REPORT ON SUMMER PROJECT

BY

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PROJECT NAME: NASA X-HAB WATER DELIVERY SYSTEM

SPONSOR: NASA SPACE LIFE AND PHYSICAL SCIENCES DIVISION

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1 Introduction

1.1 Previous Investigations

As part of the eXploration Systems and Habitation (X-HAB) Academic Innovation Challenge program of National Aeronautics and Space Administration (NASA), The Ohio State University was selected to improve the performance of NASA's existing Vegetable Production System (VEGGIE), which is a deployable plant growth unit for International Space Station (ISS). During the academic year 2015-2016, The Ohio State University student team developed a passive water delivery system using capillary water transport principle (Jenson et al. 2016). The major design improvement made was directly connecting the water reservoir to the plant-rooting pillows using a single-interface capillary cord design. Harvestable plants were successfully grown from seeds using the single interface system. In addition, Nomex®, a fabric material composed of short nylon based fibers, was identified as the material for wicks. Finally, the water reservoir was modeled as a propellant management device (PMD) to ensure consistent and long term watering of the VEGGIE system. The PMDs are made of materials that utilize surface tension and adhesive forces to improve stability and fluid delivery. The team recommended using a sponge PMD in order to mitigate bubble obstruction, decrease system weight, and ensure reliable water delivery to the capillary interface.

The primary objective of the 2016-2017 project was to continue improvements of the water delivery system of the VEGGIE system. Components of VEGGIE that were investigated for the upgrade of the water delivery system were plant-rooting pillows, capillary interface and water reservoir. A design prototype of the upgraded system was developed, and its primary components were:

- Collapsible reservoir to easily indicate water level and reduce maintenance time
- New interface system to reduce leakage between the reservoir and root pillow, and improve the reusability of the system
- Direct delivery tubes using Nomex® wicks
- PMDs to mitigate water placement and bubble movement within the reservoir

The collapsible reservoir design mitigated the issues of water placement and fill level indication by creating a flexible reservoir. The final design featured a square prism reservoir with a rigid top and bottom sheet, while the sides of the reservoir were flexible. Between the top sheet and the collapsing sides, a flexible convex sheet that provided space in the top of the reservoir for the water delivery tubes and PMD structures. Interface between root pillow and water reservoir was provided by using a single solid piece on each side of the delivery point. PMDs (sponges) were used to control water placement over the water delivery points within the reservoir. The design was successful in promoting plant growth.

1.2 Present Goals

The goals for the Summer 2017 project were:

- Investigate the possibility of use of semi-porous substrates for root support and nutrient delivery
- 3-D printing of the semi-porous substrate for plant production
- Determine the safety of food production with renewable growth substrate.

2 Literature Search

2.1 Semi-Porous Membranes

One of the alternatives for growing plants in microgravity is to use semi-porous substrates for root support and nutrient delivery. Semi-porous substrates could potentially be used in conjunction with a collapsible reservoir, as a way to maintain hydraulic continuity and reduce pressure differentials within the reservoir. The semi-porous substrate model is based on the non-linear tendency of root membranes to uptake water and is dependent on parameters such as root depth, and amount and placement of extractable water (Gardner, 1991). SVET-GEMS complex, the Bulgarian-built plant growth unit, used a similar system (Jones and Or, 1998 and 1999; Bingham et al. 2000). The system used a granular matrix material for root support and nutrient delivery. Growth rate and development of the plants in space compared well with plants grown on earth. In this case, the water delivery was dependent on the adhesion forces rather than capillary action, and therefore, circumvented the problems associated with a capillary system. The current literature search investigates the possibility of use of semi-porous membranes for root support and nutrient delivery, with a focus on microgravity systems.

Water reservoir sizing is dependent on the amount of water uptake by roots of the plant. A mathematical description of the process of the uptake of water by the plant root is needed to model the hydrological cycle. Based on literature review it was found that many models (Ahuja and Nielsen 1990; Klepper 1990; Molz 1971) are based off a common theory that flow through the plant is analogous to flow through a resistance network and can be expressed as F=((H_p-

$H_s))/((R_p-R_s))$, where F is the steady state transport of water from a unit volume of soil to a plant leaf, Hp is the hydraulic head in the plant at some point, Hs is the hydraulic head in the soil, Rp is the resistance to water movement in the plant, and Rs is the resistance to water movement in the soil. Molz (1971) presents an uptake model in one dimension as some variation of the general equation, and is given as

$$\partial\theta/\partial t=\partial/\partial z\ ((D(\theta)\partial\theta)/\partial z)-\partial K(\theta)/\partial z-S(z,R,t,\theta) \qquad (1)$$

where θ is the soil water content, D is the soil water diffusivity, z the depth, k the unsaturated conductivity, and S is the sink term describing the uptake process.

Gardner (1991) developed on the above equations and used a model to represent the non-linear behavior of the root membranes to estimate the water uptake by roots. The model represents the uptake process as the water level in a sink moving downward through the soil profile. This model could be executed by using only two parameters - a root depth parameter, and an extractable water parameter. In essence, the model replaces the sink term (as indicated above) by assuming that the non-linear flow function for plant roots results in a limited zone of uptake which can be represented by a moving sink. The depth distribution of this sink will depend on the local root density. The rate of movement of the sink downward is determined by the transpiration rate and the volume of extractable water in the soil. Gardner (1991) also assumed that below the sink, but within the root zone, there is sufficient water uptake by the roots so that a constant value for the diffusivity parameter can be considered. Therefore, the highly 'efficient' root system with low vertical resistance could continue to extract water at the potential rate until the water stored in the profile was exhausted. In an infinite system, steady state is eventually achieved so that the water content (θ) will be

$$\theta=\theta_0 \quad \text{for } z<0 \qquad (2)$$

$$\theta=\theta_i-(\theta_i-\theta_0)\exp[-TZ/D(\theta_i-\theta_0)] \qquad (3)$$

The z = 0 represents the position of the sink, and D represents the effective diffusivity of the composite medium of roots and soil and ranges between 0.01 m^2/day to 0.04 m^2/day and 0.01 m^2/day seems to be applicable for many of the crops for which data have been analyzed. The sink moves downward with the velocity, $v=T/((\theta_i-\theta_0))$. Therefore, the water uptake can be predicted using the above equation. Presently, the team is in the process of developing the transport equations for the water uptake and these equations will be finalized as the prototype is being developed.

