Effects of Intermittent Illumination on the Plant Growth

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Effects of Intermittent Illumination on the Plant Growth

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Introduction

By any means, agriculture production of our country should be maintained extensively and forever, to insure the stabile supply of food for our people. We must not only develop the agriculture production capacity corresponding to the needs of consumers which are various in their kinds with that purpose, but also must overcome the price competitions of farm products happening simultaneously with the import liberalization. Moreover, the environment surrounding agriculture threatens to become very severe owing to such situations as aging of persons who have been engaged in agriculture production or falling of work force due to the detachment of young people from the agricultural fields. As one of the means which may be useful for solving these problems, establishment of a plant factory supplied with a system controlling the micro-weather environment, and cultivating systematically the crops all the year round, has attracted attentions. For controlling the environmental factors such as light, temperature, humidity, carbon dioxide density, the preferable liquid culture conditions might be realized by this cultivation system. Being exempt from the influences from the natural disasters such as the long rain, the sunshine lack, a typhoon, it becomes possible to produce farm products stably and deliberately. It becomes also possible to supply consumers with farm products of high quality and safety. By introduction of this cultivation system, automation of cultivation management, reduction of labor and cancellation of work-force-lack might be put within our powers. The plant factory is vastly different from greenhouse and vinyl-house. The cultivated area is isolated from the outside environments, and the inside environment is positively controlled. Artificial illumination light, air-conditioning machine, humidifier and carbon dioxide generating machines have been equipped in the plant factory. There are a few problems, for example, that the use of artificial illumination light needs a large amount of electric power, and that the heat energy occurring from the illumination must be removed by air conditioning facility. Viewed from such a point of view, the plant factory is to be classified into three types of illumination, such as 'full artificial', 'artificial and sunlight', 'full sunlight'. Adoption of a liquid cultivation system has been prevalent in the plant factory, as this makes it easy to control and manage the basement of the root zone level in this system. Generally speaking plants cultivated in the plant factory are mainly green leaf ones, and the main cultivation methods have been Nutrient Film Technique, (NFT), and Deep Flow Technique, (DFT)[7]. Furthermore, usually movement benches are to be utilized for the effective use of the cultivation area, and a few devices aiming at concentration and

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efficiency of the workings (raising of seedling, fixing of planting, harvesting and movement) are equipped to the plant factory. Plant growing rate, total amount of crops and their qualities may be remarkably improved by controlling the environment. Production system in which the respective process have been automated will become one of the most important factors in the future agriculture. This production system has a few excellent characteristics or functions, such as 'planned production', 'anniversary production', 'perfect control of environment', 'automation of working' and 'crops supplied with high added value'. Before the successful prevalence of such plant factory, however, there stand serious bottle necks. Firstly, there is a problem of how to compensate the cultivation expense and how to master the cultivation technology. Perfect controlling is almost impossible, as there are various kinds of farm products in the plant factory, but it may become possible provided that cultivation technology is put on the way of development by dint of the detailed examinations of the cultivation conditions. However, the cultivation expense is assumed to be of vast sum, which is considered to be a serious problem to be solved in a hurry[5]. In other words, the success or failure of this factory depends on how to reduce the initial cost for construction and how to minimize the running cost for illumination, air conditioning and so on.

The purpose of this study[3,4] is to obtain some basic data for estimating the effect of intermittent illumination on growth of plant and to ascertain the relationship between photosynthesis and intermittent illumination, as well as to discuss the utilization efficiency of the controlled illumination and the possibility of large reduction of electricity expenses.

History of plant factory

Originally, plant factory was established in Europe from 1950's to 60's, and the perfect controlling type was developed in America when it was put on its way in 1970's[5]. It was studied flourishingly for a while, but a large-scaled factory utilizing sunlight illumination was outgrown from economical problems such as 'electricity expense' as it occurred in 1980's. The perfectly controlling type had attracted attentions in the chilly regions, such as North Europe or Canada. The studies in our country were commenced in 1980's, and recently our country has become one of the most advanced countries in this field.

