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DEVELOPMENT OF AN ENVIRONMENT-CONTROLLED VEGETABLE GROWTH SYSTEM

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ABSTRACT

This study was carried out to develop an environment-controlled vegetable growth system. The control objects considered were light, temperature, humidity, CO_2 concentration and the conditions of nutrient solution such as pH, EC and dissolved oxygen. A monitoring system was developed to measure the above environmental factors, fresh weight and CO_2 consumption rate.

The overall performance of the developed system was reasonably acceptable for vegetable growth. By the lettuce growing test, it was shown that the developed system had a good repeatability, and the growth responses could be measured satisfactorily.

Key word : Growth system, online monitoring, CO_2 consumption, fresh weight, artificial light, temperature, humidity, nutrient solution

INTRODUCTION

The characteristics of Korean agriculture can be described as widespread small farms, rice-centric farming, drastic decrease in rural population, and increase of aged labor. Therefore, the Korean agricultural structures have to be changed to a high-quality and low-cost oriented farming industry from the traditional rice monoculture. One of the solutions is to introduce high-level horticultural production facilities such as glass houses.

To disseminate the high-level horticultural production facilities, first of all, it is necessary to study the environmental factors affecting plant growth and effective arrangement of plants in the limited space. In this respect, this study was carried out to develop an environment-controlled vegetable growth system, which is able to observe the growth responses of plants, and to develop and evaluate a control algorithm for optimum plant growth. Also, it can show the instrumentation and automatic control system of incoming 'Vegetable Factory.'

The specific objectives of this study were as follows; (a) to develop a phytotron to measure growth responses by fresh weight and CO_2 consumption rate, and to control the environmental factors of light, temperature, humidity, CO_2 concentration and the conditions of nutrient solution. (b) to develop a computer program for both online monitoring and controlling environmental factors and growth responses. (c) to evaluate the performance of the system by lettuce cultivation.

MATERIALS AND METHODS

Outline of Vegetable Growth System

Fig. 1 shows the schematic diagram of the environment-controlled vegetable growth system developed in this study.

The developed system consists of the components which measure and control environmental factors affecting plant growth, such as light period, light intensity, the temperature, humidity, CO_2 concentration in the air, and the temperature, electric conductivity and pH of nutrient solution. Other additional instruments were used to measure CO_2 consumption rate as a short-term growth response, and fresh weight as a long-term growth response.

Also, the electric units for the system consisted of magnetic contactors for driving metalhalide lamps and cooler, mechanical relays for driving fluorescent lamps, humidifier, nutrient circulation pump, several solenoid valves for CO_2 gas and nutrient solution, and solid state relays for driving air and nutrient solution heaters. The wiring diagram of electric units is shown in Fig. 2.

Measurement of Fresh Weight

Long term reponses of plant growth are the height, fresh weight, stem diameter, leaf area, et al. For most vegetables in the stage of nutritional growth, fresh weight would be enough to represent long term growth response.

Fig. 3 shows the device which weighs a group of hydroponic plants with a tension load cell. The nutrient solution was maintained to have a constant level to eliminate the error due to the variation in buoyancy force. The level of nutrient solution was controlled by solenoid valve at the drain with a level switch consisting of reed switch and floating magnet.

Measurement of CO_2 Consumption Rate

The phytotron was assumed as a semi-closed system as shown in Fig. 4, the balance in CO_2 gas can be represented as follows.

$$\frac{V}{22.4}\frac{dc}{dt} = \frac{v}{22.4}(C_1 - C_2) + B - P \qquad (1)$$

where V = the volume of enclosure (l)

$\frac{dc}{dt}$ = the time rate of CO_2 concentration (ppm/sec)

v = ventilation rate (l/sec)

C_1 = CO_2 concentration at the inlet (ppm)

C_2 = CO_2 concentration at the outlet (ppm)

B = flow rate of CO_2 supplied (μmol/sec)

P = net photosynthetic rate (μmol/sec)

In this study, the CO_2 concentration was kept constant ($dc/dt = 0$), and the phytotron was sealed so that the air ventilation rate is approximately zero ($v = 0$). Consequently, Eq. (1) is simplified by Eq. (2).

$$P = B \qquad (2)$$

The amount of CO_2 supplied to the phytotron to maintain a constant CO_2 concentration is equivalant to the amount of CO_2 consumed by plants, and equivalant to the net photosynthetic rate of the plants.

