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New Frontiers in Food Production Beyond LEO

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New technologies will be needed as mankind moves towards exploration of cislunar space, the Moon and Mars. Although many advances in our understanding of the effects of spaceflight on plant growth have been achieved in the last 40 years, spaceflight plant growth systems have been primarily designed to support space biology studies. Recently, the need for a sustainable and robust food system for future missions beyond Low Earth Orbit (LEO) has identified gaps in current technologies for food production. The goal is to develop safe and sustainable food production systems with reduced resupply mass and crew time compared to current systems. New soilless water and nutrient delivery systems are needed to avoid constant resupply of bulky single-use porous media. Autonomous plant health and food safety monitoring systems are needed to ensure that the food produced is suitable for supplementing crew diets with fresh and nutritious salad crops. Newly identified plant species and cultivars with improved contents of antioxidants, vitamins, and minerals are needed for growth under the elevated CO_2 concentrations found in spacecraft. These improvements in food production technologies will enable the design of sustainable life support systems for manned exploration missions beyond Low Earth Orbit.

Nomenclature

APH = Advanced Plant Habitat
BPS = Biomass Production System
ISS = International Space Station
HACCP = Hazard Analysis Critical Control Point
KSC = Kennedy Space Center
LADA = Joint Russian - U.S. Plant Greenhouse
LEO = Low Earth Orbit
PTNDS = Porous Tube Nutrient Delivery System

I. Introduction

THE goal of space agriculture is to develop safe and sustainable fresh food production systems with reduced resupply mass and crew time. Plant growth systems have been deployed in LEO for the last 50 years on numerous platforms (Salyut, Space Shuttle, Mir, and ISS) to characterize the effects of microgravity on plant physiology and to determine if plant growth, development, and reproduction is the same as it is on Earth.[1,2] Space agricultural ground

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studies conducted concurrently on Earth by NASA, universities, private enterprises, and international space agencies have been more extensive and concentrated on designing and characterizing plant-based bioregenerative life support systems that could feed human colonies on the Moon or Mars.[3,4] These ground studies found that a growing area of about 40-50 m^2 and ~90 kg of fertilizer mass were required to produce one person's dietary calories from plants for 1 year with a light input of 40 mol m^{-2} d^{-1}. A larger area would be needed if plants in variable gravity environments did not grow at the same rate as in 1g. Spaceflight experiments found that two indirect effects of microgravity can reduce plant growth in LEO: capillary-driven moisture redistribution causes poor rootzone aeration, and the absence of buoyancy-driven convection causes poor mass and heat transfer to leaves and plant organs.[2,5] These findings were used to design root modules and chamber subsystems (e.g., BPS and APH) that effectively mitigated these indirect effects of microgravity so that plant growth in microgravity was similar to growth in 1g at moderate light levels.[6-9] However, these modified spaceflight plant growth systems primarily support space biology experiments where the mission ends at the completion of the experiment. The root modules are not recycled after plants are harvested and are often discarded as sample return mass is limited. Currently, the state-of-the-art root module for plant growth in microgravity is the single-use, 0.2 m^2 Advanced Plant Habitat (APH) science carrier that uses ~4 kg of consumable porous substrate media. Scaling from the APH to a salad machine to grow 13 crops/year of lettuce requires resupplying ~52 kg of media, which becomes waste that is not easily recycled in microgravity after its nutrients are depleted. These practices are adequate for conducting plant biology experiments for science, but they are unsustainable for fresh food production systems.

NASA has identified the need for robust ‘Pick-and-Eat’ systems for supplementing crew diets with fresh leafy green crops in near term LEO, cislunar, and lunar missions.[10] Currently, the challenges are to develop and demonstrate the performance of substrate-free, gravity-independent, water delivery systems to safely grow salad crops adapted for growth in spacecraft environments for supplementing crew diets in future cislunar, lunar and martian missions.

