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# DIGITAL IMAGE PROCESSING OF PLANTS IN TWO WAVE BANDS OF RED AND INFRARED FOR EVALUATION OF GROWTH

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EGUCHI H., HAMAKOGA M. and MATSUI T. *Digital image processing of plants in two wave bands of red and infrared for evaluation of growth.* BIOTRONICS **12**, 1–10, 1983. In an attempt to extract clear pattern of plant image from the background, two wave bands of red ($R$; about 670 nm) and infrared ($I$; about 900 nm) regions were selected on the basis of spectral characteristics of leaf reflectance and used for taking $R$ and $I$ images in phytotron glass room by a TV camera. These images were digitized for computation and denoted as respective matrixes of $M_R$ and $M_I$ where each matrix element was expressed as reflectance (%). From $M_R$ and $M_I$, difference in reflectance between $R$ and $I$ bands was given as $M_S=[c_{ij}]=M_I-M_R$, where the element, $c_{ij}\leqq 25\%$ was treated as '0', and the element, $c_{ij}>25\%$ was treated as '1'. In $M_S$, the plant image was clearly separated from the background, and the plant growth appeared in increase in the number of digits of '1'. So, sum($P$) of the elements of $M_S$ was used as a parameter for evaluation of the growth: The fresh weight was represented reliably by a regression equation on $P$ even when the plants were grown at different air temperatures of 22°C and 25°C. The temperature effect on the plant growth was observed in increase in the fresh weights calculated from the regression equation in course of time. Thus, digital image processing of plants in red and infrared regions could be used as a tool of non-destructive and on-line measurement for the evaluation of plant growth.

## INTRODUCTION

Non-destructive and on-line measurement of plants can give important information upon plant responses to environmental factors in course of time. Digital image processing of plants (*3–7*) can be applied to such instrumentation in the hope that the plant information obtained can be used in the control system (*1, 2, 8, 9*) for optimalizing the environment. For reliable image processing, it is essential to extract the clear plant image separated from the noises. However, when plant image is taken in the glass room or in the greenhouse, this image usually contains the background composed of many kinds of light reflecting media. This background makes necessarily the plant image indefinite and disturbs adequate image processing of plants. Thus, the processing method must be further developed for obtaining the clear pattern of plants by removing the background noises.

The present paper deals with digital image processing in two wave bands of red and infrared regions in an attempt to eliminate the background and evaluate plant growth in an on-line system.

## MATERIAL AND METHODS

*Cucumis sativus* L. var. Hort. Chojitsu-Ochiai was used in this experiment. The plants were potted in Vermiculite moistened with nutrient solution and grown under respective air conditions of $22\pm1$°C and $25\pm1$°C at $70\pm5\%$ relative humidity in a phytotron glass room. Six cucumber plants were set in an array in the phytotron glass room. TV camera (Silicon vidicon camera, HV-13287, Hitachi Electronics, Ltd.) was fixed at a constant distance from plants and at a camera angle of 55° to the normal. Figure 1 shows the schematic diagram of the system used. Camera drive was controlled by the computer signal and synchronized with illumination to the plants: The plants were illuminated for 3 min once a day at 4:00–4:03 a.m. (before sunrise) by tungsten light (5 incandescent lamps of 500W) with an intensity of 10 W $m^{-2}$ (in visible light region), and at the same time, the plant image was taken by the TV camera. The image was displayed on TV monitor and digitized into video memory (Video densitometer 520A, NAC Inc.) with 240 (lines)$\times$256 (pixels) meshes. The digitized image was transmitted to CPU (TOSBAC-40C, Tokyo Shibaura Electric Co., Ltd.) and filed in disk memory (BLK 4201Z, Tokyo Shibaura Electric Co., Ltd.). The digitized image was denoted as a matrix ($M$), where the arrangement of the elements ($x_{ij}$) was expressed as

