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Two demonstration growout systems for off-world production of nutritionally rich crops to supplement resupplied staples

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Abstract

The most practical scenario for food production on off-world sites (i.e., Moon and Mars), incorporate the continuous resupply of long storage-life, high density staple crops and the on-site production of additional nutritionally rich vegetables, leafy greens, fruiting and medicinal crops. Together, combining high-density, long storage-life staples supplemented with fresh, edible crops will provide necessary nutrients, while also enhancing dietary variety. Anecdotal evidence also supports the psychological benefits for astronauts of growing crops, rooted in the enjoyment of eating and caring for plants. Highlighting the need not to forget the numerous herbs and spices, leafy greens, and fruiting crops that make any meal into a 'five-star' experience.

Two different types of growout modules have been constructed by students at the University of Alabama, Huntsville designed to operate as flow through media bed. The first is a traditional continuous flow media bed (2 @ 3 ft x 6 ft) and the second, six vertical tower systems, reflecting what NASA has pictured for a Mars colony. Using these two systems, a wide variety of research is being conducted on multiple crops looking at the best crops to grow, how to maximize productivity per volume, what environmental parameters are most important, what crops can be grown together and other growout issues. In addition, this research project has been recognized with a small grant from the Alabama Space Grant Consortium (NASA). Finally, design and construction details will be available via social media and web pages to help encourage and support school STEM Projects and 'citizen-scientist'.

Keywords: BLSS, crop production, media beds, vertical towers, hydroponics systems

Introduction

Why the interest now? For over fifty years, we have been waiting for a means to return to the Moon and the ultimate goal Mars. Projects have come and gone with studies and even flight hardware tested (NASA Artemis project), but we seem no closer to either the Moon or Mars than we were fifty years ago. SpaceX changed all this with a renewable first stage boaster to orbit that can lift off, return and fly again within weeks (in multiple cases close to 30 times). Elon Musk, founder of SpaceX has made it his life goal to colonize Mars within his lifespan. The currently under testing Starship is the most powerful reusable rocket ever built. In addition to being designed for full and rapid reuse, it will carry 100-150 tonnes to Mars. Thus, it was no surprise when Musk announced in September of 2024 that he hoped to land an uncrewed mission on Mars in 2026, a crewed mission in 2028 and build a self-sustaining city in about twenty years [1]. This helps explain the pressing need to define what self-sustaining colony means in terms of food crop production and the research, system development and large-scale demonstration that will be required.

Albeit with a different strategy and focus, Blue Origin is also involved in long term space flights and support of astronauts. Its development of the New Glenn rocket suggests an interest in flying missions to the Moon or Mars with significant payload. Although not involving human missions at this time, the project indicates a technical capacity to consider doing so in the future. At any rate, Blue Origin's capacity to deliver payloads up to Mars is of primary relevance for the work described here.

Blue Origin's development of the low Earth orbit "Orbital Reef" project, designed to accommodate a 10-person crew, also illustrates its interest in long-term space mission support. While the differences with a LEO space station and a flight to the Moon or Mars for colonization are obvious (in particular in the gravity experienced by the astronauts and colonizers) so are the similarities in term of having to support the physical and mental well-being of a crew.

The most practical scenario for Biological Life Support Systems (BLSS) and food production on off-world sites such as the Moon and Mars [2], incorporate the continuous resupply of long-storage-life staple crops packed at high density and volume, such as wheat flour, barley, rice, and others with storage life in excess of 15 years [3], and the on-site production of additional nutritionally rich vegetables, leafy greens and fruiting plus medicinal crop. Although, sophisticated nutritional analysis has been conducted over the past decades to develop the optimal mix of staples and on-site grown crops to meet the nutritional requirements of the crew [4,5]. Overlooked in all these scenarios is that unless the food actually tastes good and is appealing to the crew, little good will come of the most sophisticated analysis and earth-based demonstration projects. Thus, the need not to overlook the numerous herbs and spices, leafy greens, and fruiting crops that with the proper chef make any meal into a 'five-star' experience. This research project examines production methods for some of the obvious and lesser-known crops that need to be included in any "gourmet" BLSS system.

