

Sustained Salad Crop Production Requirements for Lunar Surface

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ABSTRACT

A long-duration lunar outpost will rely entirely upon imported or preserved foods to sustain the crew during early Lunar missions. Fresh, perishable foods (e.g. salad crops) would be consumed by the crew soon after delivery by the re-supply missions, and can provide a supplement to the diet rich in antioxidants (bioprotectants) that would serve as a countermeasure to radiation exposure. Although controlled environment research has been carried out on the growth of salad crops under a range of environmental conditions, there has been no demonstration of sustainable production in a flight-like system under conditions that might be encountered in space. Several fundamental challenges that must be overcome in order to achieve sustained salad crop production under the power, volume and mass constraints of early Lunar outposts include; growing multiple species, sustaining productivity through multiple plantings, and minimizing time for crew operations. In addition, issues associated with nutrient replenishment, maintenance of water balance, and environmental compatibility need to be addressed. A project has been initiated in the Space Life Sciences Laboratory at Kennedy Space Center to address these questions using two salad production chambers that were built for flight operation as a part of a small business innovative research program (SBIR) Phase 2 grant.

INTRODUCTION

The use of higher plants for life support and dietary supplementation for long duration space missions has been studied by NASA for over 50 years (Myers, 1954; Tibbitts and Alford, 1982; Hoff et al., 1982; Miller and Ward, 1966). Tests in the 1960s and 1970s by Russian researchers included higher plants to support human crews and were carried out in closed systems. In the 1980s NASA conducted experiments at NASA's Kennedy Space Center (KSC) to evaluate the feasibility of using plants as part of a bioregenerative life support system in the biomass production chamber [(BPC) Wheeler and Strayer, 1997]]. Ongoing research is occurring in the Japanese Closed Ecology Experimental Facility (CEEFF) and the European Space Agency's Micro-Ecological Life Support System Alternative (MELISSA) project (Wheeler et al., 2001).

In addition to the physiological and nutritional benefits of providing fresh food for crew on long duration space missions, positive psychological benefits may be achieved as well (Wheeler and Martin-Brennan, 2000). The production of a salad crop growing system or "salad machine" on early Lunar missions would require optimal use of limited area, mass and electrical power (Kliss et al., 2000). The productivity of lettuce, onion, radish, tomato, and pepper at a range of temperature, CO₂, and light levels anticipated for these early missions has been

completed (Richards et al., 2006). In addition, the effects of reduced pressure on growth, productivity and bio-protective value of radish and lettuce are being studied (Stutte et al., 2006; He et al., 2007; Levine et al., 2008). However there has been limited study of the ability to sustain production of salad crops in the small plant growth systems being considered for early Lunar habitats.

A 418-day study to demonstrate the feasibility of continuous production of potato in a large (113 m³) closed chamber was performed in the BPC at KSC in the mid-90's (Stutte et al., 1999). Four growth cycles of potato grown in either "batch" or "staggered" production were maintained under hydroponic conditions. Production was higher in the "staggered" vs. "batch" production systems, due in large part to the increased light interception through side-lighting of the canopy. The experiment revealed the accumulation of bioactive compounds in the nutrient solution that altered plant growth and development, including a tuber inducing factor (TIF) that accelerated the time for potato induction, shortened internode length, decreased time to maturation, and significantly reduced the total yield per plant (Stutte, 1999). As a result, changes in experiment management to increase planting density and decrease the plant/harvest cycle were required to maintain yield and life support functions (Stutte et al., 1999).

Multiple cropping of wheat and potato on a shared nutrient solution has also been attempted. The differences in demand for nutrients during different stages of development resulted in changes in nutrient balance that had a negative effect on overall yield of both crops (Barta and Henderson, 1998).

