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Effects of lighting and air movement on temperatures in reproductive organs of plants in a closed plant growth facility

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Abstract

Temperature increases in plant reproductive organs such as anthers and stigmas could cause fertility impediments and thus produce sterile seeds under artificial lighting conditions without adequately controlled environments in closed plant growth facilities. There is a possibility such a situation could occur in Bioregenerative Life Support Systems under microgravity conditions in space because there will be little natural convective or thermal mixing. This study was conducted to determine the temperature of the plant reproductive organs as affected by illumination and air movement under normal gravitational forces on the earth and to make an estimation of the temperature increase in reproductive organs in closed plant growth facilities under microgravity in space. Thermal images of reproductive organs of rice and strawberry were captured using infrared thermography at air temperatures of 10–11 °C. Compared to the air temperature, temperatures of petals, stigmas and anthers of strawberry increased by 24, 22 and 14 °C, respectively, after 5 min of lighting at an irradiance of 160 W m^{-2} from incandescent lamps. Temperatures of reproductive organs and leaves of strawberry were significantly higher than those of rice. The temperatures of petals, stigmas, anthers and leaves of strawberry decreased by 13, 12, 13 and 14 °C, respectively, when the air velocity was increased from 0.1 to 1.0 ms^{-1}. These results show that air movement is necessary to reduce the temperatures of plant reproductive organs in plant growth facilities.

Keywords: Bioregenerative life support systems; Reproductive organs; Rice; Strawberry; Temperature; Thermal images

1. Introduction

Plant growth and reproduction in space have been of increasing concern as the possibility increases for long-term manned space flights. The feasibility of maintaining long-term manned space missions is dependent on growing crops in Bioregenerative Life Support Systems (BLSS) or space farms that will provide food, CO_2/O_2 conversion and water purification. For space farming, the movement of heat and gases between plant surfaces and their environment is affected by the absence of buoyancy dependent convective transport, limited ventilation and high ethylene concentrations in plant growth facilities causing poor development of plant reproductive organs and poor yields in space (Monje et al., 2003). They also discussed heat and mass transfer in space farming. Yamashita et al. (2006) discussed heat and mass transfer in Martian greenhouse dome under the low atmospheric pressure and low gravity.

In space farming, the utilization of closed plant culture facilities is anticipated. In such facilities without adequate air circulation systems, there may be adverse effects on the crops. Insufficient air movement around plants increases the resistance to gas diffusion in the leaf boundary layer and thus limits photosynthesis and transpiration of plants (Yabuki and Miyagawa, 1970; Monteith and Unsworth, 1990; Jones, 1992), resulting in suppression of plant growth and development. Therefore, the enhancement of gas exchange in leaves and resulting plant growth would be dependent on appropriate control of air movement in controlled environment facilities (Tibbitts and Kozlowski, 1979; Kitaya et al., 2000a).

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On earth, convection occurs with uneven temperature distribution. Air movements are induced by convection even in a closed chamber with no forced ventilation system. There is, however, no natural convective or thermal mixing under microgravity conditions in space because buoyancy is considered to be negligible under microgravity conditions. The limited convection would reduce plant growth by limiting heat and gas exchange on plant leaves. Effective air movement in a closed plant production system is thus essential to enhance the heat and gas exchange between plants and the ambient air, and consequently promote growth of plants in space.

Several space flight experiments with plants have observed poor seed production and genetic aberrations (e.g., Merkies and Laurinavichyus, 1983; Mashinsky et al., 1994; Salisbury et al., 1995). Space-specific stress caused chromosomal anomalies in cells of plants grown in space (Krikorian, 1996). Bubenheim et al. (2003) reported that pollen from super-dwarf wheat grown on the Mir space station contained only one nuclei due to a high level of atmospheric ethylene (1.2 μmol mol^{-1}), while normal viable pollen is tri-nucleate. Carbon dioxide enrichment and air exchange in plant growth chambers allowed pollen and ovule development to occur normally (Musgrave et al., 1997), and absence of convective air movement caused disorder of pollen development under space flight conditions (Musgrave and Kuang, 2003).