Jones and Or (1998) have developed a new capillary-driven root module design for growing plants in microgravity and this requires minimal external control. Unlike existing systems, the water supply to the capillary-driven system is passive and relies on root uptake and media properties to develop driving gradients, which operate a suction-induced flow control valve. A collapsible reservoir supplied water to the porous membrane, which maintained hydraulic continuity. Sheet and tubular membranes consisting of nylon, the authors tested polyester and sintered porous stainless steel. While finer pore sized membranes allowed greater range of operation, they also reduced the liquid flux and decreased the system efficiency. The ideal membrane for a particular system should be based on a balance between the maximum anticipated liquid uptake rate and maximum operating matric head (suction) of the system. The authors also found that a minimum of 10% air-filled porosity was necessary for adequate aeration. Plants were grown in the module for more than 80 days where oxygen content within the media was maintained near atmospheric levels and nutrient solution was continuously supplied to plants. Substantial gradients were observed across the membrane when the membrane hydraulic conductivity was much less, than peak transpiration rates, and this effectively reduced the media water content and the ability to transfer water to plant roots. Polyester and sintered porous stainless-steel membranes were found to be hydraulically restrictive. Nylon and sintered porous stainless-steel membranes provided unrestricted flow at peak transpiration rates.

Jones and Or (1999) also investigated the microgravity effects on water flow. Plants grown in porous media are part of a bioregenerative life support system designed for long-duration space missions. Reduced gravity conditions of orbiting spacecraft (microgravity) alter several aspects of liquid flow and distribution within partially saturated porous media. The authors evaluated the suitability of conventional capillary flow theory in simulating water distribution in porous media measured in a microgravity environment. Data from experiments aboard the Russian space station Mir and a U.S. space shuttle were simulated by eliminating the gravitational term. Qualitative comparisons with media hydraulic parameters measured on Earth suggested narrower pore size distributions and inactive or nonparticipating large pores in microgravity conditions. Evidence of accentuated hysteresis, altered soil-water characteristic, and reduced unsaturated hydraulic conductivity from microgravity simulations were attributed to a number of proposed secondary mechanisms, which included enhanced interfacial flows and altered liquid-solid forces.

Similar to the studies conducted by Jones and Or (1998 and 1999), Bingham et al. (2000) also studied the effects of microgravity on water supply and substrate properties in porous matrix root support systems. The authors focused on upgrading the plant growth facilities on the Mir Orbital Station (OS) and used them to study the full life cycle of plants. The SVET-GEMS complex, which is the Bulgarian-built plant growth unit (also known as the greenhouse) on the Mir OS since 1990, was used to grow wheat. The root module occupied the bottom part of the greenhouse and used a granular matrix material for root support and nutrient delivery. The growth rate and development of these plants compared well with earth grown plants indicating that the root zone water and oxygen stresses that have limited plant development in previous long-duration experiments were not present. The movement of substrate particles in microgravity, combined with the effect of gravity on the shape of the water meniscus, appeared to trap air bubbles in the particulate pores. These air bubbles caused drastic changes in hydraulic conductivity and affected oxygen diffusion to plant roots.

A porous-membrane technique has been successfully used in root studies of field-grown soybean (Beyrouty and Oosterhuis 1989). In order to evaluate this technique on other crops, a study was conducted to compare growth parameters of individual soybean, cotton, Gossypium hirsutum L., and corn, Zea mays L., plants grown with and without their root systems confined within porous membranes. Results indicate that plant species respond differently to root confinement. Root confinement reduced all shoot growth and yield parameters of the crop species; however, the reduction was generally greatest for cotton. Apparently, cotton is less adaptable to the restricted rooting volume. Root confinement reduced levels of potassium and phosphorus in soybean and nitrogen in corn and cotton. Fertilizer rates higher than soil test recommendations should be applied to membrane-grown plants to prevent reductions in nutrient levels. It may be possible that modifying the size or shape of the membrane will enhance root and shoot growth of specific crop plants like cotton and increase the ability of this technique to be used on a broader spectrum of crop plants.

Where field retrieval of entire plants including clean roots may be important, porous membrane rooting envelopes are a method of choice (Drew 1993). Purple osier willow (Salix purpurea L.) stem cuttings (clone SP3) were field rooted in buried porous membrane envelopes permeable to water and nutrients. Ramets were grown for two and four months, and then separated into component parts for dry weight analysis. At two months, cuttings grown in rooting envelopes were no different in shoot dry weight from plants grown in clay pots or in soil. Tests indicated that rooting envelopes might be reused at least once without affecting shoot or total plant dry weight. Likewise, membrane pore sizes of 0.45, 1.2 and 3 μm did not affect SP3 dry weight in four month tests. The importance of matching plant material and experiment duration to envelope size was illustrated by the limitation of growth by envelope edges at four months compared to two months.

Growing plants to facilitate life in outer space, for example on the ISS or at planned deep-space human outposts on the Moon or Mars, has received much attention with regard to NASA's advanced life support system research. With the objective of in situ resource utilization to conserve energy and to limit transport costs, native materials mined on Moon or Mars are of primary interest for plant growth media in a future outpost, while terrestrial porous substrates with optimal growth media characteristics will be useful for onboard plant growth during space missions. Based on ground-based measurements, Deepagoda et al. (2014) examined water retention, oxygen diffusivity and air permeability characteristics of six plant growth substrates for potential applications in space, including two terrestrial analogs for lunar and Martian soils and four particulate substrates widely used in reduced gravity experiments. To simulate reduced gravity water characteristics, the predictions for ground-based measurements (1 g) were scaled to two reduced gravity conditions, Martian gravity (0.38 g) and lunar gravity (0.16 g), following the observations in previous reduced gravity studies. We described the observed gas diffusivity with a recently developed model combined with a new approach that estimates the gas percolation threshold based on the pore size distribution. The model successfully captured measured data for all investigated media and demonstrated the implications of the poorly understood shift in gas percolation threshold with improved gas percolation in reduced gravity. Finally, using a substrate-structure parameter related to the gaseous phase, we adequately described the air permeability under reduced gravity conditions.

