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Significant reduction in energy for plant-growth lighting in space using targeted LED lighting and spectral manipulation

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ABSTRACT

Bioregenerative life-support systems involving photoautotrophic organisms will be necessary to sustain long-duration crewed missions at distant space destinations. Since sufficient sunlight will not always be available for plant growth at many space destinations, efficient electric-lighting solutions are greatly needed. The present study demonstrated that targeted plant lighting with light-emitting diodes (LEDs) and optimizing spectral parameters for close-canopy overhead LED lighting allowed the model crop leaf lettuce (*Lactuca sativa* L. cv. 'Waldmann's Green') to be grown using significantly less electrical energy than using traditional electric-lighting sources. Lettuce stands were grown hydroponically in a growth chamber controlling temperature, relative humidity, and CO_2 level. Several red:blue ratios were tested for growth rate during the lag phase of lettuce growth. In addition, start of the exponential growth phase was evaluated. Following establishment of a 95% red + 5% blue spectral balance giving the best growth response, the energy efficiency of a targeted lighting system was compared with that of two total coverage (untargeted) LED lighting systems throughout a crop-production cycle, one using the same proportion of red and blue LEDs and the other using white LEDs. At the end of each cropping cycle, whole-plant fresh and dry mass and leaf area were measured and correlated with the amount of electrical energy (kWh) consumed for crop lighting. Lettuce crops grown with targeted red + blue LED lighting used 50% less energy per unit dry biomass accumulated, and the total coverage white LEDs used 32% less energy per unit dry biomass accumulated than did the total coverage red + blue LEDs. An energy-conversion efficiency of less than 1 kWh/g dry biomass is possible using targeted close-canopy LED lighting with spectral optimization. This project was supported by NASA grant NNX09AL99G.

1. Introduction

Planetary exploration and expansion of humanity into the solar system to establish permanent settlements are grand challenges of the 21st century (NASA, 2010, 2012). The goal of human exploration set by the Global Exploration Roadmap is a first human mission to Mars by 2040 (ISECG, 2013). Standard mission-to-Mars scenarios envision a crew of 6 people and a total mission duration of approximately 1000 days (Drysdale et al., 2003), requiring a total mass of consumables (food, water, oxygen) that current heavy-lift vehicles are unable to launch at once. Resupplying consumables with a cargo vessel like the Automated Transfer Vehicle (currently used to resupply the International Space Station) would not be cost effective, either, since the average cost to launch a kilogram of mass into Low-Earth Orbit has been estimated to be $10,000 (Futron Corporation, 2002). *In-situ* Resource Utilization might be used to recover water and oxygen from Lunar or Mars regolith, but it does not directly enable generation of food (ISECG, 2013). Thus, bioregenerative life-support systems coupled to controlled-environment food-crop growth modules are needed for food production on the Moon or Mars (Massa et al., 2006; Wheeler et al., 2001, 2003). Such systems could sustain a crew at distant space destinations since seeds can be stored viably for a long time and/or (re)generated in space for very long missions.

High energy radiation on both the Moon and Mars also is a problem for both humans and higher plants that human explorers will have to address, most likely by using some form of radiation shielding. In addition, any pressurized structures at or near the planetary surface must withstand tremendous differences in

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temperature between night and day (from −233 °C to +123 °C), large pressure differentials, and the likelihood of frequent micrometeorite impacts. Thus, human habitats and crop-growth modules very likely will be sheltered or located underground (ACCESS Mars, 2009). Moreover, sunlight will be reduced or not available at all times due to local conditions such as long dust storms on Mars, the periodically increased distance between Mars and the Sun, or extended dark periods on most locations of the Moon (Cockell and Andrady, 1999; Cockell, 2001; Horneck et al., 2003; Rontó et al., 2003; Salisbury, 1992; Wheeler, 2004), making electric lighting a more reliable option for growing food plants in space (Massa et al., 2006). However, it has been estimated that 40 to 50 m^2 of cropping area, in continuous use, would be necessary to fully sustain each crew member (Mitchell et al., 1997), which would require considerable energy for a traditional electric crop-lighting scenario (Drysdale, 2001). Ikeda et al. showed that 45% of the total power needed for growing lettuce in a controlled environment under fluorescent lights was consumed by lamps and ballasts and 35% by air-conditioning to reject waste heat (Ikeda, 1991).

Several ground-based bioregenerative Life-Support-System studies have been conducted since the 1970s, all including electric or hybrid (electric + solar) lighting (Gitelson et al., 1989; Masuda et al., 2005; Nitta, 2005; Tako et al., 2010; Lasseur et al., 2010). Experiments using the Minitron II growth-chamber/cuvette system to determine maximum growth response for hydroponic lettuce using red-rich incandescent lighting had an associated power cost per unit growth area ranging from 1 to 10 kW/m^2 (power density, where the area term refers to crop-growth area) and an energy consumption per unit dry biomass produced between 953 and 1680 kWh/g (Knight and Mitchell, 1988). NASA's Biomass Production Chamber (BPC), which also was not designed for optimal light delivery but as a closed plant-production system with HPS lamps (Wheeler, 1992), used 2.1 kW/m^2 of electrical power for lighting (Wheeler et al., 1996), which translated into 4.7 kWh/g for 'Waldmann's Green' lettuce (Wheeler et al., 2008). An engineering concept for an inflatable Mars surface greenhouse estimated that a greenhouse module of 90 m^2 using HPS lamps 12 h/day at 1000 $\mu mol/m^2/s$ would require 2.47 kW/m^2 (Hublitz et al., 2004). Using an intracanopy light-emitting diode (LED) system to grow cowpea crop stands in a controlled environment, Massa et al. (2005) reduced power density to 0.83 kW/m^2, which corresponded to 1.02 kWh/g of dry plant biomass. More recently, Gomez et al. (2013) showed that intracanopy LED lighting during high-wire greenhouse tomato cultivation enabled the consumption of 4.3 times less energy for supplemental lighting than with overhead HPS lamps. In recent years, LED plant research has indeed become more active in the horticulture greenhouse industry because of potential energy savings, as indicated by the study of Dueck et al. (2012) on hybrid supplemental lighting utilizing overhead HPS lamps and "interlighting" with LEDs.