Artificial Lighting System

The artificial lighting system used in this study consisted of 500W low pressure mercury lamps (2 EA), 200W tungsten halogen lamps (6 EA), 40W fluorescent lamps (4 EA). The lamps were placed about 40cm high from the growth bed, and the interior of lamp cover was coated with white paint to utilize the reflected light.

To prevent heat transfer from the lights system to the growth chamber, a clear pair-glass was installed to separate the lamps and growth chamber, and heat was removed by cooling fans at the rear side of light cover. Each lamps were regulated by magnetic contactors or mechanical relays which are opened or closed with signals generated by the microcomputer system.

Temperature and Humidity Control

To control temperature and humidity, air inlet ducts were mounted at the upper portion and air outlet ducts were at the lower portion of the growth chamber. The air in the chamber was circulated continuously through a duct on the wall of the chamber at the flowrate of 4.2 m^3/min by circulation fans. Inlet and outlet baffles were installed between the chamber and duct so that the air in the growth chamber can be mixed well. Inside the duct, the air passes through cooling fins of cooling and dehumidifying device, electric heater, and ultrasonic humidifier.

The air temperature in the phytotron was measured with a resistance temperature detector, Pt-100 at three midstream locations; at the upper duct for air reentering port, at the lower duct for air leaving port and in the middle of main chamber for plant growth area.

Relative humidity was calculated by the dry and wet bulb temperatures measured with Pt-100 sensors. The numerical expression proposed in ASAE D271.2 was used for the calculation of the relative humidity by using these two temperatures.

Temperature and humidity controls were implemented with the average value of dry bulb temperatures and claculated relative humidity. Based on the measured signals, the microcomputer actuated the heater, cooler and humidifier according to the specific algorithm shown in Fig. 5. The air conditioning equipment was controlled by on-off or PWM operation using a PID controller embodied in the microcomputer software.

CO_2 Concentration Control

The CO_2 concentration in the phytotron was measured by a commercial nondispersive infrared CO_2 analyzer (HORIBA; APBA-250E), which has an analog meter and outputs 4~20mA proportional signal.

Liquified CO_2 gas was used to regulate CO_2 concentration. It was supplied through a solenoid valve operated by pulse in case the CO_2 concentration in the phytotron was lower than initial setting value. The pulse duration of opening was kept constant while the time of close was varied depending on the amount of difference.

The rise of concentration in the phytotron per single supply was adjusted to be about 30 ppm with the pressure and flow control valve. The amount of CO_2 supplied was determined from counting the number of valve opening.

Nutrient Solution Control

The electric conductivity (EC) and pH in the nutrient solution were measured by commercial EC and pH indicators (HANNA; HI8510, HI8931) which have digital meters and output 4~20mA proportional signals.

In order to keep the optimum pH value, sulfuric acid (H_2SO_4) is added when pH is high while sodium hydroxide (NaOH) is added when pH is low. When EC is low, the supplement of nutrient ion in the solution was performed by addition of enriched solutions which were separated at the condition of non-deposition. When EC is high, water was added to dilute the solution. To suply the acid, alkali, enriched solution, and water from the reservoirs to the nutrient solution tank, five commercial dosing pumps (HANNA; ASP1G) were used.

Additionally, oxygen was supplied into nutrient solution by an air pump so that dissolved oxygen can be maintained at the state of saturation.

