaf areas. During the image normalization process, the brightness for all images was adjusted to provide a mean gray value of 128 to every normalized image. Furthermore, the minimum and maximum gray levels of the normalized images were applied to those of the original images (Park et al., 2014). Pixel information was used as the standard reference for pixel-value analysis; 300-pixel leaf areas, having a gray value within a range of 1.96 times above or below the average gray value, were analyzed to satisfy the 95% confidence interval.

Acquired images were analyzed using two different methods to calculate the number of pixels in the leaf area of each lettuce plant. Image processing methods designed to count pixels and detect leaf areas in the selected area are shown in Figure 2. The figure depicts the procedural steps required to calculate pixel counts in leaf areas, based on the morphological analysis and pixel-value analysis methods.

The two methods presented in this paper have different characteristics. First, the image processing algorithm based on the morphological analysis method detects leaves that match the shape of lettuce leaves after non-ROI areas are eliminated. The morphological features of the lettuce image include area, perimeter, major axis length, minor axis length, leaf shape, and so on. Relatively, color features of the lettuce image include mean, ranges, and ratios using red, green, blue, and so on. Image analysis based on morphological features can be applied to various shape factors, which might lead to quicker leaf area detection; however, it often incorrectly recognizes the background as a leaf area. On the other hand, because the pixel-value analysis method evaluates whether a pixel is a leaf pixel based on all pixel values, image analyses performed using pixel color features (and a simple algorithm) can provide more accurate leaf area detection than morphological analysis. However, additional time is often required to analyze the entire image.

To develop a calibration model that relates the pixel counts of lettuce samples to their actual fresh weights (measured without roots using a digital scale), simple linear regression and polynomial regression methods were used to identify models that explain relationships between the pixel counts in the image and the actual fresh weights of lettuce (Kataoka et al, 2003). The accuracy of the model was evaluated by comparing fresh weights determined by the calibration model and a digital scale in terms of coefficient of determination (R^2), a standard error of calibration (SEC), and a standard error of prediction (SEP).

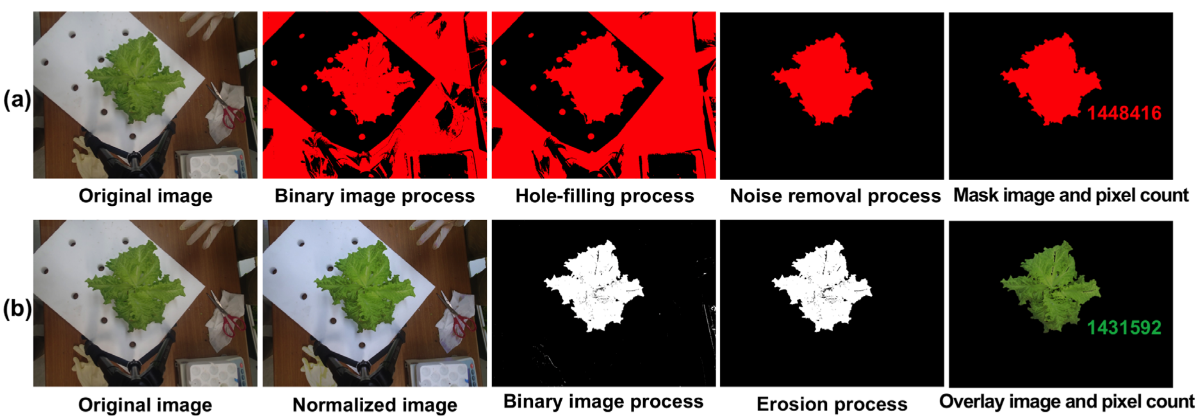

Figure 2. Image processing methods for counting pixels using a morphological analysis (a) and pixel-value analysis (b).

Results and Discussion

Table 1 shows the ranges of red (R), green (G), and blue (B) gray values and pixel ratios in lettuce leaves obtained by counting the number of green pixels in the acquired lettuce images, based on an investigation of 300-pixel leaf areas.

A correlation study showed high correlations between the pixel counts of lettuce canopy cover and their actual fresh weights. The morphological analysis and pixel-value analysis methods produced correlation coefficients (r) of 0.9211 and 0.9184, respectively. As a result, we developed regression equations using the calibration samples; we then evaluated the feasibility of using the calibration equations for estimating the fresh weights of lettuce, using the 30 validation samples. When comparing calibration models based on simple linear and polynomial regression analysis methods, the 2nd order polynomial equations provided more accurate prediction performance ($R^2 > 0.9549$) than did the simple linear regression models ($R^2 > 0.9246$).