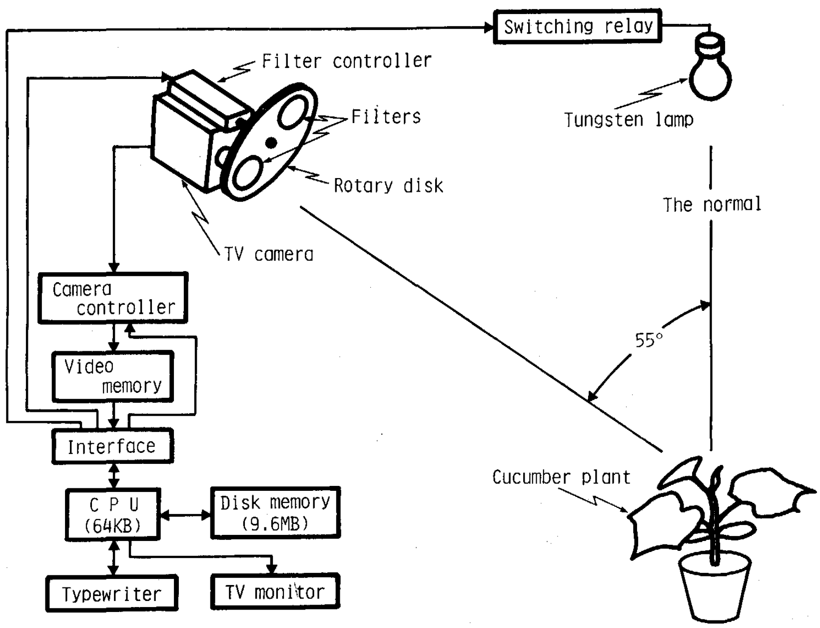


Fig. 1. Schematic diagram of image processing system.

$$M=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ & \cdots\cdots & & \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}, \quad m=240,\ n=256 \tag{1}$$

Each element ($x_{ij}$) was evaluated as reflectance (%) of the light and displayed as a digital symbol of the reflectance.

## RESULTS AND DISCUSSION

Figure 2 shows a photograph taken by a still camera with the panchromatic film. In this panchromatic image, there were many kinds of backgrounds brighter than the plants. The spectral reflectances of the background media appeared in different patterns as shown in Fig. 3. Most of them were flat in wave length regions of 400–1000 nm. The brighter background media of aluminium, stainless steel and the steel painted in olive reflected 50–70% of the light. The reflectance in concrete was almost constant at about 30% in this wave length region. In black polyethylene film, sandy and clayey soils, the reflectances were remarkably lower than others, which were less than 20%. On the other hand, the spectral reflectance in the cucumber leaf was characterized by a small peak at about 15% in about 550 nm, a dip at about 6% in 670–680 nm and a broad peak at 60–70% in infrared region. Thus, the leaf reflectance appeared in a specific spectrum, but this reflectance and the background reflectances overlapped each other. These patterns indicated that extraction of the plant image could be disturbed by the background noises in any of the wave length regions of light. Therefore, for clear extraction of the plant image from the background, it is necessary to use two or more images taken