In addition to providing much needed variety in food preparation, BLSS through the cultivation of a variety of plants plays a crucial role by contributing to all major functional aspects of long-term life-support systems (e.g., specialty food production, carbon dioxide reduction, oxygen production, water recycling, and waste management). Furthermore, fresh crops are not only beneficial for human physiological health providing both trace nutrients and vitamins, but also been shown to have a positive impact on crew psychological well-being, acting as a countermeasure to psychological or behavioral conditions on long term missions. [6,7].

In recognition that a diet composed exclusively of shelf-stabled packed food items would be nutritionally inadequate, the 2020 NASA Technology Taxonomy under TX06.3.5 Food Production, Processing and Preservation section [8] specifically includes development of food production technologies that include bioregenerative food system, vegetable production systems and plant habitats. This research reflects goals proposed by the Science Mission Directorate, Biological and Physical Sciences Division for 2016-2025. One of the expected outcomes of the studies on Plant Biology is the "great value in adding fresh food on a regular basis to the crew's diet" [9].

On several occasions, NASA has encouraged research into extra-terrestrial food production and been involved in several small-scale demonstration projects. One of the more interesting approaches has been through the use of a Centennial Challenges (CC) program used to "develop and execute public prize competitions" [10]. The Deep Space Food Challenge (DSF) was designed to "create novel food production technologies with minimal inputs, and maximum safe, nutritious, palatable food outputs for long-duration space missions" [11]. Among the goals was to provide supplemental food for a crew of four for a three-year round-trip mission to Mars, grow the largest possible food crop with minimal inputs and finally create a "variety of palatable, nutritious and safe foods that require little processing time for crew members". Recently, the three Phase 3 winners have been announced [12] for ground test validation of the proposed technology and three awards granted. The U.S. winner and recipient of the $750,000 grand prize was Interstellar Lab of Merritt Island, Florida. Led by Barbara Belvisi, the small business combines several autonomous phytotrons and environment-controlled greenhouses to support a growth system involving a self-sustaining food production mechanism that generates fresh vegetables, microgreens, and insects necessary for micronutrients. Although it should be pointed out that of the nine "phytotrons" only six are for production of leafy green crops, insects or mushrooms and each is only the size of the Veggie systems on the ISS. This is hardly sufficient production to supplement a crew of four for three years. An additional system design proposed looks very much like the traditional stacked towers used by several other research systems including most notably the EDEN project from ESA [13,14].

Another NASA success is in education collaborations, which suggests that at least some of this needed research may be generated in different ways, including significant *citizen-science contributions* [7]. A prime example to this approach is a 2015 NASA established partnership between Fairchild Tropical Botanic Garden and NASA Science Mission Directorate. Growing Beyond Earth (GBE) is now underway in 500 middle and high schools from 48 states nationwide and 10 countries [15]. GBE is unique in its focus on classroom based scientific research, enabling high school student community 'scientists' to actively contribute data toward NASA mission planning. Each classroom receives a Fairchild-designed plant habitat analogous to the Vegetable Production System currently on the ISS [16].

Anderson [6] reviewed the numerous gaps in research to enable plant growth in future space and off-world missions. Although most of the research and production system designs over the years have been focused on zero-gravity systems (since the only system for demonstration was the ISS), this research proposal focuses more on off-world sites with a gravity well that although less than earth normal are still a significant fraction of 1g. The reason being the significantly longer time that will be spent there compared to the short travel times to the Moon and relative short time to Mars. In addition, almost by definition, space, power and labor will be extremely limited during the short flight to and from these off-world sites as compared to off-world sits.

The phrasing currently being used by the NASA Human Research Program (HRP) roadmaps is a plant growth system that operates as a "Pick-and-Eat" system [8] or as "cut-and-come-again". As outlined in this report: "the intent is that the salad or fruit crops grown in the system will grow robustly with minimal resources, require minimal processing (e.g., disinfection), and can be consumed raw". Although this type of system does not provide a significant contribution to the daily caloric intake of the crews, it does supplement vitamins and nutrients that are degraded during processing and storage over long-term missions, such as several years on Mars, and provide variety and interest in the diet.