2.2 3-D Printing

3D printing or additive manufacturing is a process of making three dimensional solid objects from a digital file. The creation of a 3D printed object is achieved using additive processes. In an additive process an object is created by laying down successive layers of material until the object is created. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object. 3D printing is the opposite of subtractive manufacturing which is cutting out or hollowing out a piece of metal or plastic with for instance a milling machine. 3D printing enables one to produce complex (functional) shapes using less material than traditional manufacturing methods.

This portion of the literature search focuses on 3-D printing of the porous substrate. Nanocellulose has a variety of advantages, which make the material most suitable for use in biomedical devices (Rees et al., 2015). The material is strong, allows for production of transparent films, provides a moist environment, and can form elastic gels with bio-responsive characteristics. Rees et al (2015) explored the application of nanocellulose as a bio-ink for modifying film surfaces by a bio-printing process. Two different nanocelluloses were used, prepared with TEMPO mediated oxidation and a combination of carboxymethylation and periodate oxidation. The combination of carboxymethylation and periodate oxidation produced a homogeneous material with short nanofibrils, having widths <20 nm and lengths <200 nm. The small dimensions of the nanofibrils reduced the viscosity of the nanocellulose, thus yielding a material with good rheological properties for use as a bio-ink. The nanocellulose bio-ink was thus used for printing 3D porous structures. They also demonstrated that both nanocelluloses did not support bacterial growth, which is an interesting property of these novel materials. This study showed how nanocellulose might be formulated to manufacture substrates and gels that may be deposited as a bio-ink through a printing process. Based on the printing of grid structures, the researchers concluded that the C-Periodate nanocellulose was suitable for being used as bio-ink. This was most probably due to the higher consistency and appropriate rheology of the C-Periodate nanocellulose achieved in this study. The nanocelluloses form 3D structures where the tracks have an open porosity and the potential to carry and release antimicrobial components.

Lignocelluloses are composed of cellulosic nano-fibrils, which can be disintegrated by chemical, mechanical and enzymatic methods in order to obtain nanocellulose. Further, nanocellulose can also be synthesized by bacterial method in a suitable culture. Nanocelluloses have many interesting properties (viz. nano-dimension, renewability, low toxicity, biocompatibility, biodegradability, easy availability and low cost) which make them ideal nanomaterials for diverse applications. Mondal (2017) presented a review of researches on recent advances in nanocellulosic materials. Various methods of nanocellulose preparation and their properties, surface modifications of nanocellulose, and applications of nanocellulose in the diverse fields have been discussed in the paper.

2.3 Food Borne Pathogens

Data from the Centers for Disease Control and Prevention (CDC) identified produce as either the first or second leading vehicle in food-borne disease outbreaks attributed to a single commodity within the United States for the period 2006-2008. Furthermore, outbreak surveillance data of produce items compiled by the CDC during the period 2000-2009 revealed that leafy greens were the most common item associated with food-borne disease, followed by tomatoes and cantaloupes. Based on data compiled from the CDC website on outbreak surveillance (http://www.cdc.gov/outbreaknet/surveillance_data.html), the most common bacterial pathogens are Salmonella, Escherichia coli, Shigella, and Campylobacter jejuni. Among the different plants studied, it was found that Salmonella was found most in green leafy salad and tomatoes, Escherichia coli was found most in lettuce and green leafy salad, and Shigella and Campylobacter jejuni were found most in green leafy salad. In a similar study conducted by U.S. Department of Health and Human Services, 14 pathogens were identified as the most prevalent food-borne pathogens (https://www.fda.gov/food/resourcesforyou/healtheducators/ucm091681.htm). In this study, the bacterial pathogens that are particular to plants were Salmonella, Shigella, Staphylococcus aureus, Vibrio cholera and Yersinia enterocolitica. The most common symptoms are diarrhea, fever, vomiting, headache, nausea, and stomach cramps.

3 Investigations Conducted

3.1 3-D Printing

The objectives of this phase of the investigation are:

- Find 3-D printing facilities, both on-site and off-site
- Develop a 3-D model of the semi-porous structure that will support plant growth.

The semi-porous structure, impregnated with suitable nutrients, can be used instead of the plant root pillows with arsulite. The root pillow is heavy and bulky, and if new material is to be used for each batch of crops, that would require a large payload. Substantial reduction of growth substrate is desirable to reduce payload required for transporting fresh substrate and disposal of used substrates. By producing suitable growth substrate on board, it is possible to reduce unique-purposed supply payloads, and thus increasing equivalent system mass (ESM) of generic supplies. In this case, growth substrate can be produced as needed using 3-D printing capability and general-purpose filaments that are already on board of a space vessel.

3.2 Microbial Study

The purpose of the microbial study was to detect the presence of bacterial pathogens on the plants harvested from the microgravity plant growth system. Sustainable food crop production is critical for long term manned space missions. Improving ESM of plant growing substrate is a high priority for space food production, and reusing growth substrate for multiple crops is one way to quickly improve ESM of the food production system. Major considerations of this approach are food safety, and plant growth performance. Increased microbial load on fresh vegetative crops from extended use of growth substrate is of concern, requiring development of on-board testing of microbial load for food safety.

The first phase of the experiments, conducted during Summer 2017, involved determination of microbial counts of substrates. Experiments were conducted with arsulite, which is the substrate in the plant pillows. Approximately 5 grams (g) of arsulite were collected every 5 days from beginning of growth cycle (90 days). Samples were vortexed to suspend in deionized water. About 1 ml of suspended solution were pipetted onto agar plates and incubated at 40 degree centigrade (°C). Growth of cells were monitored periodically (3 to 5 days throughout the entire growth cycle). Experiments were conducted in triplicates.

4 Results Obtained

4.1 3-D printing

4.1.1 Available Resources

The following facilities were found:

On-site:

- EEIC Robotics Lab, located in Hitchcock Hall and in under the College of Engineering - Printers available are 3D Systems VFlash and MakerBot Replicator 2.
- Tech Hub (614-292-8883, techhub@osu.edu) located at 2059 Milikin Road, Columbus, Ohio - Printer available is MakerBot Replicator Z18.
- Center for Design and Manufacturing Excellence (CDME) located in Scott Laboratory and Stillman Hall - Printers available are 3D Systems ProJet 3500 HD, 3D Systems ProJet 660 Pro, Afinia H400, Afinia H800, FormLabs 2, IC3D custom-built, and Mcor 300+.

