µG-LilyPond™: Preliminary Design of a Floating Plant Pond for Microgravity

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Versatile, reliable, and efficient space crop production systems can provide nutritional supplementation and a psychological benefit to the crew, while potentially reducing the mass of food provision for deep space exploration missions. Aquatic plants have enormous potential to provide atmosphere regeneration, edible biomass production, biofuel generation, and even metabolic wastewater treatment, but have been little studied as potential food crops for space applications. µG-LilyPond™ is an autonomous environmentally controlled floating plant cultivation system for use in microgravity. The system expands the types of crops able to grow in space to include aquatic floating plants. µG-LilyPond™ is designed to be low maintenance, robust, volume efficient, and versatile. It features passive water delivery, full life cycle support via vegetative propagation, and close canopy lighting. Through a NASA STTR Phase I project, Space Lab and the University of Colorado at Boulder established feasibility of floating aquatic plant cultivation in microgravity and developed the plant growth chamber system concept. In Phase II, the team is developing an engineering demonstration unit (EDU) that will verify and validate the µG-Lilypond™ design. The EDU will demonstrate low-TRL technologies (water transport, nutrient medium recycling, harvesting, close canopy PAR delivery, and radiant heat dissipation), as well as extensibility to support higher rooted plants. Finally, the µG-Lilypond™ water transport and harvesting capabilities will be tested in a relevant microgravity environment via a Blue Origin suborbital flight. This paper reviews the µG-Lilypond™ system concept, performance predictions, and prototype demonstrations to date.

Nomenclature

CU = University of Colorado at Boulder
EDU = Engineering Demonstration Unit
ESM = Equivalent System Mass
MLE = Mid-deck Locker Equivalent
MOE = Measure of Effectiveness
MTL = ISS Moderate Temperature Loop
PAR = Photosynthetically Active Radiation
PPFD = Photosynthetic Photon Flux Density
STTR = Small Business Technology Transfer program
TRL = Technology Readiness Level

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I. Introduction

VERSATILE, reliable, and efficient space crop production systems can provide nutritional supplementation and a psychological benefit to the crew, while potentially reducing the mass of food provision for long duration space exploration missions. NASA's technology roadmap notes that self-sufficiency of life support systems is crucial for long-duration exploration missions, which will be achieved through resource recovery, system closure, high-reliability, integrated autonomous control systems, and minimal resource use. Regenerative space life support technologies that recycle consumable materials and recover resources from waste products will increase life support self-sufficiency, through reduced requirements for resupply.[1] Ultimately, fully regenerative life support will require food production to recover nutrients and close the carbon loop in a spacecraft habitat. Plant-based food production systems also provide other life support functions, such as CO_2 removal, O_2 production, water recovery, and waste recycling. Experiments investigating plant growth and cultivation in space began in the 1960s, supported by numerous plant growth systems. Ref. 2 provides a detailed review of twenty-two plant growth systems developed for space life science studies. The reliability and capability of space plant growth chamber designs have evolved significantly over time from decades of lessons learned. Currently, there are two plant growth chambers in operation on the International Space Station (ISS): Vegetable Production System (Veggie) and Advanced Plant Habitat (APH). These plant growth chambers represent the culmination of lessons learned from decades of plant science experiments in microgravity. However, challenges still remain that prevent continuous crop production through multiple plant life cycles. These challenges include reliance on one-time use substrate (increasing consumable mass costs); reliance on the crew to manually harvest and propagate crops (increasing crew time costs), and persistent challenges with reliable water and nutrient delivery to plant roots in microgravity. In addition, state of the art space plant growth chambers do not support growth of floating aquatic plants, which are a potentially valuable addition to the crew diet and to regenerative space life support architectures.

Space Lab Technologies, LLC (Space Lab), in collaboration with the University of Colorado at Boulder (CU) are developing an innovative space crop production system called μG-LilyPond™. This growth chamber concept expands the types of crops that can be grown in microgravity to include aquatic floating plants as nutritional supplements to the crew diet. μG-LilyPond™ also provides increased autonomy, reliability, volume efficiency, and mass efficiency in production of a variety of food crops (both aquatic and land plants). This paper provides an overview of duckweed as a new space crop, the μG-Lilypond™ growth chamber concept, preliminary performance predictions, and prototype demonstrations to date.

II. Duckweed: An Attractive Edible Plant for Crew Diets

Even though plants provide valuable human life support, producing food, reducing toxic carbon dioxide into breathable oxygen, and even purifying wastewater, they have not yet been used in this capacity for human spaceflight. This is partially due to the high resource costs for growing plants in space (e.g. energy, water, and volume for equipment). Therefore, an attractive space crop is one that minimizes the use of mass, volume, crew time, and energy, while also maximizing CO_2 consumption, growth rate, harvest index, and nutritional density. A desirable space crop is one that thrives in a high CO_2 environment, while requiring little space, infrastructure, or crew time for cultivation and preparation. It grows fast, does not waste energy on creating inedible parts, is nutrition packed, and tastes good.

Most bioregenerative life support systems concepts developed thus far have been based on higher land plants.[3] Ref. 3 cites several difficulties with land plants for food production that include 1) gravitropic complications in reproduction; 2) challenges in nutrient delivery due to loss of convection in microgravity; and 3) the need to dispose of large volumes of inedible biomass. Ref. 3 suggests that plant aquaculture may solve these problems. In addition, many aquatic plants are consumed by human populations around the world, such as water chestnuts, watercress, etc. Aquatic plants have enormous potential to provide atmosphere regeneration, edible biomass production, biofuel generation, and even metabolic wastewater treatment, but have been little studied as potential food crops for space applications.[4] In particular, small floating macrophytes like Duckweed (family Lemnaceae) can offer valuable fresh food supplementation to crew diets during long-duration exploration missions. Also known as water lentils or water meal, the tiny flowering plants are 100% edible (with no inedible biomass), nutritionally dense, exceptionally fast growing, and able to thrive in nutrient rich wastewater. Space Lab, in collaboration with the CU, is working to establish duckweed as a nutrient dense space crop for deep space exploration. Duckweed is the smallest flowering plant in the world,[5] found free-floating on still or slow flowing fresh-water bodies all over the globe. The Lemnaceae family includes 37 species in 5 genera, *Lemna, Spirodela, Landoltia, Wolffia,* and *Wolffiella*[6]. Figure 1 shows an example of three commonly studied genera.[7] Several distinct characteristics make this plant attractive for space applications:

Figure 1. *Spirodela* (large), *Wolffia* (small), and *Lemna* (medium).[7]

1. *100% Harvest Index:* The plant has little fibrous tissue, and thus no inedible biomass. All sequestered CO_2 goes to crew diet.
2. *Can be Eaten Raw:* The plant can be consumed as a fresh vegetable. It is a ‘pick-and-eat’ crop that can be easily incorporated into crew meals, with little preparation time.
3. *Vegetative Propagation:* Though it is a flowering plant, duckweed primarily reproduces through vegetative budding. Over a 10-day period, an individual mother frond may produce up to 10 daughter fronds before dying.[5] This continuous plant propagation requires no crew time for pollinating or replanting.
4. *High Growth Rate:* Duckweed is among the fastest growing plants in the world, doubling its mass in 1-3 days under ideal conditions.[8] This allows *very* high biomass yield per growth area.