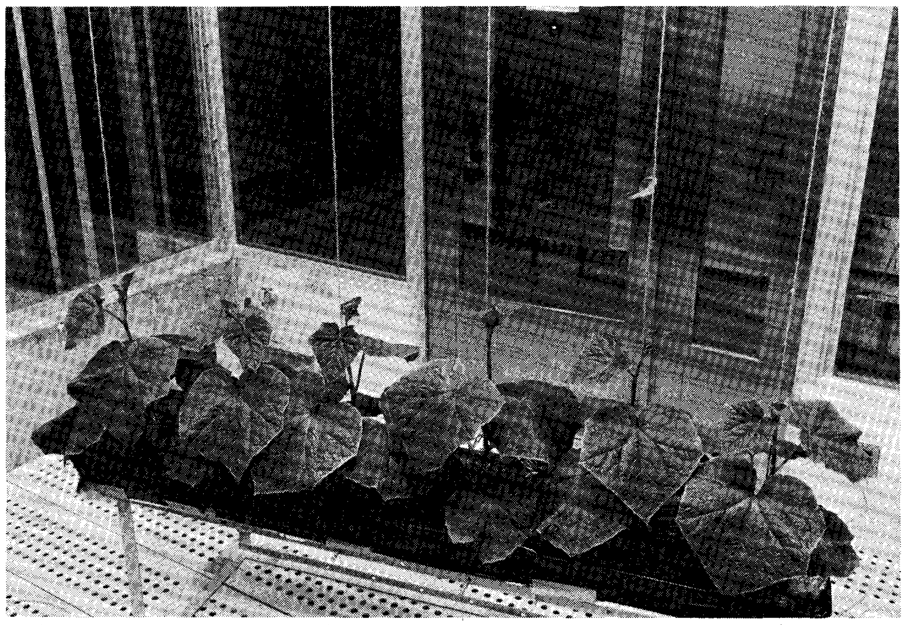

Fig. 2. Panchromatic photograph of 25 days old plants taken in a phytotron glass room by a still camera (the plants were grown at air temperature of 22°C).

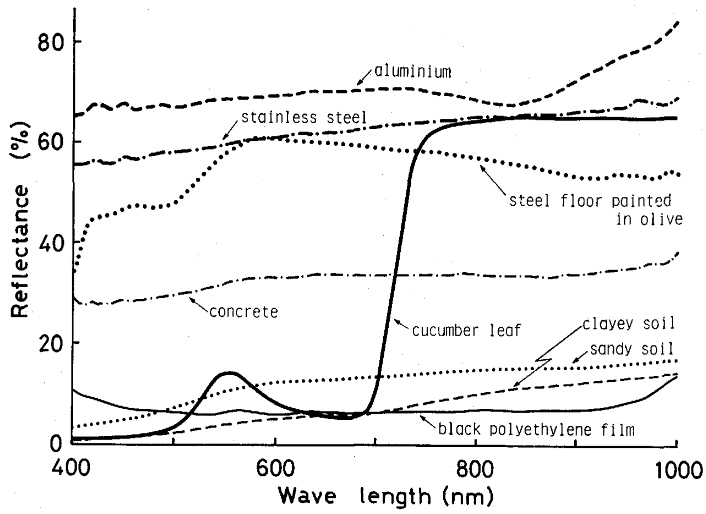


Fig. 3. Patterns of spectral reflectances of the cucumber leaf and the backgrounds in phytotron glass room.

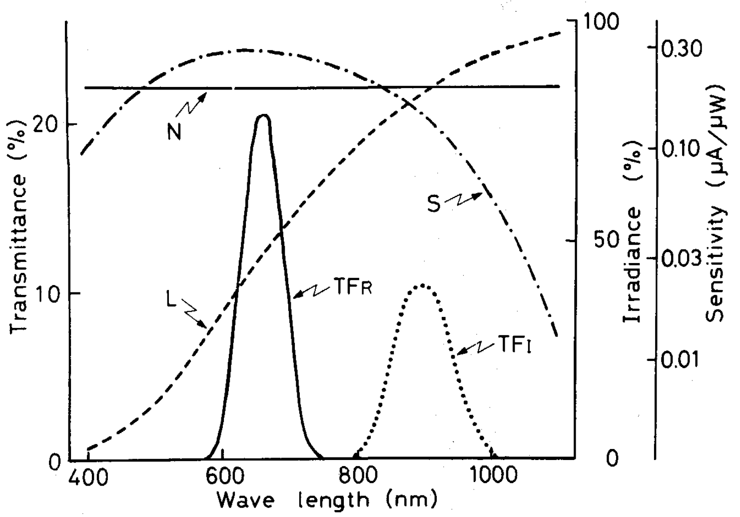


Fig. 4. Spectral characteristics of transmittances ($TF_R$ and $TF_I$) of filters, light energy (L), camera sensitivity (S) and reflectance (N) of neutral test card (90% reflectance).

in different wave length regions for image processing. In this experiment, the two wave bands were selected for taking the plant images, on the basis of the characteristics of spectral reflectance in the leaf; one was the red band (*R*; absorbing region), and the other was the infrared band (*I*; highly reflecting region).