Table 1. Ranges of R, G, B gray values and ratios of pixels in a lettuce leaf. M-1.96σ indicates a minimum value and M+1.96σ indicates a maximum value in the range

	Mean	M-1.96σ	M+1.96σ
R	104.48	57.78	151.18
G	151.78	107.33	196.23
B	57.26	5.04	109.47
R/G	0.68	0.53	0.84
G/B	3.04	0.91	5.16
B/R	0.54	0.20	0.87

Figure 3 shows the polynomial regression equations with pixel counts based on the morphological analysis and pixel-value analysis. In the figure, the predictor variable x represents the number of pixel counts, and the outcome variable y represents the fresh weight of lettuce. In terms of coefficient of determination (R^2), there were no significant differences between the two polynomial regression models based on the two different image processing methods; both generated an $R^2 > 0.95$. However, when data ranges with different fresh weights were used, there was a slight difference in the ability to fit the model. That is, it appeared that the polynomial model provided more accurate estimations of fresh weights < 30 g than for estimations of fresh weights > 30 g. The difference might be related to a problem with areas that are overlapped by relatively large leaves in lettuce plants with fresh weights over 30 g.

Results of the calibration and validation processes based on the polynomial model are shown in Figure 4. When calibration samples were used to compare actual fresh weights to the values predicted by the morphological- and pixel-value-based polynomial models, the R^2 values of the actual and predicted fresh weights were 0.9739 and 0.9549, respectively. This suggests highly linear relationships between the actual and predicted values. In the validation analysis, there were strongly linear relationships between the actual and estimated fresh weights of lettuce, showing $R^2 > 0.93$ and SEPs (standard error of prediction) < 4.6 g, which suggests that over 95% of the data variability could be explained by both regressions.

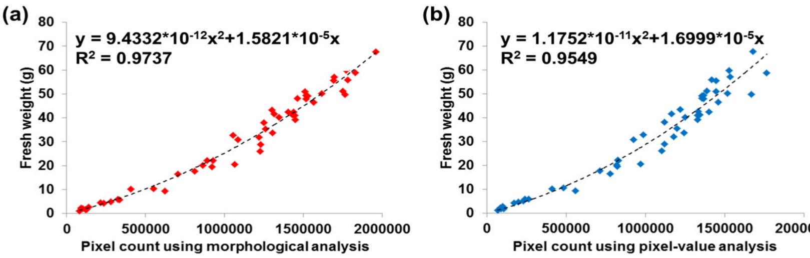

Figure 3. Calibration curves for morphological images (a) and pixel-value images (b) relating pixel count (X) and fresh weight (Y).

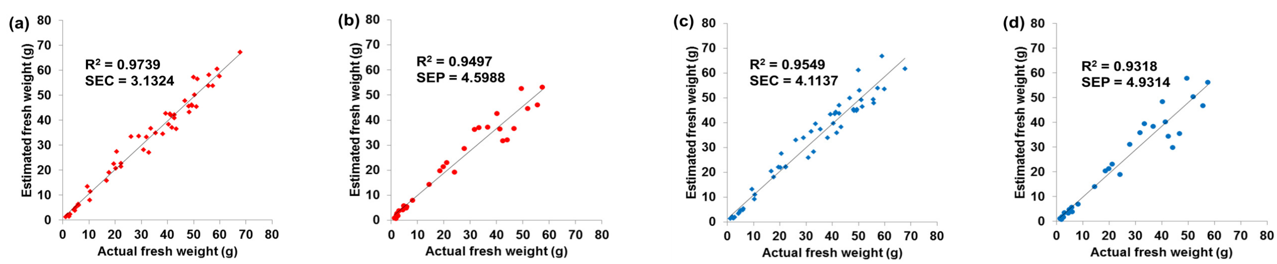

Figure 4. Relationships between lettuce fresh weights determined by the two image processing methods, i.e., morphological (a and b) and pixel-value analysis (c and d), and a digital scale when calibration and validation samples were used.