1. Plant factory of overseas

Christensen farm located in the Kingdom of Denmark almost succeeded in establishing the management supplied with current system in its plant factory in 1957. Since then, it has been one of the most successful plant factories in the world. Cress-leaf has been produced in this plant factory. It takes six days to finish the serial manufacturing processes from seeding to harvesting on the moving chain conveyers. The sale is directly connected supermarkets, and it is said that it may become a sample of a radish farm in our country. Lusner company in Australia developed a solid cultivation system, in which they tried at first to supply the tower greenhouse with sunlight illumination type which is to be followed by an artificial illumination. Subsequently, however, they failed to put it on the practical scale prevented by the huge construction cost and running cost. General electric company, General foods company and General mills company tried the construction of plant factories with full artificial illumination type in U.S.A., but they were left for from the stage of success. Fight farm took over its technology from General mills company, and they succeeded in putting their products on a commercial base. The scale of Fight farm consists in producing 363ton of spinach in a year and in being supplid with cultivation area of 4,459m^2 and with 1.5MW consumption of electricity. High pressure sodium lamps of 1kW for illumination were used in this plant factory and the heat energy collection device called water jacket fixed for reducing of cooling load had been added to the lamps. The sum of electricity consumption for illumination held 66 percent in total. There have been few problems in electricity consumption for illumination in Hytaker company, Archer-daniel mitterand company, and in Agronortic company supplied with sunlight illumination type. A cultivation system for tomato has been developed by the state university of Rutgers in U.S.A. attempted from a point of improving the working efficiency. The tomatoes are cultivated on the moving beds, being pinched at the tops at first step. Fixing of planting and harvesting are carried out together in the work room. Artificial illumination is used in accordance with the amount of sunlight illumination, in order to utilize effectively the continuous cultivation and the space of greenhouse.

2. Plant factory in Japan

The studies of the plant factory in our country were commenced by Hitachi Ltd.. After the accumulation of fundamental data of plant factory executed in Hitachi Ltd., its technology was made to be cooperated with the bio-farm technique of JR or Daiei Inc. before it was put on a practical scale. The respective companies such as Mitsubishi Electric Co. Ltd., Toyo Engineering Co. Ltd., IHI Co., Ltd., the Electricity Central Research Institute, and so on launched on the plant factory studies and even a farmhouse like Miura farms started the research. There are large number of plant factories supplied with artificial illumination in our country, and our controlling technology for the plant factory has reached a high level in the world. The plant factory supplied with both sunlight and artificial illumination type has been being developed at the Electricity Central Research Institute, and it is considered to save energy in such a manner as air conditioning utilizing electricity in night. At the same time, the possibility of crop rotations in such sorts as a lettuce, spinach and strawberry has been studied and a slope cultivation with mist sprayer has come to be adopted for a new technologies. In order to reduce air conditioning cost, the study of spot air conditioning system for plant has been tried in IHI Co. Ltd.. A plant factory with artificial illumination, the area of which counted around 3,300m^2, was built at Kushiro city by Toyo Engineering Co. Ltd., and leaf lettuce was cultivated in the experimental fields. Approach to and realization of an intermittent illumination system have been tried in Mitsubishi Electric Co. Ltd..

3. Merit of plant factory

A characteristic and an advantage of the plant factory are summarized as follows;

(1) The crops could be produced without limitation of time and space.

Not only plant production through all the year round but planned or controlled production matched with demand trend is not impossible. As geographical conditions may be put out of considerations, production becomes possible in sterile and chilly places where a crop can not grow up. As this can be constructed at any geographical sites, irrespective of the accessibilities to the city, transportation expense is assumed not to be too expensive, and the fresh crops may be supplied quite at a low price for a consumers.

(2) Plant production becomes possible even in a narrow area.

In a small country with large population like our country, technology which enables us to produce large quantities of agricultural products in a narrow area becomes necessary.

(3) Crops of high quality may be supplied.

Because plants are cultivated under a certain environmental condition that, generally, is suited for them in a plant factory, crops with high nourishment and good taste may be produced. Being exempt from the consideration for early harvesting for the transportation, the crops may be harvested at the stage of full ripeness and can be transported immediately after that.

(4) The crops of no pollution and no pesticide may be produced.

The plant factory is intercepted from the outside world. Therefore, provided that the facility and the inside of plant factory have been sterilized at first, it is possible for us to prevent it from an invasion of illness or of harmful insect. The crops produced in that plant factory may be sold with high added value.

(5) Saving labor for cultivation may be realized completely.

Laborers are able to work at the stationary situation with the aid of moving cultivation beds and the congregations of work may be evaded by controlling the environmental factors and the growth stages with the aid of computer. Hence the cancellation of a lack of laborer can be realized.

On the other hand, the plant factory has a lot of problems. In particular, compared with field-and greenhouse-cultivations, it makes it necessary to pay a large amount of initail cost not only for constructing facilities but for settling the running cost for artificial illumination and air conditioning, making economy-and energy-consumptions quite a big problem in plant factory. This problem seems to be one of the main factors to prevent the advance and spread of the plant factory[6].

Light and plant growth

In order to reduce the vast running cost for illumination which is considered to be one of the big problems in the development of the plant factory, it is necessary to understand the relationship between light and plant growth[2,8].

