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Potential Use of a 24-Hour Photoperiod (Continuous Light) with Alternating Air Temperature for Production of Tomato Plug Transplants in a Closed System

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***Abstract*. To evaluate the potential use of a 24-hour photoperiod for transplant production in a closed system, tomato (*Lycopersicon esculentum* Mill.) plug transplants were grown for 17 days either under a 24-hour photoperiod with a photosynthetic photon flux (*PPF*) of 200 μmol·m^{-2}·s^{-1} or under a 16-hour photoperiod with a *PPF* of 300 μmol·m^{-2}·s^{-1}, resulting in the same daily integrated PPF (17.3 mol·m^{-2}). Air temperatures were alternated between 28 °C during the first 16 hours and 16 °C for the subsequent 8 hours of each day. Fresh weight, dry weight and leaf area were 41%, 25%, and 64% greater, respectively, under the 24-hour photoperiod than under the 16-hour photoperiod. Physiological disorders (e.g., chlorosis and/or necrosis) were not observed under the 24-hour photoperiod, probably due to the alternating air temperature. Floral development of plants originating from both treatments did not differ significantly. Electric energy use efficiency of the closed system was 9% greater under the 24-hour photoperiod than under the 16-hour photoperiod. These results suggest that using a 24-hour photoperiod with relatively low *PPF* can reduce both initial and operational costs for transplant production in a closed system due to the reduction in the number of lamps.**

Closed systems for transplant production with artificial light have several potential benefits, such as higher quality of transplants, shorter production period, and smaller use of resources, compared with conventional systems (Kozai, 1999). In the closed system, environmental conditions (*PPF*, photoperiod, air temperature, etc.) can be controlled as desired independent of outside weather because 1) the outer structure consists of opaque and thermally insulated materials, and 2) energy and mass exchanges between inside and outside the system are controlled or limited. In other words, environmental conditions that are difficult to obtain in a conventional greenhouse (e.g., 24-h photoperiod, etc.) can be employed in the closed system. To explore a potential use of such conditions in the closed system, their effects on the growth and development of transplants, and use efficiency of resources (e.g., electric energy, water, CO_2, etc.) need to be investigated.

The use of a 24-h photoperiod (continuous light) with a relatively low *PPF* has the benefit of reducing both initial and operational costs for transplant production. Under the relatively low *PPF* condition, the number of lamps can be decreased, resulting in the reduction in the consumption rate of electric energy for lamps. Since the consumption rate of electric energy for lamps is almost equal to the rate of heat generation in the closed system, the requirement for cooling (the number and a capacity of air conditioners) can be decreased. It is also expected that fewer lamp fixtures will be required under the 24-h photoperiod because of the smaller number of lamps and the extension of lamp lifetime.

Transplants exposed to a low *PPF* for a long photoperiod generally accumulate more dry matter than transplants exposed to a high *PPF* for a short photoperiod under the same daily integrated *PPF*. This phenomenon was reported in *Acheme* (Vlahos et al., 1990, 1991), lettuce (Craker and Seibert, 1982; Koontz and Prince, 1986; Oda et al., 1989; Kitaya et al., 1998), and radish (Craker, et al., 1983). However, physiological disorders characterized by chlorotic and necrotic spotting on leaves have been reported to occur when tomato was grown under the 24-h photoperiod at constant air temperatures (Arthur et al., 1930). Hurd (1973) suggested that floral development of tomato and its flowering would be delayed under a long photoperiod. However, low-temperature exposure and/or a daily alternation of the air temperature were effective in preventing such physiological disorders (Withrow and Withrow, 1949; Hilman, 1956; Omura, 2001) and in permitting normal development of flowers (Lewis, 1953; Wittwer and Tuebner, 1956; Calvert, 1957; Saito and Ito, 1962).

The objective of this study was to evaluate the potential use of a 24-h photoperiod with alternating air temperature for production of tomato plug transplants in a closed system.

