Plant Growth Research for Food Production: Development and Testing of Expandable Tuber Growth Module

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Controlled and reliable growth of a variety of vegetable crops is an important capability for manned deep space exploration systems for providing nutritional supplementation and psychological benefits to crew members. Because current systems have been limited to leafy vegetables that require minimal root space, a major goal for these systems is to increase their ability to grow new types of crops, including tuber plants and root vegetables that require a large root space. An expandable root zone module and housing was developed to integrate this capability into the Veggie growth system. The expandable module uses a waterproof, gas-permeable bag with a structure that allows for root space to increase vertically throughout the growth cycle to accommodate for expanding tuber growth, while minimizing the required media mass. Daikon radishes were chosen as an ideal tuber crop for their subterraneous tuber size and rapid growth cycle, and investigations were done to study expanding superabsorbent hydrogels as a potential growth media. These studies showed improved water retention, but restricted oxygen availability to roots with pure gel media. It was determined that these hydrogels could be integrated in lower proportions into standard soil to achieve media expansion and water retention desired. Using the constructed module prototype and ideal gel and soil media mixture, Daikon radishes were grown in the system to test the capability and success of the system through a full growth cycle.

Nomenclature

ABS	=	Acrylonitrile Butadiene Styrene
APH	=	Advanced Plant Habitat
CLP	=	Cross-linked Polyacrylamide
DAP	=	Days after Planting
DSG	=	Deep Space Gateway
DST	=	Deep Space Transport
HDPE	=	High Density Polyethylene
ISS	=	International Space Station
LDPE	=	Low Density Polyethylene
LED	=	Light Emitting Diode
TCHR	=	Tissue Culture for In Vitro Explant Propagation
Veggie	=	Vegetable Production System

I. Introduction

With the advancement of deep space exploration technology and NASA's plan to send manned missions to the moon and Mars, the need for more reliable, cost effective, and long term life support solutions is greater than ever. Food production is a necessary capability for long-term deep space travel, reducing payload mass, supplementing crew diet and nutrition, and providing important psychological benefits. The benefits of food production capabilities become even more important as long-term Mars habitation becomes a reality. The Food Production team aims to provide a reliable, effective and efficient means of producing food during missions through plant growth research and technologies, with the eventual goal of developing a comprehensive plant growth system, capable of producing a variety of crops with minimal maintenance or energy requirements.

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Previous systems for plant growth used only for flight experiments are small, limited in their utility, and are not integrated as a life support system. [1] In order to produce reliable systems for growing food on the International Space Station (ISS), Deep Space Gateway (DSG), Deep Space Transport (DST) and Orion Spacecraft, the team must address different research questions in relation to plant breeds, soil and media, water and nutrient delivery systems, housing and environment control, lighting and other factors. The overarching project includes collaboration from several teams and systems including the Veggie and Advanced Plant Habitat (APH) programs undergoing testing on the ISS.

The contribution from this project includes the design and production of an expandable growth chamber for bulbs, root vegetables, and tuberous plants. Up to this point, the various growth systems have focused almost entirely on lettuce and other leafy vegetables. [1] Ideally, the system should also be capable of growing plants whose edible mass lies beneath the surface, because of the valuable nutrients they can provide, but the restricted volume of Veggie plant pillows and APH arcillite containers does not allow for this type of root growth. The new chamber provides a way for plant tubers and nutrient media volume to expand during the growth cycle, while minimizing the mass of growth media needed, and allowing for water and nutrient delivery throughout the growth cycle. This growth chamber is being tested in conjunction with water delivery methods and evaluated for potential integration in the Veggie growth system.

II. Module Design

A. Requirements

The most important requirement for the tuber module is the ability to effectively expand to allow for successful growth of a variety of tuber plants, while minimizing the mass of necessary growth media. The module must be capable of integrating with the existing Veggie growth system. Other desirable characteristics include transparency, or another means of monitoring root growth and health, simple means of root harvest and reusability of the module for multiple crop cycles.

B. Concept

Based on the most important requirements for the tuber module system, a concept was designed that would provide a passive means of vertical root zone expansion through a mechanical process. This concept includes an expanding root zone module, a removable lid with watering spout, and a module housing unit. The figures featured in this section provide 3D models that accompany the descriptions of the system and its functionality. The module design is depicted in Fig. 1.

A cylindrical bag comprises the root zone module, and takes its shape from rings spaced evenly throughout the length of the bag. These rings are designed to be held by the root zone base, which has two arms that bend to apply pressure to the inside of the rings. The bag begins in a collapsed position, with all rings held by the base. As the tuber expands through the root zone and presses on the base, the rings are released one at a time, expanding the bag and providing increased available volume to the tuber. Once the tuber has expanded to fill the entire bag and is ready to be harvested, the greens can be removed, the lid removed from the top of the module, and the tuber root harvested from the planting media. This simple design creates a clean system that minimizes maintenance requirements and allows for the module to be reusable between growth cycles. The expansion and harvest process is modeled in Fig. 2.

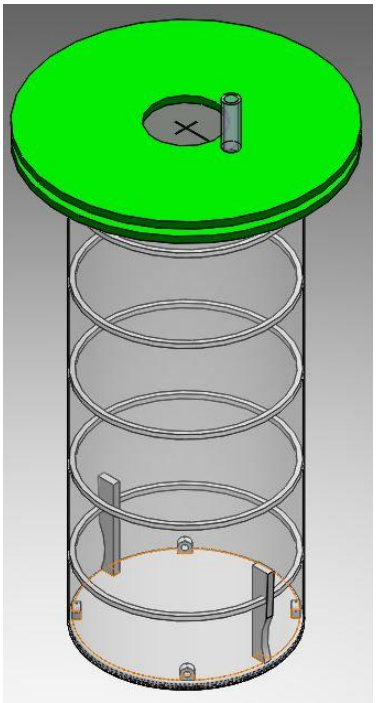


Figure 1. Module bag design concept.

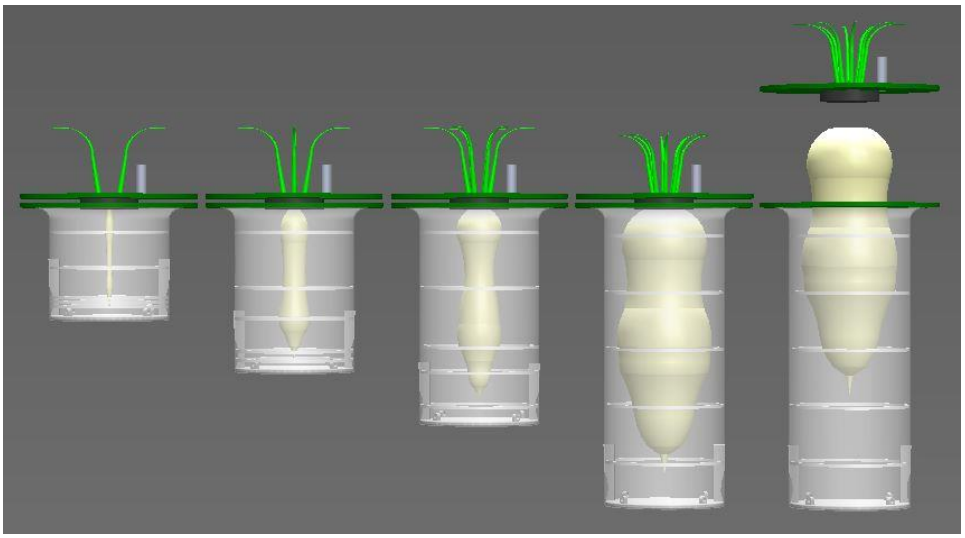


Figure 2. Growth cycle expansion and removal.