Figure 2. *Lemna minor*.

5. *Small Size:* Flat leaf-like ovoid parts, called fronds, range from 1-20 mm across and are typically less than 1 mm thick. The plant requires very little infrastructure to contain its shallow aerial and root zones.
6. *Grows in Shallow Water:* This free floating aquatic plant is common in lakes, ponds, canals, rice fields, and ditches.[9] It can even grow in a trickle of water over vertical surfaces, such as seepages in cliffs,[9] on mud, or on water that is only millimeters deep.[10] Thus they can grow on still, thin films of water in shallow, stacked trays. Duckweed’s small size, rapid growth, and 100% harvest index affords edible biomass production that is several times more volume efficient than that of other typical land-based crops.
7. *Thrives in Elevated CO_2:* Duckweed grows readily under a range of CO_2 concentrations (up to 5%),[11] providing a high capacity for cabin CO_2 sequestration and oxygen production, in a cabin atmosphere. They have inactive, *permanently open stomata*, allowing continuous CO_2 uptake.
8. *Grows in 24-Hour Light:* With no dark period required, CO_2 can also be sequestered continuously.[11]
9. *Robust:* Duckweeds grow naturally on Earth in a wide range of growing conditions, including temperatures, CO_2, pH, nutrient composition, light intensity, etc. Therefore, duckweed growth should also be robust to an uncertain spacecraft environment (tolerating changes in pressure, temperature, CO_2, humidity, etc.). Furthermore, duckweed can grow in the dark with sucrose, allowing survival/recovery from power failure, and can be stored in a dormant state with little to no growth, providing capability to quickly recover in the event of crop loss.
10. *Have Been Grown in Low Earth Orbit:* Prior flight experiments indicate tolerance to radiation and microgravity environments, including NASA STS-4 Getaway Special (1982), Russian satellite Bion 8 (1987), Russian satellite Bion 10 (1992), NASA STS-60 Getaway Special (1994), and STS-67 (1995). On STS-67, Ref 12 noted microgravity effects on cell structure, which may be responsible for increased growth in simulated microgravity.[13]
11. *Preferential Uptake of Ammonia-N*, bestows a high capacity for human wastewater treatment.[4]
12. *Nutrient Dense:* When grown in nitrogen rich water, water lentils contain up to 45% protein with an amino acid composition similar or better than that of legumes such as soy or pea and meeting World Health Organization recommendations for human nutrition.[14,15] Duckweed fat contains 48 to 71% polyunsaturated fatty acids, with an omega-6 to omega-3 ratio <1 (similar to flaxseed).[16] Duckweeds are also a good source of beta-carotene (vitamin A), ascorbic acid (vitamin C), tocopherols (vitamin E), and the carotenoids zeaxanthin and lutein.[16,17] Antioxidants zeaxanthin and lutein protect the human eye (and other organs) against radiation damage,[18,19] which is very important for crew diets. These antioxidant vitamins and omega-3 fatty acids cannot be manufactured in the human body and are best taken up in food.[19] Fresh duckweed can deliver essential nutrients to the crew.
13. *Palatable and Bioavailable:* High nutritional quality would be of little value if the plant were not palatable or interfered with bioavailability of beneficial minerals and vitamins. Ref. 10 provides anecdotal reports of duckweed used throughout South Asia as a human food source. Burmese, Laotians, and Northern Thai people consume the genus Wolffia as a vegetable. Thai people refer to duckweed as “Khai-nam” or “eggs of the water” and regard it as highly nutritious.[20] While some duckweed species contain oxalic acid, which produces a bitter taste (like in spinach), oxalic acid content varies widely among species. In fact, *Wolffia* species do not product oxalic acid. Further, controlled growth conditions can reduce its accumulation, such as the concentration of ammonia in the water supply, pH, or light incidence.[10,21] Currently, two companies (Parabel in the United States and Hinoman in Israel) grow and market duckweed as a human food product due to its high nutritional quality.

III. µG-LilyPond™: Preliminary Design Overview

µG-LilyPond™ is an autonomous environmentally controlled plant cultivation system for use in microgravity that expands the types of crops that can be grown in space to include aquatic plants; is low maintenance (autonomous operation); performs reliably in its expected microgravity spacecraft environment (via passive water recycling); is efficient (minimal volume, mass, power, and water consumption); and allows autonomous full life cycle support via continuous vegetative propagation. Through a Phase I STTR award, Space Lab, in collaboration with the University of Colorado at Boulder, established feasibility of the µG-Lilypond™ concept, culminating in a conceptual chamber design. Subsequently, through STTR Phase II funding, the Space Lab and CU team is now developing a ground-based engineering demonstration unit (EDU) of the growth chamber, to demonstrate lower technology readiness level (TRL) functionality for duckweed production and extensibility of the growth bed to support higher rooted land plants.

A. Concept of Operations

The µG-LilyPond™ concept of operations (Figure 3) shows system operation from the perspective of a crew member. First, the crew will assemble the hardware, power it up, and inoculate the growth trays with an initial stock of duckweed fronds. The fronds will rest in shallow growth beds with conditioned, fertilized water. They'll grow and reproduce, and nutrients will be autonomously replenished. When the biomass grows dense, it is autonomously harvested. If there is a fault, the crew will be able to shut the system down for repairs. The system will need to be periodically cleaned. We are investigating autonomous cleaning methods to minimize crew maintenance time.

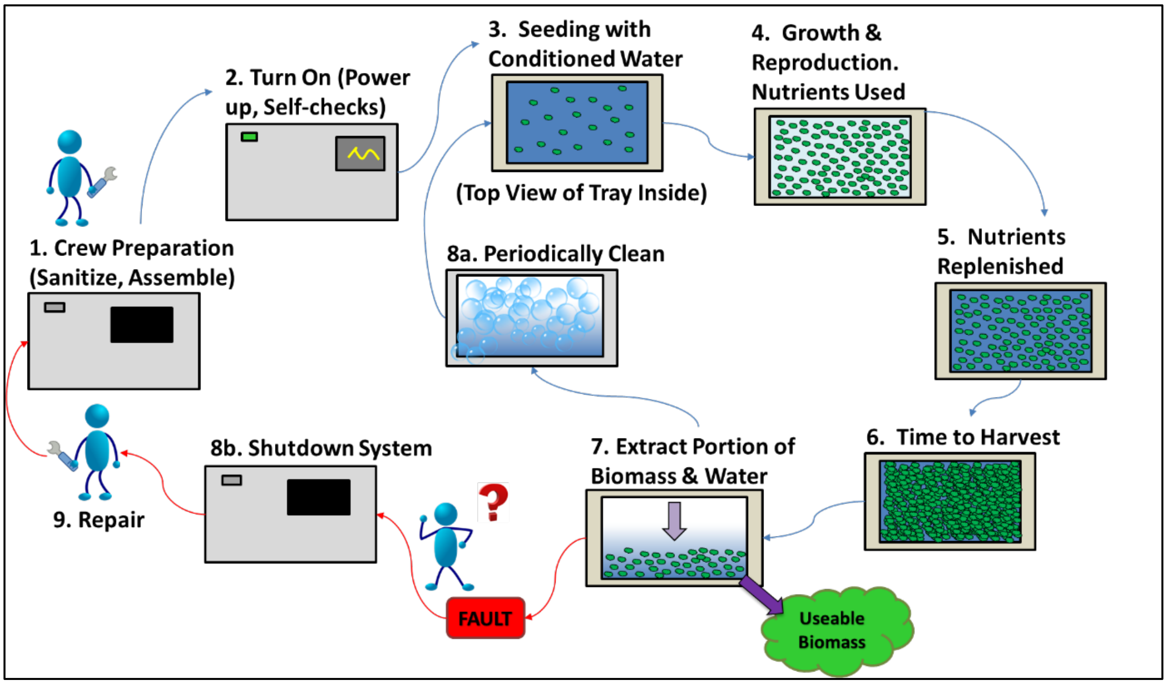


Figure 3. µG-LilyPond™ concept of operations diagram.