Materials and Methods

Closed system. Detailed description of the closed system used in the present experiment was previously reported by Ohyama et al. (2000a). This system (2.1 m long × 1.3 m wide × 1.9 m high, volume = 4.6 m^3) was covered with thermally insulated walls consisting of 5-cm Styrofoam sandwiched between a pair of 5-mm wooden panels, where the number of air exchanges was about 0.1 h. The closed system had three shelves each with eight high-frequency fluorescent lamps (FHF32EX-W; Matsushita Electric Industrial Co., Osaka, Japan) and fans (EF-25ASB; Mitsubishi Electric, Tokyo, Japan). Cooling was provided by a home-use air conditioner (consisting of an AS22CHR evaporator and an AO22CHR condenser, Fujitsu General Ltd., Kawasaki, Japan). According to the catalog, a coefficient of performance for cooling (COP) was 2.5, which was obtained when the air temperatures inside and outside the room were 27 and 35 °C, respectively (Japanese Industrial Standard Committee, 1999). The closed system was placed in a room, where the air temperature was kept at 20 °C. CO_2 concentration inside the closed system was maintained with a CO_2 controller (ZF9P; Fuji Electric Co., Tokyo, Japan), a solenoid valve, and a liquid CO_2 container.

Plant material and growth conditions. Tomato (*Lycopersicon esculentum* Mill., cv. Momotaro) seeds were sown in 128-cell plug trays (Nisshin Nohkoh Sangyo Inc., Gunma, Japan) filled with a commercial substrate (50 vermiculite : 50 peatmoss (v/v), Yanmar Agricultural Equipment Co., Ltd., Tokyo, Japan). Trays were placed in darkness for 3 d (Day 0 to 2) for germination at an air temperature of 25 °C in the closed system.

After germination (Day 3), the transplants were grown in the same closed system for 14 d at a photoperiod of 24 h·d^{-1} with a *PPF* of 200 μmol·m^{-2}·s^{-1} (Treatment P24-200), or a photoperiod of 16 h·d^{-1} with a *PPF* of 300 μmol·m^{-2}·s^{-1} (Treatment P16-300). In both treatments, daily integrated *PPF* was 17.3 mol·m^{-2} (200 μmol·m^{-2}·s^{-1} × 24 h × 3600 s·h^{-1} = 300 μmol·m^{-2}·s^{-1} × 16 h × 3600 s·h^{-1}). The

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PPF on the tray surface was adjusted with a light output controller (NQ21575-321; Matsushita Electric Works Co., Osaka, Japan) instead of modifying the number of the lamps. For Treatment P16-300, air temperature was maintained at 28 and 16 °C during the photoperiod and the dark period, respectively. For Treatment P24-200, it was maintained at 28 °C during the first 16 h and at 16 °C for the subsequent 8 h of each day. Horizontal air current speed above the transplant canopy was maintained at about 0.4 $m \cdot s^{-1}$ with the fans. CO_2 concentration inside the closed system was maintained at 1000 $\mu mol \cdot mol^{-1}$ throughout the experiment. Subirrigation was applied once every 2 to 3 d with a commercial nutrient solution containing N, P, and K at 122, 21 and 157 $mg \cdot L^{-1}$, respectively (½-strength Otsuka Hydroponics Composition, Otsuka Chemical, Tokyo, Japan). The seedlings were grown in the closed system for 17 d after seeding. At this stage they had 2 to 3 unfolded leaves, and are generally considered marketable in Japan. Fifteen seedlings were selected randomly, and were then transplanted in a plastic pot (diameter = 12 cm; 1 seedling/pot) filled with the commercial substrate. These plants were grown for 32 to 62 d in a plastic greenhouse (lat. 35°50'N, long. 139°50'E) during the period from 1 Sept. 2000 to 14 Jan. 2001.