The top of the bag is comprised of a circular panel, which attaches to a lid with two small openings for the stem and greens of the plant, and for the watering tube. This lid is removable, providing protection to the media during the growth cycle, and allowing access to the root zone of the plant for harvest. The watering tube allows for simple watering of the individual plants using a syringe. Upon completion of the growth cycle, the greens can simply be clipped, the lid removed, and the tuber pulled from the bag, as shown in Fig. 2.

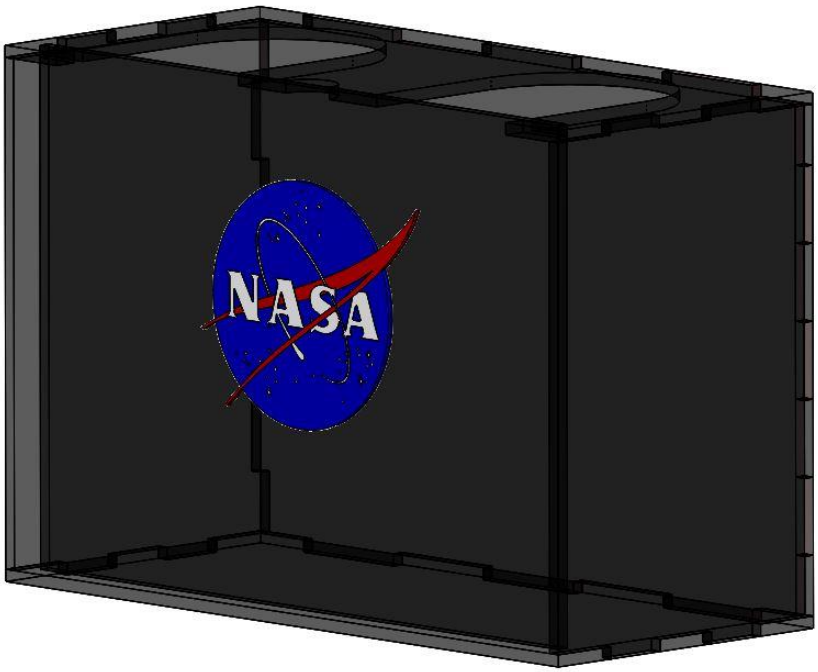


Figure 3. Module housing design concept isometric view.

The housing for the tuber bags is a rectangular box, which can hold two modules. They can be easily slid in and out of the housing, and rest by the top panel on the roof of the housing. The front panel of the housing slides up and out for a simple method of root zone visual monitoring. Two housing units are sized to fit side by side in a single Veggie unit, for a total of four plants per unit. Fig. 4 depicts the fully assembled system, and an image of module removal and harvest, as it would look in the Veggie system.

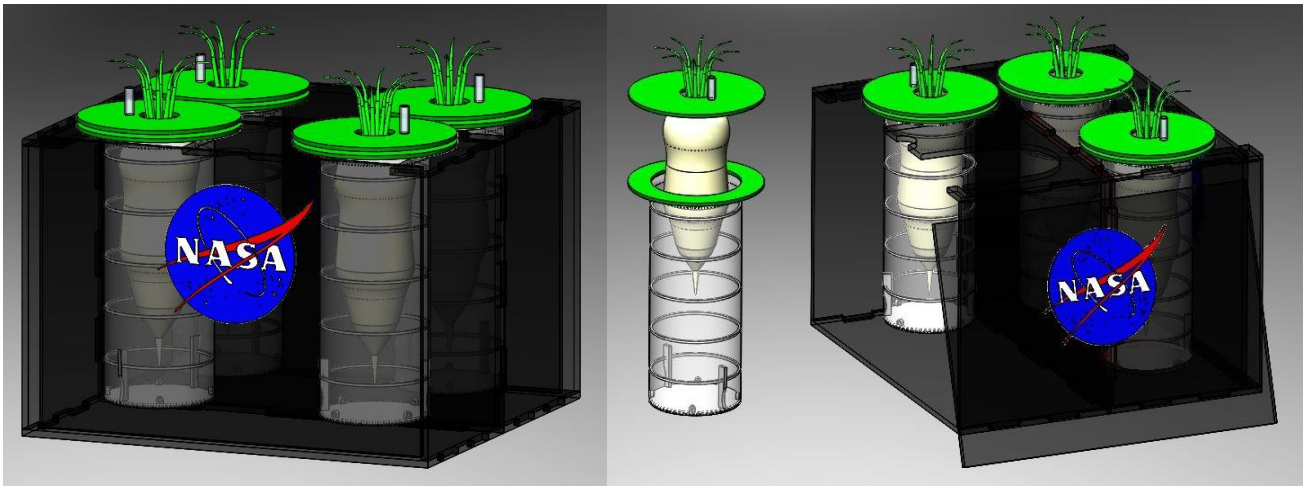


Figure 4. Full system design concept. *Fully assembled system during growth cycle (left) and during a removal for harvest (right)*

III. Plant and Media Selection

A. Plant Candidates

This system centers on the capability of growing any plants which produce subterraneous tubers. These tubers are plant organs used for storage of nutrients. Candidates for future tuber growth systems are potatoes, yams, sweet potatoes, carrots, radishes and others. For the purposes of testing this system, radishes are an ideal candidate because of their rapid growth cycles of less than 50 days, in some cases, 25 to 30 days from plant to harvest, compared to 60 or more days for carrots, potatoes, and other species. This quick turnaround can allow for minimal time between tests and redesigns, and rapid harvest in an implemented system.

Most common radishes actually produce tubers above the soil level, which is obviously not ideal for testing expansion of the root zone. Some species, however, are known for growing beneath the soil, including White Icicle (*Raphanus raphanistrum var. Sativus*), Daikon radish (*Raphanus sativus var. Longipinnatus*), and Black Spanish radishes (*Raphanus sativus var. sativus*). For testing of this system, Daikon radishes were chosen as the ideal candidate, for their size and elongated growth characteristics. Daikon radishes have a typical growth cycle of around 50 days, and reach a diameter of up to three inches and a length of over 12 inches. For a smaller system, these can be harvested at a much smaller size, allowing for a testing growth cycle as short as 30 days.