II. Space Food Systems

Human exploration will not be possible if the crew is not provided with a safe, palatable, and nutritious food system. However, the food system itself is part of a larger life support architecture, thus, its design must also balance the use of resources (water, food preparation time, stowage volume, launch mass, and power requirements) during each mission. Currently, the state-of-the-art is the International Space Station (ISS) food system, which utilizes ambient-stored, prepackaged food to deliver ~1.8 kg food and packaging $crewmember^{-1}$ day^{-1}.[11] A recent appraisal of the current food system by NASA’s Advanced Food Technology Project concluded that it is inadequate for 5-year missions beyond LEO.[12] The two main causes of long term storage (i.e. > 3 years) were inadequate nutritional content of the food and inadequate acceptability of the food leading to insufficient intake by the crew.

Long term storage reduces the nutrient stability of food, and also reduces the content of several vitamins in multivitamin supplements.[13] Ongoing testing has indicated that processing to prevent food spoilage reduces some nutrients in the pre-packaged food system (e.g., potassium), and that some nutrients also degrade to inadequate levels over the storage times required for long duration missions (e.g., Vitamins B1, C, and K).[14] Thus, the consumption of fresh produce can supplement these nutrients to the the stored diet, as well as, provide antioxidants and phytochemicals in a natural, whole-food form.

III. Water Delivery Systems

Soilless water and nutrient delivery systems (hydroponics and aeroponics) avoid the constant resupply of bulky single-use porous media, but both face challenges for containment, providing sufficient aeraton to the roots, and liquid / gas separation issues.[8] On Earth, hydroponics (e.g., nutrient film technique, NFT) is an efficient plant growth system because it allows precise control of rootzone aeration and nutrient delivery[15], and it is envisioned as a leading technology for food production in early lunar and martian habitats.[3,4,16] Two soilless candidate water and nutrient delivery systems are being developed and evaluated at the Kennedy Space Center: a Porous Tube Nutrient Delivery System (PTNDS) and an On-Demand watering system. The PTNDS system utilizes ceramic porous membranes held under suction for watering plants that are seeded and germinated directly on the tubes.[17] The On-Demand system actuates a pump and a solenoid using feedback from a moisture sensor to maintain constant rootzone moisture in a foam or porous media matrix. These systems provide for active control of root zone moisture, which differs from

Veggie. The Veggie pillow system is a passive watering system that uses capillary forces to water the plant root zone from a water reservoir that must be refilled by an astronaut on a regular basis.[18]

The performance of these candidate water delivery systems was evaluated at NASA KSC in ISS environmental conditions (300 umol m^{-2} s^{-1} PAR, 3000 umol mol^{-1} CO_2, 40% relative humidity, and 23°C) by comparing their plant productivity against productivities of an NFT hydroponic system and an APH root module (Figure 1). The NFT system provided aeration and nutrients via a thin film of recirculating nutrient solution to a sloped, covered trough.[15] The APH root module was separated into four independently controlled quadrants and the baseline design utilizes a particulate substrate (1-2 mm arcillite) fertilized with a slow-release fertilizer. The moisture in each quadrant was individually controlled using feeback from a pressure sensor that is in equilibrium with the matric potential in the porous media.[8]

