BREE495
Engineering Design 3

Design of a Nutrient Delivery System for a Lunar Greenhouse

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Abstract

This capstone project was completed for BREE 490 and BREE 495 classes in the department of Bioresource Engineering at McGill University, and it is in collaboration with the Canadian Space Agency's Outer Space Agriculture System Project (OASYS) to the feasibility of a miniature lunar greenhouse for growing radishes. A passive nutrient delivery system was developed to provide adequate hydration, nutrient supply, and aeration to radish roots without relying on external power. The design accommodates nine radishes arranged in a three-by-three grid, each housed in individual cups containing arcillite (a clay-based growth medium), solid nutrients, and wicks extending into a water reservoir below. The system is intended to be simple, reliable, and compatible with robotic manipulation. A first prototype was constructed to evaluate system feasibility. However, some critical components had to be modified, resulting in the growth experiment being terminated early. The final sections of this report outline recommendations for future iterations, including testing with solid nutrients and suitable synthetic fiber wicks to ensure more accurate performance evaluation.

Acknowledgements

We would like to extend our sincere thanks to the Canadian Space Agency for the opportunity to participate in the OASYS project. We are especially grateful to our CSA mentor, Mr. Andrew Karim, and the entire team of OASYS mentors for their invaluable guidance and support throughout the project. We also wish to thank our academic mentor and course instructor, Dr. Mark Lefsrud, as well as Dr. Grant Clark, for their continuous mentorship and all the expertise and knowledge they shared with us during our design process. Additionally, we appreciation the support from William Boyd Dumais at the engineering shop for his help in constructing the water reservoir. Finally, we are thankful to the many students in the Department of Bioresource Engineering who offered their assistance, advice or generously lent us materials when needed.

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List of Acronyms and Abbreviations

ABS = Acrylonitrile Butadiene Styrene
ASTM = American Society for Testing and Materials
APH = Advanced Plant Habitat
BLSS = Bio-regenerative Life Support System
BREE490 = Engineering Design 2 (Department of Bioresource Engineering, McGill University)
BREE495 = Engineering Design 3 (Department of Bioresource Engineering, McGill University)
CSA = Canadian Space Agency
CEA = Controlled Environment Agriculture
CVCM = Collected Volatile Condensable Material
ISS = International Space Station
NASA = National Aeronautics and Space Administration
NDS = Nutrient Delivery System
NFT = Nutrient Film Technology
OASYS = Outer Space Agriculture System
PLA = Polylactic Acid
PONDS = Passive Orbital Nutrient Delivery System
PVC = Polyvinyl chloride
TML = Total Mass Loss
Veggie = Vegetable Production System

1. Introduction

The exploration of space has always been driven by humanity's innate curiosity and desire to achieve what was once thought to be impossible. Over 50 years after the Apollo program saw 12 astronauts walk on the Moon, space agencies are now working toward a long-term lunar presence. The Artemis program, led by the National Aeronautics and Space Administration (NASA), marks a significant step in this vision. Artemis III, set to launch in 2027, will send four astronauts — including the first Canadian—to the Moon (NASA, 2024). As we set our sights on establishing a sustained presence on the Moon and, eventually, Mars, the challenge of self-sufficiency becomes a central concern. Future lunar and martian habitats will rely on robust bio-regenerative life support systems (BLSS) to produce food locally, reducing dependence on resupply missions from Earth (Liu, Yao, Fu & Feng, 2021).

Significant progress has already been made in microgravity plant cultivation aboard the International Space Station (ISS), with two notable systems, namely the Advanced Plant Habitat (APH) and the Vegetable Production System (Veggie) that have demonstrated successful growth of crops in space (NASA, 2020). Additionally, there has been one attempt to grow plants on the moon, on the Biological Experimental Payload, part of the Chang'e 4 mission in 2021 (Xie et al., 2024). Although only one seedling germinated, the experiment yielded valuable insights into how plants respond to the Moon's unique conditions (Xie et al., 2024).

The lunar environment presents significant challenges for agriculture. From the abrasive regolith and reduced gravity to its lack of atmosphere, intense radiation, and extreme temperature swings between lunar day and night, these all pose significant obstacles to plant growth (Lunar Surface Innovation Consortium (LSIC), 2024). Nevertheless, research is intensifying. Space agencies, in collaboration with private industry and the public, are actively exploring technologies and strategies for lunar farming. For example, the Deep Space Food Challenge, a competition hosted by NASA and the Canadian Space Agency (CSA) aims to inspire the public to design innovative space-based food production technologies (NASA, n.d.). The OASYS project is another example of the CSA engaging the public, particularly university students, in the development of lunar agricultural systems.

The project outlined in this report is the design of a subsystem for a larger project within the Canadian Space Agency (CSA), called the Outer Space Agriculture system (OASYS). This report follows the BREE490 report which detailed a literature review, initial findings and preliminary design for this capstone project. In this report, a summary of the goals and motivation of OASYS will be outlined followed by a specific description of the problem statement for our design. With the aid of a Pugh chart, the alternative design choices will be briefly mentioned followed by an in-depth conceptual design review. Next, the prototyping and testing phase is detailed. The report concludes with a discussion section, explaining future works and recommendations we propose for our client and for the next iteration of OASYS.

2. Project Overview

The Canadian Space Agency created a project named the Outer Space Agriculture system (OASYS), which is the design of lunar greenhouse being developed by different engineering undergraduate capstone teams and graduate students across Canada. The motivation for OASYS is the need to advance food production technologies to sustain human nutrition for future lunar missions (Canadian Space Agency (CSA), 2021). Ensuring that astronauts have nutritious food is a critical component of all human space exploration missions. While food is currently being delivered in shipments to feed the astronauts on the ISS, this will not be possible for long-duration missions to deep space (CSA, 2021).

This project was specifically created to verify the feasibility of a miniature greenhouse and the ability of plants to survive the lunar night. The primary goal of the OASYS project is to design a fully automated mini greenhouse to grow radishes. Furthermore, the completion of this project will advance technologies needed for future lunar missions and will assess different technologies' abilities to mitigate or eliminate the risks associated with the lunar night. Finally, it will aid in determining exact requirements related to the size, mass, and energy constraints of a mini greenhouse. Radishes were selected because they are tolerant of cold temperatures, reach maturity in as few as 27 days, have all edible parts and it is a crop that has been previously studied in microgravity.

The greenhouse will be a controlled growth environment and for this iteration of the project, it must remain operable for a minimum of 6 weeks, where it will go through at least one entire growth-harvest cycle. The growing area of the greenhouse is constrained to a volume of 30cm x 30cm x 30cm and will be maintained at a pressure of 0.5 atm, humidity between 45%-70% and temperatures between 5°C-30°C. Additionally, while the vessel will be maintained at a lower pressure than on Earth, the partial pressures of essential gas constituents for plant growth, like carbon dioxide and oxygen, will remain the same as what is experienced at sea level on Earth. The growing area will be enclosed in a larger vessel in a vacuum environment where all components needed to maintain the system will be housed.