1. Photochemical reaction of plant for light

Various types in photochemical reactions of plant for light have been known. The reactions for light such as photosynthesis, photoperiodism and phototropism are the reactions peculiar to plants. To be informed of the characteristics of reactions of various crops for light is quite important to control the illumination environment or the other environments matched with it. In this study, an experiment is carried out about the relationship between photosynthesis and light, which is a basis of growth in plant.

2. Fundamentals of photosynthesis

Fundamentally, a plant grows up by means of the reaction of photosynthesis. The photosynthesis is known as a sort of working to make carbonhydrates out of the three fundamentals, namely; light, carbon dioxide in air and the water absorbed from a root[1]. The produced carbonhydrates are stored up in the respective organs, particularly in fruit or root, composing protein with other nourishments such as nitrogen absorbed from a root. Glucose is formed directly by photosynthesis, after that it changes itself into non-solvent starch immediately. Production by photosynthesis shifts from a leaf to other organs. Its reaction has been called translocation. The starch moves in a form of sucrose into the plant. After finishing the translocation, the starch is composed again at the reached organ. Composition of starch or protein in the respective organs such as fruit or root has been called biosynthesis. It has been confirmed that a plant body is maintained by various actions such as photosynthesis, translocation, storage and biosynthesis. These physiological functions are carried out, using energy brought forth by means of breathing of plant body. The phenomenon that leaf, stem and root grow up by the production from photosynthesis has been called vegetative growth. On the other hand, the phenomenon of forming flower bud and producing fruit and seed has been called reproductive growth. There are a lot of cases of antagonism between the vegetative growth and the reproductive growth. Fig. 1 shows growth process of a plant. The photosynthesis consists of the two factors of 'light reaction' and 'dark reaction'.

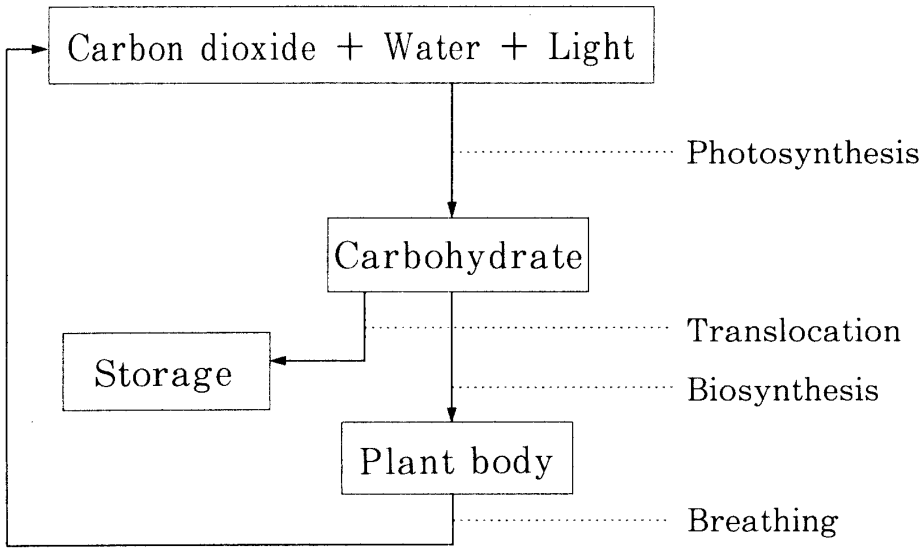


Fig. 1. Block diagram for growth process of plant.

3. Light reaction and dark reaction

Blackman made observations about 'light reaction' and 'dark reaction' in 1905. The rate of photosynthesis of a plant under the environment supplied with high CO_2 concentration and with weak illumination, increases according to the increasing of energy of illumination, but it remains unchanged when illumination level goes beyond some fixed limits. On the other hand, the rate of photosynthesis is limited by CO_2 concentration and by the degree of temperature under strong illumination. Therefore, Blackman considered that photosynthesis consists of 'light reaction' and 'dark reaction'. In other words, 'light reaction' is noted to be slower than 'dark reaction' under the condition of week illumination, and the rate of total reaction is fixed to be decided by the rate of light reaction. Strong illumination is an enough condition for the occurrence of 'light reaction', but the rate of total reaction is to be limited by 'dark reaction'. Furthermore, Warlbrug measured the quantity of photosynthesis as the quantity of O_2, using pressure gauge. He ascertained the fact that the quantity of photosynthesis enhances with the illumination having repeated short periodical irradiations, rather than with the one having continuous irradiations. It shows that 'light reaction' is to be done in short time, and 'dark reaction' is to be finished during the dark period. He also explained that a part of photochemical reaction is to be lost on photosynthesis in the plant put under the illumination with continuous irradiations due to the fact that 'dark reaction' controls the rate of total reaction. It was clear that 'light reaction' was finished in less than 0.1ms, while 'dark reaction' took approximately 20ms. Accordingly, in case of illumination with continuous irradiations, on account of the fact that the illumination during 'dark reaction' in the plant can not be utilized in photosynthesis, it is to be wasted during the period. It is estimated that a quantity of photosynthesis per illumination increases in case of the intermittent illumination method rather than in the continuous illumination method, as irradiation for the plant must be stopped during the dark reaction period. In this experiment, plants were intermittently irradiated and the relationship between the growth of plant and intermittent illuminations was investigated in detail.