B. Requirements

The primary function of the µG-LilyPond™ system is to produce living aquatic plant biomass. The biomass should be edible, nutritious, and acceptable to the crew. µG-Lilypond™ should produce this biomass autonomously (with minimal crew intervention), safely, reliably, and efficiently. To accomplish these objectives, the µG-LilyPond™ system must provide the *following functions*: maintain temperature and humidity, maintain atmospheric conditions, manage water (deliver, condition, recycle), enable plant propagation (with daily harvest), enable biomass harvest or collection, deliver photosynthetically active radiation (PAR), process & communicate data, regulate power, mitigate pathogen and biofilm growth, and structurally contain and protect the plants and growth chamber subsystems. In short, the goal of any plant growth chamber is *to provide plants with the nutrients, water, light, and atmospheric conditions that maximize the production of edible, nutritious biomass*. The primary Measures of Effectiveness (MOEs) listed below quantify the value of the system to the user, serving as metrics for design trades and for system validation.

MOE1. Biomass Production Rate (g dry biomass produced/day-m^3)
MOE2. % Edibility (combination of taste, digestibility, pathogen load, toxicity, and viability)
MOE3. Nutritional Quality (weighted combination of protein, antioxidant, and vitamin content)
MOE4. Safety (likelihood of harm to spacecraft or crew)
MOE5. Robustness (performance variation over mission given variation in operating conditions)
MOE6. Autonomy (duration of continuous operation, without intervention)
MOE7. Efficiency (kilograms dry biomass produced per kilogram of equivalent system mass, or ESM)
MOE8. Usability (combination of learnability, memorability, error rate, and psychological impact)

Furthermore, the design must incorporate the following environmental constraints for growing *duckweed* plants:

- *Nutrients:* Duckweed thrives on nutrient-rich water & dissolved organic compounds. The plants utilize a variety of N sources, including urea, and prefers ammonium over nitrate. They require potassium and phosphorous in low amounts and concentrate these elements during periods of rapid growth. Duckweed can also metabolize sugar if nutrients are depleted, without light. Duckweed is renowned for its capacity to remove and sequester nutrients or other compounds from wastewater, so the medium must not contain elements toxic to humans.
- *Temperature:* In general, temperature should remain between 6°C to 33°C for maintaining metabolism and between 25°C to 31°C for optimal growth.[11] Temperature requirements are ecotype dependent.
- *Sunlight:* Increasing PAR intensity increases growth up to ~400-600 μmol m^{-2} s^{-1} with photoinhibition occurring above ~1000 μmol m^{-2} s^{-1} (species dependent). [11] Light requirements are also ecotype dependent.
- *Salinity:* Duckweed can tolerate fresh to slightly brackish water and saline water nutrient medium may be used.
- *pH:* pH ranges of 3 to 10 and 5 to 7 are tolerable and optimal for growth, respectively (species dependent).
- *Biomass Density:* Mat density above 100% surface coverage limits yield (about 400 g to 800 g fresh mass m^{-2}).[22]
- *Water Velocity:* Still water is preferable and should not exceed 0.3 meters per second.[22]
- *Water Depth:* Duckweed grows on films of water only millimeters thick, but shallow water must be kept cool.
- *Water O_2 Concentration:* Duckweed appears to grow equally well in both aerobic and anaerobic water.[11]
- *Air CO_2 Concentration:* A large range of CO_2 is tolerable for growth (50 ppm up to 5%).
- *Submersion: Wolffia* species can grow when submerged but the effect of submersion on other genera is uncertain.

C. Functional Overview and Subsystem Definition

The growth chamber preliminary design includes eight subsystems to autonomously control the plant growth environment, which are depicted in the μG-Lilypond™ functional architecture (Figure 4) and described below.

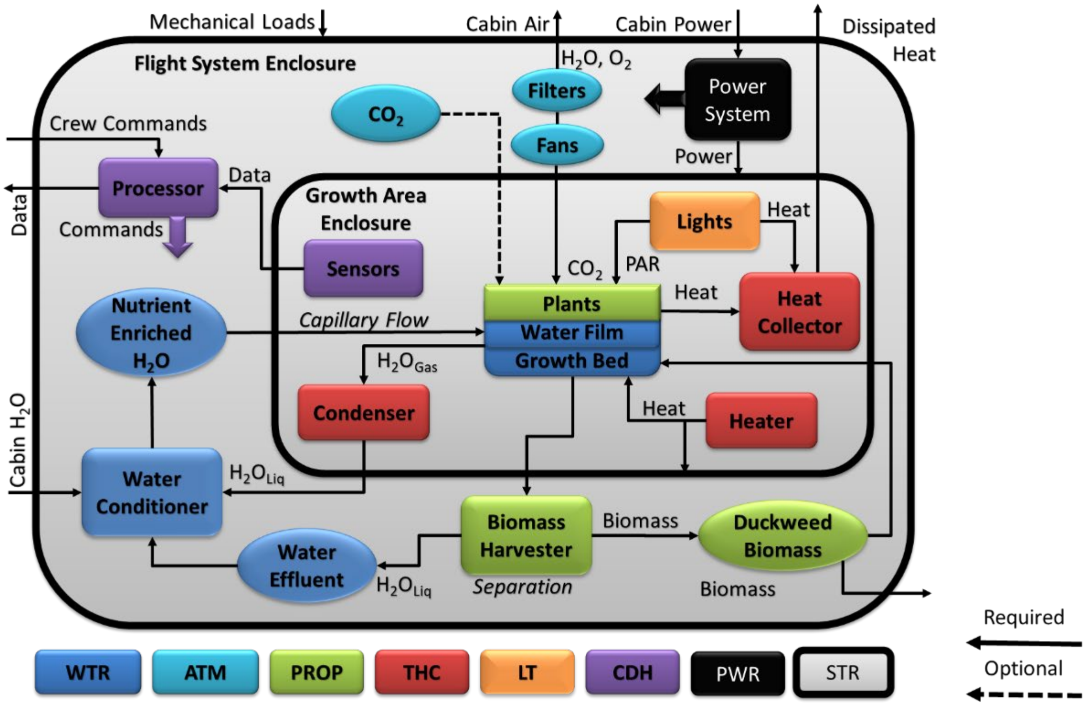


Figure 4. μG-Lilypond™ functional architecture.