Measurements and calculations. At the end of the transplant production period (Day 16), fresh weight (FW), dry weight (DW), leaf area (LA), and stem length (SL) were measured. The number of unfolded leaves (NL) was also counted. To determine the flowering position on the main stem, the number of emerged leaves before the differentiation of the first flower cluster (NF_F) was counted 31 to 61 d after transplanting.

During the transplant production period, the use efficiency of electric energy (U_E) and water (U_W) in the closed system were estimated. We defined the use efficiency of a resource as the ratio of the amount of a resource contained in usable products to the amount input into the closed system. If no waste of the resource is generated in the closed system during the transplant production period, the use efficiency of the resource will be 1. From this definition, U_E was expressed by the following equation (Ohyama et al., 2000a):

$$U_E = G/(W_l + W_a + W_e) = G/W_T \quad [1]$$

where G is the amount of chemical energy stored in the transplants through CO_2 exchange during the transplant production period ($MJ \cdot m^{-2}$); W_l, W_a, and W_e are electric energy consumed by lamps, air conditioner and other equipment (e.g., fans, sensors, etc.), respectively, in the closed system during the transplant production period ($MJ \cdot m^{-2}$); and W_T is the sum of W_l, W_a, and W_e.

Similarly, U_W was expressed by the following equation (Ohyama et al., 2000b):

$$U_W = (C_p + C_s + D)/(I + H) \quad [2]$$

where C_p and C_s are the amounts of water increased in the transplants and substrate, respectively, during the transplant production period ($kg \cdot m^{-2}$); and D, I and H are amounts of condensed water at the evaporator of the air conditioner, irrigated water, and humidified water, respectively, during the transplant production period ($kg \cdot m^{-2}$). Since the condensed water at the evaporator of the air conditioner can be reused for irrigation and humidification, D is included in the numerator of Eq. (2).

Eq.(2) can be further expressed as follows, since D equals to the amounts of evapotranspirated water (E) and water transferred by ventilation from outside to inside the closed system (V) during the transplant production period ($kg \cdot m^{-2}$).

$$U_W = (C_p + C_s + E + V)/(I + H) \quad [3]$$

Strictly, Eq.(3) can be applied to the closed system only if V is negative in value. Since the absolute humidity inside the closed system was higher than that outside during the present experiment and thereby V was negative, we applied Eq.(3) to the present analysis.

G was estimated as a product of the increase in dry weight during the transplant production period of 17 d and a conversion factor of 20 $kJ \cdot g^{-1}$ reported by Larcher (2003). W_l, W_a, and W_e were measured during the transplant production period with a wattmeter (A-11, Osaki Electric Co., Ltd, Tokyo, Japan). From the measurements of W_l, W_a, and W_e, electricity cost per transplant was estimated based on the electricity rates in Tokyo, Japan (The Tokyo Electric Power Co., Inc., 2003).

C_p was estimated from the difference between FW and DW. C_s was estimated from the measurements of FW, and tray weights at the start and end of the present experiment. Water contained in the substrate at the start of the present experiment was assumed to be 0 $kg \cdot m^{-2}$, and thus, was treated as a part of I. I was estimated from the measurements of tray weights before and after irrigation. D was estimated from the increase in the reservoir weight where all of the water drained from the air conditioner was collected. No supplemental humidification was used, hence H = 0. E was estimated from the changes in the tray weights between the irrigations. V was estimated from the difference between D and E.

Each treatment was replicated twice. Fifteen trays were used in each treatment (15 trays × 128 transplants =1920 transplants). Fifteen to thirty transplants were harvested on day 16 for measurements of FW, DW, LA, SL, and NL. Fifteen plants originating from both treatments were used to determine NF_F. For the statistical analysis, a *t* test (TTEST PROC, SAS Institute, Cary, N.C.) was applied for comparing the data in each treatment.

Results and discussion

Growth and development of transplants. FW, DW and LA on day 16 were 41%, 25%, and 64% greater, respectively, in Treatment P24-200 than in Treatment P16-300 even under the same daily integrated *PPF* (Table 1).