To take two images in respective wave bands of *R* and *I*, two kinds of interference filters of $F_R$ and $F_I$ (*4*) were used, where the peaks of transmittances were at 670 nm and at 900 nm, respectively. Figure 4 shows the spectral characteristics of the filters, the tungsten light, the camera sensor and neutral test card with 90% reflectance (Eastman Kodak Co.). As observed in the spectral transmittances, the

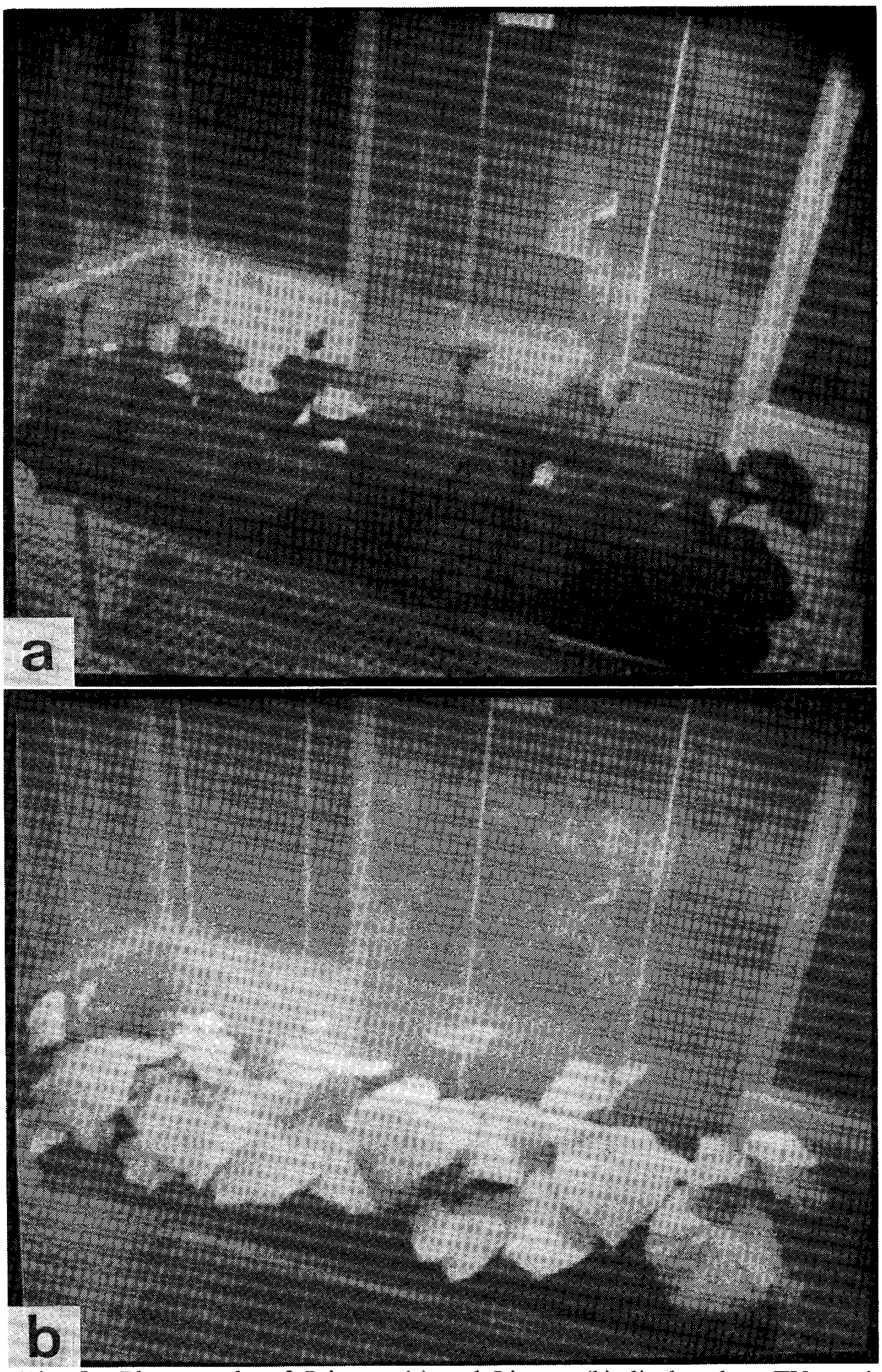


Fig. 5. Photographs of $R$ image (a) and $I$ image (b) displayed on TV monitor (the plants were grown at air temperature of 22°C, and the images were taken when the plants were 25 days old).