B. Media Investigation

In order to adapt the proposed tuber module to have the correct growth capabilities, various new root media were researched and tested. Largely this research centers around water retaining gel crystals, which are becoming increasingly popular as a growth media additive. These gels are desirable for this system for their ability to expand and retain root zone water. Several types were investigated, including Smart Tech TCHR, a tissue culture media for in vitro explant propagation, as well as Hydrosource and Miracle-Gro cross-linked polyacrylamide (CLP) crystals.

TCHR is a heterogeneous substrate polymer developed by Smart Tech Ltd. for use in explant propagation and plant cloning technologies. It has both powerful water binding and diffusion capabilities, making it ideal for providing long term water and nutrient delivery to plant roots. TCHR is extremely water absorbent, taking in up to 20 mL water per gram of crystals, but is not more water retaining than most roots, achieving equilibrium around relative humidity and allowing for 45 to 65 percent free liquid availability in a fully mixed media. [2] Its porous and soil-like structure make it better than most hydrogels for root penetration and stability. [2] Growth of carrots in TCHR media has been tested by the NASA Food Production team and been found to be successful in germination and early plant growth.

CLP is a dry superabsorbent crystalline substrate, similar to salt in texture and appearance. [3] These crystals are capable of absorbing hundreds of times their own mass in water. [3] The transparent quality of CLP was desirable to allow for root visibility, and was tested to compare to the growth capabilities of TCHR to determine the ideal gel for water retention use in the tuber module system. The CLP crystals were evaluated in germination tests to compare the three available crystal grades: fine grind (0.3 – 1mm), medium grind (1 – 2mm), and standard grind (2 – 4mm). Each of these grades were tested separately germinating Daikon radish seeds, against a control test with Q2 grade arcillite (2 – 4mm). Arcillite was chosen as the control media because it is the standard media for Veggie and APH systems.

Two tests were run with each grade. In each test, 10 mL of each grade of crystals were added to 50 mL beakers, and 50 mL of arcillite added to a fourth beaker. 40 mL of deionized water of water was added to each beaker. After allowing the gel to expand and absorb the water, three seeds were planted in each beaker (a total of six seeds per grade). The seeds were kept under red/blue spectrum light and covered with a lid for moisture retention. Each beaker was watered with 10 mL per day during germination. The seeds were monitored daily, and observations recorded.

Data was taken each day regarding the number of plants germinating, visibility of roots, stems, and cotyledons, height of the plants, and number of leaves, coloration, and overall appearance. These observations are somewhat different regarding the arcillite control test, since early germination and root growth cannot be seen without a transparent media. A curve representing the average daily plant height over the growth period is shown in Fig. 6.

Based on the plant height growth data shown in Fig. 6, it is evident that growth was not successful in any of the pure gel media, regardless of grade. Each of the CLP grades and the control were able to germinate five to six plants, and were successful in producing roots, stems and cotyledons. Unfortunately, the stem health of the seedlings in the gel media degraded before they were able to reach any significant growth.

a)

b)

Figure 5. CLP Test 1: germination setup.
a) Front view of beakers with control, fine, medium, and standard grinds (left to right)
b) Full germination setup

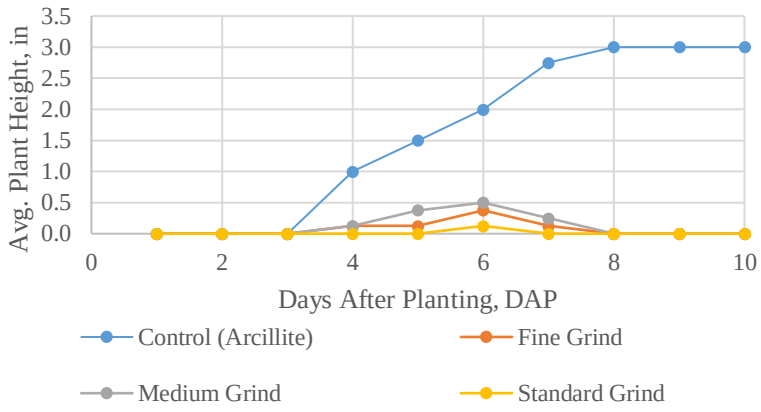


Figure 6. CLP Test 1: initial plant growth curve.

The standard grind seeds were only able to produce two plants that emerged above the media surface, although all six initiated growth. The medium grind showed the most promising growth among the three gel grades, producing leaves on five of the seedlings, with temporary growth of up to 0.75 inches. The fine grind produced leaves on all of the seedlings, but was also unable to attain much vertical growth. After eight days, all of the gel grown plants had wilted completely, and none survived. The control test showed strong growth as is usually expected after germination, and these plants were the only ones to produce true leaves. Samples of this growth can be seen in Fig. 7. These growth problems could be due to multiple factors, including overexposure to light in the root zone, restriction of oxygen in the gel, or instability of roots due to the difference between gel and soil structure.

Figure 7. CLP Test 1: plant growth visuals. *Plant growth is shown here at a) three days and b) six days, where gel plants are already showing signs of wilting and stunted growth.*

Based on these results, it was necessary to introduce a mixture of a more reliable growth media with the crystals. This negated the possibility of direct observation of root growth via transparent media, but was necessary for producing reliable growth. In order to determine an ideal mixture, a second test was devised to analyze growth using varying mixtures of arcillite and CLP gel. Based on the results of the previous test, medium grind CLP was chosen for the gel grade, and Q2 arcillite with 7.5 g/L Nutricote controlled release fertilizer. This time, 10 seeds were planted in each of four 200 mL beakers. The varying mixtures were made based on the proportions detailed below in Table 1. Gel crystals, once hydrated, fill a majority of the volume of root space, and were kept constant, while varying the mass of arcillite introduced.

Table 1. CLP Test 2: CLP and arcillite mixtures. *Test 4 used a different experimental composition, with all gel composing the bottom of the media, and an arcillite bed forming the top.*

Test	Gel Crystal Dry Mass (g)	Arcillite Dry Mass (g)
1	10	15
2	10	25
3	10	35
4*	10	20

Each of the first 3 tests were mixed based on these proportions until uniform. They were then hydrated and mixed again to ensure uniformity. Test 4 was distinctly different in composition from the other 3. This test was investigating another composition, using concentrated gel on the bottom of the beaker, with a bed of arcillite laying at the top. In order to create this composition the dry CLP was added to the beaker, hydrated, and arcillite was poured on top. The composition of each of these tests can be seen in Fig. 8.