Kitaya et al. (2001, 2003) reported that leaf temperatures increase in microgravity because sensible and latent heat exchanges between leaves and the ambient air are retarded compared to normal gravity (1.0 g). The temperature increase under decreasing gravity levels was most significant at the narrow region of the leaf blade (Kitaya et al., 2006). Poor seed production and genetic aberrations are possibly due to excessive temperature increase in plant reproductive organs such as anthers and stigmas under artificial lighting in closed plant growth facilities under microgravity conditions in space.

Terrestrial research has been initiated to study the thermal environment of plant reproductive organs to estimate the temperature increase in these organs in plant growth facilities in space. In the present study, effects of illumination and air movement on the temperature increase in glumes, petals, anthers and stigmas of plant reproductive organs were investigated under normal gravity conditions.

2. Materials and methods

Experiments were carried out in a wind-tunnel growth chamber as shown in Fig. 1. Thermal images of glumes, petals, anthers and stigmas in reproductive organs (Fig. 2) and leaves of rice (*Oryza sativa* subsp. japonica) and strawberry (*Fragaria* × *Ananassa* Duchesne) were captured using infrared thermography. The plants were cultured for 2–3 months in a greenhouse in pots containing a commercially available soil mix before placement in the growth chamber.

The experimental system with the infrared thermography (TH9100, NEC-San-ei Co., Japan) is shown in Fig. 3. In this system, temperature of surfaces was determined by measuring the intensity of infrared radiation (8–14 μm in wavelength) from the surfaces according to the Stefan–Boltzmann law. Temperatures of the organs were taken by using a close-up lens (TH91-386, NEC-San-ei Co., Japan). The minimum detection temperature was 0.06°C and the minimum spatial resolution was 95 μm × 95 μm. The emissivity value was set at 0.93 following Jones (1999). An incandescent lamp (RPF-150W, Matsushita Electric Co., Japan) system was used for lighting. The light source was placed 0.3 m above the plant organs. There was no thermal barrier between the lamp and the plants. The total irradiance in the wavelength band ranging 0.4–1.1 μm on the plant organs was approximately 160 W m^{-2} that corresponded to a photosynthetic photon flux density of 200 μmol $\text{m}^{-2}\ \text{s}^{-1}$ under this incandescent lamp. The conversion factor was 1.25 (μmol $\text{m}^{-2}\ \text{s}^{-1}$)/(W m^{-2}). The relative spectral distribution of radiant energy from the lamp used in this experiment is shown in Fig. 4. The spectral distribution was measured with a spectrometer system (USB4000, Ocean Optics Inc., USA). Air temperatures of 10–11 °C and relative humidity of 73–75% was maintained around the plants. The air temperature and relative humidity were monitored with a thermo-hygrometer (TR-72U, T&D Co., Japan). The temperature and humidity sensors were placed under a leaf without using an aspirated box. The air velocity above the organs was maintained at approximately 0.1 ms^{-1} by an air circulation system in the wind tunnel. We modified the air velocity up to 1.0 m s^{-1} by increasing the rotational frequency of the fan to determine the effects of the air velocity on the temperature of the plant organs. The air velocity was measured with a thermal anemometer (Model 6071, Nihon Kanomax, Japan).

The time constant representing the time required to reach 63.2% of the maximum temperature was obtained to indicate how rapidly the temperature of each organ increased. The time constant was calculated from the temperature increase curve over time after the lamp was turned on.

3. Results and discussion

A thermal image of reproductive organs including petals, stigmas and anthers of strawberry was taken 4 min after the lamp was turned on (Fig. 5). The image shows higher temperatures than the atmospheric air temperature after the lamp was turned on. Temperatures of anthers and stigmas were lower than that of petals. Petals facing the light source showed the highest temperatures in the thermal image.

