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Temperature affects long-term productivity and quality attributes of day-neutral strawberry for a space life-support system

Gioia D. Massa [a,*], Elaine Chase [a], Judith B. Santini [b], Cary A. Mitchell [a]

[a] Department of Horticulture & Landscape Architecture, Purdue University, West Lafayette, IN 47907-2010, United States
[b] Department of Agronomy, Purdue University, West Lafayette, IN 47907, United States

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ABSTRACT

Strawberry (*Fragaria x ananassa* L.) is a promising candidate crop for space life-support systems with desirable sensory quality and health attributes. Day-neutral cultivars such as 'Seascape' are adaptable to a range of photoperiods, including short days that would save considerable energy for crop lighting without reductions in productivity or yield. Since photoperiod and temperature interact to affect strawberry growth and development, several diurnal temperature regimes were tested under a short photoperiod of 10 h per day for effects on yield and quality attributes of 'Seascape' strawberry during production cycles longer than 270 days. The coolest day/night temperature regime, 16°/8 °C, tended to produce smaller numbers of larger fruit than did the intermediate temperature range of 18°/10 °C or the warmest regime, 20°/12 °C, both of which produced similar larger numbers of smaller fruit. The intermediate temperature regime produced the highest total fresh mass of berries over an entire production cycle. Independent experiments examined either organoleptic or physicochemical quality attributes. Organoleptic evaluation indicated that fruit grown under the coolest temperature regime tended to score the highest for both hedonic preference and descriptive evaluation of sensory attributes related to sweetness, texture, aftertaste, and overall approval. The physicochemical quality attributes Brix, pH, and sugar/acid ratio were highest for fruits harvested from the coolest temperature regime and lower for those from the warmer temperature regimes. The cool-regime fruits also were lowest in titratable acidity. The yield parameters fruit number and size oscillated over the course of a production cycle, with a gradual decline in fruit size under all three temperature regimes. Brix and titratable acidity both decreased over time for all three temperature treatments, but sugar/acid ratio remained highest for the cool temperature regime over the entire production period. Periodic rejuvenation or replacement of strawberry propagules may be needed to maintain both quality and quantity of strawberry yield in space.

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1. Introduction

Strawberry is one of the promising candidate crops for a space diet (Hoff et al., 1982; Massa et al., 2006b; 2010; Tibbitts and Alford, 1982). As a compact, non-woody fruit crop that does not necessarily require vernalization, strawberry could be a highly desirable component of a space-based food-production system. In addition to having desirable flavor and aroma attributes, strawberry contains numerous vitamins, minerals, dietary fiber, and beneficial phytochemicals such as antioxidants (Perkins-Veazie and Collins, 2001), which could benefit astronaut health and well-being (Perchonok et al., 2012). Diets including strawberry fruit extracts rich in antioxidants have been tested as a potential countermeasure for space-radiation damage to living systems and are quite promising (Rabin et al., 2005).

One important consideration for the development of space-based crop production is energy consumption by the support system. Electric lighting generally accounts for the most energy consumption in any controlled environment plant-growth system that cannot use direct or indirect solar lighting (Drysdale and Bugbee, 2003; Massa et al., 2006a), and previous work by Massa et al. (2010) investigated strawberry cultivar responses to different photoperiods with the goal of minimizing light-energy requirements. 'Seascape' was selected as a high-performing, day-neutral cultivar that produced high yields of acceptable fruit under short photoperiods of 10 h/day. A photoperiod of 10 h would allow for significant energy savings in a closed, off-Earth system.

Temperature and photoperiod interact to affect strawberry growth and development (for reviews see Darnell et al., 2003;

* Corresponding author. Present address: Mail Code UB-A, Kennedy Space Center, FL 32899. Tel.: +1 321 861 2938; fax: 321 867 7282.
E-mail address: gioia.massa@nasa.gov (G.D. Massa).

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Durner and Poling, 1988). These environmental interactions are complex and challenge general strawberry classifications based on day-length response because high or low temperatures alter typical photoperiod responses. Strawberries generally classified as "day neutral" may acquire photoperiodic flowering requirements when grown under certain day/night temperature regimes. Durner et al. (1984) found that flowering of normally day-neutral types requires long days when grown under day/night temperatures $\geq$22°/18 °C, but that flowering remains photoperiod independent at 18°/14 °C conditions or at constant 21 °C. Also, they found that temperatures >30 °C inhibit flowering of day-neutral cultivars (Durner et al., 1984), although they are less sensitive to high temperatures than are other types of strawberries (Durner and Poling, 1988). Similar findings by Nishiyama and Kanahama (2002) showed that flower-bud initiation was inhibited under short photoperiods at high temperatures of 30°/25 °C, but initiation resumed when plants were transferred to 20°/15 °C conditions or given 24-h photoperiods. In addition to changing the initiation of flowering, temperature × photoperiod combinations can modify the degree of repeat flowering (Bradford et al., 2010), a factor critical for long duration flowering under controlled environment conditions such as would be required during spaceflight. The day-neutral cultivar 'Tribute' produced many more flowers under 16-h long days than under short days across a range of temperatures (Bradford et al., 2010). Temperatures up to 26 °C were permissive for repeat flowering in 'Tribute', and that cultivar acted as an obligate long-day plant at 29 °C or as a facultative long day plant at lower temperatures (Bradford et al., 2010). Under a (short) 9-h photoperiod, flowering was inhibited above 23 °C.

