EFFECTS OF PHOTOPERIOD, CO2 CONCENTRATION, AND LIGHT INTENSITY ON GROWTH AND NET PHOTOSYNTHETIC RATES OF LETTUCE AND TURNIP

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Abstract

To collect basic data for a plant factory, growth rates and net photosynthetic rates of lettuce (Lactuca sativa L. cv. Okayama saradana) and turnip (Brassica campestris L, subsp Rapa) were determined throughout the growth period under the conditions of 12-24 hr photoperiods, 400-3200 ppm CO_2 concentrations, and 137-316 $\mu E/m^2/s$ light intensities.

At longer photoperiods, the growth rate and the net photosynthetic rate per plant of lettuce increased only slightly, whereas those of turnip increased remarkably, with increasing the CO_2 concentration or the light intensity. It was observed that the tuber of turnip grew rapidly at a high intensity of 316 $\mu E/m^2/s$ and the photoperiod of 24 hrs. Also, at the light intensity of 237 $\mu E/m^2/s$, the stomatal resistance and the CO_2 compensation point of lettuce increased with increasing the photoperiod and the CO_2 concentration. In the case of turnip, however, the stomatal resistance did not change appreciably and the CO_2 compensation point increased to a lesser extent.

Thus, these substantial differences observed experimentally are considered to be attributable to the difference between the sink volumes of lettuce and turnip.

1. Introduction

In Japan, much attention is paid to the plant factory producing vegetables under the artificially controlled environment (Hashimoto and Takatsuji, 1984). The problem of the plant factory is to establish an economical environmental control system for the accelerated growth of vegetables. Ikeda and Nakayama (1984 and 1987) have reported that a considerable reduction of light power consumption can be achieved by the low intensity, proximity irradiation process with fluorescent lamps. However, it is necessary to further improve the primary production efficiency for a broader commercialization of the plant factory.

We considered that the sink volume of photosynthetic product would closely affect the primary production rate under the environmental condition of high primary production . Thus, the growth rate, the net photosynthetic rate, the stomatal resistance, and the CO_2 compensation point of lettuce and turnip were measured throughout the growth period at various photoperiods, CO_2 concentrations and light intensities.

The results obtained were compared and discussed in terms of the sink volume. Also, the optimum environmental control for the plant factory was suggested.

2. Materials and methods

The growth cabinet used was a wind-channel type devised to have a laminer flow in the growth cabinet (Yabuki et.al.,1970). The floor area and the height of growth cabinet were 1.8 m x 0.8 m and 0.8 m, respectively. A fan was installed inside the chamber to circulate the air.

The temperature and the relative humidity of the air were controlled by an air-conditioning unit installed in the chamber. The CO_2 concentrations were regulated by injecting neat CO_2 gas from a cylinder into the chamber at the predetermined flow rates, monitored with an infrared CO_2 analyzer, and maintained within $\pm$ 5 % of the set level.

The light sources used were Metal Halide lamps, whose infrared radiation was removed by a water layer of 5 cm depth. The lamps were turned on continuously, and the dark periods were set by covering the plant with a box. The light intensity in the cabinet was controlled by ajusting the number of lamps. The light intensities were measured on a bare styrofoam-board with an LI-COR LI-185 meter and an LI-190SB quantum sensor.

Plants were grown by the water culture method. A hydroponic solution (Ohtsuka NO.1 and NO.2) was filled in the water tank (about 200 liters in volume,and 20 cm in depth), and a styrofoam-board planted with 12 stumps at 30 cm-intervals was floated on the water. In each experiment,the hydroponic solution was not renewed through the growth period , but the pH and the electric conductivity were maintained in the range of 7.0-5.0 and 1.3-1.5 mS, respectively.

Plants used for this study were lettuce (Lactuca Sativa L. cv. Okayama saradana) and turnip (Brassica campestris L, subsp Rapa). Seedlings of these plants were grown by water culture for about 3 weeks in an natural-light phytotron at 25/20 °C day/night temperatures. Then, seedlings were transferred to the growth cabinet, and were grown for 8 days under various environmental conditions after a few days of accommodation.

In each experiment, the temperature, the humidity, and the wind velocity were maintained at 23.5 $\pm$ 0.5 °C, 60 $\pm$ 2 %, and 0.6 $\pm$ 0.1 m/s, respectively.