Based on its record, NASA has shown very little interest or commitment to long-term research either in the past, the present, or the future on large-scale food production. This is most likely because the need for such research was limited and in the perceived distant future. Only the future is now, SpaceX has demonstrated and is committed to sending both significant resources and people to either the Moon or Mars in the very near-term future.

System Design

There will never be fields of waving wheat or corn on Mars, at least in this millennium. But there will be large scale hydroponics in surface greenhouses, regolith covered growout modules and subterrain lava tubes. In addition, we also need to divest our thinking that crop production on extra-terrestrial worlds require extremely complex systems utilizing state-of the-art monitoring and control systems, AI based control and futuristic system components. The reality is that plants have had millions of years to evolve to growth in a wide range of environmental conditions and possess the genetic variability to adapt to almost any environment within reason. Thus, we do not need dedicated crop research scientists or engineers to grow the crops.

So, the next question is how do we close the “Key Gaps for Enabling Plant Growth in Future Missions?” [6]. Reviewing early research efforts for examples, suggests the primary problem with systems on the ISS and many earth-based designs is first that they were designed for zero-gravity cultivation and second their small size, being only able to grow a very limited number of crops. The reality is that the majority of crew time will be living on off-world sites with only short transit times, thus both partial gravity (one sixth earth normal on the Moon and one third on Mars) should be considered a given and adequate space and resources to construct large scale growout modules.

Several different options for hydroponics system designs have been developed over the past decades and employed in many of the earth analog simulations studies. These primarily involve how the roots maintain contact with the nutrient solution, either through misting or submersion. Aeroponics is one of the first system design, utilized by Wheeler and associates at NASA’s Kennedy Space Center Breadboard Project in 1985 forty years ago. Although in those days, it was called a “continuously flowing, thin-film nutrient delivery system.” In an aeroponics system the plants are suspended from a horizontal surface and the roots grow down, suspended in the air and are periodically misted or sprayed with a nutrient solution that delivers all the macro- and micronutrients the plants need to grow. In this manner, the roots are supplied with both a high level of nutrients and high oxygen levels. The primary disadvantage of aeroponic systems is the high technical complexity, requiring more precise control and maintenance to prevent clogging of the emitters and ensure the plant roots receive adequate nutrients. One common failure mode, i.e., no power experienced by most researchers, can result in the roots drying out and loss of the plants or at least significant impact on growth. Finally, plants are usually suspended in a fixed pattern of holes with no easy adjustment to spacing or density as they grow.

The authors have a great deal of experience utilizing a continuous flow media-based hydroponic bed, where plants are grown in a grow bed filled with media, such as gravel, expanded clay pellets, or lava rocks which provides physical support for the plant roots and aids in maintaining a healthy root environment. In this design, a continuous flow of water moves from one end to the other in the bed, several centimeters below the medias surface. The water depth controlled by an outlet standpipe. After flowing through the bed, the nutrient rich water then drains back to a reservoir tank, where it is aerated, temperature regulated and pumped back into the bed. The continuous flow media bed hydroponic system was chosen over aeroponic systems for several reasons. One of the primary reasons is in a failure mode, i.e., no power, the roots remain in nutrient bath, continue to grow and can survive for not hours, but days. In addition, most aeroponic designs use a fixed pattern of holes for plants, thus limiting options as to spacing, density and limiting transplanting. With a media bed, plants can be grown in almost any spacing, density and transplanting is easy with minimal transplant shock.

To demonstrate the utility of this design, two media-based demonstration systems have been constructed or are under construction at the University of Alabama Huntsville research greenhouses by the students in the Biology Department. The first to show proof-of-concept was built on two existing greenhouse work benches in the rooftop research greenhouse (see Figures 1 and 2). These were constructed over a period of several months during the fall semester (2014) by students from the Department of Biology. They were approximately 0.76 m x 1.82 m x 15 cm (30 in x 72 in by 6 in) using construction materials (2 x 6’s, plywood and a pool liner), expanded clay media and a reservoir tank purchased from a local DIY (do it yourself) chain store. Each reservoir has a float vale to maintain water level in the reservoir and a simple aquarium heater to control temperature. As previously stated, these are designed to operate as a continuous flow through media bed, where small expanded clay pellets (1 cm in diameter) act as a support system for plants initially started in sustainable plant seed cubes. The two media bed layouts allow multiple crops to be grown at two different nutrient concentrations (high electrical conductivity for fruiting crops and lower for leafy greens). Each modular bed has 12 growout areas, each 0.31m x 0.35 m, allowing for multiple crops (up to 24) to be grown simultaneously and at different growout stages, hydroponic water quality, lighting, and limited temperature control. Thus, a wide variety of research can be conducted on multiple crops looking at the best crops to grow, how to maximize productivity per volume, what environmental parameters are most important, what crops can be grown together and other growout issues [6]. Design and construction details are available from the corresponding author.