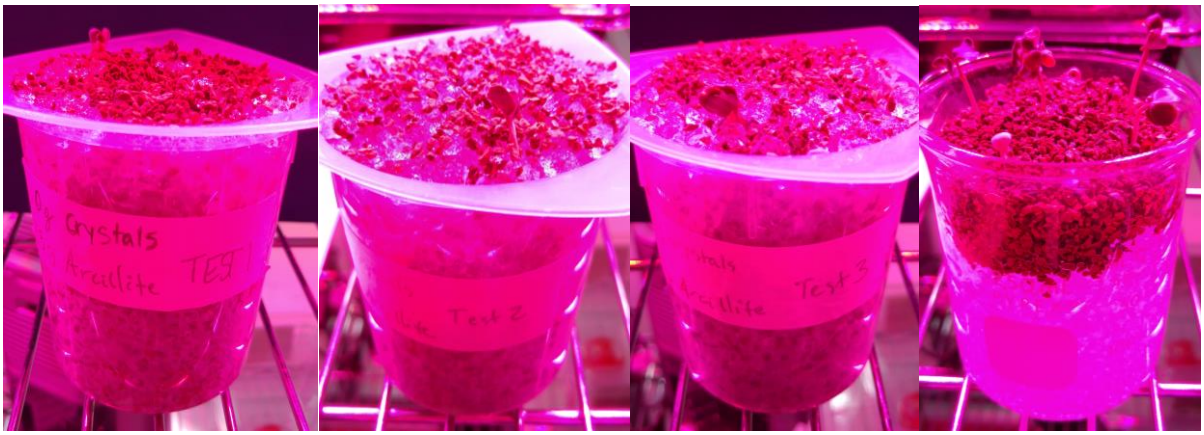


Figure 8. CLP Test 2: media composition and initial germination. *Images show Tests 1 through 4 (left to right) 4 days after planting*

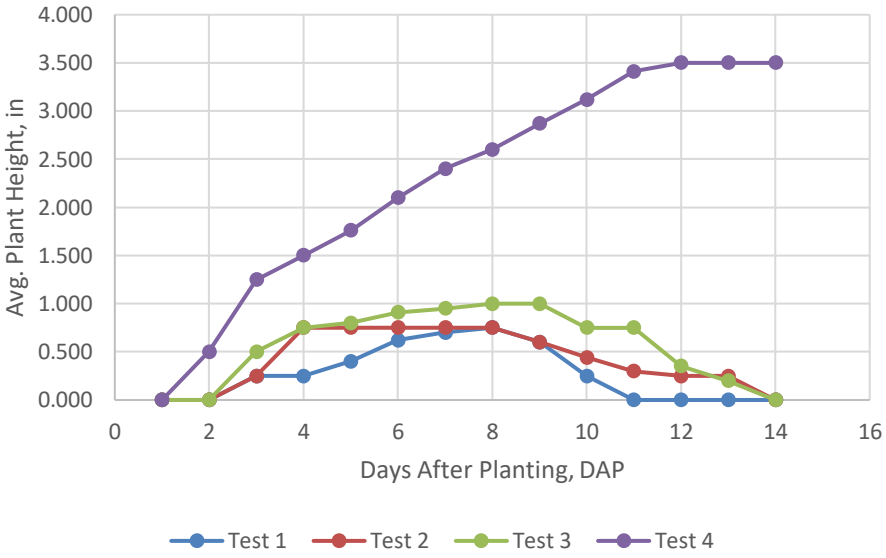
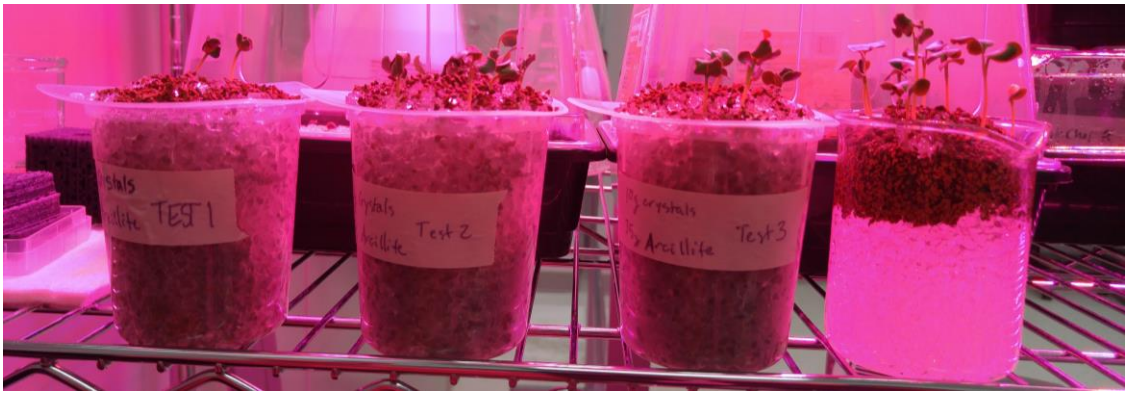


Figure 9. CLP Test 2: Initial plant growth curve.

This revised growth test showed more promising results. Test 1 had 5 plants germinate, Test 2 had 8, Test 3 had 6, and Test 4 had 9. These plants showed better stability and overall health than in the pure gel test. The coloration and robustness of stems and leaves was improved greatly, with growth improving as the mass of arcillite increased. Tests 2 through 4 all showed development of true leaves after 6 days. After around 8 days, the results in Tests 1 through 3 began to resemble those of the first gel test, with seedlings wilting and eventually dying. Test 4, however, showed significantly more growth than the other 3, and continued to grow after the others began to wilt. These results are illustrated in Fig. 9 below. Images of the plant growth in Fig. 10 provides a clear comparison of the four growth tests as well.

a)



b)

Figure 10. CLP Test 2: plant growth visuals. *Plant growth is shown here at a) four days and b) eight days.*

Test 4 continued to show growth for over 30 days with minimal watering only once every 3 days. However, as the roots of the plants continued to penetrate the arcillite, it became apparent that the roots were not penetrating the CLP gel. With the slow expansion of the gel, roots became visible on the surface of the arcillite bed. Based on these observations, it became apparent that pure hydrogels provide very high water retention, but when densely packed, restrict oxygen flow to the root zone. In the case of a dense gel structure, although water retention is high, water availability to the roots may be lower than expected, due to an inability of roots to uptake water from such a strong retention force, and the inability of roots to penetrate the gel due to a lack of oxygen. Because of this, TCHR was chosen as the ideal media gel, to be mixed with potting soil and Nutricote controlled release fertilizer in the tuber module prototype.

IV. Prototype Development

A. Materials Selection

1. Housing

The module housing could be built using most types of metal or plastics. Plastic or acrylic is ideal for this system due to its low weight and since it has no risk of corrosion. Based on the media investigations, an opaque surface is also beneficial for reducing potential light penetration to the root zone. For the prototype, the selected material was 3/16 inch black acrylic plexiglass.

2. Bag Material

In order to provide the tuberous roots with the best chance of growing, based on the media investigation, the ideal material would be a light, flexible, durable sheet material that can hold water, but will allow for gas flow to the root zone. Low-density polyethylene (LDPE) and polyolefin shrink wrap were both tested, but were found to be too rigid

when shaped to a ring structure, not allowing for fluid movement of the module. Tyvek high-density fibrous polyethylene (HDPE) was the next choice, although it is usually used as a house wrap material for building construction. The major advantage of this material is its combination of water resistance and gas permeability. Three types of Tyvek, type 10, 14 and 16 were considered, as they offer a more flexible, fabric-like structure. Type 16 could provide an improved ability for gas flow in the future, because of the pinhole structure. However, ultimately 1443R Tyvek was chosen for its flexibility and more reliable water seal.