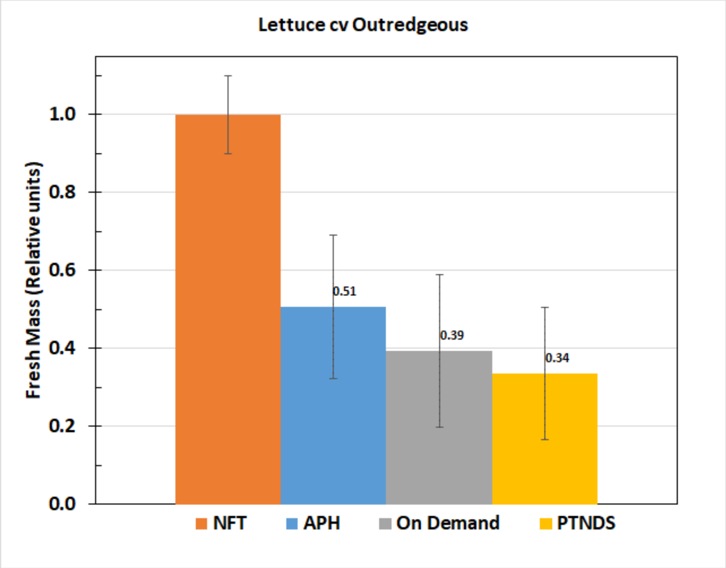

Figure 1. Comparison of candidate water delivery systems. *Fresh lettuce mass from candidate systems is compared to productivity of hydroponic NFT and APH in ISS environment.*

The NFT system produced on average (n=3) 78 g plants, which is less than the 100 g plants produced under lower CO_2 (1000 umol mol^{-1}) and higher relative humidities (65%). The productivities of the APH, On-Demand, and PTNDS systems were 51%, 39%, and 34% of the NFT, respectively. These results are consistent with observations from a recent study where the shoot fresh mass of hydroponic lettuce was twice that of aeroponic and soil cultivated lettuce.[19] It is clear that water delivery technologies that close the gap in productivity shown in Figure 1 are needed.

Future advances in water delivery systems, like the Omni-Gravity hydroponic system[20] will also be tested at KSC. The Omni-Gavity hydroponic system utilizes recent advances in microgravity fluidics to design a passive, gravity-insensitive hydroponic watering system. By exploiting conduit geometry and the wetting characteristics of the nutrient solution, surface tension will dominate the flow and mimic the role of gravity on orbit and in low-gravity environments. It is envisioned that minimal operational changes are required in order for the system to function in the gravity dominated terrestrial, lunar and Martian environments.

IV. Plant Health and Food Safety

Autonomous plant health and food safety monitoring systems could improve the confidence that the food produced is suitable for supplementing crew diets with fresh, nutritious salad crops.

A. Plant Health Monitoring

The deployment of fresh food production systems beyond LEO wil likely require that the plant chamber hardware is capable of assessing plant health without crew intervention. Currently, detecting the occurrence of poor growth can be accomplished via nondestructive measurements of plant growth rates obtained from photographic analysis of daily increments in leaf area. However, this approach detects changes that may have taken place days earlier before a visible change in leaf area is observed.

New systems that can detect poor growth before visual symptoms occur are preferred. Recent advances in remote sensing techniques for high-throughput phenotyping, that is, non-destructively capturing plant trait responses to environmental changes are available.[21] Thus, future food production systems may be outfitted with multi-sensor packages for imaging plants in near real-time over the entire growth cycle from germination to maturity. The candidate sensors to be evaluated include a range of remote sensing tools including spectroradiometry, visible to far-infrared, hyperspectral, thermal, and fluorescence to trichromatic imaging.[22-24] These systems may respond by raising alarms to changes due to nutrient deficiencies, drought, flooding, or microbial/fungal infections, thus giving time for the crew to mitigate the problems causing poor plant growth. Eventually, these systems could become autonomous using robotics.

B. Food Safety Considerations

To ensure that the 'Pick-and-Eat' fresh food produced is safe for human consumption, a Hazard Analysis Critical Control Point (HACCP) plan is needed. Critical control points throughout all phases of food production, growth, harvest and post processing are identified, evaluated and monitored via microbiological testing.[25] Appropriate control measures can be implemented to minimize microbiological risks when potential hazards are determined in the process. Microbiological testing of raw materials, water, effluent and produce provide an understanding of the microbial ecology (population density and types of bacteria and fungi) of food production systems.

HACCP plans have been implemented for food crop systems in space. For example, micro-biological analysis was performed on edible plants grown in the Russian vegetable production unit, LADA and used to develop a HACCP plan[26, 27]. Currently, similar data is being collected during crop production cycles in Veggie on ISS (Figure 2).