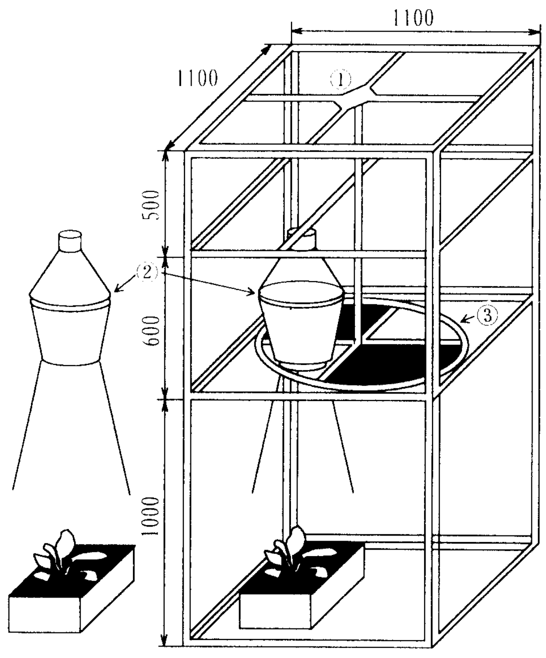
Materials and Methods

1. Materials

Radish (*var. radicula DC*) growing up in a short time was selected to be used in growing experiment. This material belongs to an early ripening variety and its root has a lot of hairs. Storable capacity of a radish is poor, because there are few starch contents in the plant. Geranium (*Pelargonium zonale*) was also adopted for measuring the amount of photosynthesis.

2. Experimental apparatus

The basic feature of the experimental apparatus for artificial intermittent illumination is illustrated in Fig. 2. This experimental apparatus was designed for this test and made in the factory of Motoda Electronics Co. Ltd.. This device frame was made by steel with its outline sizes being 1.2m long, 1.2m wide, and 2.0m height respectively. Outside of the device was made with plastic board and a shading net, without any incident light coming from the outside. Light coming from a light source was cut off by a spinning turn board connected with servo motor. Intermittent irradiation was produced by moulding various optional shapes on the



① Motor
② Light source
③ Turn board

Fig. 2. Experimental apparatus for intermittent illumination.

turn board and by regulating the motor speed. The specifications of the experimental device and the measuring instrument are shown in the following.

Timer: TB171 (Matsushita Electric Works, Ltd., 15A, 1.5W)

HID light appliance: TH39-K KKDS300V (Mitsubishi electric Co. Ltd., lamp 150W-1000W, HID150)

Light source: ML type Neo-BOC (Mitsubishi / Osram electric Co. Ltd., 400F-U, MLBOC250F-U)

Transformer: RF100V95WM (Toshiba electric Co. Ltd., 100W)

Portable multi-thermometer: IM2423A (Yokokawa Co. Ltd.)

Hygrometer: X712-1B (Techno-seven Co. Ltd.)

Illuminometer: Illuminance meter IM-3 (Topcon Co. Ltd.)

Fig. 3 shows the basic feature of the experimental apparatus for measuring CO_2 concentration of plant. The amount of photosynthesis was estimated from CO_2 concentration of plant. The change of CO_2 concentration was measured by an infrared carbon dioxide meter, and the temperature and humidity were simultaneously measured. The amount of photosynthesis was measured under the experimental apparatus for artificial intermittent illumination.