Microcomputer System

The microcomputer system for monitoring and controlling all of the devices consisted of an IBM-AT compatible 16-bit computer, 40 M byte hard disk and floppy disk, standard keyboard, monochrome monitor, dot-matrix printer, 64-channel digital I/O card, 12 bit A/D converter card with 16-channel multiplexer.

Monitoring and Control Software

Fig. 6 shows the flow chart of software for online monitoring and controlling. In this study, the Turbo C was used as a programming language to develop the software.

The main menu on the CRT monitor consists of 'INPUT', 'RUN', 'OUTPUT', 'PRINT' and 'STOP'. At normal control state, the setting values of environmental factors are monitored at the top of the CRT and sequently current controlled value and their data files are monitored by the user setting time intervals.

The stored data files can be used for the analysis of control history with the commercial data processing package of QUATTRO. The controlled states are monitored in graphic mode as well as in text mode.

Lettuce Growing Test

A variety of green-leaf lettuce (*Lactuca sativa* L.) was selected for the experiment. The lettuce had been grown for 20 days in an incubator before it was transplanted to the growth system. The nutrient solution was made using the composition recommended by Korea Horticultural Experiment Station. And styrofoam plate was set afloat in the growth bed filled with nutrient solution at the depth of 7 cm.

The environmental conditions were set as follows for 12 days ; The light intensity of 18,000~20,000 lux, the daytime air temperature of 22℃, the nighttime air temperature 18℃, the relative humidity of 80%, the nutrient solution temperature of 18℃, the CO_2 concentration of 1,000 ppm, the electric conductivity of 1.8 mS/cm, the pH of 6.8. The lighting period was the daytime of 16 hours and the nighttime of 8 hours.

For the purpose of analyzing the repeatability, the growing test was repeated three times.

RESULTS AND DISCUSSION

Performance of Vegetable Growth System

When all lamps were turned on, the light intensity was observed as high as 30,000 lux on the growth bed, and the radiation spectrum of these combined lighting system was similar to natural sunlight.

As shown in Fig. 7, the air temperature in lighting period was controlled within ±0.3℃ in the range of 10~40℃. The humidity was controlled with the accuracy of ±3% RH at the initial growth stage and ±5% RH at the final growth stage in the range of 50~80% RH. Fluctuation in the humidity control was due to the on-off operation of the dehumidifier to remove the water vapor from the transpiration of lettuce.

The accuracy of the control system for CO_2 concentration was ±20 ppm in the range of 500~1,500 ppm. Based on this result, the accuracy of the measurement system for CO_2 consumption rate by photosynthesis was ±15.4 mg_{CO2}/hr.

The accuracy of the measurement system for the fresh weight of lettuce was ±5% FS. The electric conductivity, pH, and the temperature of solution were controlled with the accuracy of ±0.1 mS/cm (0.8~4.0 mS/cm), ±0.2 pH (5~9 pH), ±0.5℃ (18~28℃), respectively. By the nutrient solution control using an EC meter, a stable condition of nutrient concentration could be maintained.

Results of Lettuce Growing Test

Fig. 8 shows the average growth tendency of lettuce growing experiments under the certain established environmental conditions. There were little difference between the three repeated experiments.

The fresh weight of lettuce increased from 7 g to 45 g in 12 days on the average. During the 3 days after transplanting, the increase in fresh weight was small because of the root developement. The next 5 days, however, the increase in fresh weight was very large. During the later growth period, the increase rate in fresh weight was less since the most part of lower leaves were not exposed to the light because of overlapping.

The change in CO_2 consumption rate was similar to the change in fresh weight, and it could be used to represent a short-term growth response.

CONCLUSIONS

This study was carried out to develop the hardwares and softwares for an environment-controlled vegetable growth system.

An online monitoring system for the measurement of the CO_2 consumption rate and the fresh weight was developed. And an environmental control system for light intensity and period, air temperature and humidity, CO_2 concentration and the conditions of nutrient solution was developed at a reasonable accuracy.

The growth system could be used to measure the growth responses of plants and to develop and evaluate a control algorithm for optimum plant growth.