Off-site:

- Columbus Idea Foundry located at 421 W State St, Columbus, OH. In order to use the available printers at this location, one needs attend relevant courses. In the future, it is planned that a membership at the Columbus Idea Foundry will be obtained (https://ideafoundry.com/about) after attending courses on 3-d printing and machining.

4.1.2 Semi-Porous Substrate Design

Design of the semi-porous substrate parts were completed using Solidworks® program. Figure 1 shows three views of the semi-porous substrate.

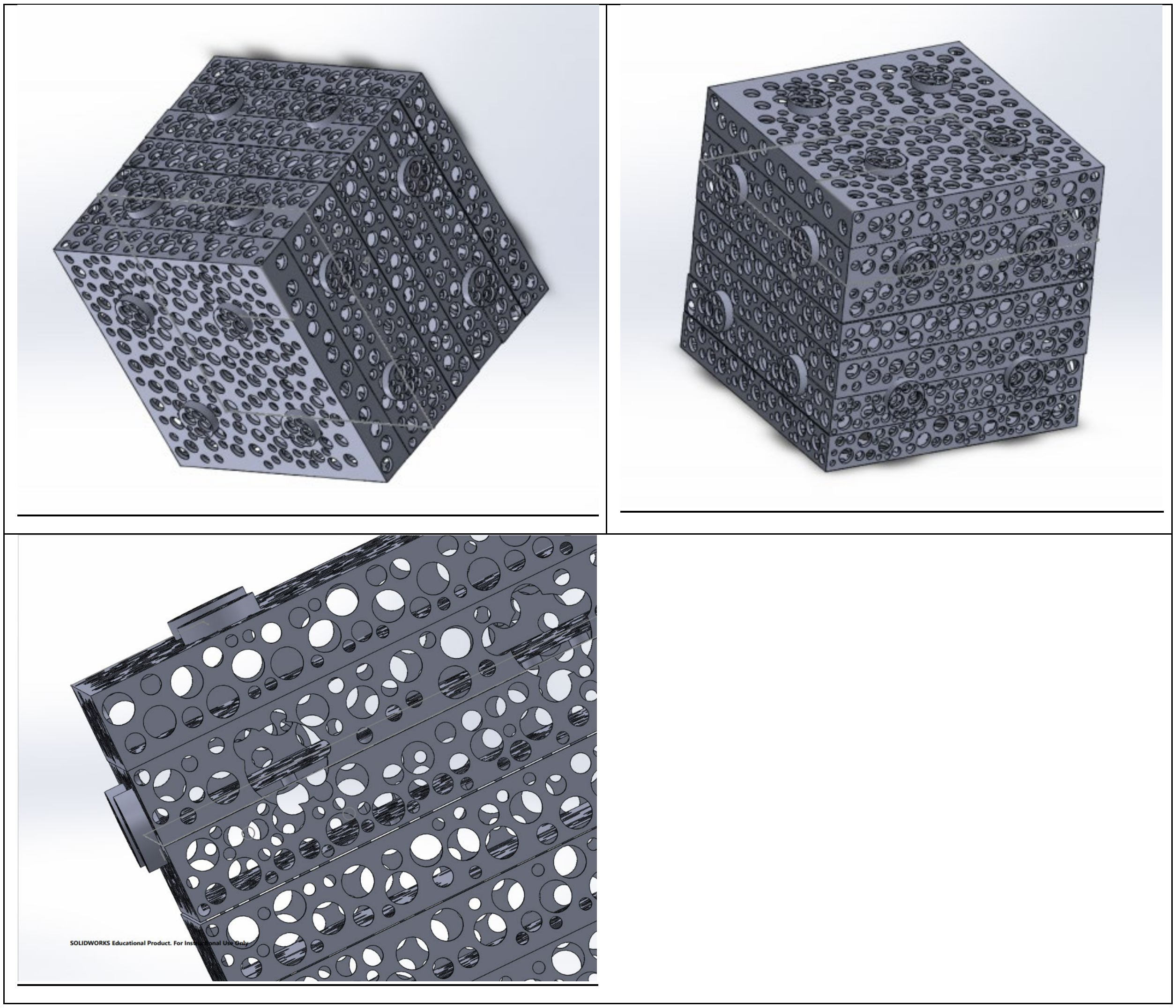

Figure 1: Conceptual Design of Semi-Porous Substrate

The direction of the reusable plant growth substrate was narrowed down to two potential designs. One design incorporated facets of the previous plant pillow with arsulite design by creating a biodegradable enclosure filled with individually printed substrate particles. The other design stemmed off the early design iteration of the semi porous growth substrate. This design incorporates 3-D printing of a hollow and porous structure with interlocking parts to make the plant growth substrate compact and easy to use in microgravity environments. The semi porous substrate has the advantage of not needing re-assembly after every growth cycle, mitigating the risk of disruption of small particles in a microgravity environment, and having a comprehensive singular network system that allows for proper water delivery, nutrient delivery, and root support.

4.2 Microbial Study

Extracts from the substrates were plated on agar plates. Three growing lettuce plants (L1, L2 and L3) were used for the study. Images of the plates from the microbial study are presented in Table 1.

Table 1: Agar Plates After Day 5	
	

Table 1: Agar Plates After Day 5


Despite repeated attempts, the agar plates became contaminated. The primary reason for this problem was unavailability of laboratory space for dedicated microbial work. Various research groups used the laboratory space for different purposes and this makes the plates susceptible to contamination. The incubator was also used by different groups and in some cases, the temperatures were changed.

As per plan, each of the colonies formed on the agar plates would have been plated in another agar plates to isolate the species. The goal was to isolate pathogens, if any, present.

The second phase of the experiments would be to determine the microbial counts of root system. Similar to the first phase of the experiment, 5 g samples of live roots would be collected every 5 days from beginning of growth cycle (90 days). Samples would be vortexed to suspend in deionized water. About 1 ml of suspended solution would be pipetted onto agar plates and incubated at 40°C. Growth of cells would be monitored periodically.