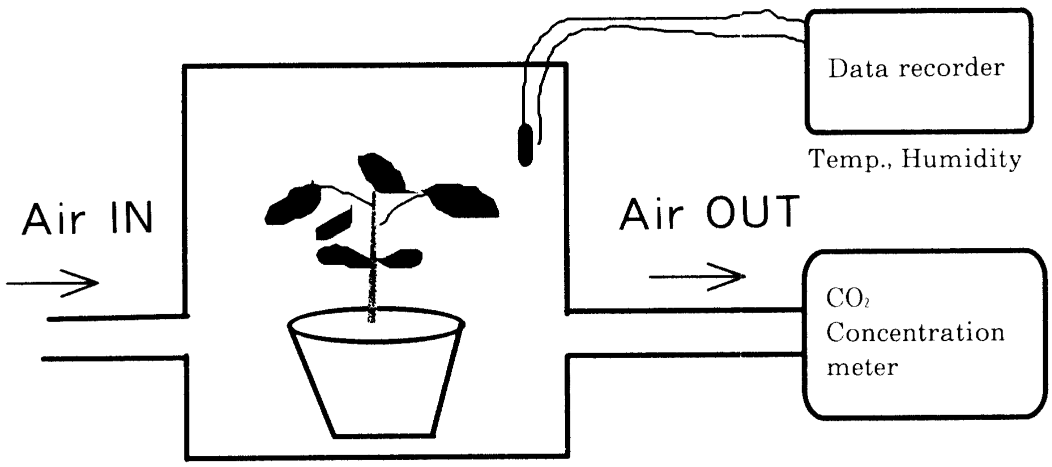


Fig. 3. Schematic diagram for measuring CO_2 concentration of plant.

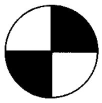
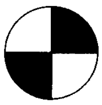
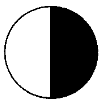
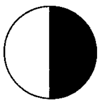
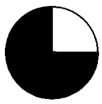
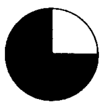
3. Experimental methods

Two nursery radishes were transplanted in one flower pot and three flower pots were set under the light source. It took us two weeks to finish one growing test, which was repeated again under different illumination conditions. At first, the radishes were left to grow up into three leaf plants under the natural irradiation condition, and then they were transplanted to flower pots. After that, intermittent illumination test was carried out for three weeks. Table 1 shows the test condition of turn-board-shape, revolution of motor, illumination time and dark time. Four growing tests were carried out under these conditions. Irradiation period for artificial illumination was twenty-four hours per a day. Fig. 4 shows each measuring part of the plant. Plant length, leaf width, number of leaf, dried and wet plant weights at the upper ground part and root length, root width, dried and wet plant weights at basement part were measured in each test. Temperature, humidity and illuminance were also measured in the respective plant growing tests. At the same time, plant growing test using continuous illumination was carried out as a control under the same conditions.

Measuring of the amount of photosynthesis using a geranium sample was carried out in two days under six kinds of conditions (Table 1). Tests were repeated sixteen times. Irradiation period for illumination was sixteen hours per a day. The amount of photosynthesis was estimated by the following factors: CO_2 concentration, total ventilation, leaf area and temperature. The formula of apparent amount of photosynthesis is as follows;

Apparent amount of photosynthesis =

Table 1. Condition of intermittent illumination

No.	Shape of turn board	Revolution (rpm)	Illumination time (s)	Dark time (s)
Test 1		60	0.250	0.250
Test 2		120	0.125	0.125
Test 3		60	0.500	0.500
Test 4		120	0.250	0.250
Test 5		60	0.250	0.750
Test 6		120	0.125	0.825

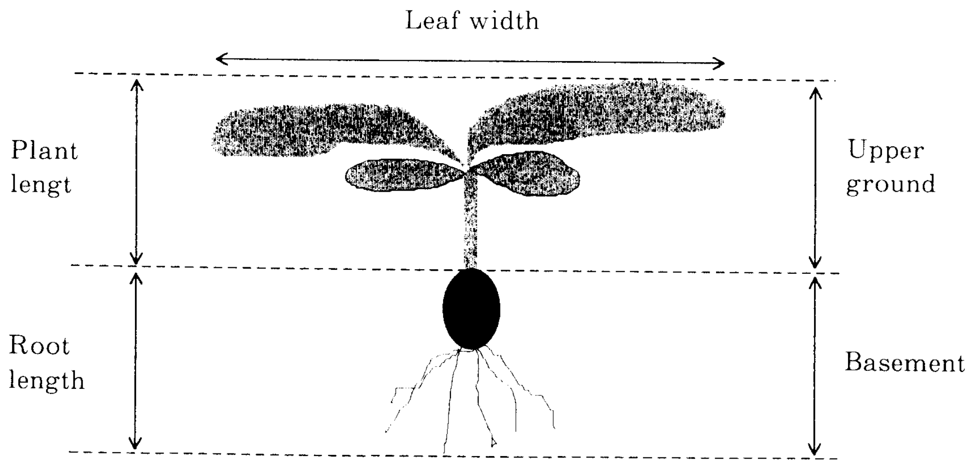


Fig. 4. Measuring parts of experimental plant.

{3217.5 × Ventilation (1/min) × CO_2 concentration (ppm)} / {Leaf area (cm^2) × (273 + Temperature (℃))}

Illumination conditions of all the tests were fixed at 40,000lux.