In LADA and Veggie, samples are returned to Earth from space for analysis to verify the efficacy of the HACCP plans. On long duration missions beyond LEO, sample return of microbial samples will be impossible, so inflight methods for verifying the HACCP plan need to be developed and implemented. New technologies using spaceflight rated sequencers and/or PCR instrumentation (e.g., MinIon and RAZOR) will be needed. The use of proxy measurements provided by plant health imaging systems could be used[21], but ultimately a HACCP plan requires near-realtime measurements of the microbial ecology of the food production system.

Process Step/Control Point	Food Safety hazard	Methods to reduce hazard	CCP
Ground processing-Pillows	Introduction of microbes via handling and materials.	Sterilize components, aseptic technique used while assembling	1
Ground Processing-Seed	Introduction of microbes via handling and indigenous microbes present on seeds	Disinfection. Certification of pathogen free seed. Use of sanitary handling practices	2
Packing	no		
Transport	no		
Integrate with Veggie hardware	Introduction of microbes via handling.	Use of sanitary handling.	3
Watering	Introduction of microbes via water supply or unsanitary handling	Water is potable quality and treated with biocide.	4
Grow	Potential contamination from air and human presence, increase in indigenous flora due to availability of nutrients.	Use of sanitary handling. Minimize handling of plants before harvest.	5
Harvest	Introduction of microbes due to harvest procedures/human handling.	Sanitized instruments should be used and gloves worn.	6
Post-harvest	Microbial presence established during plant growth and introduction via handling.	Crops should be sanitized before consumption following procedures. Veggie facility should be thoroughly sanitized.	7

Figure 2. Critical control point analysis of crops grown in Veggie.

V. Improved Plants

Newly identified plant species and cultivars with improved growth habits and contents of antioxidants, vitamins, and minerals when grown in spaceflight environmental conditions (e.g. elevated CO_2 concentrations and low relative humidities) are needed. Recent cultivar selection studies for a 'Pick-and-Eat' fresh food production system conducted at NASA KSC have found that for appropriate selection, plants must be grown in the conditions they will experience in spaceflight. The combination of varied ventilation[28,29], low humidity (45%), spectral quality[30], and elevated CO_2 (3000 umol mol^{-1})[31] affects plant germination, growth habits, biomass production, nutritional value, and even flavor. Recent findings from climate change studies suggest that plants growing in elevated CO_2 (at much lower concentrations than those typically found in spacecraft) can lose nutritional value (i.e., less zinc, iron and vitamins).[32,33] These losses may be accentuated in spacecraft atmospheres, thus, the development of genetically engineered and biofortified crops may be needed. This can be accomplished by the application of genome editing tools for crop improvement to enhance yield, disease resistance, and nutritional value.[34,35,36]

VI. Conclusion

New technologies will be needed as spaceflight plant growth systems transition from being platforms for conducting biological research to becoming fresh food production systems. These technologies include: 1) the development of sustainable, soilless water and nutrient delivery systems that minimize the use of consumables (e.g., porous media) and optimize plant growth, 2) developing autonomous plant health and food safety monitoring systems for providing safe 'Pick-and-Eat' leafy crops to supplement stored diets, and 3) the development of biofortified crops with increased minerals and vitamins to overcome potential mineral deficiencies from growing in elevated CO_2 concentrations to ensure proper astronaut nutrition and health during future cislunar, lunar and martian missions.

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References

[1] Zabel, P., Bamsey, M., Schubert, D., and Tajmar, M. Review and analysis of over 40 years of space plant growth systems, *Life Sciences in Space Research*, Vol. 10, 2016, pp 1-16.

[2] Stutte, G.W., Monje, O., Wheeler, R.M. *International Space Station Researcher's Guide to Plant Science*. Ed. A. Rai. 2015. NASA ISS Program Science Office.

[3] Wheeler, R.M. Agriculture for Space: People Places and Paving the Way. *Open Agriculture*, 2017, Vol. 2, pp14-32.

[4] Wheeler, R.M. Plants for human life support in space: from Myers to Mars. *Gravitational and Space Biology*, 2010, Vol. 23, pp25-35.