The success of the experiments will depend on the availability of proper laboratory space for microbial study.

5 Discussions

The system currently needs more testing to see if it is microbially sustainable. Ideally, this means that it will not have potential decay or infectious material throughout multiple plant growth cycles. A limitation that needs to be taken into account is acquiring a sterile lab space to run a multitude of microbial tests. This will be delved further into by the 2017-2018 capstone teams. The capstone teams for this year will refine the current 3D model for the plant growth substrate and understand the potential food safety issues from sequential crop harvesting.

6 References

- Beyrouty, C.A. and Oosterhuis, D.M. 1989. The porous-membrane technique for root studies of field-grown crops.
- Bingham, G. E., Jones, S. B., Or, D., Podolski, I. G., Levinskikh, M. A., Sytchov, V. N., Ivanova, T., Kostov, P., Sapunova, S., Dandolov, I., Bubenheim, D. B., Jahns. G. (2000). Microgravity Effects on Water Supply and Substrate Properties in Porous Matrix Root Support Systems: Acta Astronautica, 47(11), 839–848.
- Deepagodaa, T.K.K.C., Jones, S.B., Tuller, M., de Jonge L.W., Kawamoto, K., Komatsu, T., Moldrup, P. 2014. Modeling gravity effects on water retention and gas transport characteristics in plant growth substrates. Advances in Space Research 54(4): 797–808.
- Drew, A.P. 1993. Establishment of willow cuttings grown in porous membrane root envelopes. Plant and Soil : An International Journal on Plant-Soil Relationships, v148 n2 (01): 289-293
- Jones, S. B., Or, D. (1998). A Capillary-Driven Root Module For Plant Growth In Microgravity: Adv. in Space Research, 22(10): 1407-12)
- Jones, S. B., Or, D. (1999). Microgravity effects on water flow and distribution in unsaturated porous media: Analyses of flight experiments: Water Resources Research, 35(4), 929-942
- Mondal, S. 2017. Preparation, properties and applications of nanocellulosic materials. Carbohydrate Polymers, 163: 301–316.
- Rees, A., Powell, L. C., Chinga-Carrasco, G., Gethin, D. T., Syverud, K., Hill, K. E., and Thomas, D. W. 2015. 3D Bioprinting of Carboxymethylated-Periodate Oxidized Nanocellulose Constructs for Wound Dressing Applications. BioMed Research International v 2015, Article ID 925757.

Recycling of Inedible Plant Biomass NASA X-HAB Project Ohio State

Sponsor: NASA - National Aeronautics Space Administration

Technical Advisor: Dr. Peter Ling

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Team:

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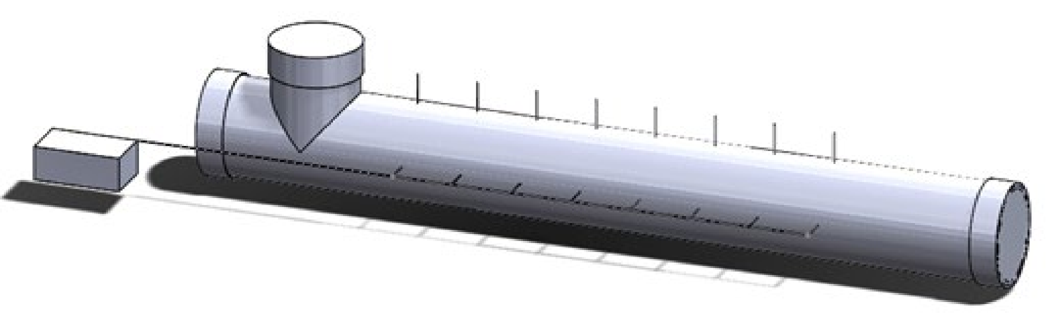
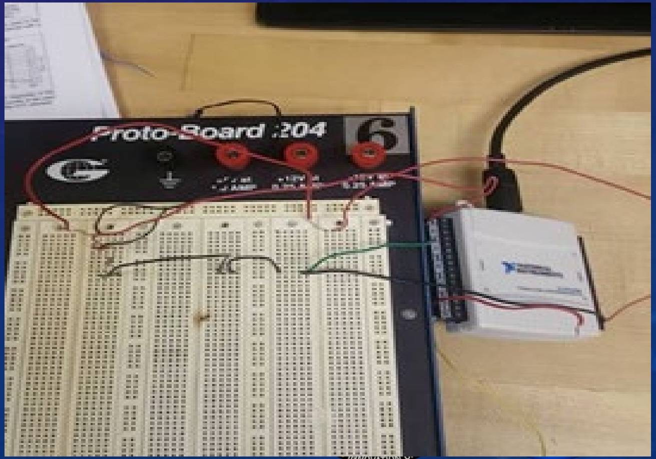
Project Overview

- Incorporate recycled inedible plant parts and transform into growing substrate for sustainable plant production
- Objectives
  - System Design - Solidworks and Data System
    - Equivalent System Mass (ESM) considerations
    - Energy requirement and crew time analyses
  - Construct System
  - Testing
    - Pretreatment and Drying, Mass, Temperature, Air Flow
  - Decomposition Analysis
  - Generate potential recipe for proper Carbon to Nitrogen ratio