Structure (STR): This sub-system provides low volume, low mass system containment and mechanical support. It isolates plants from the cabin; limits water loss from evapotranspiration; and limits the release of odor, trace contaminants, microorganisms, or particulate matter to the cabin. The EDU enclosure has a double mid-deck locker equivalent (MLE) formfactor (22 in. x 18 in. x 22 in.) that mounts inside the ISS EXPRESS Rack (Figure 5). It houses two double-sided 15" x 15" shallow growth trays to provide a large growth surface area (0.58 m^2) per unit volume (0.14 m^3). It accommodates LED panels (one double-sided and 2 single-sided), a harvester, reservoirs and pumps for water and nutrient management, ventilation control components, and electronics. The rear panel includes mounting points to the ISS EXPRESS Rack back plate and a cooling fluid inlet and outlet. The front panel includes a cabin air intake and outlet, spacecraft water source inlet and outlet, electrical connections, and access for removing growth trays or lighting panels. An ortho-grid pattern in the aluminum enclosure panels reduces structural mass while maintaining strength. At this double MLE scale, the EDU can support small aquatic plants, like duckweed, and smaller rooted land plants, such as microgreens. If scaled up to a quad MLE similar to the Advanced Plant Habitat, then larger plants could be grown in multiple growth volumes, with separate LED panels.

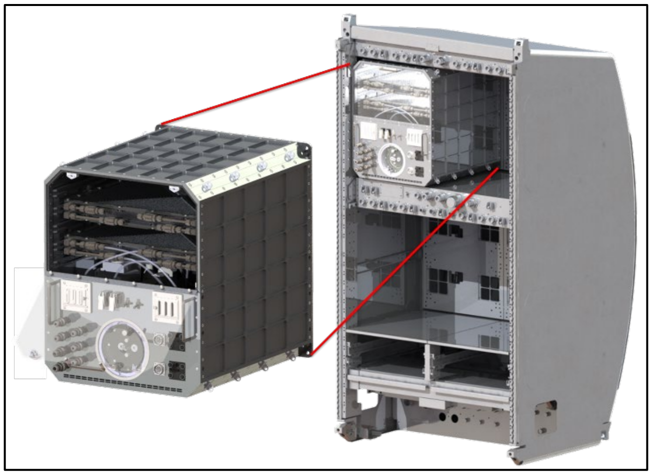


Figure 5. Depiction of µg-LilyPond™ in EXPRESS Rack.

Water and Nutrient Management (WTR): Water delivery to the duckweed plants is vital for growth and viability. Duckweed may survive up to 6 hours of desiccation but should not be left dry more than 1-2 hours. The shallower the water depth, the quicker nutrients and water lost to evapotranspiration must be replaced. Water depth will also affect thermal and mechanical stability of the water film. The flow rate of water delivered to the growth surface must exceed the rate of water loss due to evaporation, but then should remain still or slow flowing (<0.3 m/s). The water film should also maintain homogeneous water conditions, for consistent growth rates and biomass quality. The growth surface must also allow for an air volume above the plants for maximum gas exchange, necessitating maintenance of a stable air/water interface at which the plants grow. Finally, the water film lateral area must be wide enough (in all directions) to contain duckweed fronds that are 1 mm (minimum) to 10 mm (maximum) in diameter.

The *growth tray* is a crucial element of the growth chamber. Interfacial forces become dominant in microgravity; thus our approach uses capillarity to passively feed water and nutrients to the growing plants and provide a stable air/water interface. Interior corner geometry (shown in Figure 6) passively delivers water while making up for evaporative water loss. The flow channels spontaneously wet if the interior corner geometry (i.e. half angle α) meets the Concus-Finn condition for the contact angle at the fluid-solid interface. Duckweed grows on the water surface within each interior corner channel, shown in the top right corner of Figure 6.

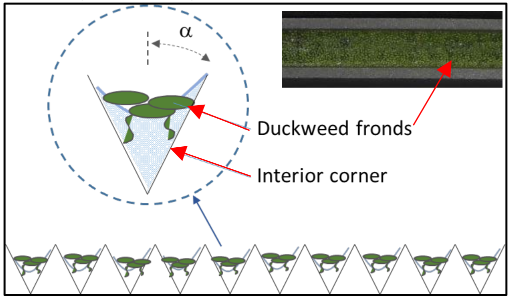


Figure 6. Growth bed using interior corners for flow capillarity.

Figure 7 depicts the current growth tray assembly model for the EDU, which contains two back to back growth beds (double sided). It not only feeds water to the growth surface, but also incorporates a lid with a window to contain water that may leave the bed; a cold plate to collect and dissipate radiant heat from the water; air inlet/outlet ports for CO_2 provision and ventilation; and a handle for ease of removal from the enclosure. The tray is instrumented with thermistors to monitor water temperature and a probe to monitor the water level in the channels. The open growth bed conceptual design tolerates biofouling and precipitates and is easy to clean in contrast to several other concepts considered. Over time, biofilm and/or precipitates will buildup which could interfere with crop growth. For that reason, the design team is investigating the use of low-

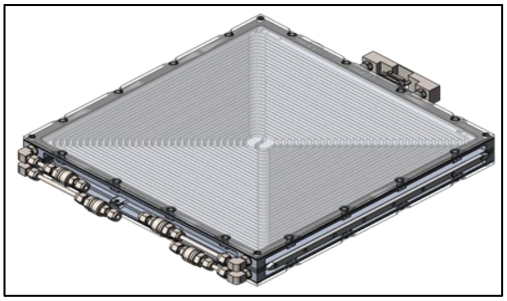


Figure 7. µG-Lilypond™ EDU growth tray.

intensity ultrasound for autonomous cleaning. This is a chemical-free approach to control the growth of algae, destroy micro-organisms and remove organic matter and precipitates that may build on surfaces. Upon activation, e.g. right after harvest, the ultrasound will loosen organic and inorganic matter that accumulate on the surface. Then, the water loop can actively flush the growth bed to remove this material. This wastewater stream would then be filtered to separate, recover, and reuse the water. Capillary flow then refills the growth bed with water and nutrients from the reservoir. Ref. 23 discusses the growth tray design in detail.

µG-Lilypond™ also features autonomous water recycling and reconditioning, to conserve consumable mass and reduce load on the cabin water reclamation systems. The Water Management System collects effluent water during biomass harvest, as well as humidity condensate, re-conditions the water in a reservoir, and then returns the conditioned water to the growth beds. The nutrient management process utilizes a mass balance technique.[24] A reservoir stores concentrated 'refill' fertilizer which replaces nutrients removed by the harvested plants. Fertilizer and pH adjusting chemicals will be injected into the mixing reservoir using small dosing pumps. Electrical conductivity, pH monitors, and small dosing pumps will control the nutrient addition and pH adjustment process.

Atmospheric Management (ATM): This sub-system maintains and monitors air circulation, allows for gas exchange with the cabin atmosphere, removes ethylene (*optionally*), and allows for CO_2/O_2 control. Adjustable speed fans will pull cabin air into the ventilation loop. Cabin air will provide sufficient CO_2 and the anticipated high concentrations are safe for duckweed growth. To maintain lower CO_2, outside air might be injected only periodically at a slow rate, while internal air is re-cycled, allowing CO_2 to naturally reduce through photosynthesis. If quicker reduction of CO_2 is needed, future designs could incorporate CO_2 scrubbing. If higher CO_2 levels are desired, future designs might also incorporate CO_2 injection from a pressurized tank or a CO_2 concentrator technology. Oxygen will be removed from the growth chamber by directly exchanging air with the cabin. A flight unit could incorporate ethylene sorbent scrubbers; however, the EDU does not include this functionality.