[5] Monje, O., Stutte, G.W., Goins, G.D., Porterfield, D.M., and Bingham, G.E. Farming in space: Environmental and biophysical concerns. *Adv. Space Res*. 2003, Vol. 31, pp 151-167.

[6] Monje, O., G. Stutte, and D. Chapman. Microgravity does not alter plant stand gas exchange of wheat at moderate light levels and saturating CO_2 concentration. *Planta*, 2005, Vol. 222, pp 336-345.

[7] Stutte, G.W., O. Monje, G.D. Goins, and B.C. Tripathy. Microgravity effects on thylakoid, leaf, and whole canopy photosynthesis of dwarf wheat. *Planta*, 2005, Vol. 223, pp 46-56.

[8] Morrow, RC, Richter, RC, Tellez, G, Monje, O, Wheeler, RM, Massa, M, Dufour, N, and Onate, B. A new plant habitat facility for the ISS. 2016, ICES-2016-320.

[9] Massa, G.D., Wheeler, R.M., Morrow, R.C., Levine, H.G. Growth chambers on the International Space Station for large plants. *Acta Hortic*. 2016, Vol. 1134, pp 215-222.

[10] Anderson, M.S., Barta, D., Douglas, G., Fritsche, R., Massa, G., Wheeler, R.M., Quincy, C., Romeyn, M., Motil, B., and A. Hanford. Key gaps for enabling plant growth in future missions. *AIAA Proceedings*, Oct. 2017. AIAA 2017-5142.

[11] Cooper, M., Douglas, G., Perchonok, M. Developing the NASA food system for long-duration missions. *J. Food Sci.* 2011, Vol. 76, pp R40-R48.

[12] Douglas, G., Cooper, M., Bermudez-Aguirre, D., Sirmons, T. 2016. Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System. NASA Human Research Program. Human Health Countermeasures Element. https://humanresearchroadmap.nasa.gov/evidence/reports/AFT.pdf?rnd=0.981214270452603

[13] Zwart, S.R., Kloeris, V., Perchonok, M., Braby, L., Smith, S.M. Assessment of nutrient stability in foods from the space food system after long-duration spaceflight on the ISS. *J. Food Sci.* 2009, Vol. 74, pp H209-H217.

[14] Cooper, M., Perchonok, M., Douglas, G.L. (2017) Initial assessment of the nutritional quality of the space food system over three years of ambient storage. *npj Microgravity* 2017, Vol. 3 pp:17.

[15] Berry, W.L., and Knight, S., "Plant Culture in Hydroponics", *Plant Growth Chamber Handbook*. Iowa Agriculture and Home Economics Experiment Station Special Report No. 99 (SR-99) and North Central Regional Research Publication No. 340. Ed. by R. W. Langhans and T. W. Tibbitts, Iowa State University, 1997, pp 119-131.

[16] Furfaro, R., Gellenbeck, S., Giacomelli, G., and Sadler, P. Mars-Lunar Greenhouse (MLGH) prototype for bioregenerative life support systems: Current status and future efforts. 2017, ICES-2017-347.

[17] Dreschel, T.W., and Sager, J.C. Control of water and nutrient using a porous tube: A method for growth plants in space. *HortScience*, Vol. 24, 1989, pp 944-947.

[18] Massa, G.D., Dufour, N.F., Carver, J.A., Hummerick, M.A., Wheeler, R.M., Morrow, R.C., and Smith, T.M. VEG-01: Veggie hardware validation testing on the International Space Station. *Open Agriculture*, 2017, Vol. 2, pp 33-41.

[19] Li, Q., Li, X., and Gu, M. Growth responses and root characteristics of lettuce grown in aeroponics, hydroponics, and substrate culture. *Horticulturae*, 2018, Vol. 4, p35.