System Design - Solidworks Model

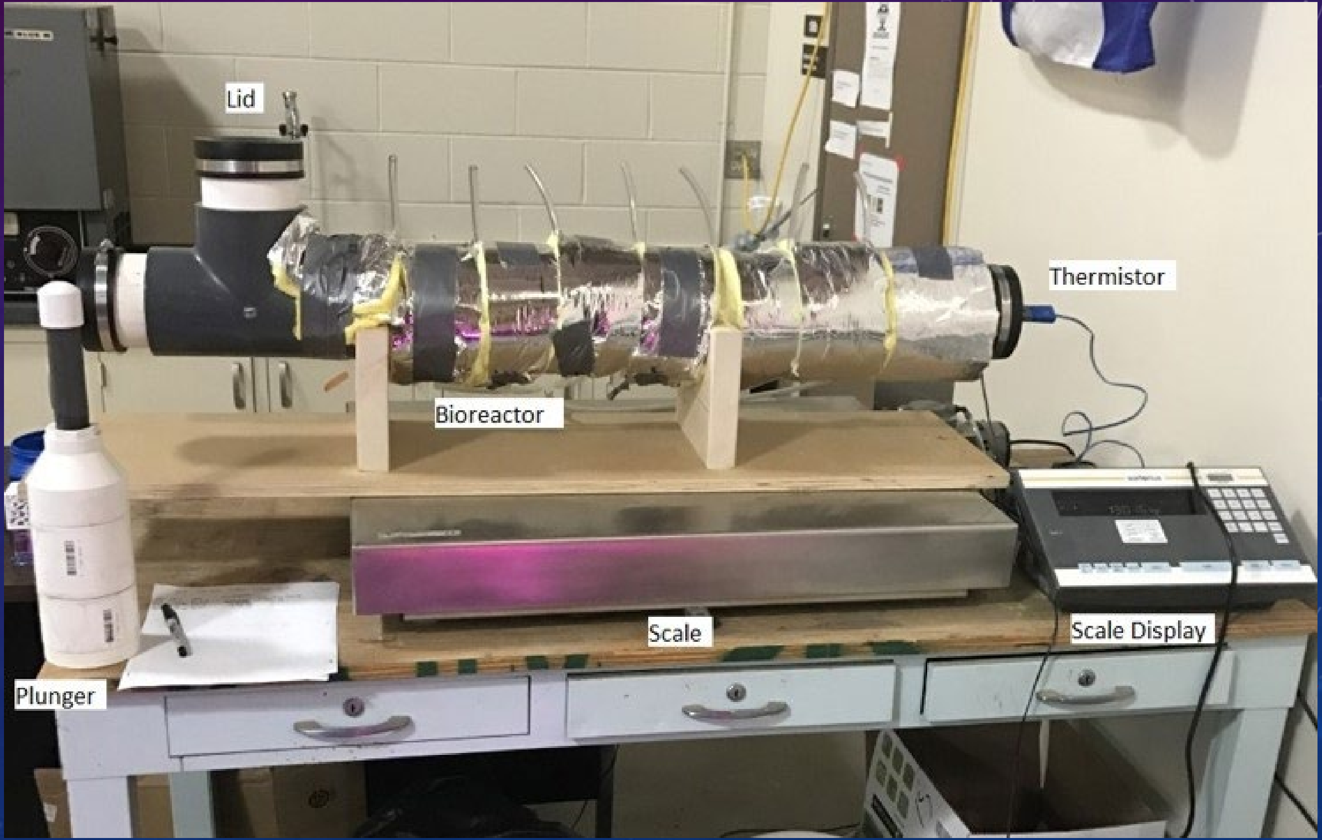


System Design - Data System

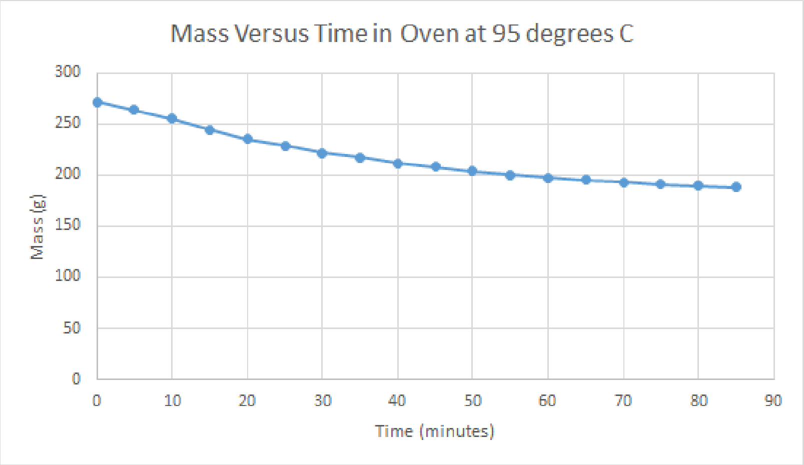


Construct System

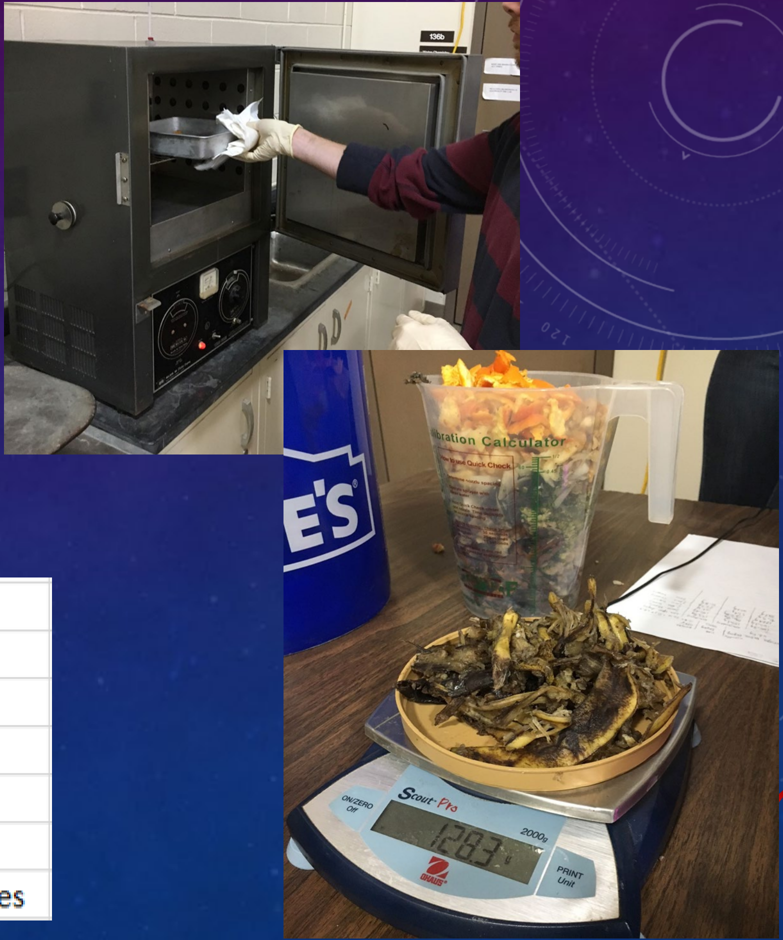
- Bioreactor
  - PVC Pipe
- Thermocouples
- Bioreactor Mount
- Air pump
- Scale
- Raw Food
- Food Shredder
- Plunger