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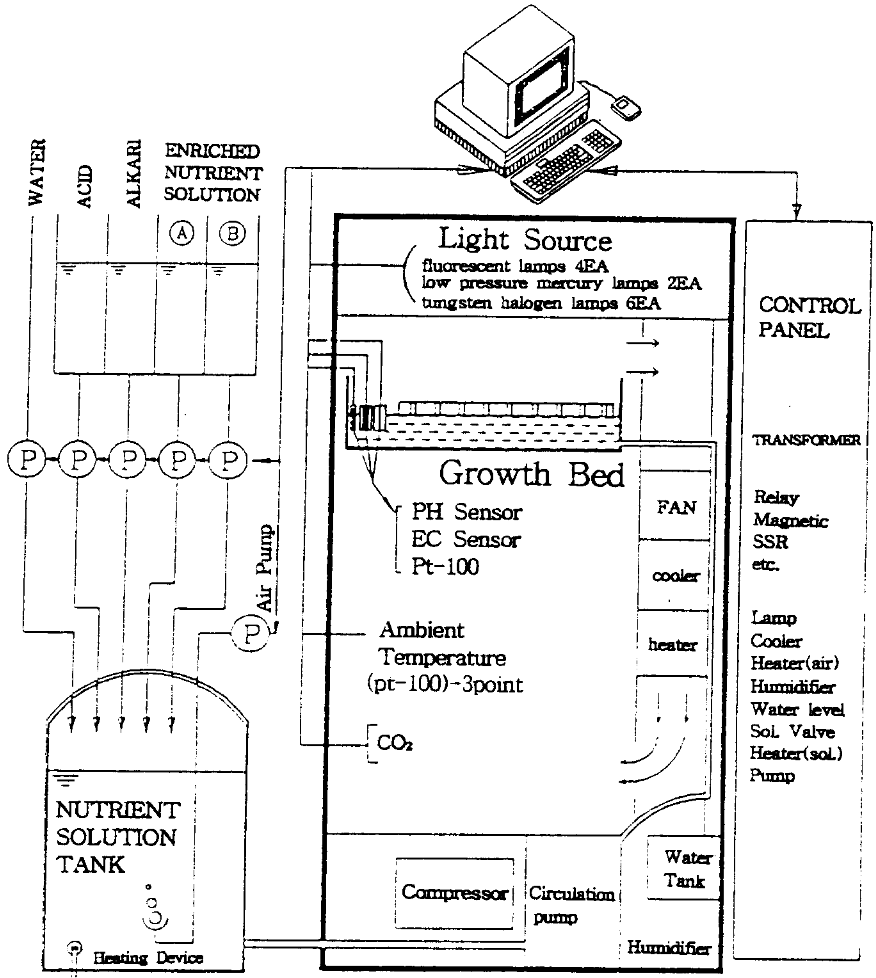


Fig. 1. Schematic diagram of fully-controlled plant growth system.

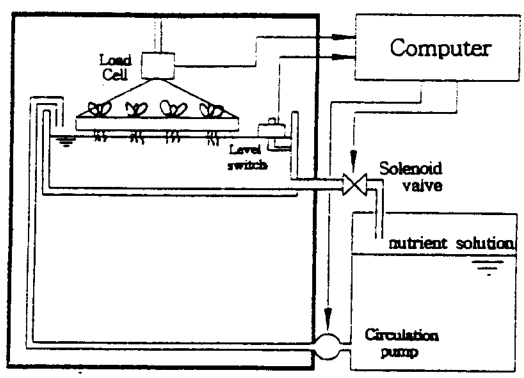


Fig. 3. Apparatus for monitoring top fresh weight.