Results and Discussion

1. Relationship between plant growth and illumination

In order to investigate relationship between plant growth and illumination, the plant height, leaf width, leaf number, dried and wet weights of the plant at both parts of upper ground and basement were measured under the conditions of continuous and intermittent illuminations. Table 2 shows differeces of leaf width, leaf number and ratio of plant height to leaf width under the continuous and intermittent illuminations. These data in the table are average values. There were no difference in leaf width, leaf number with the lapse of time through the different illumination methods, but a difference in the ratio of plant growth to leaf width was observed between continuous and intermittent illuminations. It was found out

Table 2. Relationship between plant growth and illumination

	Time (h)	Continuous illumination	Intermittent illumination
Leaf width (cm)	0	3.00	3.00
	96	10.42	11.53
	192	21.12	19.20
	336	30.83	27.28
Leaf number	0	2.00	2.00
	96	5.83	5.83
	192	8.00	7.67
	336	10.17	10.00
Ratio of plant height to leaf width	0	0.74	0.84
	96	2.51	1.73
	192	3.55	1.86
	336	3.17	1.81

that the plant under intermittent illumination grew up stretching toward height direction.

Relationship between plant weight and illumination is shown in Table 3. It was confirmed that there was a difference between the continuous and the intermittent illuminations in plant growth. In plant weight, the plant under the continuous illumination grew up better than the plant under the intermittent illumination. Concerning the dried weight ratio viewed from the upper ground to the basement, and in the comparison between the continuous and the intermittent illuminations, it was ascertained that the plant under the intermittent illumination grew up insufficiently at the part of basement. Contrasting to this fact, the plant under the continuous illumination grew up sufficiently at the both parts of upper ground and basement. Changes of plant height are shown in Fig. 5. The plant height under the intermittent illumination was constantly higher than that under the continuous illumination during the test.

Consequently, in case of intermittent illumination, apparent plant growth at the upper ground part was as same as in case of continuous illumination, but at the basement part, no

Table 3. Comparison of growth plant between upper ground and basement

	Continuous illumination	intermittent illumination
Upper ground part		
wet weight (g)	17.03	14.91
dried weight (g)	1.98	1.43
moisture content (%)	91.33	90.94
Basement part		
wet weight (g)	21.06	11.17
dried weight (g)	1.69	0.89
moisture content (%)	91.63	91.36
root length (cm)	5.53	4.68
root width (cm)	3.32	2.88
dried weight ratio (upper ground/basement)	1.02	1.58

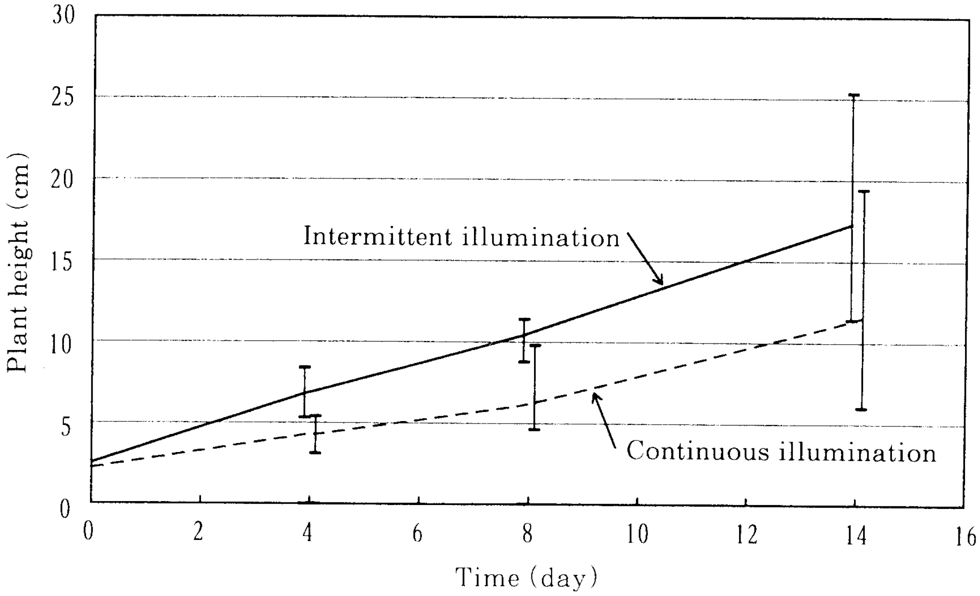


Fig. 5. Change of plant height.

sufficient root growth was noted under the intermittent illumination.