The temperatures began to increase just after the lamp was turned on and reached equilibrium values after 4 min (Fig. 6). The maximum temperature was highest in petals followed by stigmas and the anther temperature was low-

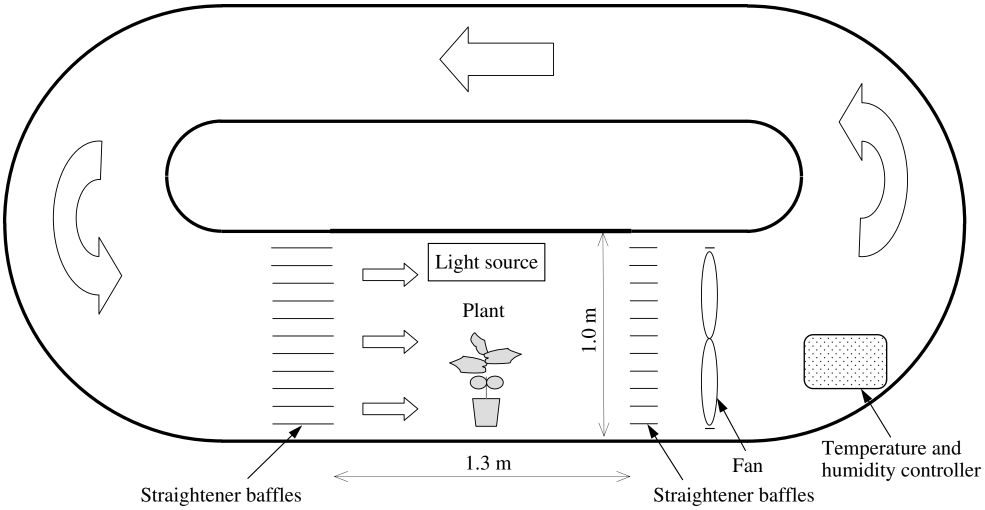
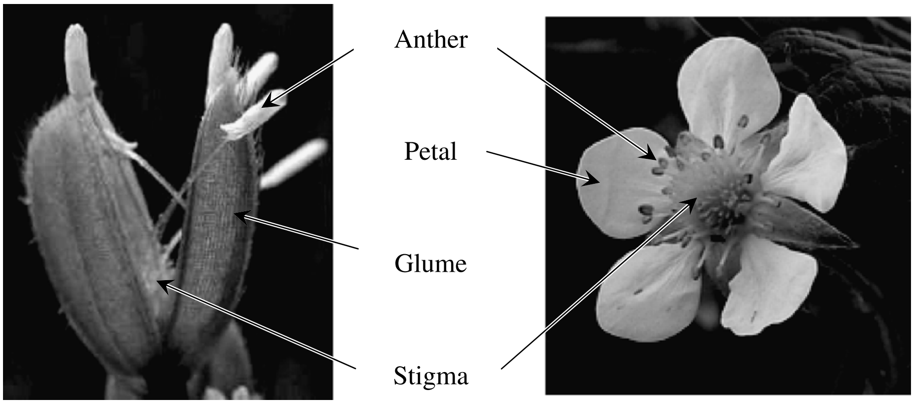


Fig. 1. Cross-sectional view of the wind-tunnel growth chamber with an air circulation system used in the experiment. Arrows indicate air flow directions.



Rice *Strawberry*

Fig. 2. Reproductive organs of rice and strawberry flowers used during the experiment.

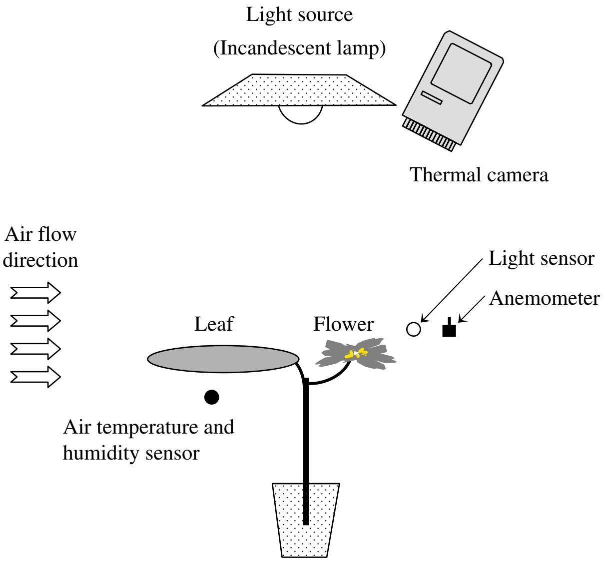


Fig. 3. Experimental set-up for capturing thermal images of plant organs under different environmental conditions.