Although there is some work on continuous production of crops in hydroponics under space-flight environment conditions, early production systems on the lunar surface will probably use some type of solid matrix (Wheeler et al., 2001). The use of a solid matrix decreases the demand for critical control of nutrients in the media, but introduces a requirement to reutilize and regenerate the nutrients in the media. The PESTO (Photosynthesis Experiment System Testing and Operation) completed a series of six plantings of *Triticum aestivum* L. USU Apogee onboard the International Space Station (ISS) in the Biomass Production System (BPS) during Increment IV (Monje et al., 2005; Stutte et al., 2005). The experiment used 1-2 mm arcillite as the substrate with no negative effect on plant growth or development.

Observations of multiple crops grown in LADA (Bingham et al., 2002) onboard the ISS suggest a decline in productivity associated with nutrient management (O. Monje, per. com.). Ground tests in a LADA prototype have shown that up to four cycles of radish can be grown in arcillite without a significant decrease in productivity (M. Hummerick, per. com.). But results obtained by Bruce Bugbee at Utah State University (unpublished) suggest that after five or more cycles the

nutrient content from a slow release fertilizer is unable to sustain productivity.

In addition to depletion of nutrients from fertilizer in a media, there are other factors that could have a negative impact on growth and yield. These include the growth of pathogenic or saprophytic microorganisms in the media and well as production and accumulation of allelopathic compounds that inhibit growth.

A number of small-scale plant growth systems have been designed to conduct science experiments onboard the space shuttle or ISS. Generally speaking these plant growth systems have a significant amount of environmental control and are designed for experimentation, not production *per se*. For example, Orbitec (Madison, WI) developed the Biomass Production System (BPS) plant growth chamber to conduct experiments on board ISS. The BPS had four small individual plant growth chambers with CO₂, temperature and relative humidity control. The growth volume was limited to approximately 250 cm² and was optimized for research applications (Morrow and Crabb, 2000; Stutte et al., 2005).

Orbitec also developed the Biomass Production System for Education (BPSe) to support student science activities in the classroom through a NASA Phase II SBIR grant. The BPSe has approximately 0.1 m² of growing area and was designed to provide a ground-based research unit to run in parallel with plant growth experiments on the space shuttle or the space station. Orbitec also developed the deployable vegetable production system, (VEGGIE) unit to produce vegetable crops to supplement pre-packaged food during long stays in space as part of a Phase II SBIR. The VEGGIE unit is a plant growing facility with the growing area of approximately 0.07 m², and has a LED lighting system. VEGGIE is an expandable chamber designed to meet the power, mass and volume limitation of ISS, and is arguably the most advanced prototype of a small scale "salad machine" that has been developed.

Both the BPSe and VEGGIE units are being used in an ongoing series of experiments to demonstrate the feasibility of sustained production of salad crops under mission relevant conditions in order to identify issues and opportunities associated with continuous production.

The project utilizes two candidate salad crops, lettuce (*Lactuca sativa* L. cv. Outredgeous) and radish (*Raphanus sativus* L. cv Cherry Bomb Hybrid II) which are being grown in a batch or staggered production mode under light emitting diodes (LEDs) in the VEGGIE units or compact fluorescent lamps (CFL) in the BPSe's. The effect of the production system on plant growth, yield and quality are being assessed. This report provides the results from the initial four plantings of lettuce obtained from this ongoing experiment.

MATERIALS AND METHODS

EXPERIMENT SETUP

Plant Material: One red, loose leafed lettuce cultivar (*Lactuca sativa* L. cv Outredgeous) was used in this test. This cultivar was selected based on its rapid growth rate under mission relevant conditions, known responses to spectral quality and relatively high bioprotective potential (Stutte et al., 2009). Seeds were planted at a density of 6 seeds/pot, and then thinned to 1 plant/pot after 7 days.