filters of $F_R$ and $F_I$ made it possible to take the two images reliably in the respective wave bands of $R$ and $I$. These filters were attached to a rotating disk in front of the camera lens and alternated with each other by turning the disk which was manipulated by the computer signal synchronizing with camera drive, as illus-

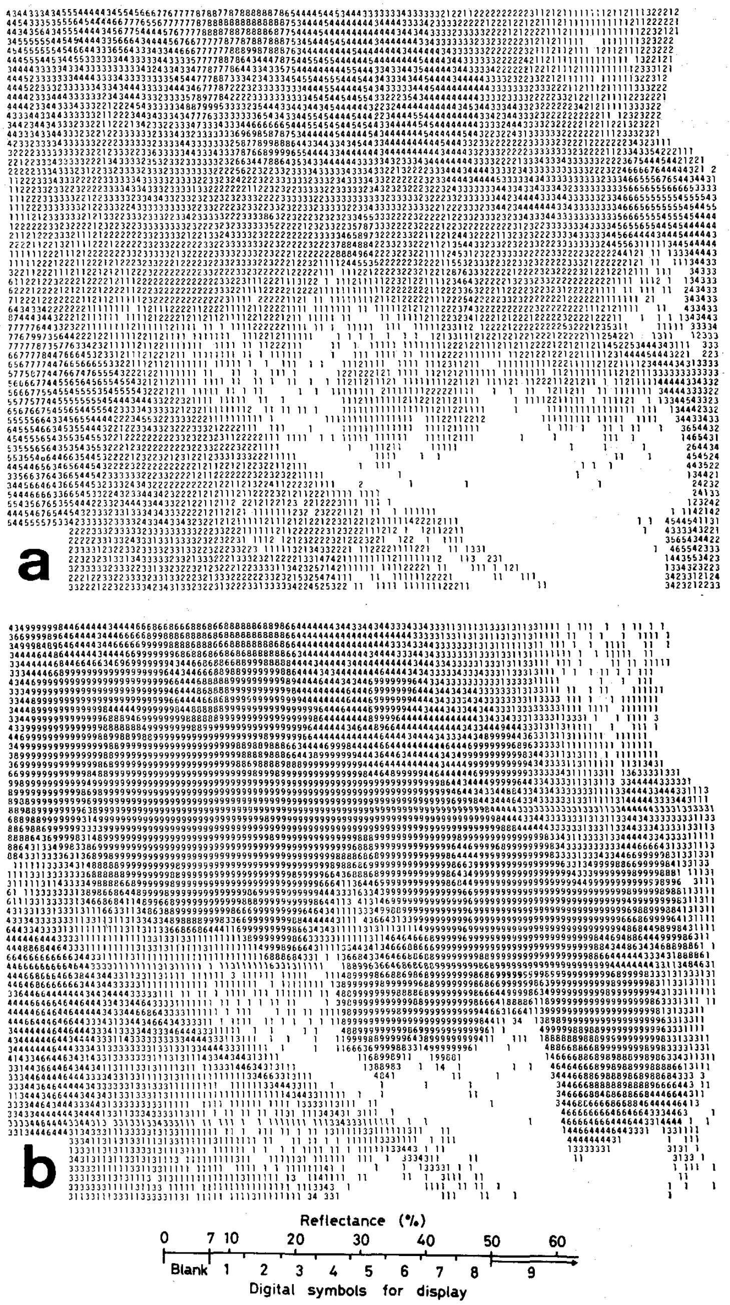


Fig. 6. Digital displays of $M_R$ (a) and $M_I$ (b) derived from $R$ and $I$ images shown in Fig. 5; reflectances are symbolized as illustrated on the scale (odd rows and columns of matrix elements are omitted).