2. Relationship between the plant growth and energy of illumination

In order to investigate the effect of energy of illumination on plant growth, the relationship between the accumulated energy of illumination and plant height was ascertained, and is shown in Fig. 6. The cultivation days in both the illumination methods were the same. Concerning the cultivation days it was noted that there was a physiological problem in plant growth, but it was ascertained that there was a great difference in plant height between the plant under the intermittent illumination and that under the continuous illumination. In case of the intermittent illumination, the plant grew up faster than in that of the continuous illumination, with small amount of the accumulated energy of illumination. Judging from the photosynthetic cycle, it was fixed that the plant under the intermittent illumination absorbed the energy of illumination with higher efficiency. Fig. 7 shows the relationship between the dried weight of plant and the accumulated energy of illumination. Comparing the linear correlation between the plant height and the accumulated energy of illumination, it was ascertained that the dried weight of plant increased rapidly through the both illumination methods. The dried weight of plant under the continuous illumination became greater than the one under the intermittent illumination at the end of the test. The photosynthesis of plant was sufficiently executed under the continuous illumination and the plant growth was enhanced. Nevertheless, the plant under the intermittent illumination made efficient use of the photosynthesis, while the plant growth was insufficient because the energy of illumina-

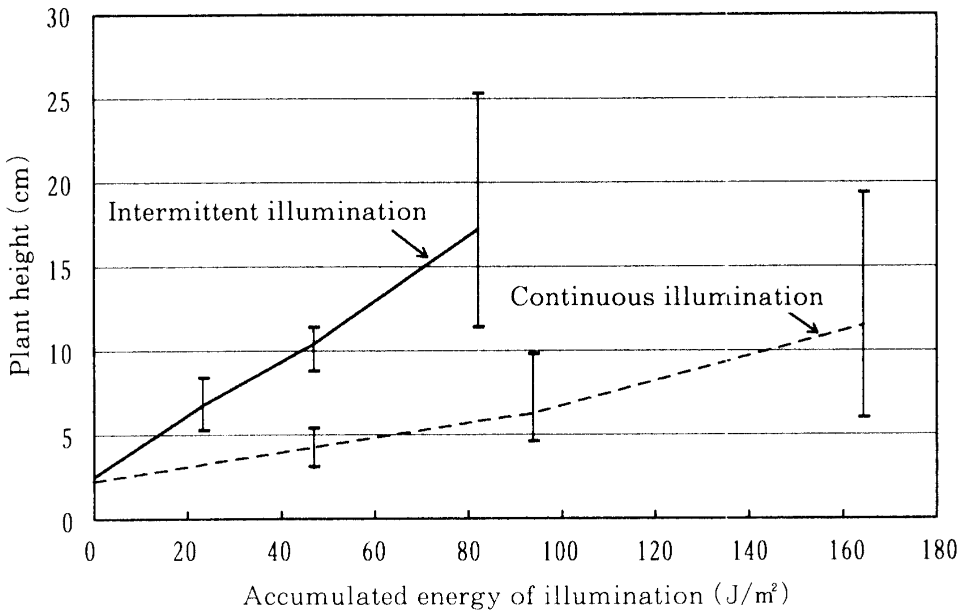


Fig. 6. Relationship between plant height and accumulated energy of illumination.

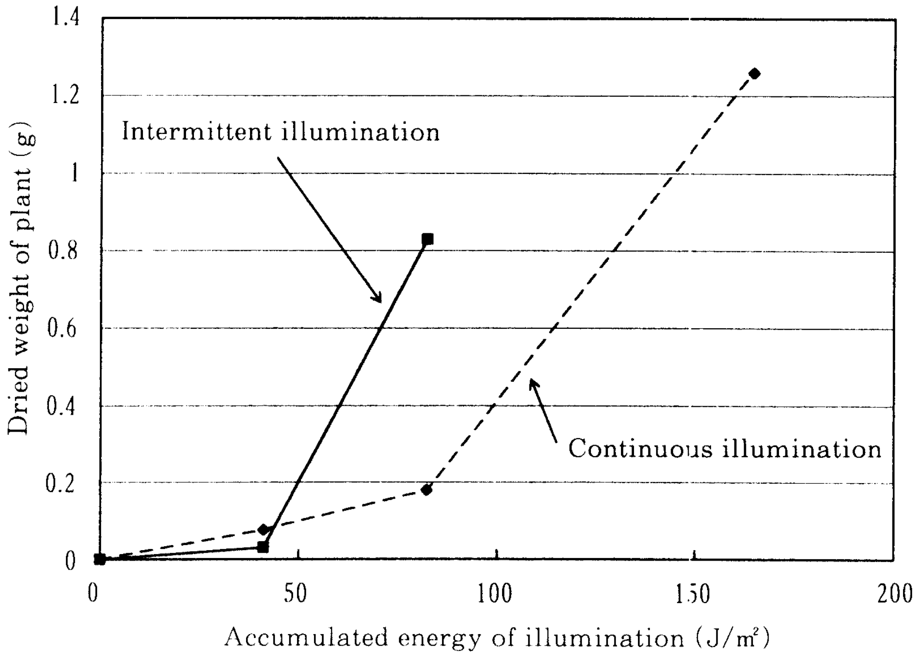


Fig. 7. Relationship between dried weight of plant and accumulated energy of illumination.

tion was used for the plant height. In other words, it was capable of making efficient utilizgation of the energy of illumination in the intermittent illumination, but the lack of absolute energy of the illumination was considered to be a problem to be solved in future.