A survey of several day-neutral cultivars for space life support examined the effects of a range of temperatures on yield of strawberry cultivars grown in controlled environments (Massa et al., 2006b). The coolest day/night temperature regime tested in that study was 18°/10 °C. That regime produced the highest berry yield and received the best organoleptic ratings. Reductions in growth temperature, however, do not have the same clear energy tradeoff as reducing lighting duration for a controlled environment plant-growth scenario such as will be used in space and on planetary surfaces. Energy is required to remove heat generated in a closed system, especially when electric light sources are used (Drysdale and Bugbee, 2003). Solid-state light sources such as light-emitting diodes (LEDs), however, lend themselves to novel heat removal approaches since heat is emitted remotely from the location of light emission (Bourget, 2008). Because of this characteristic and several additional benefits (lifespan, size, waveband selectivity, efficiency, etc.), LEDs likely will be the lighting source of choice for future food production in space, also allowing for more efficient thermal control within a plant-growth area (Massa et al., 2006a). However, due to limitations of available equipment, the controlled environments used in the present study were not lighted with LEDs.

After determining that a short (10-h) photoperiod was favorable for fruit yield and acceptability of 'Seascape' strawberry and would have energy-saving implications for controlled environment growth in space (Massa et al., 2010), there was a need to characterize the effects of several different day/night temperature regimes using this short photoperiod on growth, yield, organoleptic acceptability, and physicochemical flavor attributes. The present study details two long-duration experiments on strawberry production in controlled environments. Extending the duration of fruit production can be beneficial in a space life-support scenario because resources and crew time are limited, and inedible plant components (e.g., roots, stems, and leaves of strawberry) would need to be recycled or reused in some way (Eckart, 1994; Hanford, 2004; MacElroy and Klein, 1984; Wheeler, 1996). Therefore, the longer plants continue producing, the better for system efficiency.

Due to the limited production capacity of available controlled environment equipment, two independent experiments were conducted. In experiment 1, we tested the hypothesis that temperature would have a significant effect on fruit yield and organoleptic acceptability of day-neutral 'Seascape' strawberries grown under a short photoperiod, and we used the lowest previously tested temperature regime (18°/10 °C) as our intermediate value. Fruit were analyzed for organoleptic (OL) acceptability by volunteer sensory panels. Organoleptic analyses are commonly used in food science to determine human perceptions of flavor (Meilgaard et al., 1999; Barrett et al., 2010), so we included taster perceptions of sweetness, tartness, bitterness, color, aroma, texture, and overall approval. We used two rating scales, a standard 9-point hedonic scale (Jones et al., 1955) that inquires about the degree to which tasters prefer a particular characteristic, as well as a 10-point objective scale to quantify degrees of attribute perception, without expressing preference (Massa et al., 2010).

For experiment 2, we applied lessons learned from experiment 1 and tested the hypothesis that temperature would have a significant effect on fruit physicochemical (PC) attributes related to flavor (sugar, acid, pH). These PC properties are commonly used to evaluate fruit quality and to compare environmental treatments or cultivars (e.g. Kallio et al., 2000; Chandler et al., 2003). Some researchers have tested both OL evaluations and PC flavor properties (e.g. Gunness et al., 2009; Darbellay et al., 2002; Resende et al., 2008; Pelayo-Zaldívar et al., 2005), but the degree of correlation between these factors varies. Sweetness, for example, typically has a high correlation with Brix, a measure of sugar content (Darbellay et al., 2002; Resende et al., 2008), so we were interested to see if similar trends existed between experiments 1 and 2. We also tested the secondary hypothesis that staggering pollination and harvest date based on plant maturity would enhance overall fruit yield over a long duration.

2. Materials and methods

2.1. Plant material

For each experiment, thirty rooted crowns of strawberry (*Fragaria x ananassa* L.) cultivar 'Seascape' (US Patent 7614) were obtained from the Indiana Berry and Plant Company (Huntingburg, IN). This cultivar was selected based upon previous studies (Massa et al., 2010).

2.2. Experiment 1

Leafless crowns were planted in Pro-Mix 'HP' high-porosity, peat-based medium (Premier Horticulture, Inc., Quakertown, PA), in 16.5-cm-diameter plastic pots. Ten plants were selected randomly and placed in each of three growth chambers, each with a growing area of 0.76 m^2 (123.5 cm × 61.9 cm, 13.2 plants/m^2) (Conviron E-8 Chambers, Controlled Environments Limited, Winnipeg, Manitoba, Canada). The chambers were randomly set for one of three different diurnal temperature regimes: 16.0°/8.0 °C, 18.0°/10.0 °C, or 20.0°/12.0 °C (all ±0.2 °C). Relative humidity was set for 70% days and 80% nights (±3%). Lamp height was adjusted to provide 350 µmol m^{-2} s^{-1} of photosynthetic photon flux (*PPF*) at the top of the plant canopy. Light measurements were taken with a quantum sensor (Apogee Instruments, Inc., Logan, UT). Lamps were a mixture of cool-white fluorescent (110 W) and incandescent (40 W) with a total input wattage of 1420 W in each chamber (1100 W fluorescent: 320 W incandescent). Photoperiod in each chamber was 10 h on a 24-h light/dark cycle. Daily light integral (DLI) was 12.6 mol m^{-2} day^{-1}. Temperature, humidity, and photoperiod were set to ramp in the chamber to provide diurnal transitions, with a ramping duration of 1 h at the beginning