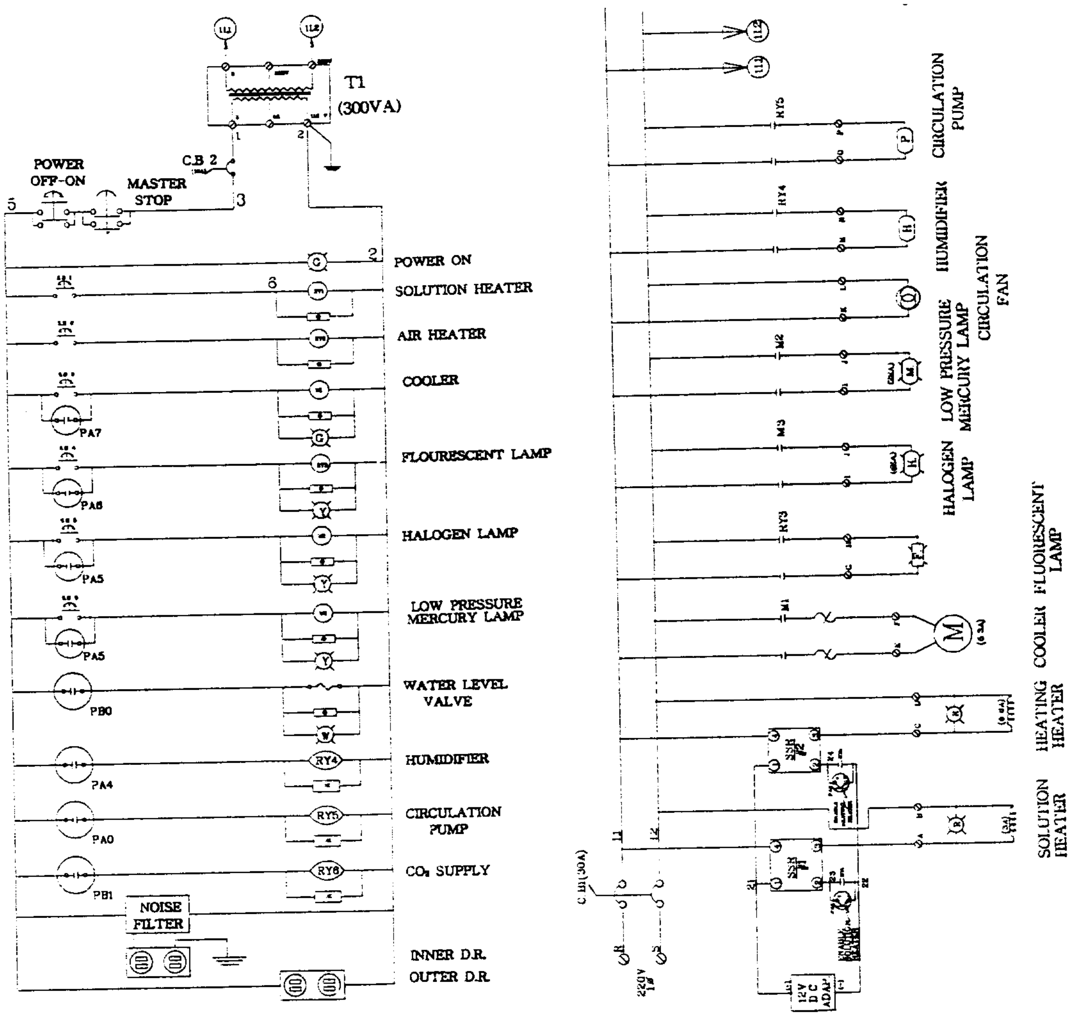


Fig. 2. Relay-ladder diagram (driving unit and control unit).

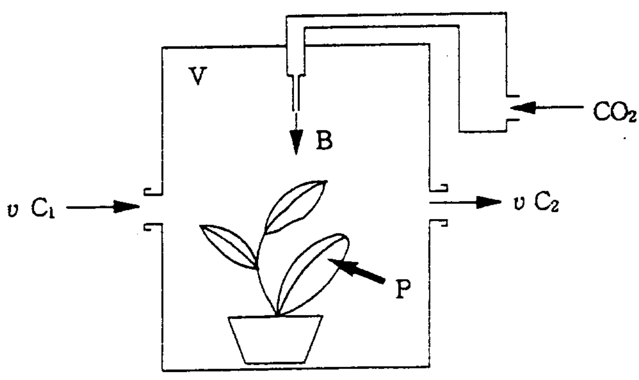


Fig. 4. Diagram of enclosure methods.