The greenhouse will be powered by solar panels and will generate enough power needed for operating during lunar days and lunar nights. The greenhouse will have a designated "Keep Alive" mode for during the lunar nights, at which point no solar energy will be able to be generated. This mode is intended to conserve power while still maintaining necessary internal conditions during the frigid and dark nights.

A list of requirements for the OASYS were provided by the CSA that all subsystems must comply with to achieve mission objectives. All 21 requirements are listed in Table A1 in Appendix A, but only a few of these are explicitly relevant to our subsystem. One very important requirement is that all subsystems minimize the mass of their components as this minimizes the cost and energy requirements of space. Additionally, it is important that the materials selected are suitable for space conditions, which was elaborated on in the previous BREE 490 report.

There are currently 5 other capstone teams from universities across the country working on different subsystems of the lunar greenhouse and are outlined in table 1.

Table 1. The different universities working on the OASYS and their corresponding subsystem being designed.

University	Subsystem
Manitoba University	Overall system design
University of British Columbia	Automated harvesting
University of British Columbia	Health monitoring
Polytechnique Montréal	Pressure vessel design
Simon Fraser University	Humidity moisture control

The OASYS project was launched in September 2024 and will have multiple iterations in the coming years with new capstone groups each year. Therefore, there are still some subsystems of the greenhouse that have not and will not be addressed this year, leaving some gaps and assumptions that must be made by current groups. For example, no one is designing the lighting system, temperature regulation, monitoring CO_2 and O_2 levels, or waste management. Future iterations aim to expand the project's scope by developing these additional subsystems and potentially exploring the cultivation of a wider variety of crops. This report aims to serve as a jumping-off point for the capstone design group who works on the next iteration of the nutrient delivery system.

3. Problem Statement

Resupply missions for long-term space travel is costly and risky, so alternative means of feeding astronauts must be developed. Therefore, the motivation of this project is to sustain astronaut nutrition for long term trips to the moon. The moon does not contain the proper environment and resources necessary for plant growth. To overcome this, plants must be grown in a controlled environment and must be provided with sufficient water, nutrients and aeration to grow successfully.

Based on this motivation, the goal of this project is to supply optimum hydration, nutrients, structure and aeration to the radish roots in the OASYS greenhouse. This encompasses the structure and growing media that houses the plants, and the mechanism that will supply water and nutrients to the root zones. The main objectives, requirements and specifications are listed below:

Objective 1. Design an autonomous water delivery system
- Requirement 1.1. No in situ set up
- Requirement 1.2. Must be fully automated (no human input) for one whole growth cycle.
  - Specification 1.2.2. System holds enough water required for one growth cycle.
- Requirement 1.3. Minimize power input during the lunar night
  - Specification 1.3.1. Max power consumption during the night is TBD

Objective 2. Growth medium is suitable for radish formation
- Requirement 2.1. Growth medium provides adequate structure for radish hypocotyl
- Requirement 2.2. Growth medium provides adequate pore space for aeration of radish roots
- Requirement 2.3. Minimize growth of unwanted biological material in root zone

Objective 3. Devise a nutrient delivery method
- Requirement 3.1. Protect system from clogging and salt build up
- Requirement 3.2. Supply optimum nutrient levels to radishes throughout their growth
- Requirement 3.3. Minimize power input during the lunar night

Specification 3.3.1. Max power consumption during the night is TBD

Objective 4. Design a structure to house the plants that efficiently use space and resources

Requirement 4.1. Growth medium is contained into a zone sufficient for 9 radishes.

Specification 4.1.1. 3x3 planting scheme

Requirement 4.2. Minimize space needed for system equipment

Specification 4.2.1. Growth area must be contained in a $(30cm)^3$ volume

Requirement 4.3. All materials meet low outgassing properties

Specification 4.3.1. All materials have a Total Mass Loss (TML) of less than 1%

Specification 4.3.2. All materials have a Collected Volatile Condensable Material (CVCM) of less than 0.1%.

4. Evaluation of Alternative Designs

An extensive literature review was conducted in BREE490 on space agriculture technologies, controlled environment agriculture systems and technologies used on Earth, and specific requirements for radishes. This research was used to outline potential design solutions for this project and ultimately compare them using a Pugh chart.

The options in the Pugh chart have three primary components: water delivery, nutrient delivery, and growth medium. The combinations of these options are listed in tableTable 2, but it is important to note that not all of the options from each category can be combined with one another. Preliminary possibilities of these options were analyzed, and some were ruled out based on inadequate oxygen supply or incompatibility with radishes. Options deemed potentially possible were evaluated in the Pugh chart in table 3.

Table 2: Summary of design alternatives.

	Option 1	Option 2	Option 3	Option 4
Passive Watering System	Wicking	Deep Water Culture		
Active Watering System	Ebb & Flow	Nutrient Film Technology	Porous Tube	
Growth Media	Hydrogels	Arcillite	Combination of media	No growth media
Nutrient Delivery	Solid Slow-Release Fertilizer	Liquid Nutrient solution (delivered in water system)		

Several assumptions of radish growth and the controlled environment within the pressure vessel were made throughout the design process and are listed later in this report in tableTable 4. These assumptions were accounted for when ranking the alternative designs in the Pugh chart which can be seen in table 3. Furthermore, the interface of this subsystem with other OASYS subsystems was considered during the development of our design, as it is critical that they can work together seamlessly.

As shown in the Pugh chart, passive watering with arcillite growth medium and solid nutrient delivery was rated the highest and was selected as the final design. It was prioritized to make this design a completely powerless and passive system to improve reliability there will be no human input or manipulation for one whole growth cycle, as per the requirements.

Table 3. Alternative design options compared and weighted using a Pugh chart.

Pugh Chart																			
characteristic	weight	PW + hydrogels + aeration piping		PW + arcillite +SND		PW+ SF+LND*		ebb&flow + hydrogels+LND*		ebb&flow +SF+LND*		NFT+SF+ LND*		ebb & flow + arcillite + LND		porous tube matrix + arcillite+ SND		porous tubes+SF+ LND*	
		rating	weighted	rating	weighted	rating	weighted	rating	weighted	rating	weighted	rating	weighted	rating	weighted	rating	weighted	rating	weighted
reusability	5	0	0	1	5	0	0	0	0	1	5	1	5	1	5	1	5	1	5
aeration	5	0	0	1	5	1	5	0	0	1	5	1	5	1	5	1	5	1	5
simplicity	4	0	0	1	4	1	4	1	4	-1	-4	1	4	-1	-4	0	0	1	4
reliability	4	0	0	1	4	0	0	-1	-4	-1	-4	-1	-4	-1	-4	-1	-4	-1	-4
resistant to lunar envrionment	4	0	0	-1	-4	-1	-4	0	0	-1	-4	-1	-4	-1	-4	-1	-4	-1	-4
power consumption	3	0	0	0	0	0	0	-1	-3	-1	-3	-1	-3	-1	-3	-1	-3	-1	-3
mass	3	0	0	0	0	1	3	1	3	0	0	1	3	0	0	-1	-3	-1	-3
consistency of growth medium	3	0	0	1	3	1	3	0	0	1	3	1	3	1	3	1	3	1	3
structural support	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
space required	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
total score			0		17		11		0		-2		9		-2		-1		6

PW= passive watering **SF**= substrate free **NFT**= nutrient film technology
SND= solid nutrient delivery **LND**=liquid nutrient delivery * assumes LND needs pH monitoring and automatic adjusting

5. Design

This section presents the conceptual design of a nutrient delivery system, which features radishes grown in individual cups filled with arcillite. A slow-release solid fertilizer was mixed into the arcillite to supply nutrients, while water was delivered passively through capillary action using wicks. Each cup is also fitted with a silicone cover over the top.
The conceptual design emphasizes a lunar grade design, with modifications for the prototype discussed in the following section. Material selection was a key consideration for lunar applications and is addressed in detail in the following sections. The section begins by outlining the assumptions made during the design process, followed by a detailed explanation and justification of each design component and the materials selected. Finally, the sequence of events that we recommend for growing the radishes is given along with a final mass balance calculation.