The net photosynthetic rates per plant (NPR) of lettuce and turnip were determined by measuring the CO_2 concentration decrease rate in a closed system composed of an infrared CO_2 analyzer (model ZFD, Fiji Electric Co.) and a transparent acrylic cylinder (50 cm high, 30 cm in diameter). NPR was calculated from the time required for 10 % decrease in CO_2 concentration in the closed system. The reproducibility of NPR measurement was within an error of 10 %.

The CO_2 compensation point was measured with the same apparatus, and was considered as the equilibrium CO_2 concentration in the closed system.

The stomatal resistances at the adaxial and the abaxial surfaces of a leaf were measured with an LI-COR LS-20S porometer. The total stomatal resistance of both surfaces (r) was calculated from Eq.(1).

$$1/r = 1/rsa + 1/rsb \qquad (1)$$

where, rsa and rsb are resistances of the adaxial and abaxial surface, respectively. Data were obtained by averaging the measured values for 4 stumps (2 leaves/stump).

3. Result

3.1 Growth

The effects of CO_2 concentration on the growth of lettuce and turnip at the photoperiods of 12 hrs and 24 hrs are shown in Figure 1. At 24 hr photoperiod (continuous illumination), 237 μE/m2/s light intensity, and 2 100 ppm CO_2 concentration, lettuce and turnip grew acceleratedly, and the fresh weights increased by about 10 times in a week. However, at 24 hr photoperiod, the effect of CO_2 enrichment on the growth rate of lettuce was not so remarkable as compared to that at 12 hr photoperiod (Figure 1-a). On the contrary, the growth rate of turnip increased remarkably with CO_2-enrichment both at 12 hr and 24 hr photoperiods (Figure 1-b).

Table 1 shows the fresh weight (M) and the dry weight increase (Δm) of lettuce after 7 day culture under the continuous illuminations of 137 and 237 μE/m2/s light intensity. At the continuous illumination of 237 μE/m2/s light intensity, M and Δm increased only slightly with increasing CO_2 concentration. However, at a lower light intensity of 137 μE/m2/s, the effect of CO_2 concentration became greater, and M and Δm with 137 μE/m2/s were close to those with 237 μE/m2/s at 3 200 ppm CO_2 concentration.

As shown in Figure 2, it was also observed that the degree of increase in the growth rate of lettuce with increasing light intensity at 24 hr photoperiod decreased as compared to that at 12 hr photoperiod. At a high light intensity of 316 μE/m2/s, there was only a slight difference in the growth rate of 12 hr and 24 hr photoperiod. Thus, at 24 hr photoperiod, the growth rate of lettuce increased so slightly with increasing CO_2 concentration or light intensity as to level off.

3.2 Net photosynthetic rate per plant (NPR)

Figures 3 and 4 show the effects of CO_2 concentration on NPR of lettuce and turnip throughout the growth period at the photoperiods of 12 hrs, 18 hrs, and 24 hrs. As shown in Figure 3, it was found that the increase in NPR of lettuce with CO_2-enrichment lowered with increasing the photoperiod at 237 μE/m2/s light intensity in the region of 400-3200 ppm CO_2 concentration. On the other hand, NPR of turnip increased with CO_2-enrichment at 24 hr photoperiod (Figure 4). Thus, the trends in NPR agreed well with those of the growth rate shown in Figure 1.

Figure 5 shows the effect of light intensity on NPR of lettuce at the photoperiods of 12 hrs and 24 hrs under 1 100 ppm CO_2 concentration. In the region of 137-316 μE/m2/s light intensity, NPR of lettuce increased remarkably at 12 hr photoperiod, but only slightly at 24 hr photoperiod. As shown in Figure 6, NPR of turnip increased remarkably with increasing light intensity at 24 hr photoperiod. Further, at a high light intensity of 316 μE/m2/s and the photoperiod of 24 hrs, it was observed that the tuber of turnip grew quite rapidly (Figure 7).

3.3 Stomatal resistance and CO_2 compensation point

The Stomatal resistance and the CO_2 compensation point of lettuce and turnip were measured at the photoperiods of 12 hrs and 24 hrs and CO_2 concentration of 400 ppm and 2 100 ppm. As shown in Figure 8, the stomatal resistance (r) of lettuce increased with CO_2-enrichment at 237 μE/m2/s; the increase in r throughout the growth period became greater at the photoperiod of 24 hrs and the high CO_2 concentration. In the case of turnip, r increased also with CO_2-enrichment but no appreciable difference was observed between the 12 hr and 24 hr photoperiods (Figure 9).