Propagation (PROP): This sub-system enables autonomous biomass harvesting for continuous vegetative plant propagation. Duckweed growth rate is very dependent upon biomass density. Harvest rates of 10-35% biomass per day are recommended in literature. Note that a higher density (of at least 30 grams of dry mass per square meter) will also serve to prevent algal growth. Biomass collection components must accommodate the expected size range of duckweed fronds (1 to 5 mm). The EDU may need to harvest 10-15 grams of dry mass (or 200-300 grams of fresh mass) per day. The EDU incorporates a three-phase separator (Figure 8) to collect effluent while leaving the harvested plants in a removable mesh bag. This harvester also serves as a liquid gas phase separator to remove air entrapped in the water transport loop before it returns to the growth beds. In Phase I, Space Lab demonstrated that a rotary sieve concept is very effective in separating duckweed from effluent.

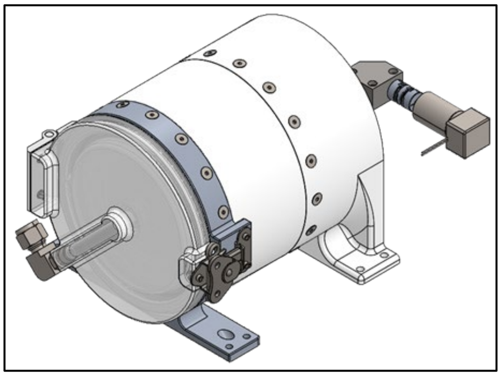


Figure 8. µG-Lilypond™ harvester.

Thermal and humidity control (THC): This sub-system maintains air and water temperature and collects excess water vapor. The air and water temperature should remain between 6 and 33 ºC for biomass survival and between 24 +/- 4 ºC for optimal growth. Duckweed crop loss may occur rapidly if water temperature is >33 ºC. Also, the flight system should not dissipate more than 500W of sensible heat or 70W of latent heat to the cabin air when operated as an ISS payload. Because of lighting proximity to the growth bed (1.0-in), LED radiant heat will be the primary heat load into the bed. Significant heat dissipation will be needed to maintain temperature, which may occur through evaporation or conduction through the growth beds. The growth bed will be enclosed with a transparent guard to help attenuate the heat input from lighting. Finally, a significant amount of water vapor will be produced through evapotranspiration from the growth trays. Ideally, humidity output to the cabin should not exceed humidity input (on an average daily basis). A µG-Lilypond™ demonstration flight unit would utilize the ISS Moderate Temperature Loop (MTL) to transport internal heat to the cabin active thermal control system for rejection to space. Thus, the ground-based EDU is designed to interface to a simulated MTL. A cold plate, sandwiched between two growth beds, dissipates heat via conduction. The cold plate will contain a water coolant loop that will interface to the MTL. Evaporation from the growth bed surface provides an additional means of cooling. Humid air passes through a heat exchanger to condense humidity, thereby controlling the relative humidity in the ventilation loop. The water transport loop will then transport condensate for reuse in water conditioning.

Lighting (LT): This sub-system includes LEDs that allow spectrum, photoperiod, and intensity adjustment. PAR intensity should be uniformly distributed across the growth bed for even biomass growth even when mounted only a short distance from the crop canopy (for volume and power efficiency). The lighting panel, shown in Figure 9 fits the rectangular growth bed form-factor with LEDs on the top and bottom, allowing illumination of growth beds above and below the fixture. Pulse width modulation controls efficient LEDs in a typical DC/DC converter design. The current EDU lighting panel contains blue, red, green, and far red bulbs, for spectral quality control, and requires only 75W to provide $1200\ \mu mol\ m^{-2}\ s^{-1}$ to a 225 in^2 surface. Customized optics provide extremely uniform light intensity across the growth bed, when mounted only 1" away from the water surface. Current models indicate a standard deviation of ~2% of the total photosynthetic photon flux density (PPFD) across the growth area (Figure 9, right). White LED panels are also available, which have similar uniformity and power consumption.

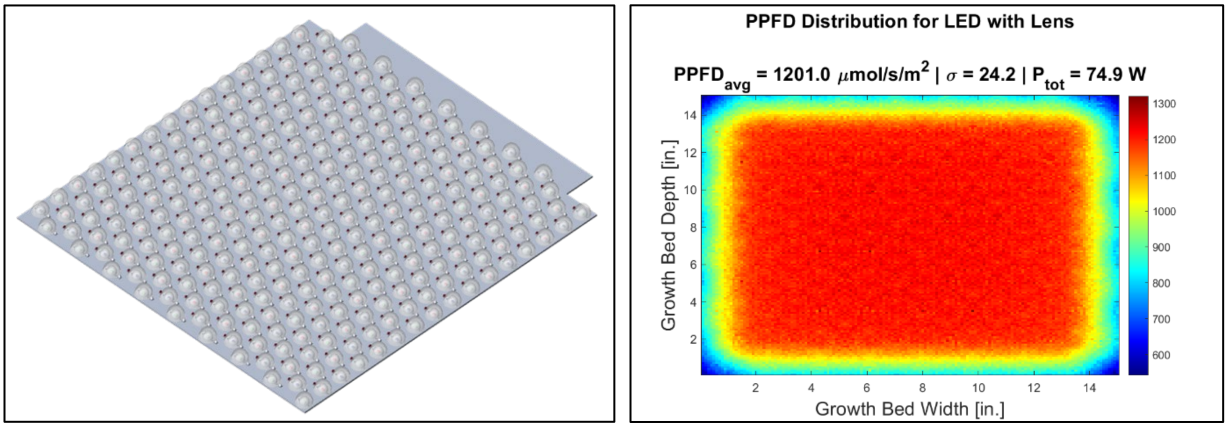


Figure 9. µG-Lilypond™ LED panel (left) and PPFD simulation (right).

Command and data handling (CDH): Autonomous environmental control and autonomous biomass harvesting minimize crew time needed for operation. CDH is required to monitor system parameters and variables; control actuators; display data for system operators; execute crew commands; detect/diagnose system faults and alert the crew; and collect housekeeping data (temperature, voltage, and current). The EDU CDH will monitor CO_2, relative humidity, air temperature, and volumetric flow rate of the ventilation loop; water temperature of each of the four growth beds; electrical conductivity, pH, temperature, pressure (for leak detection), and flow rate of influent in the water transport loop; pressure and motor current in the harvester. µG-Lilypond™ will utilize Space Lab's radiation tolerant Perseus Processing Unit for Command and Data Handling. The Perseus Processing Unit includes an FPGA and application specific interfaces. Both Ethernet and RS-422 will be available for external communications.