5.1. Assumptions

Table 4. Assumptions made during the design process.

Assumptions	
1.	Confined in the pressure vessel, the system will act as a completely closed loop and there will be no losses of heat, transpiration, humidity, etc. to the external environment.
2.	The radish growth cycle on Earth is 28 days.
3.	The radish growth during the lunar night is not significant, therefore including 14 days of darkness, the radish growth cycle on the moon will be 42 days.
4.	The radishes will grow to a height of 15 cm.
5.	The radish seed will be planted on day 1 of the lunar day
6.	Robotic arms will be capable of thinning seedlings after germination.
7.	The volume of root zone required for a radish is 1/3rd of what the rest of its biomass takes up.
8.	The weight of the radish is 100% water (for initial water consumption calculations).

5.2. Materials

Proper material selection is critical for spacecrafts and other materials entering the vacuum environment of space. Requirements critical to this project are that materials meet outgassing requirements in terms of total mass loss and collected volatile condensable material. Outgassing is a phenomenon where materials release mass in the form of gas, typically in response to extreme temperature fluctuations or vacuum environments (Finckenor, n.d.). While outgassing occurs naturally, it is often accelerated under certain conditions, such as those experienced during space missions. High outgassing rates can cause various issues, including increased radiation penetration, voltage breakdowns, altered heat transfer patterns, and the condensation of gases on other surfaces (Scialdone, et. al., 2000). Additionally, air trapped within materials expands in the vacuum of space, potentially damaging the material if it is not properly vented during launch. To prevent such issues, it is crucial that materials used in space missions have low outgassing rates at the operating temperatures expected during launch, and that any released gases do not condense on surrounding surfaces (Scialdone, et. al., 2000). For this project, it was assumed that the total mass loss (TML) due to outgassing is less than 1%, with the collected volatile condensable mass (CVCM) remaining below 0.1%. This is consistent with the American Society for Testing and Materials (ASTM) E-595 standard test method for TML and CVCM from outgassing in a vacuum environment (Scialdone, et. al., 2000). To ensure all materials selected for this project meet these

corresponding requirements, the NASA outgassing database was used. This database lists materials that have been tested in accordance with the ASTM-E-595 standard (NASA, 2017).
Beyond outgassing requirements, lightweight materials are very important for reducing fuel, and therefore money, needed for the mission. It has been calculated that each gram costs $1000 to send to space, so selecting lightweight materials was imperative to minimize the cost of a project (Boone, 2022).
Finally, food safety is critical for astronaut safety and preventing contamination which could be difficult to maintain in a closed environment like the OASYS greenhouse. Materials were considered food grade and safe for use for this project if they followed the Food and Drug Act (FDA) of Canada. Under the FDA, materials that come in contact with food are safe for use when they contain no known carcinogens, and no recognized risks associated with their use. Therefore, beyond sterilization of all materials prior to launch, food grade materials in accordance with the FDA were chosen (Canada Plastics, 2023).

5.3. Design Components

5.3.1. Growth Structure

This section outlines the components of the growth structure, including the water reservoir, lid, and cups as seen in figure 1. All of these were fabricated from Acrylonitrile Butadiene Styrene (ABS), an opaque thermoplastic polymer known for its high tensile strength and resistance to chemical and thermal stress (AdrecoPlastics, n.d.). ABS is also food safe and meets outgassing requirements, making it suitable for use in space applications (NASA, 2017). Additionally, it is compatible with 3D printing, allowing for rapid and cost-effective fabrication of custom components.

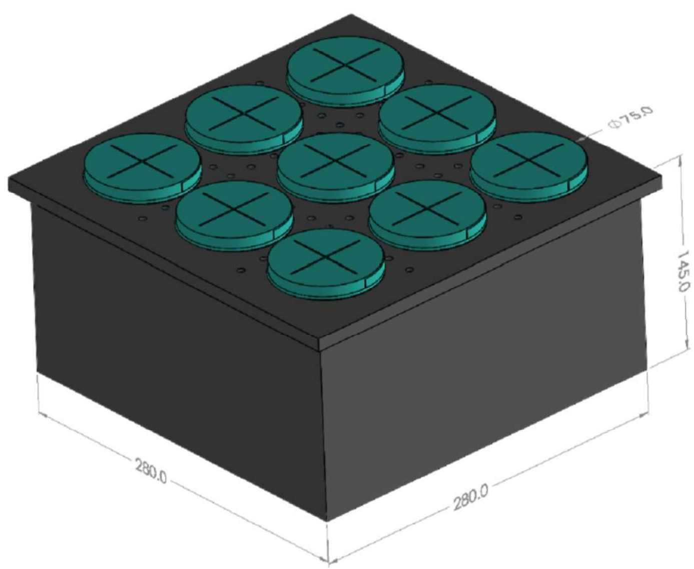


Figure 1. Growth structure overview, featuring the water reservoir, the lid and the cup covers.

5.3.2. Lid

The radishes grow in a 3x3 configuration in individual cups, which are supported by a lid over the reservoir (fig. 2 (a)) The lid extends over the entire 30cm x 30cm growing area, with a lip of 1cm around the outside of the reservoir. The lip extends down 1cm around the outside surfaces of the reservoir to help keep the reservoir secure in case of disruption (fig. 2 (b)).