The same tendency was observed in CO_2 compensation point (Table 2). The CO_2 compensation points of lettuce and turnip increased with CO_2-enrichment, particularly at 24 hr photoperiod. However, the CO_2 compensation point of turnip increased to a lesser extent than that of lettuce. From these results, the CO_2 concentration in leaves of lettuce is considered to be elevated.

4. Discussion

In plant factory, it is required that plants are grown acceleratedly to improve the utilization factor of equipment. Thus, the continuous illumination or the longer photoperiod of about 350 μE/m2/s light intensity is semi-commercially performed under CO_2-enrichment.

As shown in Figure 1, lettuce and turnip grew acceleratedly, and the fresh weights incresed by about 10 times in a week. However, it was found that at the longer photoperiod, the effect of CO_2 concentration or light intensity on NPR of lettuce decreased remarkably as compared to that of turnip. This means that the light utilization efficiency becomes lower under the accelerated growth conditions for lettuce.

For improving light utilization efficiency, it is necessary to investigate the reason for these decreases. We consider that the difference between NPR of lettuce and turnip is attributable to the difference in the sink volume. In other words, it is supposed that in the case of the small sink volume like lettuce, the stomatal resistance and the CO_2 concentration in leaves increase under the condition of high CO_2 concentration and high light intensity , decreasing the CO_2 uptake rate.

As shown in Figure 8 and Table 2, r and CO_2 compensation point of lettuce increased remarkably at the photoperiod of 24 hrs and the high CO_2 concentration. These results suggest that the photosynthetic product is accumulated in the leaves of lettuce, and that the CO_2 concentration in leaves of lettuce increases under the condition of the high CO_2 concentration and high light intensity. In the case of turnip, however, little difference in r between 12 hr and 24 hr photoperiods was observed, and the extent of increase in CO_2 compensation point became clearly smaller than that of lettuce at 24 hr photoperiod. By considering the fact that the turber of turnip grows rapidly at the continuous illumination of 316 μE/m2/s and the CO_2 concentration of 1 100 ppm (Figure 7), the differences between the results of lettuce and turnip are reasonably explained by the differences in the sink volume.

From the above discussion, it may be concluded that in the case of lettuce with the small sink volume, the light efficiency for the primary product decreases when the integral amount of light energy illuminated per day is increased too much. In order to avoid the decrease in light efficiency, the condition of a continuous illumination of low light intensity or a intermittent illumination of high light intensity is effective. In the case of plants with the large sink volume like turnip, however, high light intensity and high CO2 concentration accelerate the growth rate without lowering the light efficiency.

The theory described above are derived from the experiments with lettuce and turnip. Further studies may be necessary for the generalization of the theory.

5. Acknowledgements

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Table 1 - Effect of CO_2 concentration on M and Δm of lettuce under continuous illumination of 137 and 237 μE/m2/s light intensity.

Light intensity (μE/m2/s)	CO2 conc. (ppm)	M* (g)	Δ m** (g)
237	400	175	7.07
	1 100	205	9.37
	2 100	210	10.3
	3 200	197	9.29
137	400	144	5.33
	1 100	173	7.30
	3 200	193	8.66

Results are the average of 4 stumps
* : fresh weight after 7-day culture (initial fresh weight, 35g)
** : increase in dry weight after 7-day culture

Table 2 - Effects of CO_2 concentration and photoperiod on CO_2 compensation point of lettuce and turnip. (Light intensity, 237 μE/m2/s; Air temp.,23.5 °C)

CO2 conc. (ppm)	Photoperiod (hr)	Treatment day (day)	CO2 compensation point (ppm) lettuce	CO2 compensation point (ppm) turnip
400	12	9	75	60
	24	9	75	60
2 100	12	5	-	60
	24	5	-	80
	12	9	100	-
	24	9	130	-