[20] Mungin, R. M., Weislogel, M. M., Hatch, T. R., McQuillen, J. B., "Omni-gravity Hydroponics for Space Exploration," 49th International Conference on Environmental Systems, ICES-2019-242, 7-11 July 2018, Boston, Massachusetts

[21] Park B., Yoon SC. 'Real-Time Hyperspectral Imaging for Food Safety'. In: Park B., Lu R. (eds) *Hyperspectral Imaging Technology in Food and Agriculture*. 2015. Food Engineering Series. Springer, New York, NY

[22] Gowen, A.A., O'Donnell, P.O., Cullen, P.J., Downey, G., and Frias, J.M. Hyperspectral imaging – an emerging process analytical tool for food quality and safety control. *Trends Food Sci & Technol*, 2007, Vol. 18, pp 590-598.

[23] Huang, P., Luo, X., Jin, J., Wang, L., Zhang, L., Liu, J., and Zhang, Z. Improving high-throuput phenotyping using fusion of close-range hyperspectral camera and low cost depth sensor. *Sensors*, 2018, Vol. 18, p2711.

[24] Tewey, K., Lefcourt, A.M., Shilts, P., Tasch, U., Kim, M.S. Hyperspectral, time-resolved, fluorescence imaging system for large sample sizes: Part I. Development of high energy line illumination source. *Transactions of the ASABE*, 2018., Vol 61, pp 381-389

[25] United Fresh Produce Association Food Safety & Technology Council. White Paper on Microbiological Testing of Fresh Produce. 2010.

[26] Hummerick, M.E., Garland, J.L., Bingham, G., Sychev, V.N., Podolsky, I.G. Microbiological analysis of Lada Vegetable Production Units (VPU) to define critical control points and procedures to ensure the safety of space grown vegetables. 2010, AIAA Tech. Paper 2010-6255.

[27] Hummerick, M.E., Garland, J.L., Bingham, G., Sychev, V.N., Podolsky, I.G. A hazard analysis critical control point plan applied to the Lada vegetable production units (VPU) to ensure the safety of space grown vegetables. 2011, AIAA 2011- 5277.

[28] Kitaya, Y., Kawai, M., Tsuruyama, J., Takahashi, H., Tani, A., Goto, E., Saito, T., Kiyota, M. The effect of gravity on surface temperature and net photosynthetic rate of plant leaves. *Adv. Space Res*., 2001, Vol. 28, pp 659-664.

[29] Musgrave, M.E., A. Kuang, S. W. Matthews. Plant reproduction during spaceflight: importance of the gaseous environment. *Planta*, 1997, Vol. 203, pp S177-S184

[30] Mickens, M.A., Skoog, E.J., Reese, L.E., Barnwell, P.L., Spencer, L.E., Massa, G.D., and Wheeler, R.M. A strategic approach for investigating light recipes for 'outredgeous' red romaine lettuce using white and monochromatic LEDs. *Life Sci. Space Res*., 2018, Vol. 19, pp 53-62.

[31] Lanoue,J., Leonardos, E.D., Khosla, S., Hao, X., and Grozinski, B. Effect of elevated CO2 and spectral quality on whole plant gas exchange patterns in tomatoes. *PLOS ONE*, 2018, Vol. 13, p8.

[32] Loladze, I. Hidden shift of the ionome of plants exposed to elevated CO2 depletes minerals at the base of human nutrition. *eLife*, 2014, Vol. 3, p e002245.

[33] Dong, J., Gruda, N., Lam, S.K., Li,X., and Duan,Z. Effects of elevated CO2 on nutritional quality of vegetables: a review. *Frontiers in Plant Sci*., 2018, Vol. 9, p 924

[34] McGloughlin, M.N. Modifying agricultural crops for improved nutrition. *New Biotechnology*, 2010, Vol. 27, pp494-504.

[35] White, P.J., and Broadley, M.R. Research Review-Biofortification of crops with seven mineral elements often lacking in human diets – iron, zinc, copper, calcium,magnesium, selenium, and iodine. *New Phytologist*, 2009, Vol. 182, pp49-84.

[36] Jaganathan, D., Ramasamy, K., Sellamuthu, G., Jayabalan, S., and Venkataraman, G. CRISPR for Crop Improvement: An Update Review. *Frontiers in Plant Science*, 2018, Vol. 9, p985.