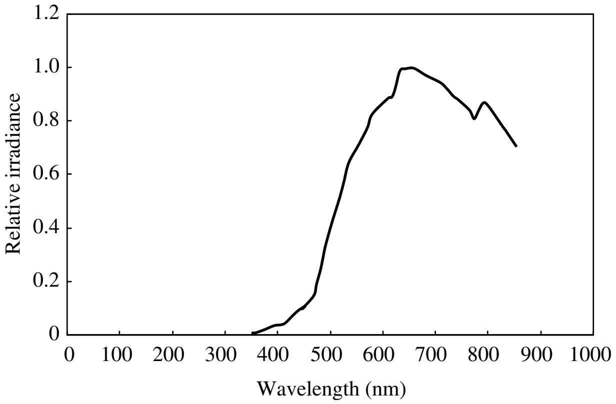


Fig. 4. Spectral distribution of radiant energy (relative irradiance) from the incandescent lamp used.

est. The temperature rise was more rapid in petals than in stigmas and anthers. Values of the time constant for maximum temperature increase of petals, stigmas and anthers

Fig. 5. A thermal image of reproductive organs of strawberry 4 min after starting supplemental lighting with incandescent lamp light. Irradiance: 160 W m^{-2}, air temperature: 11 °C, relative humidity: 73%, air velocity: 0.1 m s^{-1}.

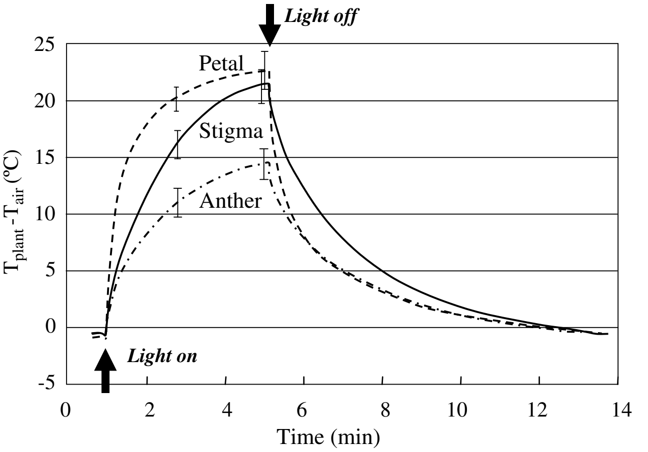


Fig. 6. Time course for temperatures (T_{plant}) of petals, stigmas and anthers of strawberry plants while turning the light on and off. The tissues facing the lamp were selected as measurement points. Bars indicate standard deviations ($n = 3$). Light source: incandescent lamp, irradiance: 160 W m^{-2}, air temperature (T_{air}): 11 °C, relative humidity: 73%, air velocity: 0.1 m s^{-1}.

after lighting were 28, 73 and 72 s, respectively. The difference in heating trends among the organs may be dependent on the heat capacity per surface area of each organ. The temperatures decreased after the light was turned off and reached equilibrium values after approximately 7 min. Mean temperatures of petals, stigmas and anthers of strawberry were 0.5(±0.3) °C lower than the surrounding air temperature under the dark (Fig. 6) due to the latent heat transfer associated with transpiration (the value in parenthesis is the standard deviation).

Reproductive disorders were reported under high temperature (30–33 °C) conditions. Early development and differentiation of barley anthers were very sensitive to high-temperature (30 °C day/25 °C night) causing major alterations in gene expression (Abiko et al., 2005). Fertilization of bell pepper was sensitive to high temperature (33 °C) (Erickson and Markhart, 2002). Temperatures of reproductive organs rose significantly after the lamp was turned on in the current experiment. This temperature rise can cause reproductive disorders when ambient air temperatures are maintained at 20–30 °C.