Figure 1. The prototype herbs and leafy greens continuous flow media bed.

Figure 2. Prototype veggies and fruiting crops continuous flow media bed.

A wide variety of crops have been raised in the two systems (Table 1 and Figure 3) over the past eight months with no significant problems. And other than planting, harvesting and bi-weekly water quality checks, there has been no significant maintenance requirement, by design.

Table 1. Crops successfully cultivated in the two media bed systems (scientific name provided in italics).

Herbs		**Leafy Greens Crops**	
Basil Genovese	*Ocimum basilicum*	Celery	*Apium graveolens*
Basil Red Rubin Red		Chard Swish Bright Lights	*Beta vulgaris*
Basil Compact Prospera		Chard Swish Chard Rhubarb	
Chives	*Allium schoenoprasum*	Lettuce Buttercruch	*Latcuca sativa*
Cliantro	*Coriandrum satiuum*	Lettuce Green Butter Salanova	
Dill Fernleaf	*Anethum graveolens*	Lettuce Outrageous	
Mint	*Mentha*	Lettuce Red Butter Solanova	
Mustard Green Amara	*Brassica juncea*	Lettuce Waldmann's Dark Green	
Oregano	*Origanum vugare hirtum*	Lettuce Romane Sunland	
Parsley	*Petroselinum crisum*	Pac Choi-Joi Choi	*Brassica rapa*
Rosemary	*Rosmarinus officinalis*	Pac Choi-Win-Win Choi	
Sage	*Salvia offincalis*	Pak Choi Dwarf	
Tyme German White	*Thymus*	Spinach	*Spinacia oleracea*
Watercress	*Nasturtium officinale*		
Vegies Crops		**Medicinal Crops**	
Beans, snap	*Phaseolus vulgaris*	Bee Balm	*Mondarda didyma*
Beets	*Beta vulgaris*	Chamomile	*Matricaria chamomi*
Cellery Conquistqador	*Apium graveolens*	Chrysantheymum	*Chrysandtheymum m*
Cucumbers Corinto	*Cucumis sativus*	Comfrey	*Symphytum officinale*
Peas, Snow	*Pisum sativum*	Fennel	*Foeniculum vulgare*
Peppers- King Arthur	*Capsicum annuum*	Golden Oregano	*Origanum vulgare A*
Peppers Hot -Pot-a-peno	*Capsicum annuum*	Holy Basil	*Ocimum tenuiflorum*
Radish	*Raphanus sativus*	Lavender	*Lavandula angustifol*
Spinach	*Spinacia oleracea*	Motherwort	*Leonurus cardiaca*
Tomato Red Robin	*Solanum lycopersicum*	Pineapple Sage	*Salvia elegans*
Tomato Tinny Tim			
Turnips Hakuren	*Brassica rapa*		

Figure 3. Currently grown harvested crops.

The next stage for this research project will be the construction of up to six stand-alone vertical towers (Figure 4), supported by a research grant from the Alabama (NASA) Space Grant Consortium. These vertical towers would more closely reflect production modules often pictured in NASA drawings for Mars habitats and reflect several earth-based analogs. These might be employed on the Moon and Mars in surface greenhouses, regolith covered growout modules or underground facilities using lava tubes. As with the media beds, the system uses readily available materials from DIY stores and simple construction skills and tools. Six growout systems would provide ample room for multiple crops (herbs, leafy greens, veggies, and medicinal plants). Each tower systems would be a standalone research module to allow replicate studies, looking at lighting, nutrient levels, pH, temperature, crop density, and other production variable. These six systems would be used for both research and outreach to school STEM projects through social media outreach and campus visits.