Power (PWR): This sub-system regulates input power from the spacecraft. The growth chamber must withstand up to 45-minute EXPRESS Rack power loss without substantial battery power. PWR must also comply with SSP 57000 electrical interface requirements for the EXPRESS Rack. Spacecraft power source is 25.5-29.5 V at 1-20 A. The estimated power budget required for the µG-Lilypond™ chamber ranges from 225-600 W, depending upon LED intensity, assuming ~200W for system control, power regulation, and actuators and the remaining power for lighting (25W-400W). Utilizing continuous (24-hour photoperiod) lighting at lower levels will allow lower power usage without loss of yield. PWR contains an LED power regulation module, a CDH power regulation module, and a power distribution system to regulate instrumentation voltages. The power distribution system includes both electromechanical and solid-state relays and relevant housekeeping sensors.

IV. µG-LilyPond™: Preliminary Yield Predictions

Space Lab anticipates that this system design will meet or exceed user expectations for each of the Measures of Effectiveness (MOE) identified in Phase I (Table 1). At a minimum, the flight system must produce a positive amount of living biomass per day and should produce biomass in amounts greater than or equal to other food crops being considered for space life support. The advantage of small entirely edible aquatic plants like duckweed is that shallow stacked trays can increase the growth area to volume ratio. Space Lab predicts yields **>*75 grams dry mass*** $m^{-3}\ day^{-1}$ in a 0.16 cubic meter growth volume, containing 0.58 m^2 of growth area over two double-sided trays. This value assumes a relative growth rate of 0.62 under optimal growth conditions. This is approximately *3.5 times higher than the estimated volumetric yield of white potatoes* (a high yield food crop considered for space applications). With this yield, the plants could consume up to 25% of a crew member's CO_2! If equivalent system mass is used to approximate system cost, then the yield per ESM is an indicator of efficiency. Phase I ESM estimates ranged from 330 to 350 kg, which is *about half that of a typical plant growth chamber* for space applications (based on values in Ref. 25).

Table 1 µG-Lilypond™ Performance Predictions.

Measure of Effectiveness (MOE)	Expectation	Goal
MOE1. Biomass Production Rate (g dry biomass produced day^{-1} m^{-3})	✓>75 (increases with larger chambers – economy of scale)	>21 (White Potato, Estimated)
MOE2. Edibility	✓Met through crop selection & food safe design (HACCP)	Palatable, digestible, non-toxic, pathogen-free
MOE3. Nutritional Quality	✓Met through crop selection	Nutrient dense
MOE4. Safety	✓No significant hazards identified.	System poses no harm to spacecraft or crew
MOE5. Robustness	✓Met through crop selection & robust design methodology.	All other goals met over all potential operating conditions
MOE6. Autonomy (duration of continuous operation, without intervention)	✓~5 minutes per day for harvest anticipated; 1 hour of cleaning every few months.	<1 Hour/week of crew time
MOE7. Efficiency (proxied by ESM)	✓330 to 350 kg	<650 kg
MOE8. Usability	✓Equal to or better than state of the art plant growth chambers	Learnable, memorable, low error rate, satisfactory

V. µG-LilyPond™: Prototype Demonstrations & Preliminary Testing

A. Phase I STTR – Bench Top Tests & Analysis for Feasibility

Feasibility of Passive Water Delivery to Plants: In Phase I, CU designed and manufactured interior corner growth bed test articles to determine feasibility for water provision by capillarity (left panel of Figure 10, above). Analysis and experiments showed that the achievable capillary flows were more than two orders of magnitude greater than the expected rates of evaporation and evapotranspiration (about 0.2 L m^{-2} h^{-1} from analysis) as well as the uptake rate of water by duckweed (0.018 L m^{-2} h^{-1}).

Feasibility of Autonomous Harvest & Effluent Extraction: In Phase I, Space Lab provided a baseline harvester design to both collect and separate effluent and biomass from the growth bed. Space Lab then built and successfully tested a prototype, showing the baseline design exceeded expectations for separating effluent water and biomass (second from left panel of Figure 10).

Close Canopy Lighting Simulation: The use of shallow stacked growing trays to increase volume efficiency necessitates lighting that is very close to the plants (<1.5"). This 'close canopy' lighting creates significant challenges in maintaining light uniformity across the growing surface and maintaining safe temperatures at the plant surface for healthy growth. However, custom optics mounted over the LEDs can provide significantly improved light uniformity over the growing surface, while copper layers within the panel can provide thermal conduction for heat dissipation. In Phase I, Space Lab simulated light uniformity for a panel located 1.0" from the growth bed using commercially available optics and was able to achieve a PPFD standard deviation <4% of the total PPFD. In the Phase II EDU panel design, the standard deviation has been reduced to <2% of total PPFD, showing optics can indeed mitigate the risk of non-uniformity for close canopy lighting. Finally, analysis shows that the copper layers will be able to carry away the heat produced by the LED circuitry.

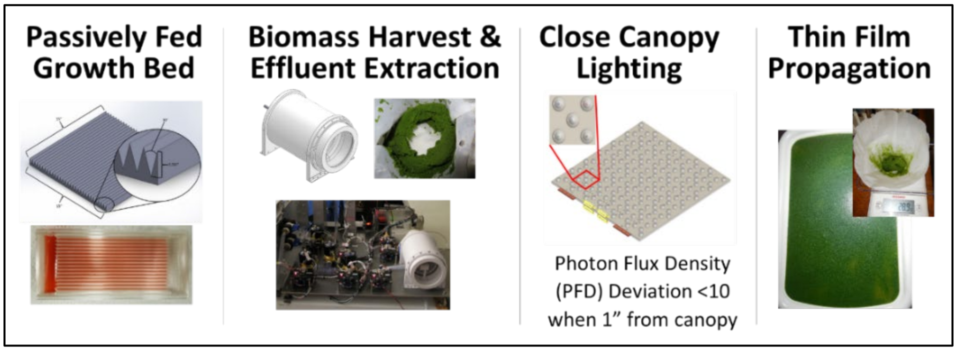


Figure 10. Phase I STTR bench top tests & analysis for feasibility.

Feasibility of Autonomous Floating Plant Propagation: In addition to harvesting and water extraction, Space Lab also demonstrated propagation of duckweed plants in shallow water films in Phase I (right panel of Figure 10). Space Lab grew a culture of Lemna minor and Wolffia arrhiza on a plastic tray with about 10 mm of water depth. Both thin film cultures were maintained successfully through periodic harvesting, nutrient addition, and pH adjustment for 5 weeks. The growth experiments demonstrated continuous duckweed cultivation on thin films of water and illuminated the need for frequent pH adjustment for thin film growth (due to a smaller buffering capacity), as well as the importance of maintaining a minimum mat density to shade the water column and prevent algal growth.