Conclusions

This study was conducted to predict the fresh weights of lettuce using two different image processing methods, i.e. morphological analysis and pixel-value analysis. Such machine vision approaches can be used to detect the leaf area of lettuce. The number of pixels in the leaf area was used to develop the regression model to estimate the fresh weights of lettuce plants. Both the developed models showed coefficients of determination greater than 0.93. SEPs obtained from the model validation were less than 5 g. This demonstrated the ability of these image processing methods to measure lettuce fresh weights; these measurements can be used as an index to evaluate plant growth.

Conflict of Interest

The authors have no conflicting financial or other interests.

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References

Bumgarner, N. R., W. S. Miller and M. D. Kleinhenz. 2012. Digital image analysis to supplement direct measures of lettuce biomass. HortTechnology 22(4):547-555.

Casadesus, J., Y. Kaya, J. Bort, M. M. Nachit, J. L. Araus, S. Amor, G. Ferrazzano, F. Maalouf, M. Maccaferri, V. Martos, H. Ouabbou and D. Villegas. 2007. Using vegetation indices derived from conventional digital cameras as selection criteria for wheat breeding in water-limited environments. Annals of applied biology 150(2):227-236.

Campillo, C., M. H. Prieto, C. Daza, M. J. Monino and M. I. Garcia. 2008. Using digital images to characterize canopy coverage and light interception in a processing tomato crop. Hortscience 43(6):1780-1786.

Chaudhary, P., S. Godara, A. N. Cheeran and A. K. Chaudhari. 2012. Fast and accurate method for leaf area measurement. International Journal of Computer Applications 49(9):22-25.

Easlon, H. M and A. J. Bloom. 2014. Easy Leaf Area: Automated digital image analysis for rapid and accurate measurement of leaf area. Applications in plant sciences 2(7):1400033.

Ide, R and H. Oguma. 2010. Use of digital cameras for phenological observations. Ecological Informatics 5(5):339-347.

Karn, A., C. Ellis, R. Arndt and J. Hong. 2014. An integrative image measurement technique for dense bubbly flows with a wide size distribution. Chemical Engineering Science 122:240-249.

Kataoka, T., T. Kaneko, H. Okamoto and S. Hata. 2003. Crop growth estimation system using machine vision. In Advanced Intelligent Mechatronics, 2003. AIM 2003. Proceedings. 2003 IEEE/ASME International Conference on (Vol. 2, pp. b1079-b1083). IEEE.

Kim, H. J., W. K. Kim, M. Y. Roh, C. I. Kang, J. M. Park and K. A. Sudduth. 2013. Automated sensing of hydroponic macronutrients using a computer-controlled system with an array of ion-selective electrodes. Computers and Electronics in Agriculture 93:46-54.

Lati, R. N., S. Filin and H. Eizenberg. 2011. Robust methods for measurement of leaf-cover area and biomass from image data. Weed Science 59(2):276-284.

Lee, W. S., V. Alchanatis, C. Yang, M. Hirafuji, D. Moshou and C. Li. 2010. Sensing technologies for precision specialty crop production. Computers and Electronics in Agriculture 74(1):2-33.

Li, Y., D. Chen, C. N. Walker and J. F. Angus. 2010. Estimating the nitrogen status of crops using a digital camera. Field Crops Research 118(3):221-227.

Macfarlane, C., M. Hoffman, D. Eamus, N. Kerp, S. Higginson, R. McMurtrie and M. Adams. 2007. Estimation of leaf area index in eucalypt forest using digital photography. Agricultural and forest meteorology 143(3): 176-188.

Neeser, C., Martin, A. R., Juroszek, P and D. A. Mortensen. 2009. A comparison of visual and photographic estimates of weed biomass and weed control. Weed Technology 14(3):586-590.

Park, S. H., H. Lee and S. H. Noh. 2014. Multispectral wavelength selection to detect ‘fuji’ apple surface defects with pixel-sampling analysis. Journal of biosystems engineering 39(3):166-173.

Sandmann, M., J. Graefe and C. Feller. 2013. Optical methods for the non-destructive estimation of leaf area index in kohlrabi and lettuce. Scientia horticulturae 156: 113-120.

Son, D., S. H. Park, S. Chung, E. S. Jeong, S. Park, M. Yang, H.-S. Hwang and S. I. Cho. 2014. Correlation analysis between growth factors of seed sprouts and pixel counts of leaf area. Journal of biosystems engineering 39(4):318-323.

Stewart, A. M., K. L. Edmisten, R. Wells and G. D. Collins. 2007. Measuring canopy coverage with digital imaging. Communications in soil science and plant analysis 38(7-8):895-902.