FW and DW were greater in Treatment P24-200 than in Treatment P16-300 possibly because use efficiency of *PPF* (net photosynthetic rate/*PPF*) was generally higher under low *PPF* than under high *PPF* (Oda et al., 1989; Vlahos, 1991). The increase in LA and hence light interception in Treatment P24-200 also might have led to the increases in FW and DW. SL was 17% shorter in Treatment P24-200 than in Treatment P16-300. NL in both treatments did not differ significantly, possibly because the average air temperature in Treatment P24-200 was the same as that in Treatment P16-300 (24 °C). These results suggest that the quality of transplants with respect to growth is higher in Treatment P24-200 than in Treatment P16-300 because the size of the transplants, expressed in DW, FW etc., is a major factor affecting early growth after transplanting and harvest (van de Vooren et al., 1986).

Under the 24-h photoperiod, physiological disorders (e.g., leaf chlorosis and/or necrosis) were often observed in tomato (e.g., Arthur et al., 1930). Such disorders and other growth abnormality were also reported in Acheme (Vlahos, 1990), chrysanthemum (Warrington and Norton, 1991), coleus (Arthur et al., 1930), eggplant (Murage, 1996), geranium (Arthur et al., 1930), potato (Tibbitts, et al., 1990), radish (Warrington and Norton, 1991), and sweet pepper (Nilwik, 1981). However, these abnormalities were not observed in our Treatment P24-200 possibly due to exposure to low air temperature (Withrow and Withrow, 1949) and/or the alternating air temperature (Hilman, 1956; Omura et al., 2001).

Proper floral development is one of the important factors affecting quality of tomato transplants. In the present experiment, no significant differences were observed in NL_F of the plants originating from Treatment P24-200 (8.9) and Treatment P16-300 (8.7), possibly because of the exposure to low air temperature or alternating air temperature (Lewis, 1953; Wittwer and Tuebner, 1956; Calvert, 1957; Saito and Ito, 1962). Hence, the quality of transplants with respect to the floral development did not differ between treatments. These values of NL_F of plants originating from both treatments were similar to those reported in greenhouses except for production in summer season. In summer season, increases in NL_F resulting in a delay of flowering were

Table 1. Growth characteristics on day 16 of tomato transplants grown in a closed system under the 24-h or 16-h photoperiod.

Measurements	Treatment		Significance
	P24-200	P16-300	
Fresh weight (mg/transplant)	2684	1909	*
Dry weight (mg/transplant)	191	153	*
Leaf area (cm^2/transplant)	48.3	29.4	*
Stem length (cm)	9.8	11.8	*
Number of unfolded leaves	3.7	3.9	NS

NS,*Nonsignificant or significant at $P \leq 0.05$.

often observed because of unfavorably high air temperature in greenhouses. Our previous report (Ohyama et al., 2003) showed that NL_F of plants originating from the closed system with the same environmental conditions as Treatment P16-300 was lowered by 1.7 to 2.8 compared with that from the conventional greenhouse during summer. Therefore, in the present experiment, the quality of transplants in both treatments with respect to the floral development may be higher than or comparable to that of conventional transplants grown in greenhouses.

Use efficiency of electric energy and water. Although the daily integrated *PPF* in Treatment P24-200 was the same as that in Treatment P16-300, W_l and W_a were 14% and 18% greater, respectively, in Treatment P24-200 than in Treatment P16-300 (Table 2) because the ratio of *PPF* to W_l was generally greater at higher PPF when the light output controller was used. W_e in Treatment P24-200 was equivalent to that in Treatment P16-300 because the fans and the sensors were operated continuously during both treatments. Despite greater W_T, U_E was 9% greater in Treatment P24-200 (0.0047) than in Treatment P16-300 (0.0043) possibly due to the high use efficiency of *PPF* and greater LA. These results suggest that reduction in the operational cost by using the 24-h photoperiod with the low *PPF* is possible.