Figure 4. Tower growout media bed systems.

To minimize construction costs, almost all of the system components were purchased from a local DIY chain store and Amazon.com. This was done not just to save money, but to make the design and construction within the reach of school, non-profits, and committed ‘citizen-scientists’. Thus, the tower itself is a metal heavy 5-tier duty utility shelf (Figure 4). The media beds are constructed with 1x6 common softwood boards with a ¼” plywood base and 1x2 top plates. The liner is a backyard PVC (polyvinyl chloride) pond liner and the pump a simple submersible fountain pump. The media was clay pebbles from Amazon, whose originally purpose was for backyard ornamental gardens. LED (light-emitting diode) lights have come down in cost the past few years and are now almost cheaper than the standard fluorescent grow lights, especially when cost of bulb replacement is considered. Thus, the cost for one tower system including all the miscellaneous parts, plus PVC plumbing fittings is approximately $1300. Half of this cost is for the LED lights and expanded clay media. Construction is very simple requiring only the minimal construction skills.

It quickly became apparent that the large number of seedlings required for transplant into the dozen plus media beds was far above the current seedling system capacity. Thus, a small seedling production system was designed and constructed using as a base a 5-tier steel utility shelving unit (Figure 5). A total of six planting trays (46-1/2"L x 15-1/2"W x 2"H), two planting trays per shelf was thus accommodated. Each planting tray holds a standard 1020 propagation trays with drainage holes. Each propagation tray could hold a maximum of 104 -1.25” planting cubes. Full Spectrum LED Plant Grow Light were suspended over each try, allowing for different light levels or intensity. A submersible fountain pump in a small reservoir was controlled by a timer that turned the pump on for 15 minutes several times a day. This flooded each of the planting trays and then drained quickly. Because of the drainage holes in the propagation trays, each of the planting cubes was then watered from below as many times a day as needed.

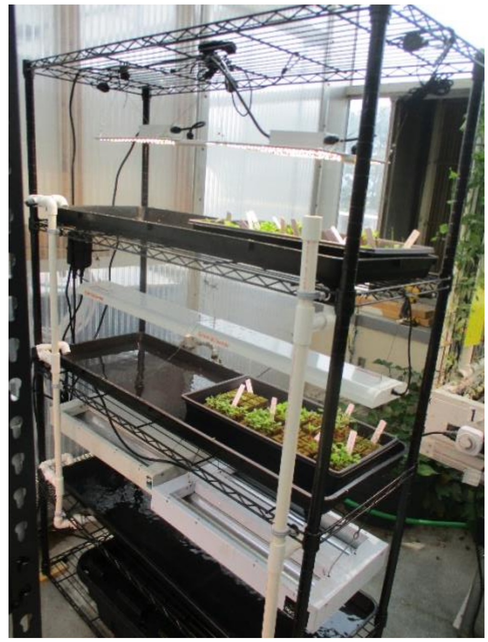

Figure 5. Seedling production systems.

Discussion

This project addresses the practicability of continuous flow and vertical beds for producing crops in simulated lunar or Martian environments. The preliminary results described here indicate that a large variety of crops can indeed be cultivated with low maintenance, low failure, and high resilience, making the system of interest here attractive for future deployment in extraterrestrial settings with limited or nonexistent local environmental resources.

This work is being actively pursued: several more tower modules are being constructed over the next few months to provide our student workforce a practical construction experience. The list of successfully grown crops will be reviewed and expanded. In phase with our academic mission and with NASA’s emphasis of participatory innovation models, this project also fulfills a pedagogical function. Several student interns will be hired during the upcoming semesters to manage the systems: i.e., biweekly water quality, seed selection and planting, harvesting and data recording. One of the initial goals is to routinely harvest crops on a weekly or biweekly basis to provide some consistence in crop availability. The students’ work is already being communicated in poster presentations nationally and internationally, and included in a successful Alabama/NASA Space Grant Consortium.

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Conflict of Interests

The authors declare that they have no conflicts of interest with the contents of this article.

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