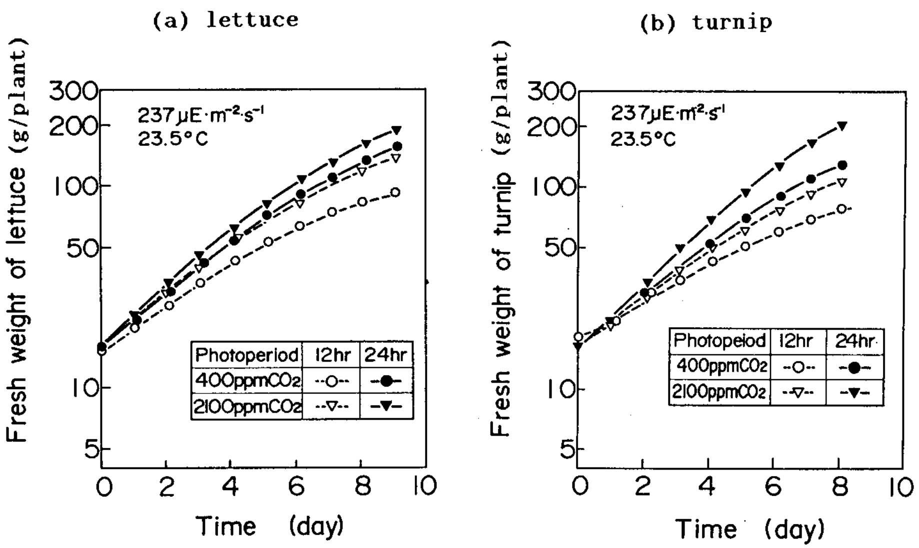

Figure 1 - Effects of CO2 concentration and photoperiod on growth of lettuce and turnip.

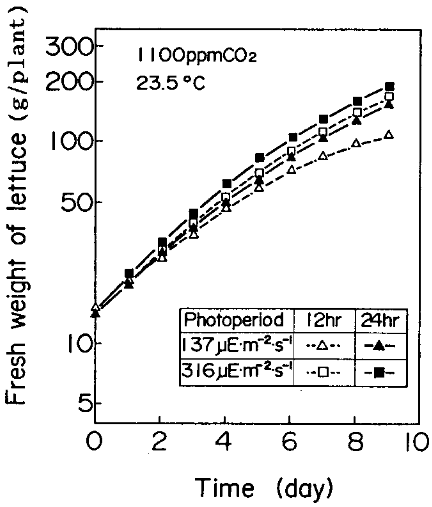

Figure 2 - Effects of light intensity and photoperiod on growth of lettuce.

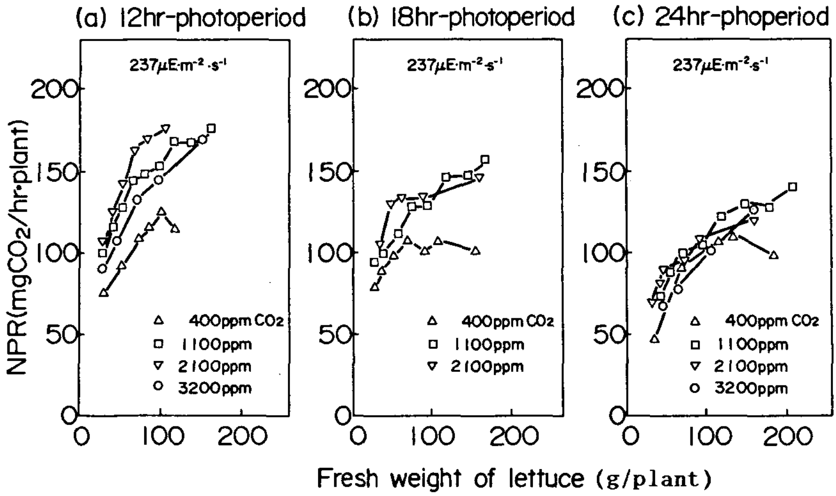

Figure 3 - Effect of CO2 concentration on net photosynthetic rate per plant (NPR) of lettuce throughout growth period.

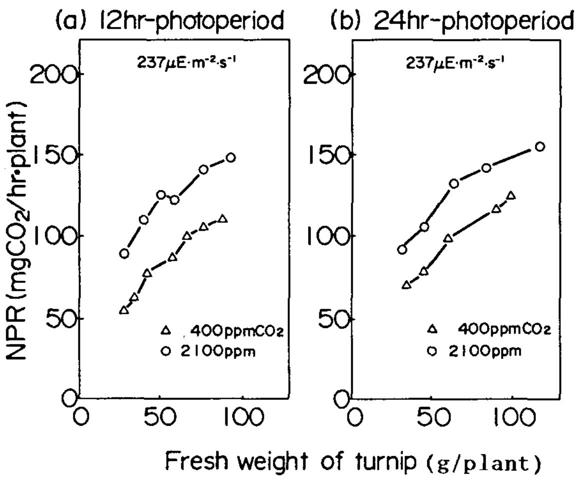

Figure 4 - Effect of CO2 concentration on NPR of turnip throughout growth period.