trated in Fig. 1. Thus, $R$ and $I$ images were automatically taken in $R$ and $I$ bands, respectively. Figure 5 shows photographs of $R$ (a) and $I$ (b) images displayed on the TV monitor. In the $R$ image, the plants appeared darker with the partially brighter background. In the $I$ image, the plants were brighter, but there were many brighter backgrounds. These $R$ and $I$ images were digitized and denoted as $M_R=$

$[a_{ij}]$ and $M_I=[b_{ij}]$, respectively, where respective elements of $a_{ij}$ and $b_{ij}$ were denoted as the reflectances (%) on the basis of the calibration by using the reflectances (90% and 18%) of the neutral test cards taken by the TV camera in the optical system used: The brightness in each image was affected by spectral characteristics of light energy, filter transmittance and camera sensitivity, and was calibrated to denote the reflected light intensity as the reflectance (%) by using two neutral test cards with 18% and 90% reflectances (*4*). Figure 6 shows digital displays of $M_R$ (a) and $M_I$ (b). As found in the displays, digits in the plant area appeared lower in $M_R$ and higher in $M_I$ than those in the backgrounds, but the plant images were not clear in both of $M_R$ and $M_I$ with the complicated backgrounds. Thus, it was difficult to specify the plant image in each of $M_R$ and $M_I$.

In an attempt to extract the plant image, the spectral characteristics of reflectance were employed: The difference in reflectance in the leaf between $R$ and $I$ bands was the largest, as observed in respective spectral reflectances in Fig. 3. Therefore, difference in reflectance between $M_R$ and $M_I$ was given by a matrix ($M_S$) as

$$M_S=[c_{ij}]=M_I-M_R \tag{2}$$

The difference in reflectance between $R$ and $I$ bands was less than 25% in the backgrounds and was remarkably larger in the plants. So, in $M_S$, the element, $c_{ij}\leqq 25\%$ was treated as 0, and the element, $c_{ij}>25\%$ was treated as 1. Thus, respective reflectances in $M_S$ were denoted as '1' in plants and as '0' in the backgrounds, by setting a threshold level of the reflectance at 25%. Figure 7 shows the digital

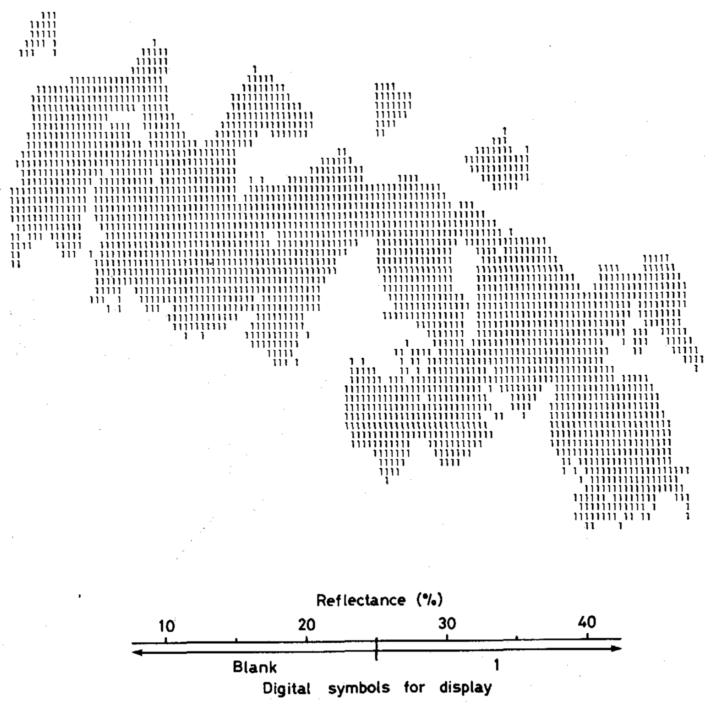


Fig. 7. Digital display of $M_S$ calculated from $M_R$ and $M_I$ displayed in Fig. 6; reflectances are symbolized as illustrated on the binary scale (odd rows and columns are omitted).