3. Sealants

A reliable and flexible sealant was needed to bond the Tyvek sheets to themselves and the module structure. Polyurethane, epoxy, and silicone sealants were all tested on the fabric. All three of these sealants had similar adhesive and waterproofing capability, but after full curing, the silicone sealant displayed the best flexibility, and was chosen for implementation in the prototype.

4. Structural Components

The custom base, top panel, and lid of the module were decided to be 3D printed from a light and durable ABS plastic, allowing for simple fabrication. Zinc coated aluminum rings were chosen to use as the structural rings of the module for their relative light weight and resistance to rust. Acrylic or plastic rings could provide a lighter alternative, but may need to be fabricated in future iterations, in order to achieve the correct shape and size. Since Tyvek fabric does not stretch to fit the ring structure, it was decided that 10 lb. low density fishing line would be used to maintain the structure of the module. ¼ inch LDPE tubing was chosen for the watering tube.

B. Construction Methods

The 6 pieces that make up the module housing were laser cut from a 24 x 24 inch sheet of 3/16 black plexiglass acrylic. These pieces were designed to interlock, and were easily assembled without the use of acrylic glue. After observing sliding of the front slide panel of the housing on the base, two channels were 3D printed using white ABS plastic and bonded with epoxy to the housing base. These allowed for easier insertion and stability of the sliding panel. The module bases, top panels, and lids were tied sequentially to four of the zinc rings for each module, and then to the module top panel.

Figure 11. Assembled module structures in housing unit.

Tyvek 1443R sheets were cut to match the length and circumference of the modules, and were adhered to themselves using silicone sealant. After curing, these cylindrical sheets were sealed to the module top panel, and then the bottom panel, forming the module bag. Velcro was used to attach the lid to the top panel of the module. Finally, the watering tubes were inserted into the module lids, and the completed modules inserted into the housing unit.

Figure 12. Sealed modules in housing unit. *Collapsed module (left) and expanded module (right)*

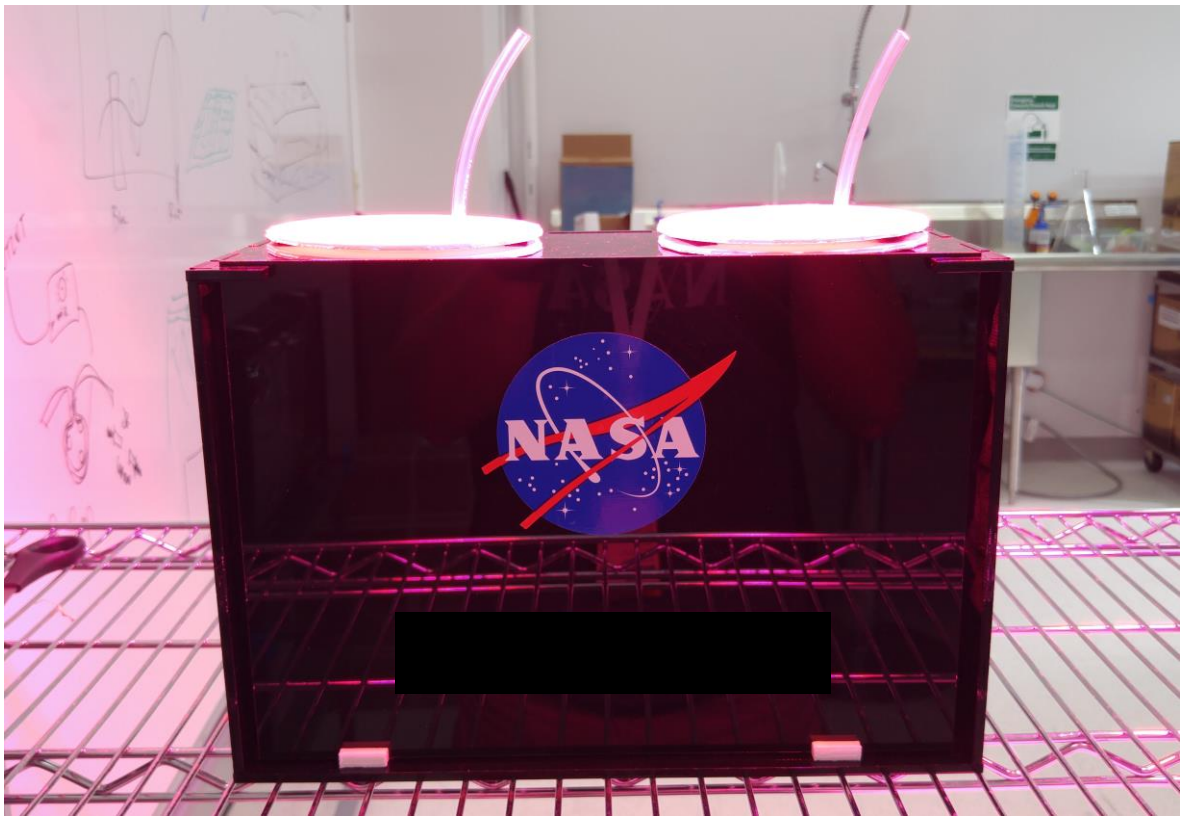


Figure 13. Fully constructed system prototype.

V. Testing and Evaluation

A. Initiation

Daikon radish seeds were planted in four pots with pure potting soil. The seeds were germinated and seedlings thinned to one plant per pot after four days. Two of the plants were chosen to be grown in the module, and two were kept to be grown in pots as controls. Planting media was made by mixing potting soil with 7.5 g/L Nutricote 70 day controlled release fertilizer, and 10 g/L TCHR crystals. Each 10 g of TCHR can hold up to 200 mL of water throughout the cycle, providing a media expansion of about 20 percent by volume. Each of the two modules were given 150g of the mixture, and when initially filled, each module was four inches in length. The control plants were given the same media mixture, and transplanted to a standard 6 inch pot. The two chosen seedlings were transplanted to the prepared modules, and the growth test was initiated under 47 W, 50-60 Hz red/blue LED light for 24 hours per day, in a Gorilla Grow Tent.