B. Phase II STTR – Engineering Demonstration Unit Development

In this two-year effort, Space Lab and CU are designing a high fidelity EDU to demonstrate key, low TRL functionality of the growth chamber (water transport, water conditioning of recycled effluent, harvesting, close canopy PAR delivery, and radiant heat dissipation). Space Lab is completing detailed designs for the enclosure, ventilation, water transport, harvesting, thermal and humidity control, lighting, CDH, and power regulation sub-systems. EDU integration and test integration is scheduled to begin in late Fall of 2020. Figure 12 shows a CAD model of the growth chamber EDU, summarizing its key features. In an iterative design approach, CU has continued to develop small growth bed prototypes to test various growth tray features (window attachment, flow path geometry, bed material, etc.) which has informed detailed design of the EDU scale growth tray. CU team members conducted experiments at the Portland State University Dryden Drop Tower, to further understand microgravity effects on a capillary-fed growth bed. Tests investigated the effects of bed material, manufacturing method, and capillary channel geometry on passive capillary flow into interior corner channels. Ref. 23 discusses the drop tower test results in more detail. In Phase II, CU will also conduct bench top experiments to investigate the use of ultrasonic transducers to destroy and remove accumulated biofilm and precipitates from the growth bed surface. The µG-Lilypond™ growth tray also allows growth of higher rooted land plants, such as microgreens, as depicted in Figure 11. A hydrogel film installed on top of the capillary flow channels regulates the delivery of water to plant roots according to water demand, while preventing water from submerging and suffocating the root. In Phase II, the project team will conduct bench top experiments with candidate hydrogel films attached to the surface of growth bed test articles to measure capacity for fluid uptake.

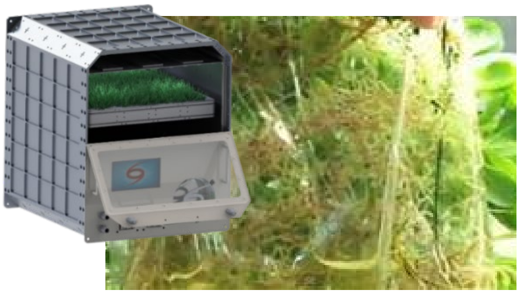
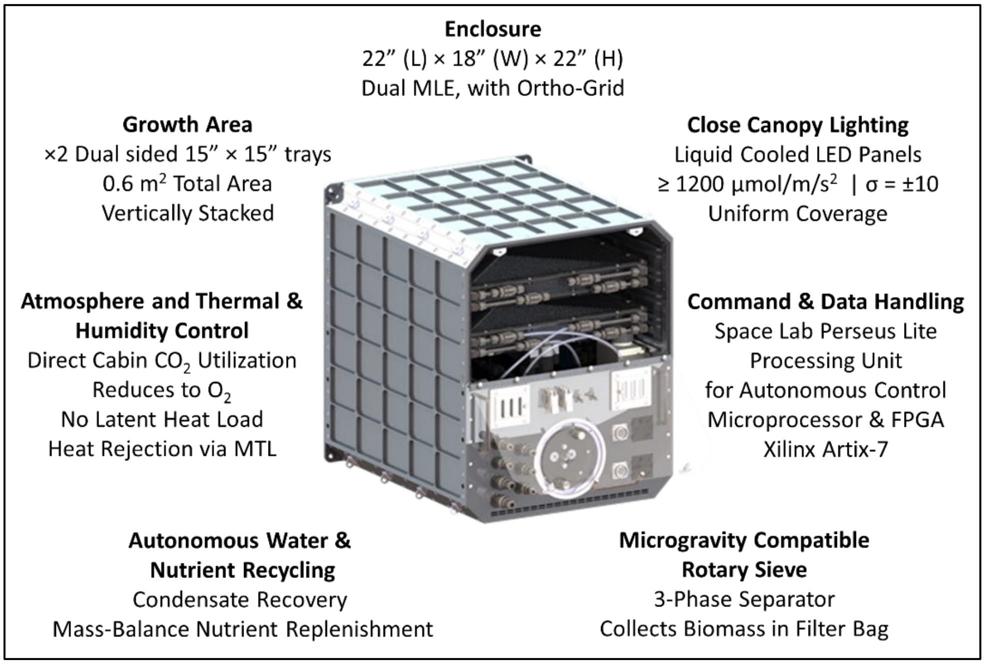


Figure 11 . µG-Lilypond™ EDU growing microgreens (left) with a hydro-membrane for plant cultivation (Mebiol, Inc.) – right.



Enclosure
22” (L) × 18” (W) × 22” (H)
Dual MLE, with Ortho-Grid

Growth Area
×2 Dual sided 15” × 15” trays
0.6 m^2 Total Area
Vertically Stacked

Close Canopy Lighting
Liquid Cooled LED Panels
≥ 1200 µmol/m/s^2 | $\sigma = \pm 10$
Uniform Coverage

Atmosphere and Thermal & Humidity Control
Direct Cabin CO_2 Utilization
Reduces to O_2
No Latent Heat Load
Heat Rejection via MTL

Command & Data Handling
Space Lab Perseus Lite
Processing Unit
for Autonomous Control
Microprocessor & FPGA
Xilinx Artix-7

Autonomous Water & Nutrient Recycling
Condensate Recovery
Mass-Balance Nutrient Replenishment

Microgravity Compatible Rotary Sieve
3-Phase Separator
Collects Biomass in Filter Bag

Figure 12. µG-Lilypond™ Engineering Demonstration Unit (EDU) model and key features.

C. µG-Lilypond™ Suborbital Flight Opportunity

Adequate testing of microgravity effects on water transport through the growth bed and on the harvesting operation requires a relevant microgravity environment. In parallel with Phase II EDU development, Space Lab will test the µG-Lilypond™ water transport loop and harvester technology on a sub-orbital technology demonstration flight, scheduled to launch in September of 2020. The primary objective of the flight experiment is to demonstrate a) water and nutrient delivery through a capillary-driven growth bed, b) water film stability, c) biomass-effluent separation during harvest, d) water lentil transport during harvest, and e) biomass removal during purging. Secondary objectives are to characterize microgravity effects on the mechanical interaction between water lentils and the nutrient solution; and to compare performance of various capillary channel geometries under consideration. A sub-orbital flight trajectory provides 2.5 minutes of microgravity which is a much longer than parabolic flights or drop towers can provide, and also sufficient to observe complete water loop operation. High definition video cameras will allow the team to visually observe fluid and plant behavior and to measure flow rate through the growth bed capillary channels.

D. Additional Research: Co-Optimization of Duckweed Biomass, Nutritional Quality & Input-Use Efficiency

In order to realize duckweed's full potential as a highly productive and nutritious crop, optimal growing conditions for production of high yields of nutritious food with the fewest spacecraft resources need to be defined in an environment relevant for space missions. Optimal light intensities that maximize growth, light-use efficiency, and nutritional quality at elevated CO_2 concentrations (up to 1%) are not defined in literature. Also, high biomass yield often comes at the cost of poor micronutrient quality, and vice versa. For example, fronds produce antioxidants to defend against damaging excess light. However, PFDs beyond those needed for optimal growth typically inhibit growth. Space Lab is collaborating with the CU to investigate novel pulsed lighting techniques to co-optimize duckweed yield and micronutrient content. This research is funded under a Translational Research Institute for Space Health grant under NASA Cooperative Agreement NNX16AO69A. The proposed study will utilize ground-based growth experiments to design a growth protocol that co-optimizes 1) edible biomass yield (and concomitant CO_2 uptake), 2) protein content, 3) micronutrient content, and 4) energy efficiency (biomass/antioxidants produced per energy input) for two duckweed species at space-relevant CO_2 concentrations up to 1%.