Fluorescent lamps are line light sources and can give a relatively uniform horizontal distribution of *PPF* at the canopy of the transplants even when the number of lamps is relatively small, indicating that the *PPF* control with modifying the number of lamps is relatively easy. If the number of lamps had been reduced to obtain the *PPF* of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ in the present experiment, instead of using the light output controller, W_l and W_a in Treatment P24-200 would have been equal to those under Treatment P16-300. In this case, U_E in Treatment P24-200 would be increased by 13% (0.0052), and initial costs for lamps and air conditioners would be reduced by 33%.

The electricity cost in Treatment P24-200 was estimated to be 3.2 to 3.5 JPY or 0.027 to 0.029 USD per transplant, and that in Treatment P16-300 was estimated to be 2.9 to 3.2 JPY or 0.024 to 0.027 USD per transplant. These costs were 6% to 7% of the market price of the tomato transplant in Japan (50 JPY or 0.42 USD per transplant). In addition, our recent estimation of the total production cost for transplants (Ohyama and Kozai, unpublished), including the costs for electricity, labor, transportation and the system construction, showed that the electricity cost accounted for 10 % of the total production cost.

Generally, the COP of an air conditioner increases (or decreases) as the air temperature outside the closed system decreases (or increases) when the air temperature inside the closed system is constant. In winter season, the COP was about 2 times greater than that described in the catalog (Ohyama et al, 2002). Moreover, because there have been increasing requirements of energy conservation in Japan, the COP of the home-use air conditioner has increased during the last decade. At present, the maximum COP of home use air conditioners (capacity = 2.5 kW) is 6.0 (The Energy Conservation Center, Japan, 2003), which is 2.4 times higher than that of the air conditioner used in the present experiment. If such an air conditioner with a COP of 6.0 had been used in winter season, W_a in both treatments would have decreased by about 75%. In this case, the electricity cost would be decreased by 13% to 17%, and U_E would increase by 24% to 25% compared with the values in the present experiment.

The values of I, E, D, and V in Treatment P24-200 were similar to those in Treatment P16-300 (Table 3) because the transplant canopy in both treatments were exposed to the same daily integrated *PPF* or the similar radiation environment. Relatively high values of U_W (0.95 to 0.96) were obtained in both treatments because of the small number of air exchanges in the closed system (0.1 h^{-1}). Although U_W was not affected by the treatment, it should be noted that the high values of U_W in both treatments contributed to reducing not only the production cost but also environmental pollution outside the system during the transplant production period in the closed system.

Table 2. Energy balance and energy use efficiency of the closed system during the transplant production period.

	Treatment	
Observation	P24-200	P16-300
Electric energy consumption		
Lamps (W_l)	476.6[z]	416.0
Air conditioner (W_a)	169.5	143.6
Other equipments (W_e)	36.3	36.1
Chemical energy stored in the transplants (G)	3.2	2.5
Heat energy transferred by air conditioner	509.7	452.1
Use efficiency of electric energy (U_E)[y]	0.0047	0.0043

[z]Cumulative amounts per planting area during the transplant production period of 17 d ($MJ \cdot m^{-2}$) are shown.
[y]U_E is dimensionless and expressed by the following equation: $U_E = G/(W_l + W_a + W_e)$.

Table 3. Water balance and water use efficiency of the closed system during the transplant production period.

	Treatment	
Observation	P24-200	P16-300
Irrigation (I)	63.8[z]	61.8
Evapotranspiration (E)	56.6	53.4
Condensed at evaporator of air conditioner (D)	53.4	52.3
Increase in the transplants (C_p)	2.1	1.4
Increase in the substrate (C_s)	5.1	5.7
Ventilation (V)	3.2	1.1
Use efficiency of water (U_W)[y]	0.95	0.96

[z]Cumulative amounts per planting area during the transplant production period of 17 d ($kg \cdot m^{-2}$) are shown.
[y]U_W is dimensionless and expressed by the following equation: $U_W = (C_p + C_s + D)/(I + H)$.

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