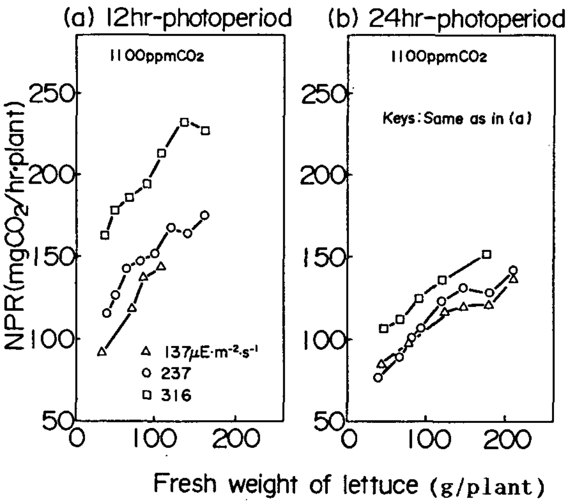

Figure 5 - Effect of light intensity on NPR of lettuce throughout growth period.

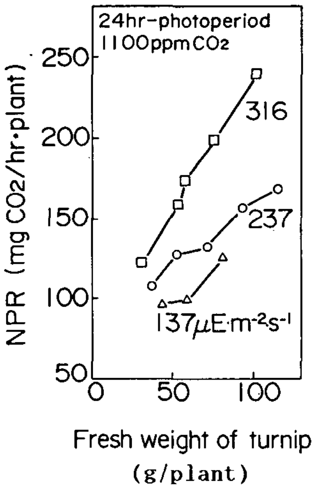

Fig.6. Effect of light intensity on NPR of turnip throughout growth period at the photoperiod of 24 hrs.

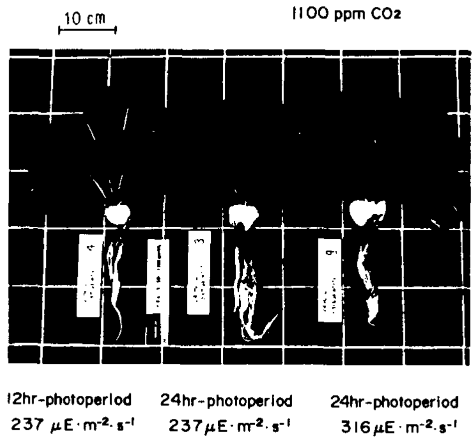

Fig.7. Photograph of hurvested turnip.

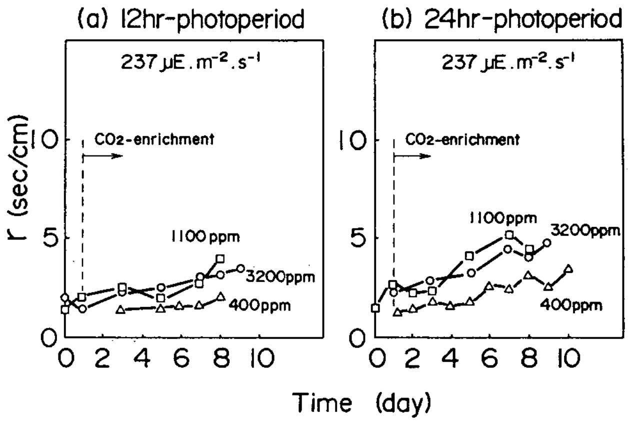

Figure 8 - Effects of CO2 concentration and photoperiod on stomatal resistance of leaf surfaces (r) of lettuce throughout growth period.

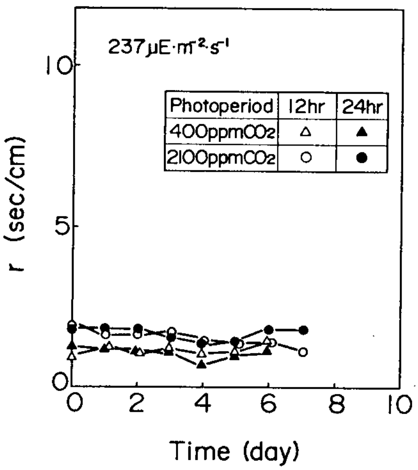

Figure 9 - Effects of CO2 concentration and photoperiod on r of turnip throughout growth period.