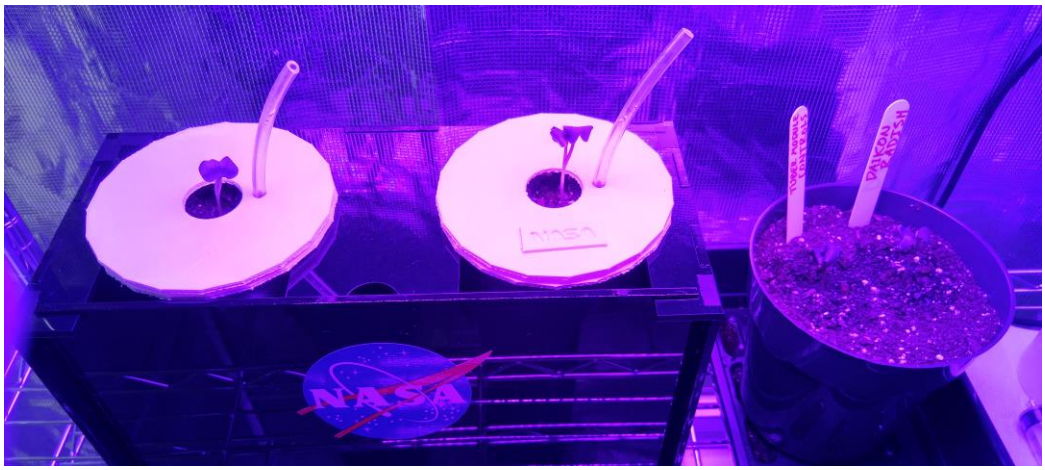


Figure 14. Growth test: top view. *Module plants (left) and control plants (right) immediately after transplant*

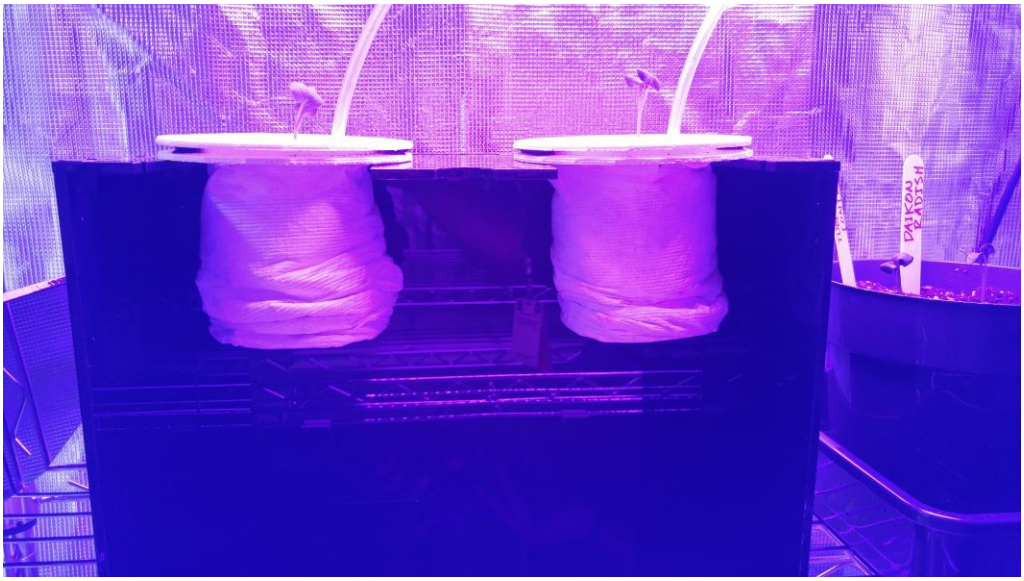


Figure 15. Growth test: front module view. *Module plants (left) and control plants (right) immediately after transplant*

B. Growth Cycle

For the first 10 days, the plants were given 30 mL of water per day, through a syringe inserted into the watering tube. This was increased to 60 mL after 10 days, 100 mL after 18 days, and 120 mL after 25 days. The control plants were given the same treatment. The control plants were also raised at 10 days to match the height of the module plants, putting the media surface at around 12 inches from the LED lights. Pictures were taken, and each of the plants and module bags were measured daily. Both modules began at a length of 3.5 in, and were also measured daily. The radish plants grew successfully for 32 days, before their harvest. Detailed images from the full growth cycle can be seen in Appendix A. Fig. 16 shows the growth curve of each plant over the full cycle, based on the plant height, measured from the media surface. Fig. 17 shows the increase in length of the module bags through the growth cycle. The data tables from the growth cycle can also be found in Appendix A.

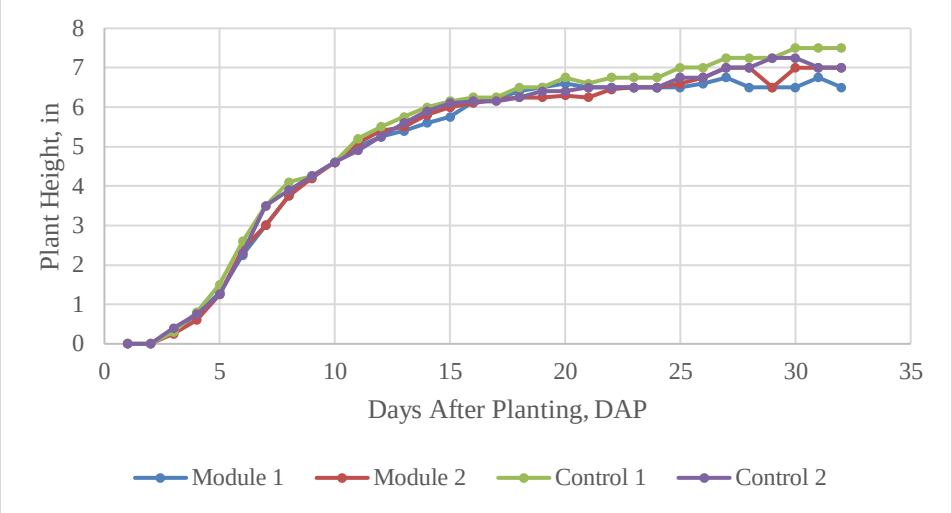


Figure 16. Growth test: plant height curve.

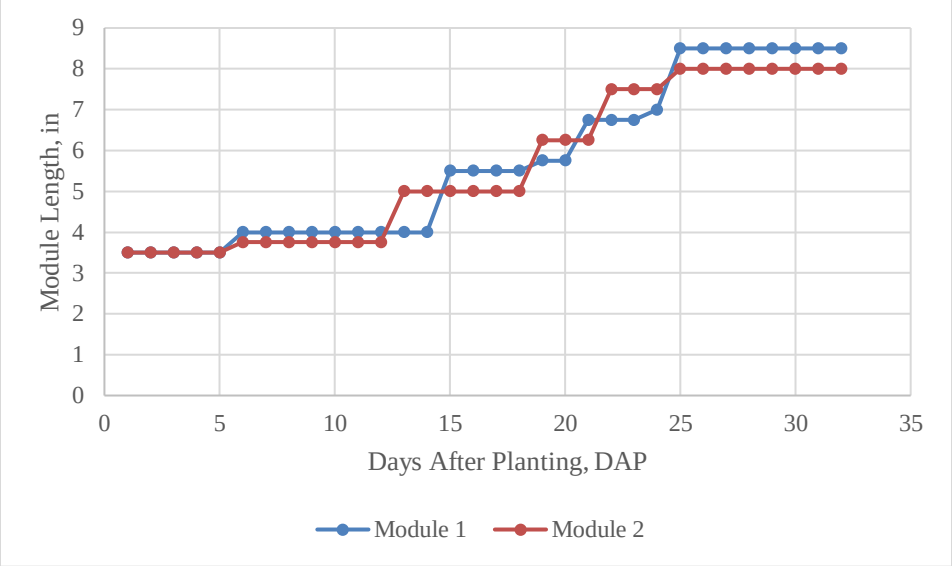


Figure 17. Growth test: module length curve.