VI. Conclusion

Through several ongoing research and development efforts, Space Lab and the University of Colorado at Boulder are working to advance the Technology Readiness Level of the µG-LilyPond™ growth chamber. The µG-LilyPond™ concept provides increased autonomy, reliability, volume efficiency, and mass efficiency in production of a variety of food crops (both aquatic and land plants). In a Phase I STTR, the team established feasibility of passive water delivery to plants. Achievable capillary flow rates were two orders of magnitude greater than that of evapotranspiration and plant uptake. A Phase I prototype harvester demonstrated reliable extraction and phase separation of duckweed plants from effluent water with a rotary sieve design. Phase I growth experiments demonstrated continuous cultivation of duckweed plants on a thin film of water, illuminating the importance of frequent pH adjustment and mat density to control algal growth. Optical simulations showed that custom LED lenses provide <2% variation in PPFD when mounted 1" from the growth bed, even at very high light intensity (up to 2000 $\mu mol\text{-}m^{-2}s^{-1}$). Finally, Phase I ESM and yield estimates indicated that µG-LilyPond™ will be able to produce at least 3 times the amount of edible biomass with about half of the equivalent system mass of other plant growth chambers producing typical crops (e.g. potatoes).

Through STTR Phase II funding, the Space Lab and CU team is now developing a ground-based EDU of the growth chamber, to demonstrate lower TRL functionality (water transport and conditioning, harvesting, close canopy lighting, and radiant heat dissipation) for duckweed production, as well as extensibility of the growth bed to support higher rooted land plants. A suborbital microgravity test of the water loop in September 2020, followed by EDU verification and validation testing in the Spring of 2021, will inform design of a future protoflight growth chamber. The goal of a future µG-LilyPond™ demo flight unit is to enable long-term multi-generational crop production research in microgravity for both aquatic plants and higher rooted land plants.

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References

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1 Barta, D. J. and Henninger, D. L., “Regenerative life support systems—Why do we need them?” *Advances in Space Research*, Vol. 14, No. 11, 1994, pp. 403-410.

2 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.

3 Bluem, V. and Paris, F., “Possible applications of aquatic bioregenerative life support modules for food production in a Martian base,” *Advances in Space Research*, Vol. 31, No. 1, 2003, pp. 77–86.

4 Escobar, C. and Escobar, A., “Duckweed: a tiny aquatic plant with enormous potential for bioregenerative life support systems,” *47th International Conference on Environmental Systems*, July 2017.

5 Journey, W. K., Skillicorn, P., and Spira, W., “Duckweed Aquaculture: A New Aquatic Farming System for Developing Countries,” The World Bank, 1991.

6 Sree, K. S., Bog, M., and Appenroth, K. J., “Taxonomy of duckweeds (Lemnaceae), potential new crop plants, *Emirates Journal of Food and Agriculture*, 2016, pp. 291-302.

7 Landesman, L., Fedler, C., and Duan, R., “*Plant nutrient phytoremediation using duckweed. In Eutrophication: Causes, Consequences and Control*,” Springer, Dordrecht, 2010, pp. 341-354.

8 Ziegler, P., Adelmann, K., Zimmer, S., Schmidt, C., and Appenroth, K. J., “Relative in Vitro Growth Rates of Duckweeds (Lemnaceae) - The Most Rapidly Growing Higher Plants,” *Plant Biology*, Vol. 17, No. 1, 2015, pp. 33–41.

9 Zhuang, X., “Lemna minor,” *The IUCN Red List of Threatened Species*, 2014. http://www.iucnredlist.org/details/164057/0 [cited 12 March 2017].

10 Leng, R. A., “Duckweed: A Tiny Aquatic Plant with Enormous Potential for Agriculture and Environment,” *Food and Agriculture Organization (FAO) of the United Nations*, Rome, Italy, 1999.

11 Landolt E. and Kandeler, R., “*Biosystematic investigations in the family of duckweeds (Lemnaceae), Vol 4: the family of Lemnaceae-a monographic study, Vol. 2 (phytochemistry, physiology, application, bibliography),”* Veröffentlichungen des Geobotanischen Instituts der ETH, Stiftung Ruebel, Switzerland, 1987.

12 Eichhorn M. and Fritsche, C., “Effects of Space Shuttle Mission STS-67 on Cell Structure in Lemna Trisulca (Duckweeds),” *ESA Space Station Utilisation Symposium*, Darmstadt, Germany, 1996.

13 Yuan, J. and Xu, K., “Effects of simulated microgravity on the performance of the duckweeds Lemna aequinoctialis and Wolffia globose,” *Aquatic Botany*, Vol. 137, 2016, pp. 65-67.

14 World Health Organization and United Nations University, “*Protein and amino acid requirements in human nutrition, vol. 935,*” World Health Organization, 2007.

15 Appenroth K-J, Augsten H., Liebermann B, and Feist H., “Effects of light quality on amino acid composition of proteins in Wolffia arrhiza (L.) Wimm. using a specially modified Bradford method,” *Biochemie und Physiologie der Pflanzen*, Vol. 177, No. 3, 1982.

16 Appenroth K-J, Sree K. S., Böhm, V., Hammann, S., Vetter, W., Leiterer, M., and Jahreis, G., “Nutritional value of duckweeds (Lemnaceae) as human food,” *Food Chemistry*, Vol. 217, 2017, pp. 266-273.

17 Ansal, M. D., Dhawan, A., and Kaur, V.I., “Duckweed Based Bioremediation of Village Ponds - An Ecologically and Economically Viable Integrated Approach for Rural Development Through Aquaculture,” *Livestock Research for Rural Development*, Vol. 22, No. 7, 2010, pg. 129.

18 SanGiovanni, J.P., and Neuringer, M., “The putative role of lutein and zeaxanthin as protective agents against age-related macular degeneration: Promise of molecular genetics for guiding mechanistic and translational research in the field,” *American Journal of Clinical Nutrition* Vol. 96, 2012.

19 Demmig-Adams, B., Adams, R. B., “Eye nutrition in context: Mechanisms, implementation, and future directions,” *Nutrients*, Vol. 5, 2013, pp. 2483-2501.

20 Bhanthumnavin, K., and McGarry, M. G., “Wolffia arrhiza as a possible source of inexpensive protein,” *Nature*, Vol. 232, No. 5311, 1971, pp. 495-495.

21 Palaniswamy, U. R., Bible B. B, McAvoy, R. J., “Oxalic acid concentrations in Purslane (Portulaca oleraceae L.) is altered by the stage of harvest and the nitrate to ammonium ratios in hydroponics,” *Scientia Horticulturae*, Vol. 102, 2004, pp. 267–275.

22 Hasan, M. R. and Rina, C., “*Use of algae and aquatic macrophytes as feed in small-scale aquaculture: a review*,” Food and Agriculture Organization of the United Nations (FAO), No. 531, 2009.

23 Nabity, J. A., Pitts, R. P., Rehmeier, J., Weislogel, M. M., Escobar, C.M., Shaffer, B. A., Escobar, A. C., “Capillary Provision of Water and Nutrients to Plants Grown in Microgravity,” *International Conference on Environmental Systems,* July 2020 (submitted for publication).

24 Bugbee, B., "Nutrient management in recirculating hydroponic culture," *South Pacific Soilless Culture Conference*, 2003.

25 Anderson, M. S., Ewert, M. K., and Keener, J. F., “Life support baseline values and assumptions document,” NASA TP-2015-218570/REV1, 2018.