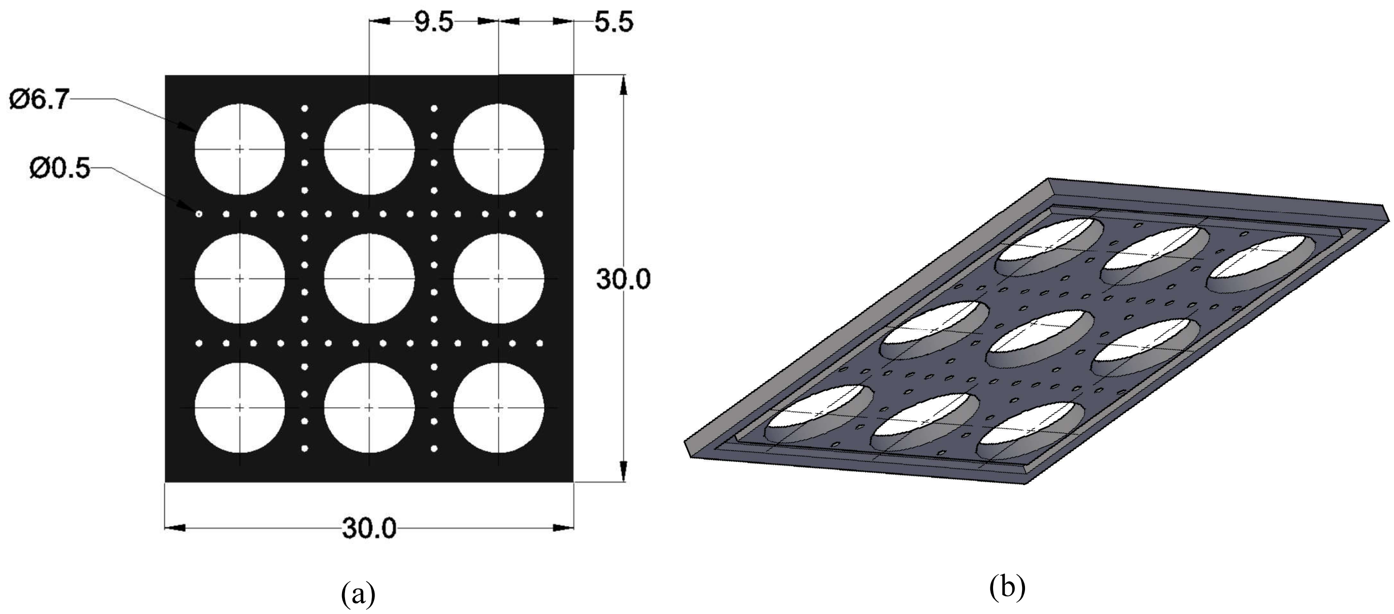


Figure 2. (a) Top view of lid (in cm) (b) 3D view of lid showing underside lip

The lid has nine holes to hold the cups and a matrix of small holes between the cup holes to allow air to flow into the root zones, which is essential for healthy plant growth and is a major consideration in space agriculture (Monje et al., 2003). The cup holes are 6.7 cm in diameter to accommodate the diameter of the cups with 0.45 cm tolerance so that they are easy to slide into and out of the lid. The air holes are 0.5 cm diameter, as this is an adequate size to allow air flow without compromising the structural integrity of the lid.

The lid and water reservoir are made of opaque black material to block light to the root zones which is an extra measure to prevent unwanted microbial growth. The air holes let light in, but since there are no nutrients in the water, it is assumed that the small amount of light do not cause significant microbial growth.

This design was successfully used in the Advanced Plant Habitat (APH) on the International Space Station. In the APH experiment, it was determined that growing radishes in a round opening is important for hypocotyl enlargement, because they are sensitive to deformity under pressure (John, Abou-Issa, & Hasenstein, 2021).

5.3.3. Cups

Each plant grows in an individual cup big enough to accommodate a mature radish hypocotyl, and the cups are situated in a 3x3 configuration in the lid, as described above. Using cups, as opposed to one continuous root zone for all nine radishes, makes cleaning and replenishing of growth medium by the Robotic Harvesting Arm easier because it prevents root matter of each plant from becoming intertwined. Additionally, a 1 cm raised lip is incorporated into the cup design to hold the cups on the lid and so the Robot Harvesting Arm can grab the cups during cleaning.

The cups are cylindrical (fig. 3(a)) and open on the top, closed on the bottom, and have openings on the side. These openings comprise of three slits for wick insertion and six “windows” for airflow. The wicks are inserted into the cup through the slits to the desired placement. The “windows” are wrapped with an oxygen-permeable membrane, which contains the contents of the cup while allowing adequate airflow to the roots. The “windows” design was adapted from the Passive Nutrient Delivery System (PONDS), where they suggested using Tyvek commercial wrap as the oxygen-permeable membrane (Levine, 2021). This helps prevent issues like root hypoxia which occurs when the roots do not receive enough oxygen (Monje et al., 2003).

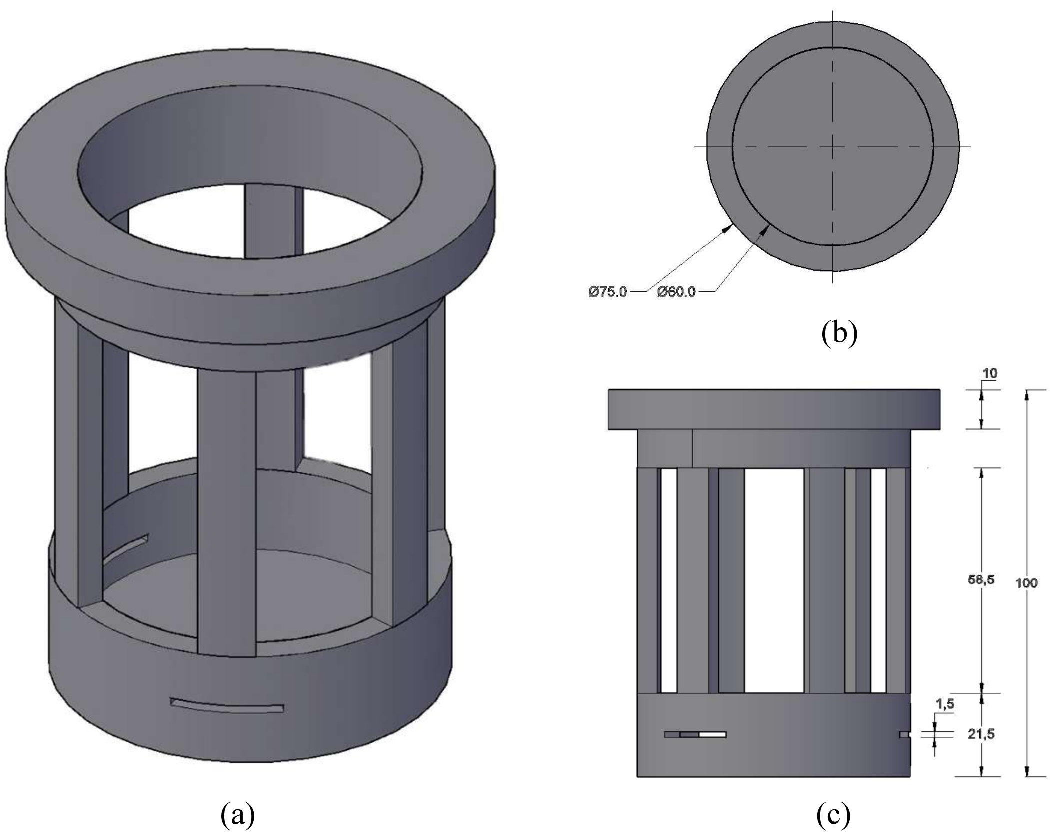


Figure 3. Cup design. (a) 3D view (b) Top View (c) Side view

The dimensions of the cup allow for an appropriate volume for the root zone and fits nine radishes in the designated volume without crowding. The necessary root zone volume was calculated as 220 cm^3 based on the rule of thumb that the root zone volume be one third of the volume taken up by the plant above the soil, as suggested by our mentor. This is an initial calculation that can be refined in subsequent versions. Assuming that the portion of a cherry belle radish that grows above the soil has an average height of 15cm and spreads about 7.5cm in diameter (Burpee, n.d.), then the volume needed in the root zone is:

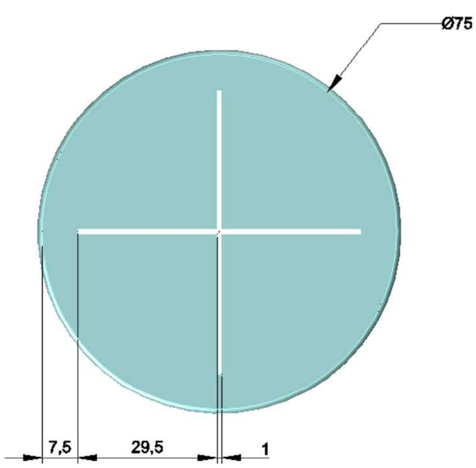
$$\frac{1}{3}\ of\ the\ volume\ taken\ up\ by\ a\ radish\ plant = \frac{\pi r^2 h}{3} \quad (1)$$

$$= \frac{\pi \times \left(\frac{7.5}{2}\right)^2 \times 15}{3} = 221\ cm^3 \approx 220\ cm^3$$

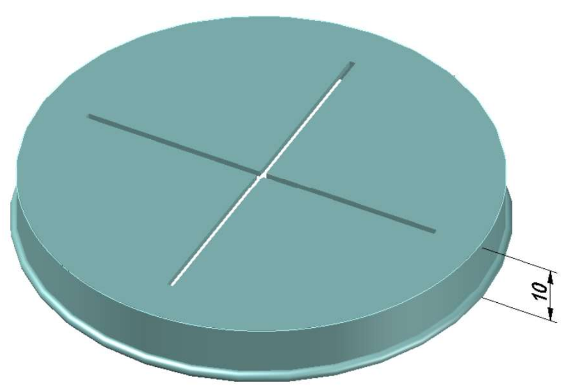
The diameter and height of the cups to satisfy this volume also needed to ensure that nine radishes fit in the 30 cm x 30 cm area. To ensure the cups were not touching and were not touching the wall of the reservoir, the cups were designed to have a height of 9.0 cm with a 1.0 cm tall lip (fig. 3 (c)). The lip of the cup extended to an outer diameter of 7.5 cm and inner diameter of 6.0 cm (fig. 3 (b)). The inner diameter of the lip was equal to the inner diameter of the rest of the cup. The rest of the cup components have a thickness of 1.25 mm, based off the minimum recommended thickness of a 3D printed part, except for the base of the cup which has a thickness of 2.5mm because it will hold the weight of the arcillite. This made the outer diameter of the main section of the cup to be 6.25 cm.

5.3.3.1. Cup Covers

The top opening of the cups will be covered to block light to the growth medium and keep the growth medium contained. The hole cover stretches over the whole opening of the cup and has two perpendicular slits that extend most of the length of the diameter and cross in the center as seen in Figure 4.



(a)



(b)

Figure 4. Silicone cup cover. (a) Top view (b) 3D view.

On the APH, it was demonstrated that radish hypocotyls are highly sensitive to mechanical pressure (John, Abou-Issa, & Hasenstein, 2021). The cover was therefore made of a flexible silicone material that will allow radish seedling to emerge successfully and the hypocotyl to grow correctly. The low resistance will also facilitate easy harvesting of the radishes. The cover can be reused for several cycles, minimizing mass requirements.

The covers are made of Mold Star 16FAST, which has a Shore Hardness of 16A (Smooth-On, n.d.). When cast at 1 mm thick, this material is flexible enough to allow the radish seedling to emerge unobstructed and the hypocotyl to grow without mechanical stress, while keeping the arcillite contained in the cup in case of a disturbance.
The hole covers were made by casting silicone in a mold, which had to be created and is shown Figure 5. This is a two-part mold where the parting line of the mold is at the bottom surface of the cover as this was the most feasible. There is an extrusion of the two crossed lines that create the opening. There is a hole where silicone can be poured in. The mold has four dowels to help secure the sides in place when the silicone is curing. Detailed dimensioned drawings of this two-part mold can be found in figure B1 figure B2 in Appendix B.

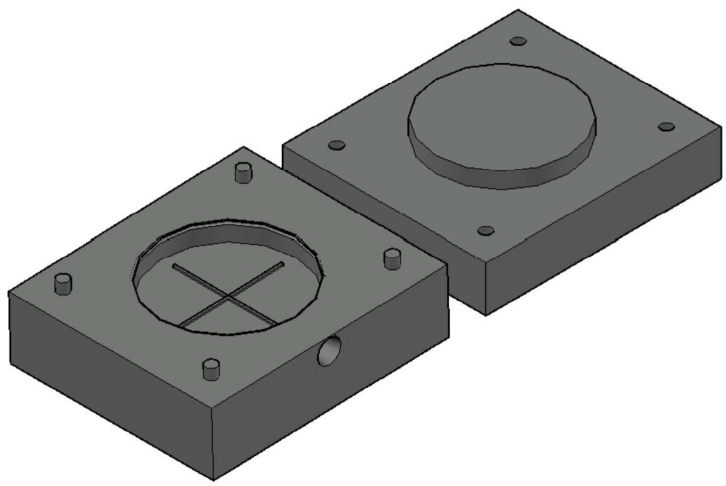


Figure 5. Cup cover mold.

5.3.4. Growth Medium

A porous granular growth medium was chosen for this design so to be compatible with a solid fertilizer. A soilless solid growth medium provides structural support for roots while reducing the risk for harmful microbial growth. In a highly controlled environment, the use of soil makes it hard to control the possibility of both good and bad microbial growth because it is an organic substrate. Additionally, astronaut safety is of top priority and a person's body becomes more susceptible to illness when they leave Earth, therefore it is even more essential to ensure no microbes that can be harmful to human health of the possibility of growing (Flemming et al., 2012).
Specifically, the growth medium chosen for this system is arcillite, a calcined montmorillonite and illite clay that has a porous structure, neutral pH, low density and good hydrophilicity (John, Abou-Issa & Hanstein, 2021). It is sold under the brand Turface and is used commonly on sports fields to balance porosity for optimum water holding capacity, drainage rates and oxygen levels and it also resists compaction; a list of its properties are shown in Table 55 (Turface Athletics, n.d.). While these properties are ideal for sports fields, they also prove excellent as a growth medium in controlled environment agriculture. Arcillite has been widely tested in space agriculture experiments, both on Earth and aboard the International Space Station (ISS). Notably, NASA's Veggie and Advanced Plant Habitat (APH) systems successfully utilized arcillite to grow plants

in microgravity (John, Abou-Issa & Hanstein, 2021; Massa et al., 2020). The extensive research and positive results from these missions provide strong evidence supporting arcillite as a reliable and effective growth medium for space-based applications.

Table 5. Turface Properties (Turface Athletics, n.d.).