Figure 7 shows the effect of air movement on the temperature of leaves and reproductive organs of both strawberry and rice. Leaf temperatures were higher than other organs of both strawberry and rice. Temperatures of reproductive organs and leaves of strawberry were significantly higher than those of rice. Temperatures of reproductive organs and leaves decreased with increasing air velocities. For strawberry, the temperatures of petals, stigmas, anthers and leaves decreased by 12.8(±1.8), 11.9(±1.5), 13.1(±1.8) and 14.1(±1.9) °C, respectively, when the air velocity increased from 0.1 to 1.0 m s^{-1}. For rice, the temperatures of glumes, stigmas, anthers and leaves decreased by 4.6(±0.6), 4.8(±0.8), 4.9(±1.0) and 9.3(±1.8) °C, respectively, when the air velocity increased from 0.1 to 1.0 m s^{-1}.

The control of air movement was shown to be important to enhance gas exchange between plants and the ambient air, and thus promote growth of plants in a closed plant production system especially when maintaining a large number of plants at a high density (Kitaya et al., 2000b; Shibuya et al., 2006). The current experiment confirmed the importance of air movement for reducing temperatures of reproductive organs.

Arabidopsis and wheat plants grown in space were found to produce and develop flowers, but their flowers produced more sterile seeds than did ground control plants (Merkies and Laurinavichyus, 1983; Mashinsky et al., 1994; Salisbury et al., 1995). There is a possibility that the difference was caused by an increase in temperature of reproductive organs such as anthers and stigmas due to limited convection. Musgrave and Kuang (2003) reported that absence of convective air movement negatively impacted pollen development under space flight conditions.

The observed temperature increases would be larger for smaller organs such as anthers and stigmas under microgravity conditions. Leaf temperature increase under microgravity condition was more significant at the narrower region of the leaf blade of barley due to the increased resistances to water vapor and heat transfer in the leaf boundary layer (Kitaya et al., 2006).

The boundary layer resistance is usually less and the surface temperature is lower at the narrower regions of the leaf blade for convective situations under normal gravity conditions. The boundary layer resistance, however, would be mostly constant regardless of the leaf width under the microgravity condition. Therefore, net temperature increase with decreasing gravity levels was larger at the narrower regions of the leaf. Low net photosynthetic rates caused by an excessive increase in leaf temperature would also reduce plant growth at the reproductive growth stage as well as the vegetative growth stage.

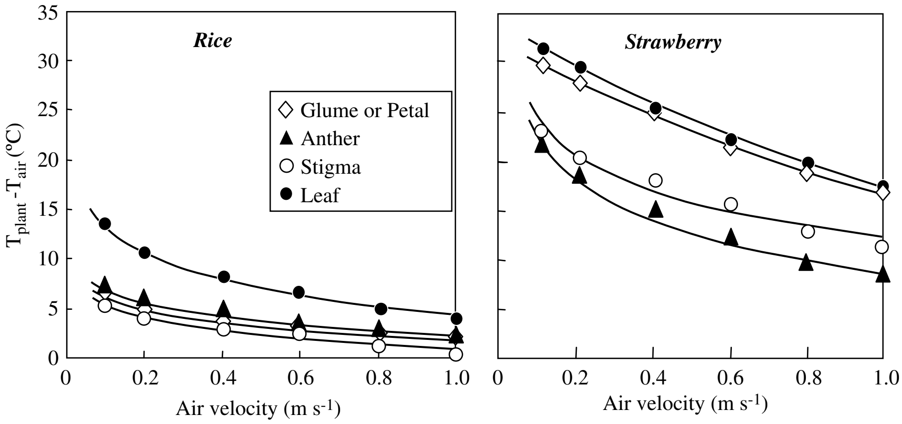


Fig. 7. Effect of air velocity on temperatures (T_{plant}) in reproductive organs and leaves of rice and strawberry. Mean values ($n = 3$) and logarithmic approximation curves are shown. Light source: incandescent lamp, irradiance: 400 W m^{-2}, air temperature (T_{air}): 10 °C, relative humidity: 75%.

In the current study, it was confirmed that air movement was essential to avoid temperature increases in plant reproductive organs and leaves. Reduced air convection under microgravity conditions in space would limit plant growth by reducing heat and gas exchanges between plant organs and the ambient air. Proper air movement is essential to promote plant growth during vegetative and reproductive growth stages.

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