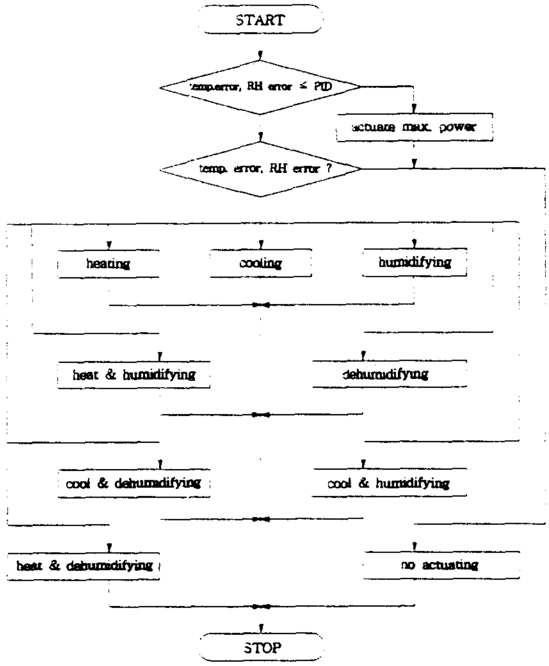


Fig. 5. Flow chart of temperature and humidity control algorithm.

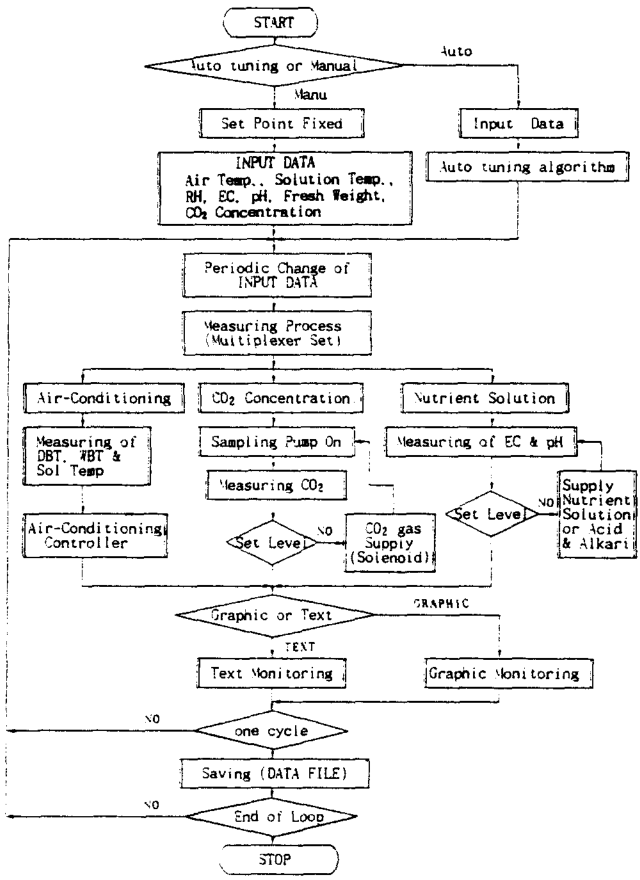
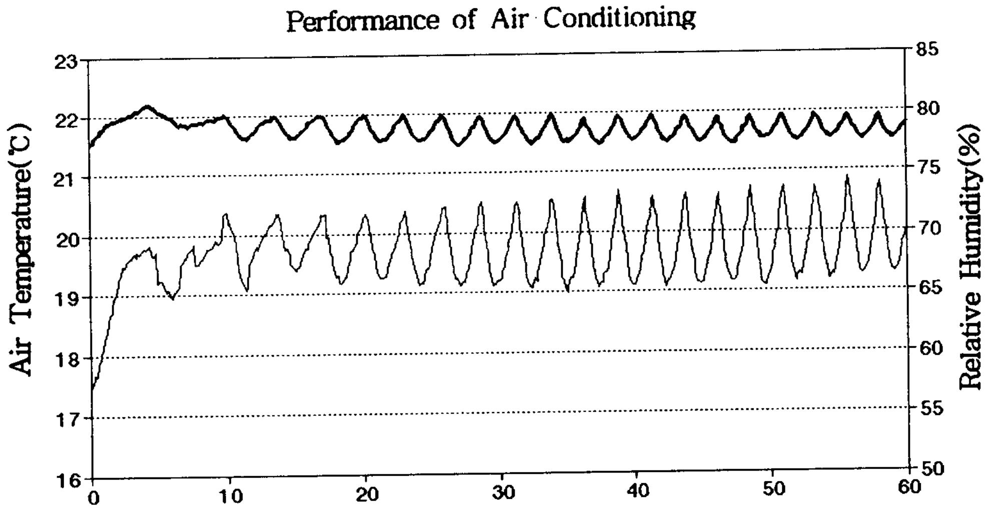
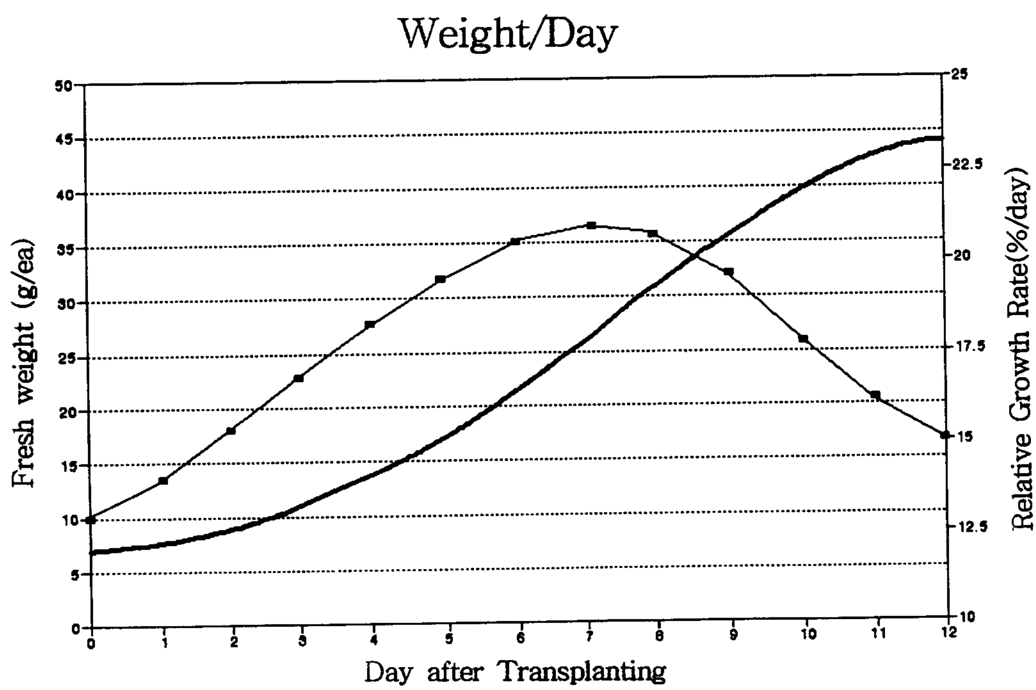


Fig. 6. Flow chart of environmental control program.



(—— air temperature, —— relative humidity)

Fig. 7. Performance of air-conditioning during the growth period.



(—— fresh weight, —— relative growth rate)

Fig. 8. Average growth tendency of lettuce growing experiment.