Property	**Value**
Composition	illite clay with 60% minimum amorphous silica.
Bulk Density	37 ± 2 lb/ft³ (593 + 32 kg/m3)
Total Pore Space	74%
Capillary Pore Space (water holding)	39%
Non Capillary Pore Space	35%
Cation Exchange Capacity	30 + 5 mEq/100g
pH range	6.5 + 1.0
Particle Stability	Sulfate Soundness testing (ASTM C-88) and static degradation test not to exceed 4% loss over 20 years

Commercially sold Turface is composed of particle sizes ranging in diameter from <1 mm to 4mm (Turface Athletics, n.d.). In this project the arcillite is sieved to particle sizes of 1-2mm in diameter as this will most optimally balance pore spaces for water distribution and air movement (John, Abou-Issa & Hanstein, 2021). 1-2mm particle size has been shown to mitigate root hypoxia (John, Abou-Issa & Hanstein, 2021).

One of arcillite's most important qualities is that it can be sterilized prior to use. Once sterilized, it does not promote microbial growth in the root zone because it is an inorganic substrate (Morsi et al., 2024). Flemming et al. (2012) show that plants grown in pure arcillite exhibit significantly lower microbial levels compared to those grown in arcillite mixed with Fafard, an organic substrate (Flemming et al., 2012). After sieving the arcillite to achieve ideal particle sizes, the granules can be cleaned and sterilized. The cleaning process helps remove dust that can be dangerous for crew safety and that can disrupt functionality of surrounding hardware by clogging surfaces and crevices (Massa et al., 2020). Arcillite can be autoclaved or heated in an oven for sterilization. This method can be used to allow for reuse of the substrate virtually indefinitely. Finally, 220 cm^3 of arcillite will be added to each cup based of the calculations described in section 5.3.1.1.

5.3.5. Wicks

Wicks were selected as the method of water delivery due to their simplicity and passive operation. Unlike powered systems that are vulnerable to electrical failures, wick-based irrigation requires no external energy input, making it a highly reliable solution. Each wick extends from the water reservoir into the planting cup, utilizing capillary action to draw water upward into the arcillite substrate and to the roots. At the base of the water reservoir, the wicks contact a capillary mat of the same material which ensures that even if the growing structure is not level, wicks located on higher ground can still access water from the lower end through lateral movement across the mat. This setup provides a consistent and passive supply of moisture to the radish roots, allowing them to absorb water as needed.

A synthetic fiber was chosen for use as the wicks to enable longer reuse. A specific type of synthetic fiber was not yet chosen, and rather multiple types were purchased in to be tested during the prototyping phase. Since a solid, slow-release fertilizer is being used, there is a reduced risk of salt buildup on the wicks, further enabling longer reuse without performance loss. To further improve reliability and avoid uneven watering—a common issue with wick systems—a three wick configuration will be installed in each cup, as seen in figure 6**Error! Reference source not found.**. Additionally, one wick will extend to the top of the arcillite and a seed will be attached at the appropriate place for germination with guar gum (Massa et al., 2020). Each wick will be 16 mm

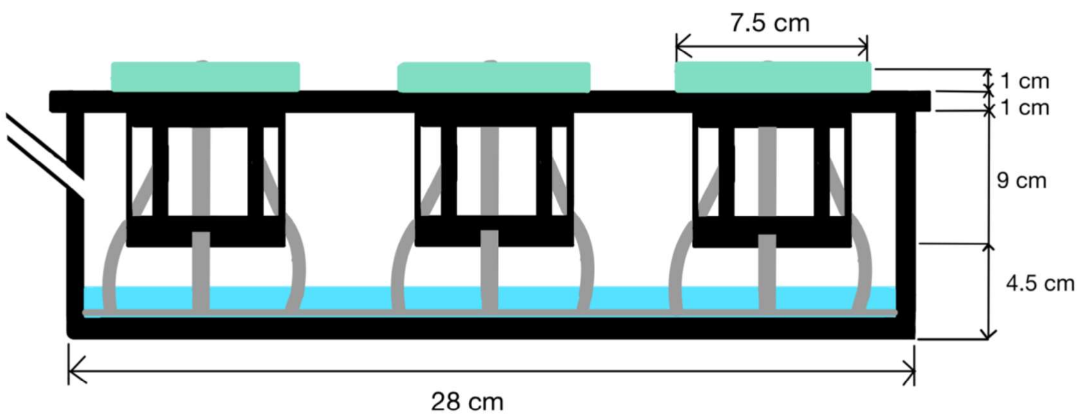


Figure 6. Cross-sectional view of reservoir and cups (image does not show growth medium, or oxygen permeable membrane).

long, 20 mm wide and 1.5 mm thick.

5.3.6. Nutrients

Arcillite lacks essential minerals and cannot support long-term plant growth on its own, therefore sufficient fertilization is needed (John, Abou-Issa & Hanstein, 2021). A solid slow-release fertilizer was selected for this design for its simplicity, low maintenance, and compatibility with passive nutrient delivery systems. Unlike liquid nutrient solutions used in hydroponics, which are prone to pH fluctuations, nutrient imbalances, and salt buildup, solid fertilizers offer better stability over time while requiring less manipulation. In hydroponic systems, power inputs are requirements for pH monitoring as well as more frequent pumping for nutrient solution replacement. With the choice of solid nutrients, this system can remain powerless. Furthermore nutrient-rich water must often be replaced after each growth cycle due to these nutrient imbalances. In contrast, solid fertilizers reduce the risk of water contamination, allowing unused water from one growth cycle to be reused in the next without requiring additional treatment.

Experimentation for the Veggie unit for the ISS found poor growth response due to the phytotoxic accumulation of inorganic nutrients when using liquid nutrients on the rooting mats that provide watering through capillary action similar to the wicking set up in this design (Stutte et al., 2011). Additionally, solid nutrients reduce the risk of salt accumulation, which can clog wicks and irrigation lines or harm plant roots (Stutte et al., 2011).

The specific fertilizer chosen for this design is Nutricote 18-6-8 T180. The fertilizer pellets have 18% nitrogen, 6% phosphorus and 8% potassium (Florikan CRF, n.d.). They are polymer coated (polyolefin type resin, talc and nonionic surfactants) and allow for the nutrients to slowly release over time to the plant (Florikan CRF, n.d.). Specifically, 80% of the nitrogen will be released over 180 days. This allows for only one nutrient application to occur at the start of the growth cycle, simplifying operations. This Nutricote fertilizer at a fertilizer dosage of 7.5 grams of Nutricote per liter of growth substrate has previously been shown to provide an adequate concentration of nutrients for radishes grown in arcillite, therefore this fertilizer dosage was chosen for this design (Massa et al., 2013). Nutricote has shown to have the most consistent release rates compared to over slow-release fertilizers (Adams, Frantz & Bugbee, 2013) , though through testing for the Veggie unit, Morsi et al. (2022) found Nutricote to release at twice the rate as the product indicates. It was estimated this was due to ion-binding substrate enhancing the diffusion gradient because of arcillite's cation exchange capacity (Morsi et al., 2022).

5.3.7. Water Reservoir

The water required for the radishes is held in a reservoir underneath the plants, within the 30cm x 30cm x 30cm growing area. All nine radishes draw their water from the same reservoir. The reservoir is closed on all sides up to the lid in order to prevent splashing.