LEDs also are promising candidates for space life support as their small size, mass, and ballast-free operation would contribute positively to reducing the Equivalent System Mass (ESM) of a space lighting system (Drysdale and Hanford, 1999) compared to traditional high-intensity discharge (HID) lighting systems. In addition, their solid-state electronics ensure reliability and safety (Tibbitts et al., 1991). LED lifetime is more than twice as long as for any other type of light source for plant growth, which would spare maintenance time for astronauts on a given mission (Bourget, 2008) and reduce the launch mass of needed spares.

Efficiencies of the Philips Luxeon LEDs per se in 2012 reached 38% for red (630 nm) emitters and 50% for blue (455 nm) (Philips Lumileds Lighting Co., 2012). High-intensity discharge lamps such as HPS and Metal Halide (MH) have efficiencies comparable to red LEDs, but, because of their intensely hot lamp surfaces, must be placed much farther away from plants than LEDs (Tibbitts et al., 1991), thereby resulting in much higher operating power required to get sufficient photosynthetic photon flux (PPF) at leaf level. Another very important advantage of LEDs is that they emit pure colors, which can be selected to match the absorption peaks of plant pigments (Tibbitts et al., 1991) and thus improve spectral efficiency for optimal plant growth and development (Kim et al., 2007). Over the past decade, studies have shown that red and blue LEDs are an effective lighting source for plant growth (Yorio et al., 2001). Even though blue light is photosynthetically less efficient than red light (Dougher and Bugbee, 2001; McCree, 1971/1972), it has important photomorphogenic effects on stem elongation, leaf expansion (Dougher and Bugbee, 2001; Hoenecke et al., 1992), and is important for water relations (Sharkey and Raschke, 1981).

Despite the energy-saving advantages of LEDs compared to traditional crop-lighting sources, when using an overhead lighting system for rosette plants such as leaf lettuce, light in a fixed-spacing growth system still is wasted falling on empty spaces between small plants before they grow. To avoid such losses, the concept of targeted lighting was investigated in the present study, switching on LEDs positioned only directly above individual plants. Changing the space between plants as they grow (variable spacing) is another option for solving this problem (Both et al., 2009; Field, 1988; Davis, 1985; Prince and Bartok, 1978), as was done at Phytofarms of America using automatic spacing (Prince et al., 1981), but that solution was designed for large-scale terrestrial agriculture and required additional energy for daily plant-position adjustments. For space applications, simplicity of operation and ESM minimization are always preferred, and with effective targeted lighting, fixed spacing between growing seedlings should not be critical.

The ultimate goal of the present study was to test the concept and demonstrate the energy efficiency of targeted lighting to grow 'Waldmann's Green' leaf lettuce under optimizing red + blue LED lighting conditions, compared to total coverage red + blue or white LED lighting.

To achieve this objective, a three-part study was conducted for hydroponic lettuce in a growth chamber using red and blue LEDs for sole-source crop lighting. First, a temporal characterization was carried out to determine kinetics of lag and exponential phases of growth; secondly, a determination was made regarding optimizing conditions of red:blue ratio during both growth phases; and finally, a comparison was conducted for efficiency of targeted vs. total coverage LED lighting. Previous studies found a power density of 2.47 kW/m^2 needed to grow plants using HID lighting (Hublitz et al., 2004), and 2.1 kW/m^2 was demonstrated for HPS lighting in the NASA Biomass Production Chamber (Wheeler et al., 1996). It was hypothesized that such figures may be lowered by at least an order of magnitude using targeted LED lighting technologies under optimizing spectral conditions, as tested herein.

2. Materials and methods

2.1. ORBITEC lighting system

Two identical custom LED lighting arrays were provided by the Orbital Technologies Corporation (ORBITEC, Madison, WI, USA). Both rectangular lighting arrays measuring 61 × 61 cm were arranged in four two-by-two 27.5 × 27.5 cm panels, each containing 36 red LEDs (λ_{max} 630 nm) and 9 blue LEDs (λ_{max} 455 nm). The red peak is 19 nm Full Width at Half Maximum (FWHM), and the blue peak is 21 nm FWHM (Fig. 1). The red LEDs are 29% efficient and the blue 41% (manufacturer data). Fig. 2a shows a detailed image of the emission surface of the array. The irradiance of red and blue, as well as photoperiod, are adjustable from custom-control software, and light intensities were measured using a spectroradiometer (Apogee) and a quantum sensor (Apogee).