Making a plant growth model about temperature and the accumulated energy of illumination was tried. The mathematical model is shown as in the following,

$$Y = \alpha \cdot \exp(\beta \cdot \theta \cdot i \cdot t)$$

where, Y : Plant height (cm)

θ : Illumination time (h)

i : Energy of illumination (w/m^2)

t : Temperature (℃)

α and β were coefficients of the plant growth model. Table 4 shows the coefficients of plant growth model. As the energy of illumination and temperature were constant in this experiment, α and β were considered as coefficients of plant growth rate in long and in short ranges, respectively. The values of α and β were different between the continuous and the intermittent illuminations excepting α in test 2. Concerning the temperature and the energy of illumination, the plant growth under the intermittent illumination was considered to be better than that under the continuous illumination.

3. Relationship between photosynthesis and illumination

In order to investigate the relationship between photosynthesis and illumination, apparent photosynthetic rate was measured under the various illumination conditions. Fig.

Table 4. Coefficient of plant growth model

	Continuous illumination		Intermittent illumination	
	α	β	α	β
Test 1	2.34	1.26	3.16	3.07
Test 2	3.17	0.94	2.93	2.61

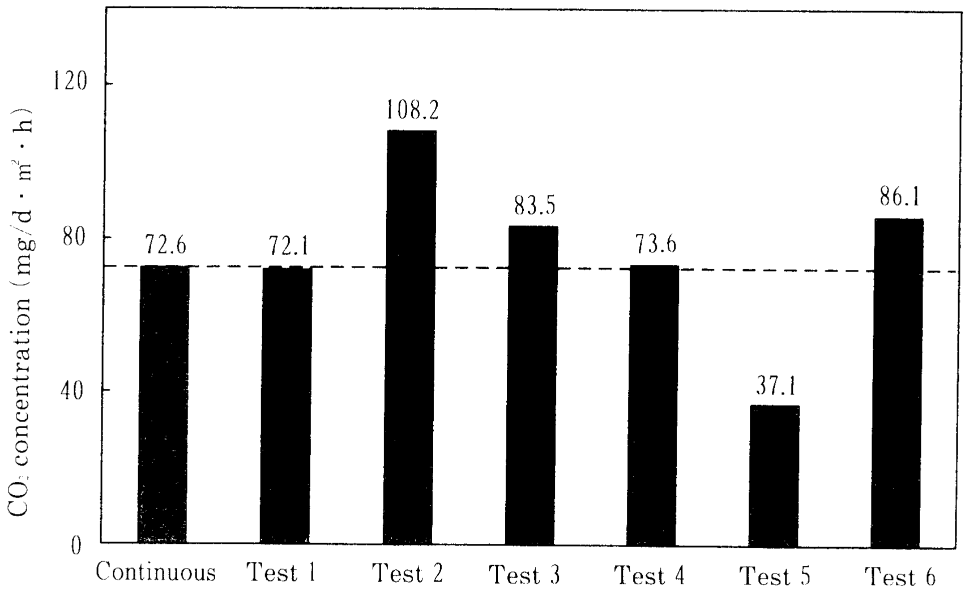


Fig. 8. Relationship between apparent photosynthetic rate and irradiation period of intermittent illumination.

8 shows the relationship between CO_2 concentration and the various intermittent illuminations. CO_2 concentration values in the test 2, 3, 4 and 6 were more than those under the continuous illumination. Although no correlation between CO_2 concentration and intermittent illumination time was to be found in these experiments, it was obvious that the intermittent illumination given to the plant, accelerated an apparent photosynthesis of the plant.

Summary

In order to investigate the relationship between the plant growth and photosynthesis, the plant growing tests were carried out under the various illumination conditions. The following results were summarized. A clear difference between the intermittent and continuous illuminations in plant growing was found in this experiment and especially, it was remarkably different in the dried weight of plant. Judging from the mathematical growth model, it was ascertained that the intermittent illumination method was valid for the plant growth. There was a difference in plant growing rate between the plant growth model and the apparent photosynthesis of view, and a significance of intermittent illumination was confirmed by the measurement of photosynthetic rate. However, no correlation between the illumination time and the dark time was to be ascertained in this experiment.

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