The reservoir was 3D printed with black material to keep light from reaching the water. Because 3D printing is done layer by layer, grooves arise in the final part between the layers. It has been shown that increased surface roughness leads to greater microbial growth (Zheng, et. al., 2021), so epoxy resin was used to coat the inner surfaces to make them smooth. The bottom of the inside of the reservoir is lined with capillary matting. The wicks coming from the plant cups touch this matting, so water can be drawn to the plants even if the vessel is at an angle and the water level varies.

Water for additional cycles will be held in another tank outside of the growing area. The reservoir is connected to the tank via a tube, and at the beginning of a growth cycle, enough water for full growth of all nine radishes will be pumped into the reservoir. As such, the pump will only need to be used between cycles to replenish the reservoir before the next growth cycle, greatly minimizing the energy required. The tube should be made out of a PTFE shrink tube to ensure a water-tight connection from the humidity control subsystem to the water reservoir. The bottom of the reservoir will have rails that will interface with the pressure vessel to hold the growth area in place which should be made from aluminum, so it is compatible with the other subsystems. The design of the tank, connection tube, pump, and rails were out of the scope of this phase of the project.

The height of the reservoir was determined by considering the volume of water to hold, making sure that the fully grown radishes are still within the designated volume, and the height of the cups and wicks. An initial estimation of the volume of water assumed that the weight of radishes is 100% water, and that a fully grown radish weighs conservatively, 50 g (Wildrose Heritage Seed Company, n.d.). Then, for the full growth cycle of nine radishes, the amount of water is about 450g or 450mL. The height of the radish leaves was assumed to be 15 cm based on observations of radish growth at the CSA. It is important that the leaves remain in the growth volume so that they don't interfere with other equipment like the Robotic Harvesting Arm or the Plant Health Monitoring equipment.

The lid, discussed in section 5.3.1.2, that sits on top of the reservoir has a 1cm lip that extends out the side of the reservoir on all four sides. To remain in the required volume, the reservoir therefore has a footprint of 28cm x 28cm. The thickness of the walls is 0.5cm, and an epoxy resin layer of

0.2cm coats the inside surfaces. Epoxy resin is helpful for keeping the reservoir watertight and smooth to prevent the growth of microbes.
The height of the cups accounts for an appropriate growth volume for the radish roots, and the height of the cups that extend below the lid into the reservoir is 9cm. The total height of the reservoir accommodates the height of the water, length of the cups and wicks as well as ensuring that the fully grown radishes fit inside the growth volume. The height of the reservoir was therefore determined to be :

$$Height\ of\ Reservoir =$$
$$(Thickness\ of reservoir) + (Thickness\ of\ epoxy\ resin) + (Height\ of\ water)$$
$$+(Thickness\ of\ capillary\ mat) + (Length\ of\ wicks) + (Height\ of\ cup)\ + (Thickness\ of\ lid)\ (2)$$
$$= 0.5cm + 0.2\ cm + 0.7cm + 1cm +\ 3.3cm + 9cm + 0.5cm = 14.5\ cm$$

The height of the reservoir at 14.5cm maintains the height of the fully grown radishes in the volume, with a margin of 1 cm.
When the greenhouse lands on the Moon, it is possible that it will be positioned on non-level terrain, and the system will not be level. With this in mind, the maximum acceptable slope at which this subsystem can remain functional is 4.5%. This calculation is outlined in Appendix B.

5.4. Sequence

Now, the sequence of events to operate the system will be explained. On the moon, there are lunar days and lunar nights that are both 14 Earth days long. During the lunar night, the photovoltaic panels on the greenhouse will not collect any energy, so the greenhouse will enter a Keep Alive state. The growth time of the radish is assumed to be 28 days on Earth, and it is assumed that the radish does not grow at all during the lunar night. Therefore, the radish will start growing at the beginning of the first lunar day until the lunar night on Day 15, when it will stop growing, and resume on Day 29 until the end of the second lunar day on Day 43 of the cycle.
In many Earth-based hydroponic systems, it is common to thin seedlings. Thinning is when multiple seeds, usually two or three, are placed in one cup, and the weaker seedling is killed, or thinned, and the healthier one continues growing to maturity. The thinned seedling can either be fully removed or cut in a way that prevents it from growing back. Thinning helps improve the success rate of the seeds as they may not germinate or germinate in the wrong orientation (Burpee, n.d.).
The system will be assembled on Earth. Care must be taken to sterilize all components of the system, including the seeds, to ensure there is no microbial contamination (Massa et. al, 2020). The cups will be fully assembled with wicks, oxygen-permeable membrane, arcillite and Nutricote, and a lid cover. The seeds will be attached to the wicks with guar gum at the appropriate position. The cups will be inserted into the lid, which will be fastened to the reservoir. When the greenhouse is positioned on the Moon and a lunar day is about to start, the reservoir will be filled with water from the external tank, and the Nutrient Delivery System will be functional.
Table 6 outlines the key steps once the growth cycle has started.

Table 6: Growth Cycle Sequence.

Day	Event
Day 0	Start of first Lunar Day
Day 7	Radish seedlings are thinned.
Day 15	Start of Lunar Night. Radishes don't grow, in alignment with assumptions.
Day 29	Start of second Lunar Day. Radishes resume growing.
Day 42	Mature radishes are harvested. End of growth cycle.

The system will be reset to be ready to start growth again on the beginning of the next Lunar Day. Materials were chosen to be useable for multiple growth cycles but will be up to a future team to plan how often the growth medium, nutrients, and wicks will need to be replaced.

5.5. Mass Balance

Because this iteration is the first of the OASYS project, the total mass requirement is not finalized, and the masses of the subsystems of this iteration will inform the final requirement. The mass of the prototype is not the final suggested mass balance of the subsystems because the materials used were different than those in the lunar version of the design. Therefore, the mass of the system is calculated as the sum of all of the components as they were designed for the lunar version. Also, since the materials were chosen to meet outgassing requirements, it is assumed that the density of the materials would be the same on the Moon as on Earth. It is assumed that the ABS plastic will be 3D printed and that it must have 100% infill.

The densities of the materials were found in the literature. Table 7 outlines the densities of each material.

Table 7: Densities of Materials.

Material	Density (g/cm^3)	Components
ABS plastic (British Plastics Federation)	1.05	Reservoir, lid, cups
Epoxy resin this source	1.68	Reservoir coating
Water	1.00	Water
Arcillite (bulk density) density arcillite	0.64	Growth medium
Nutricote	0.0075	Nutrients
Polyester (woven, porous) polyester wicks	0.10	Wicks
Seeds (to seeds)	0.011 (g/seed)	Radish Seeds

These densities were then used to calculate the mass of each component based off the volume of material of the components in the design. The masses are shown in the table 8. The total mass of the subsystem is about 4251.1 g, and with an uncertainty margin of 20%, it is 5101.3 g.