The plant height growth curves are all very similar, with the control plants growing slightly taller than the module plants. Each of the modules expanded similarly, remaining at specific heights, and then expanding in quick bursts, matching the expected expansion based on the mechanical design of the ring structure. Module 2 did not expand to the full length, but did expand to the last ring level. This discrepancy in length was due to the root and media structure, which slightly twisted the module bag. This can be seen in the harvest data and images in the next section.

C. Harvest

The harvest was conducted at 32 DAP. This is an early harvest for Daikon radishes, but is acceptable, as the focus of this growth test was proof of concept for the functionality of the module expansion, rather than crop production. The images below in Fig. 18 and 19 show the module and control plants, respectively, before the harvest. The plants were first measured in height, and then their leaves cut, counted, weighed, and their total area measured using a LI-COR LI-3100C area meter.

Figure 18. Growth test: pre-harvest module plants. *Front view with visible modules (left) and top view (right)*

The modules showed successful expansion and successful crop growth overall. Module 2 (on the left in Fig. 18) did experience minimal leakage, around 2 mL per day, from a seal in the last 5 days of the growth cycle, while Module 1 had no leakage. Discoloration of the lower parts of the Tyvek wrap did appear at the bottom of the modules where the media and water were saturated, but did not cause any leakage or other deterioration of the modules.

Figure 19. Growth test: pre-harvest control plants. *Front view with (left) and top view (right)*

The harvested greens of the control and module plants showed notable differences in the robustness, mass, area and color, with the controls slightly outperforming the module plants in all categories. The module plant leaves were a more faded green, with yellowing discoloration of some leaves of the Module 2 plant. This reduced level of growth and plant health is most likely due to the restricted media mass and root volume. A graph with a comparison of leaf numbers, total area, and average area can be seen in Fig. 20.

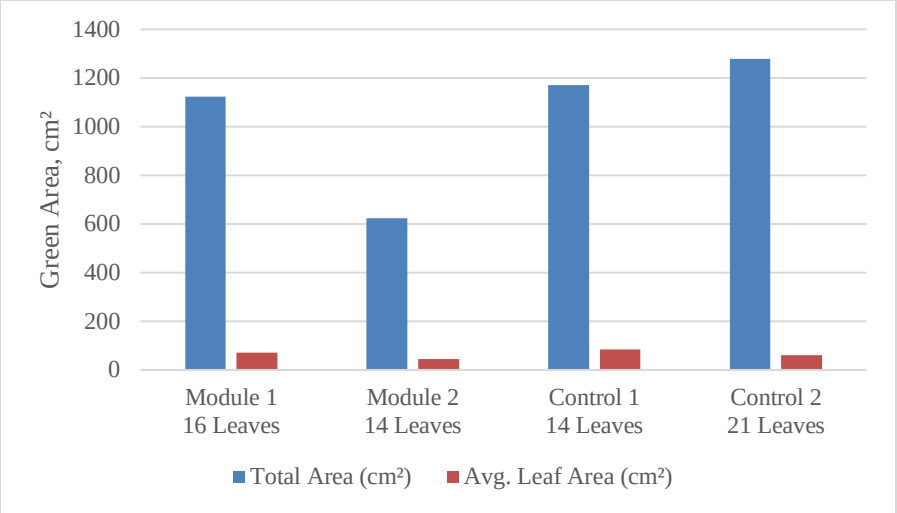


Figure 20. Growth harvest: total and average leaf area.

Next, the root media and tubers were removed from the modules and the planting pot. The roots were cleaned, measured, and weighed. A comparison of root size and color is shown in the image in Fig. 21, and Fig. 22 shows a comparison of the tuber and green mass for each plant.

Figure 21. Growth harvest: visual tuber comparison. *Left to right: Module 1, Module 2, Control 1, Control 2*

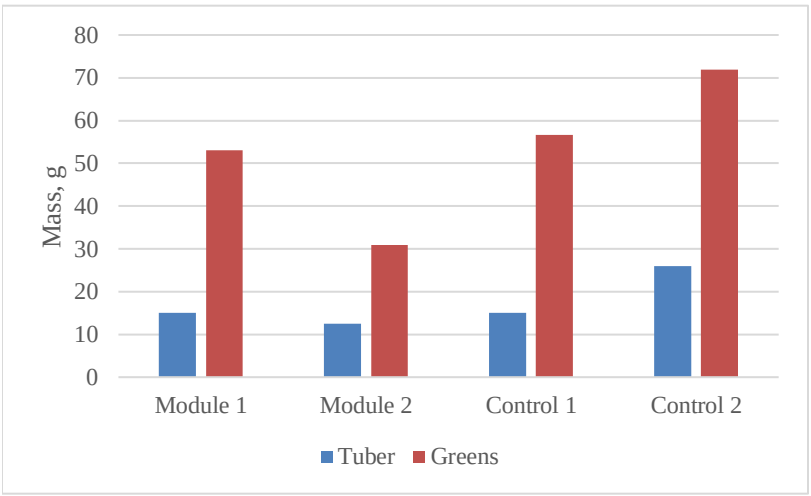


Figure 22. Growth harvest: tuber and greens mass comparison.

It is clear from the data that the control plants slightly outperformed the module plants in the overall size of the plants, as well as the edible mass production, with the Module 2 plant performing below the rest. It is unclear exactly what caused this difference in the growth of the Module 2 plants, but overall it seems that the module plants grew very well considering the restriction of their total rooting media mass and available volume. It seems from these results that that the expansion of the tuber modules served the correct purpose, allowing for similar growth capabilities, successfully producing edible mass, with a drastically minimized media mass. More detailed harvest images and tables containing harvest data can be seen in Appendix B.

VI. Conclusion

An expandable root zone module was designed to effectively grow tuber plants while minimizing the required mass of root media. The modular design was adapted to specifications for integration and use in the Veggie plant growth system. Media investigations were performed to evaluate the potential use of multiple grades and formulas of water retaining hydrogels as a way to reduce watering maintenance in the system and support autonomous plant growth. A functional tube module prototype was successfully built and was tested through full growth cycles of Daikon radish. The first growth test was successful and tubers and greens were harvested after 32 days, with growth data collected daily. The harvest data showed that all of the plants grew successfully, with the control plants producing slightly more edible mass. The module prototype still produced very successful plants with the restricted root volume and minimal media mass proving the success of the module bag concept.

With results from initial growth tests, the system can be improved for eventual integration with the Veggie growth unit and testing on the ISS for deep space exploration habitats. Future growth tests can expand focus to longer growth cycles, nutrient analysis, and experimentation with new media. These modules were also specifically designed for vertically expanding tubers, but could be modified in size or shape to accommodate for other tuber plants such as potatoes, yams, and a host of other species. One avenue for design improvement would be to design a spring-like module for a more constant expansion throughout a growth cycle. Other emerging materials could show promise for expandable root zone technology, such as flexible thin-membrane silicone elastomer chambers, and flexible 3D printing filaments such as thermoplastic polyurethane. More investigation is needed into the capabilities of these materials, as well as the compatibility of these systems with alternative methods of water. Nutrient, and air delivery, but they could serve as a more reliable and reusable alternative to the mechanically expanding tuber module.