Growth Conditions: Two approaches to growing plants on a sustained basis were evaluated. "Batch" production where all plants grown under a light cap and harvested on the same schedule, and a "Staggered" production where 1/3 of the plants were planted and harvested on a weekly basis. The replants were in the same media without additional supplementation with fertilizer. The experiment was 84 days (4 x 21 day growth cycles). The "Batch" and "Staggered" planting were conducted in a VEGGIE with LED lighting, and a BPSe with fluorescent lighting (Figure 1). There were a total of 12 plants (4 plants x 3 rows) for each chamber. In the "Batch" treatments, each harvest of 12 plants was considered a replicate. In the "Staggered" treatments, each weekly harvest of 4 plants per row was considered a replicate.



Figure 1. VEGGIE chamber with LED lighting (left) and BPSe chambers with compact fluorescent lamps (center and right) were used to determine feasibility of sustaining salad crop production through multiple growth cycles.

Environmental Parameters: The experiment was maintained in a controlled environment chamber (EGC M-48, Environmental Growth Chambers, Chagrin Falls, OH) set at mission relevant levels of 23° C, 45% RH, and 4000 $\mu\text{mol mol}^{-1}$ CO₂ respectively (Richards et al., 2006). These environmental conditions were maintained using passive control in the VEGGIE and BPSe units by altering the air flow through the plant canopy through the lamp cap.

VEGGIE and BPSe growth units provided independent light and photoperiod control at $\sim 300 \mu\text{mol m}^{-2} \text{s}^{-1}$ PAR on at 16hr light/ 8 hr dark photoperiod. PAR measurements were obtained at ~ 10 cm from LED arrays in the VEGGIE units and ~ 20 cm from CWF arrays in the BPSe's. Light canopies from both chambers had an acrylic barrier between lamps and plant growth area. Lighting in the VEGGIE systems was 90% red (640 nm), 6% blue (440 nm) and 4% green (530 nm) LEDs. The BPSe systems were illuminated with energy efficient compact fluorescent lamps (30W Mini Spiral Lamp, N:vision, Mableton, GA) that produced a spectra consisting of 44% red (600-700 nm), 16% blue (400-500 nm) and 40% green (500-600 nm).

Nutrient management: Plants were grown in 2.5 inch (6.3 cm) black plastic pots filled with 1-2 mm calcined montmorillonite clay (arcillite) that has been loaded with 17 g L⁻¹ of slow release fertilizer (Osmocote Plus™, 12-14 month formulation). Three strips of polyester capillary matting [(~ 10 cm x 1 cm) Charlies Greenhouse and Garden, Mount Vernon, WI] were embedded in the media to allow wicking of moisture from the base of the pot. The pots were placed on capillary matting and water maintained at a constant moisture level using a previously described gravity feed watering system (Stutte et al. 2005).

SAMPLE MEASUREMENTS AND ANALYSIS:

Plant Growth Measurements: At harvest, biometric measurements of plant height, canopy width, top fresh mass and plant leaf area were determined. Tissue was dried at 70° C for 72 - 96 h and dry mass determined.

Statistical Analysis: Data was analyzed using analysis of variance and mean separation between treatments at $P \leq 0.05$ with GraphPad Prism statistical software (GraphPad Software, San Diego, CA)

RESULTS AND DISCUSSION

Growth and yield of lettuce was significantly higher under the LED arrays of the VEGGIE units than the CFL lamp canopy of the BPSe's under both the batch and staggered planting systems (Figure 2). In the batch system, leaf area per plant was 7.4% larger (258 vs. 239 cm²), fresh mass per plant 17.5 % higher (9.3 vs. 7.7 g) and dry mass per plant 27% greater (0.66 vs. 0.48 g) under the LED light canopy. The results from the staggered production system were comparable, with leaf area per plant 17.7 % larger (234 vs. 192 cm²), fresh mass per plant 23.4 % higher (8.4 vs. 6.5 g) and dry mass per plant 28.3% greater (0.69 vs. 0.48 g) using the LED light canopy. There was no effect of batch and staggered planting approaches in the LED or CFL lighting treatments.

The yield of both the LED and CFL lighting systems were generally consistent with each successive planting in the batch system (Fig 3). There was a decrease in yield of the 2nd batch harvest of CFL that that may be