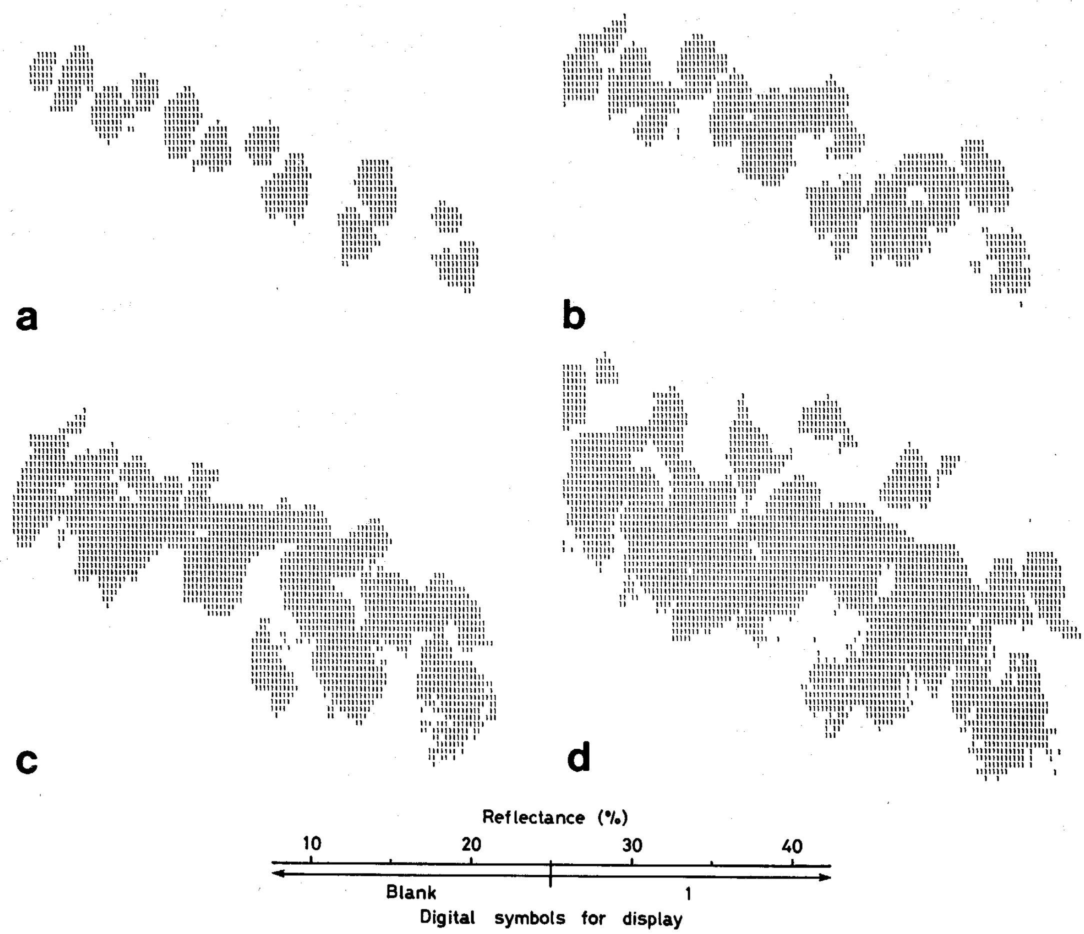


Fig. 8. Digital displays of $M_S$, where the plants were grown at air temperature of 22°C, and the images were taken when the plants were 17 (a), 20 (b), 23 (c) and 26 (d) days old, respectively; reflectances are symbolized as illustrated on the binary scale (odd rows and columns of matrix elements are omitted).

display of the $M_S$ derived from $M_R$ and $M_I$ displayed in Fig. 6, where the element, $c_{ij} \leqq 25\%$ is displayed as blank, as illustrated on the scale. The backgrounds were completely eliminated, and the images of six cucumber plants were clearly found in arrays of '1'. Thus, the $M_S$ made it possible to obtain the plant image separated from background noises in the glass room. Figure 8 shows digital displays of $M_S$ taken at different growing stages. The plant image enlarged with growing stages, and the plant growth was found in increase in number of the digits of '1'. So, the sum ($P$) of the elements of $M_S$ was calculated from

$$P = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} \tag{3}$$

Figure 9 shows relationship between $P$ and measured fresh weight of a plant. The distribution of the measured fresh weights was represented by a regression curve on $P$ at 0.1% significance level even when the plants were grown at different air tem-