Appendix A

Growth Test Images and Data

Figure A1. Growth test progression. *Module plants at 10, 12 and 14 DAP.*

Figure A2. Growth test progression. *Module plants (left) and controls (right) at 20, 26 and 31 DAP.*

Table A1. Growth test daily data.

DAP	Plant Height (in)				Module Length (in)	
	Module 1	Module 2	Control 1	Control 2	Module 1	Module 2
1	0	0	0	0	3.5	3.5
2	0	0	0	0	3.5	3.5
3	0.3	0.25	0.3	0.4	3.5	3.5
4	0.75	0.6	0.8	0.75	3.5	3.5
5	1.3	1.25	1.5	1.25	3.5	3.5
6	2.25	2.4	2.6	2.3	4	3.75
7	3	3	3.5	3.5	4	3.75
8	3.75	3.75	4.1	3.9	4	3.75
9	4.25	4.2	4.25	4.25	4	3.75
10	4.6	4.6	4.6	4.6	4	3.75
11	5	5.1	5.2	4.9	4	3.75
12	5.25	5.4	5.5	5.25	4	3.75
13	5.4	5.5	5.75	5.6	4	5
14	5.6	5.8	6	5.9	4	5
15	5.75	6	6.15	6.1	5.5	5
16	6.125	6.1	6.25	6.15	5.5	5
17	6.2	6.2	6.25	6.15	5.5	5
18	6.4	6.25	6.5	6.25	5.5	5
19	6.5	6.25	6.5	6.4	5.75	6.25
20	6.6	6.3	6.75	6.4	5.75	6.25
21	6.5	6.25	6.6	6.5	6.75	6.25
22	6.5	6.45	6.75	6.5	6.75	7.5
23	6.5	6.5	6.75	6.5	6.75	7.5
24	6.5	6.5	6.75	6.5	7	7.5
25	6.5	6.6	7	6.75	8.5	8
26	6.6	6.75	7	6.75	8.5	8
27	6.75	7	7.25	7	8.5	8
28	6.5	7	7.25	7	8.5	8
29	6.5	6.5	7.25	7.25	8.5	8
30	6.5	7	7.5	7.25	8.5	8
31	6.75	7	7.5	7	8.5	8
32	6.5	7	7.5	7	8.5	8

Appendix B

Harvest Images and Data

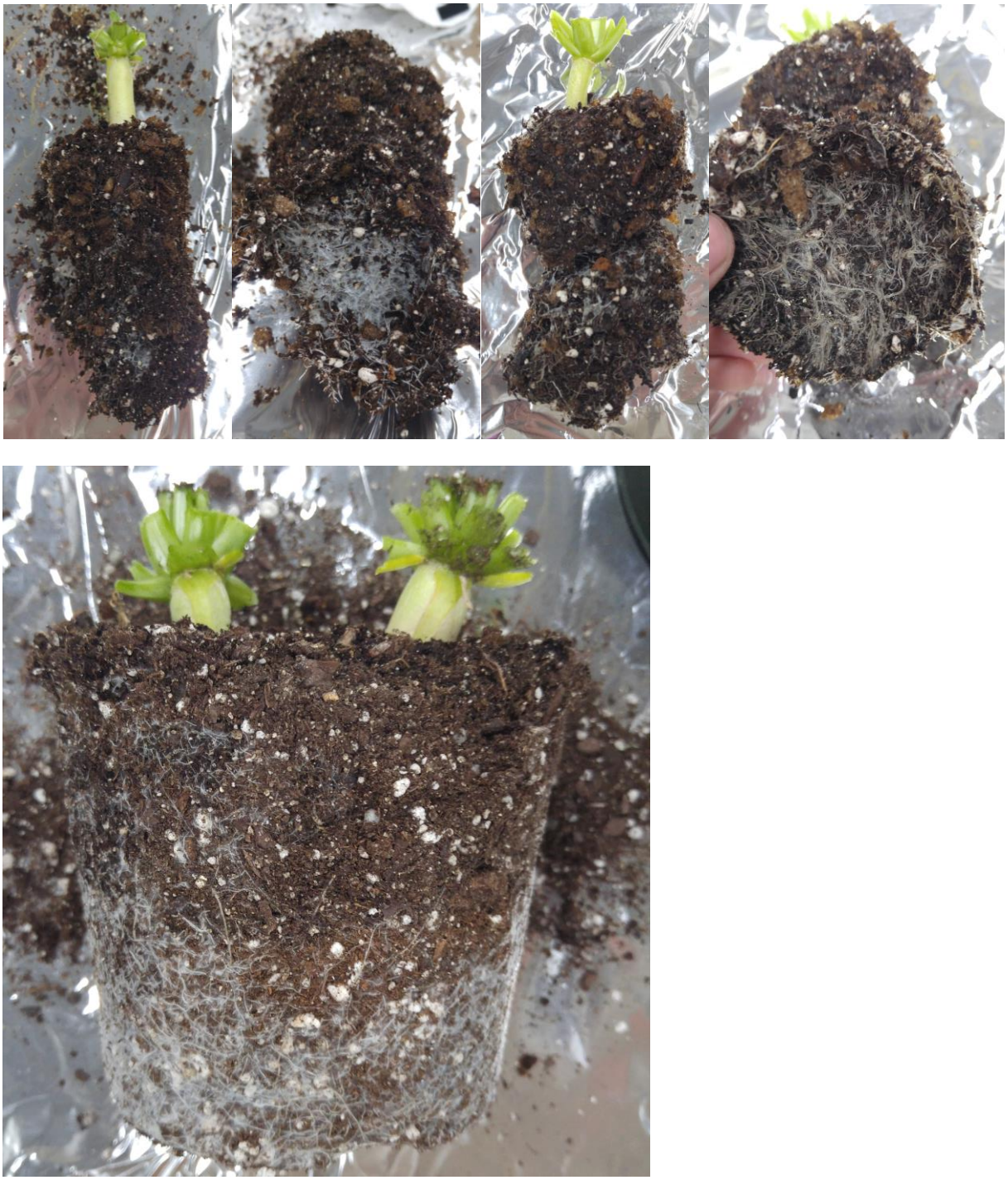


Figure B1. Harvest media removal. *Module 1 (top left), Module 2 (top right) and controls (bottom).*

Table B1. Harvest data.

	Tuber Length (in)	Tuber Width (in)	Tuber Mass (g)	Green Height (in)	Green Mass (g)	Total Leaves	Total Area (cm^2)	Avg. Leaf Area (cm^2)
Module 1	3.5	0.625	15	6.5	53	16	1123.9	70.2
Module 2	2.75	0.5	12.5	7	30.9	14	622.8	44.5
Control 1	2.7	0.6	15.1	7.5	56.6	14	1171.1	83.7
Control 2	3.6	0.75	25.9	7	71.9	21	1279.2	60.9

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