Testing - Pretreatment and Drying



Final weight after drying process (0% water) (g)=	181.5
Initial weight (with 100% water) (g) =	271.4
Water Weight: Initial - final =	89.9
40% of the water (g) = water weight *0.40 =	35.96
Initial weight of mass - 40% of water mass =	235.44
	Which occurs at: 20 minutes



Pre-processing using Air Drying

Assumptions:

- Cabin conditions 70 F, 40% Relative Humidity
- Outgoing air 70 F, 80% Relative Humidity
- Amount of inedible biomass generated per day crew 6 = 4.0124 lb/day
- Biomass moisture content 95%

To reduce moisture content to 60% -----> 1.404 lb/day removed

Air flow required (24 hours):

- 3017.69 ft3/day or 2.096 cfm
- 1533.61 Btu /day or 18.7 Watts

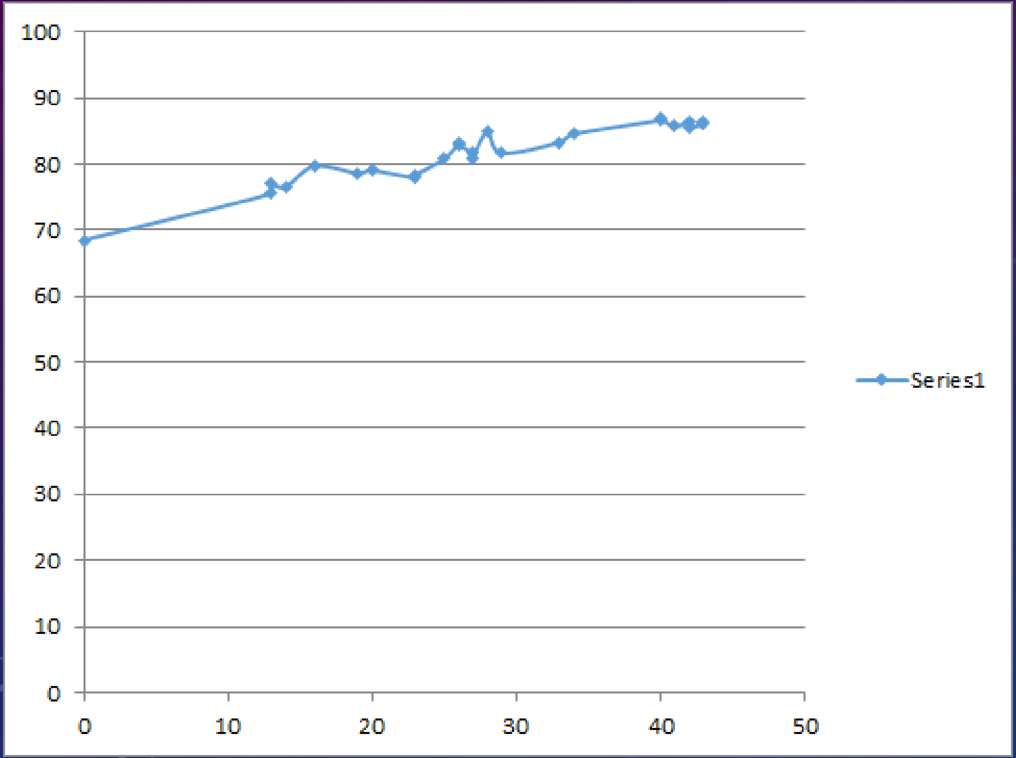
Testing - Composting Parameters

- Temperature = 60 C
- Carbon to Nitrogen Ratio = 30:1

$$M_t = M_0 * e^{-kt}$$

- Initial Mass of Compost =
- Final mass = 177.2 g
- Time = 43 days

Testing - Temperature Results



- Carbon to Nitrogen Ratio = 30:1
- Initial Mass =
- Final Mass = 1.608 kg
- Time = 43 days
- Temperature Max = 30.5 C

$$M_t = M_0 * e^{-kt}$$

Results - Experimental Design Analysis

- Finding Decomposition Rate, K

$$M_t = M_0 * e^{-kt}$$

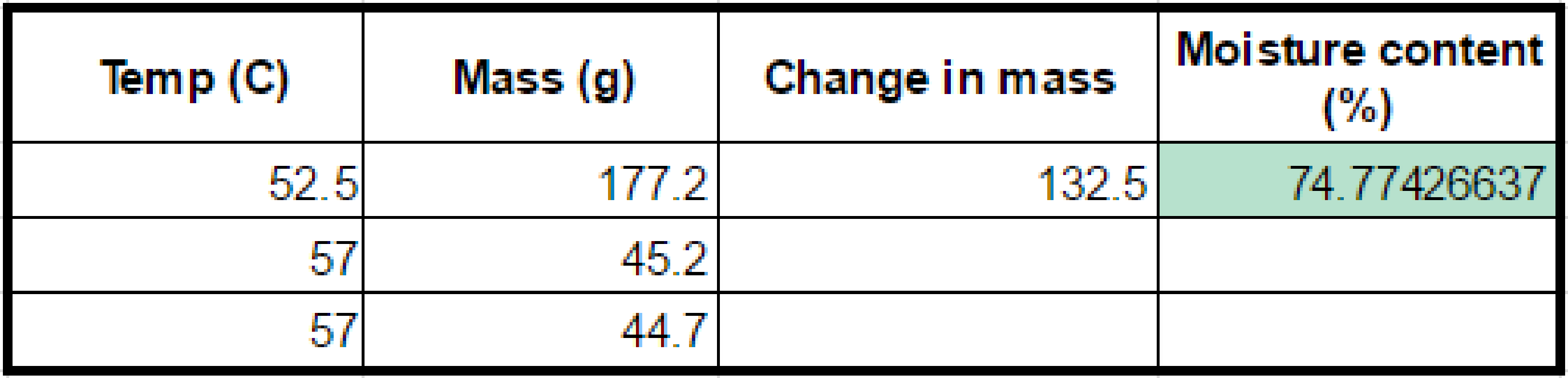
- Measuring
  - Mass of system
  - Temperature of compost - ideal = 60 C
  - Energy Used for pump