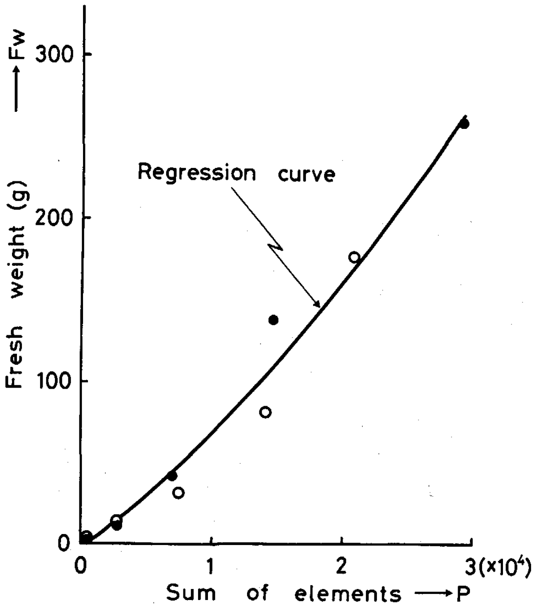


Fig. 9. Relationship between $P$ and measured fresh weight of a plant, where the plants were grown at the respective air temperatures of 22°C (○) and 25°C (●) and sampled at different growing stages.

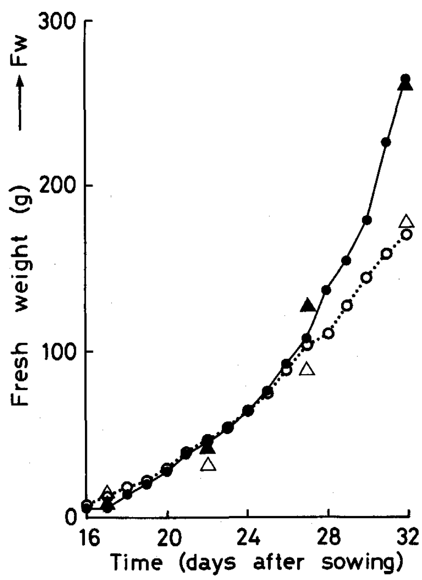


Fig. 10. Time course of measured and calculated fresh weights of each plant grown at different air temperatures; the measured fresh weights were obtained by weighing the plants grown at 22°C (△) and 25°C (▲), and the calculated fresh weights were obtained from the images of plants grown at 22°C (○) and 25°C (●).

peratures of 22°C and 25°C, as reported in the previous papers (*3*, *7*). The regression equation of fresh weight ($F_W$, g) of a plant on $P$ was given as

$$F_W = 10.34\times10^{-8}\,P^2 + 6.21\times10^{-3}\,P - 5.43 \tag{4}$$

Figure 10 shows patterns of cucumber plant growth evaluated by the fresh weight calculated from Eq. 4 and the measured fresh weights. The calculated fresh weights closed to the measured ones, and the plant growth appeared in increase in the fresh weights. The calculated fresh weight of a plant grown at 25°C began to increase faster at 27 days and finally became larger than that at 22°C. Thus, the effect of air temperature on plant growth was clearly observed in the patterns of the calculated fresh weights. This fact indicates that $P$ can be used as a reliable parameter for evaluation of plant growth through the mathematical representation.

In this experiment, the digital image processing in two wave bands of red and infrared made it possible to extract clear plant images from the background in the glass room and to represent the plant growth in course of time. In the previous paper (*4*), the authors reported that the images taken in respective bands of $R$ and $I$ are useful for analysis of vigour of plants. Thus, the digital image processing in two wave bands could be used for the evaluation of plant growth and also used for the estimation of plant vigour in an on-line system.

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