- Analyze Soil Post Degradation
  - Measure: N, Ph, K, S, Ca, and Mg
  - Ideal ratio C:N of 30:1
  - Soil testing will be done at Star Lab in Wooster, Ohio

Results - Compost Analysis

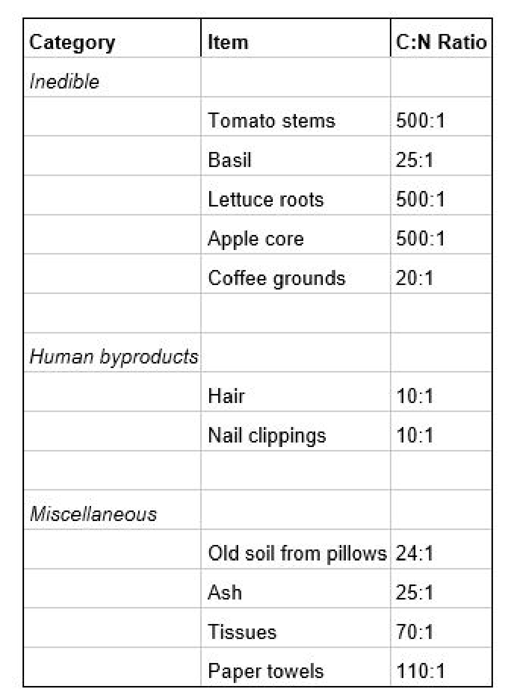
- Key takeaway being that the old rooting systems can be used by discarding the remaining roots and using the composting growth substrate
- Total solid (%) 23.45%
- Ash content (%) 28.50 %
- Carbon 23.87 %
- Nitrogen 1.51%
- Remaining Analyses
  - pH
  - SS
  - NO3-N
  - HN4 analyses
- Significant root reduction but the inorganic Rockwool substrate retains its shape

Results - Moisture Content

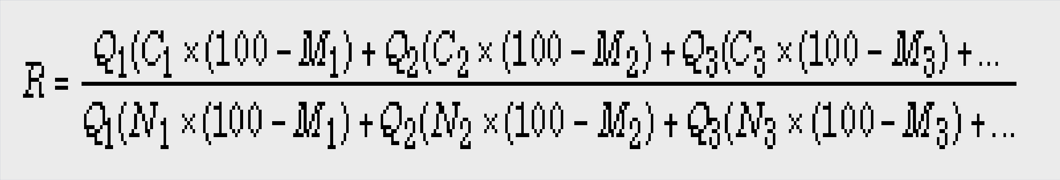


Temp (C)	Mass (g)	Change in mass	Moisture content (%)
52.5	177.2	132.5	74.77426637
57	45.2		
57	44.7		

Potential Recipe for Recycling - C:N Ratio



Category	Item	C:N Ratio
Inedible		
	Tomato stems	500:1
	Basil	25:1
	Lettuce roots	500:1
	Apple core	500:1
	Coffee grounds	20:1
Human byproducts		
	Hair	10:1
	Nail clippings	10:1
Miscellaneous		
	Old soil from pillows	24:1
	Ash	25:1
	Tissues	70:1
	Paper towels	110:1



$$R = \frac{Q_1(C_1 \times (100 - M_1) + Q_2(C_2 \times (100 - M_2) + Q_3(C_3 \times (100 - M_3) + \ldots}{Q_1(N_1 \times (100 - M_1) + Q_2(N_2 \times (100 - M_2) + Q_3(N_3 \times (100 - M_3) + \ldots}$$

R = C/N ratio

Qn = mass of material n ("as is", or "wet weight")

Cn = carbon (%)

Nn = nitrogen (%)

Mn = moisture content (%) of material

Recommendations and Conclusions

- Design Changes:
  - System Volume Increase
    - Solve Temperature problem
    - Support entire crew
- Pre-treatment:
  - Shred raw biomass *before* drying
  - Attach pre-treatment system to bioreactor to make a continuous process
- Raw Material Composition
  - Food waste
  - Human byproducts

Future Plans

- Create more effective composting process for inorganic substrate renewal
    - Convert all organic matters to mature compost
    - Reduce microbial load on root system residual
- Analyze nutrient availability through further soil testing
- Analyze chemical and physical properties of inorganic substrate
- Evaluate crop production performance using a renewed substrate

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Sources

"From Magnetic Levitation to Frozen Wax, Cargo Spacecraft to Carry Wide Range of Investigations." *NASA*. NASA, 16 July 2016. Web. 16 Nov. 2016.

Keener, Harold M., and John A. Hogan. *Biological Technologies*. Rep. Houston: Advanced Life Support Program, 2016. Print.

Ling, Peter P. *Passive Watering and Plant Biomass Recycling Systems for Exploration Habitat*.Proposal. N.p.: n.p., 2016. Print.

Loff, Sarah, and Brian Dunbar. "About NASA." NASA. National Aeronautics and Space Administration, 14 Nov. 2014. Web. 18 Nov. 2016.

Recovery in Closed Loop Systems Project (n.d.): n. pag. NASA. Web. 22 Nov. 2016. <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160006646.pdf>.

Strayer, Richard, Val Krumins, and Mary Hummerick. *Bioprocessing to Recover Crop Nutrients from Advanced Life Support (ALS) Solid Wastes: Improving Rapid Biological Processing of ALS Inedible Crop Residues*. Tech. no. 2001-01-2208. N.p.: International Space U, n.d. Print.

Trautmann, Nancy M., Tom Richard, and Marianne E. Krasny. "High-Tech Bioreactors." *Cornell Compositing*. Cornell Waste Management Institute, 1996. Web. 27 Jan. 2017.

Zeitlin, Nancy, Raymond Wheeler, and Griffin Lunn. *Plant Biomass Leaching for Nutrient*