Table 8: Mass of each component and total system

Component	Mass (g)
Reservoir (structure and epoxy resin coating)	1855.6
Lid	124.4
Cups	626.4
Water	450.0
Growth medium	1267.2
Nutrients	14.9
Wicks	12.4
Seeds	0.19
Total	**4251.1**
Total with 20% Margin	**5101.3**

5.6. Sustainability Considerations

Space exploration is widely recognized for its environmental impact, including the emission of hundreds of tons of carbon dioxide, the consumption of raw materials, and the substantial economic resources required for each mission. To maintain focus, this section addresses small-scale sustainability within the context of this project, rather than the broader sustainability challenges of space travel.

5.6.1. Economic Sustainability

The nutrient delivery subsystem was designed with mass reduction in mind by selecting reusable materials wherever possible. Given that it can cost up to $1,000 to send a single gram to space, minimizing the system's mass directly contributes to significant cost savings (Boone, 2022). This approach also supports long-term mission feasibility by reducing payload requirements and reducing costly resupply missions.

5.6.2. Environmental Sustainability

Reusable materials were prioritized in the design of the nutrient delivery subsystem, including the arcillite growth medium, silicone hole covers, cups, lid, and reservoir. While components like the wicks and solid nutrients may also be reusable, further testing is required. Reusing materials reduces reliance on virgin resources and minimizes waste generated during system operation. Additionally, using fewer components decreases launch mass, reducing the fuel required for transport to space. The greenhouse is powered by solar energy, a renewable and emission-free source. By enabling food production in space, the system also reduces the frequency of resupply missions, further lowering carbon emissions and the consumption of raw materials.

5.6.3 Social Sustainability

Providing astronauts with fresh, nutritious food enhances their health and well-being during extended lunar missions, offering a valuable alternative to the heavily processed, packaged meals currently used in space. Care must be taken to sterilize the system before launch to minimize the risk of pathogens in the system. However, since the miniature greenhouse is autonomous, the astronauts do not come in direct contact with the system, greatly reducing the chance of exposure. Moreover, the knowledge gained from controlled-environment agriculture systems—such as those developed in the OASYS project—can be translated to Earth applications. These advancements can support food security and sovereignty in remote or climate-challenged regions, including northern Canada and desert environments.

6. Prototype

6.1. Budget

This project was allocated a budget of 2000$ from the CSA to build and test a prototype of the design. The project stayed well within budget and only used 850$ of the allocated funds. The budget breakdown of all purchased materials is in table D1 of Appendix D. We were required to purchase all components for our prototype by mid January 2025. This did not allow for much time to determine what materials were required for prototyping as the chosen conceptual design was only finalized at the start of February. It was for this reason that multiples of some items were purchased to be able to test and compare which version would be most suitable. Also, the materials required for the growth chamber were not purchased and needed to be borrowed from within the Department of Bioresource Engineering. Secondly, later in the design process certain aspects of the design were altered and required materials that were not originally purchased.

6.2. Fabrication

Error! Reference source not found. shows the materials used in the development of the Earth prototype as well as the suggested materials for the lunar design. All the materials chosen meet outgassing requirements and are food safe (NASA, 2017). PLA was selected for the lid and cups for our prototype because it is more beginner-friendly 3D print with than ABS, while having sufficient properties in terms of strength. Similarly, medical gauze was selected for the Earth prototype because it is oxygen-permeable, inexpensive, easy to work with, and easier to acquire than Tyvek commercial wrap. The interface with the pressure Vessel and inlet water pipe from the humidity control subsystem were not included in the prototype because they are not critical to proving the feasibility of the design.

Table 9. Materials for Earth Prototype and Lunar Design.

Part	Earth Prototype	Lunar Design
Reservoir	PVC Epoxy Resin	ABS (3D printed) Epoxy Resin
Lid	PLA (3D printed)	ABS (3D printed)
Cups	PLA (3D printed)	ABS (3D printed)
Hole Covers	Silicone Rubber (16A Shore Hardness)	Silicone Rubber (16A Shore Hardness)
Wicks and capillary mat lining	Paper towel	Further testing required
Oxygen permeable membrane	Medical Gauze	Tyvek commercial wrap
Interface with pressure vessel	---	Aluminum
Inlet water pipe	---	PTFE Shrink Tube

The original design included synthetic fiber wicks. Two materials were purchased and tested: nonwoven polyester and polypropylene. Despite being marketed to transport water to plants, both materials did not wick when placed in water for several hours. Because of this, paper towel wicks were used instead, as suggested by our mentor who had used them successfully in previous experiments.

6.2.1. Reservoir

It was opted to make to water reservoir out of polyvinyl chloride (PVC) as this was the cheapest and most accessible option. Scrap PVC was sourced from the Bioresource engineering shop. Five pieces of PVC were cut to the desired size and glued together using PVC cement. The cement took 24 hours to dry, figure 7 shows the reservoir being clamped as it is drying. While the PVC cement provided a strong connection between the sides, because the box would hold water, an epoxy resin layer was added to the inside surface to ensure the box was watertight. A square of capillary matting was then cut out and placed on the bottom surface of the reservoir.

Figure 7. The constructed reservoir made of PVC was clamped as the cement dried.

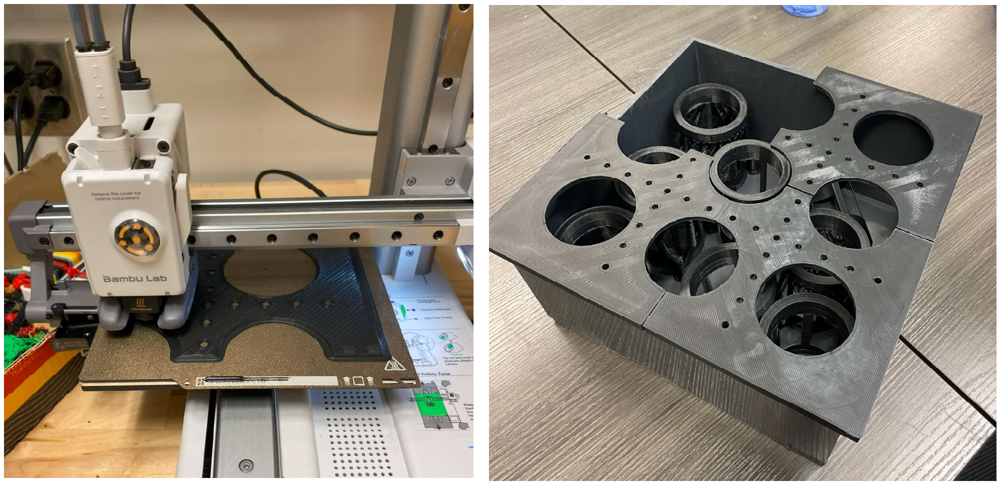
6.2.2. Lid

The lid was fabricated via 3D printing. However, since there were no available printers with an adequate bed size to print the entire lid in one piece, it had to be printed in four quarters. Since the lid is a symmetrical square, it was simple to make the breaks so that the lid was four identical quarters. Dowel pins and holes were added to the faces to add structural integrity when assembled. A test print of the dowels and holes was performed ahead of time to test if they could be printed without supports and if the tolerance was adequate.

Difficulties arose when 3D printing due to bed adhesion, which led to failed, but still usable, prints. Because the piece is flat and extends almost to the edge of the print bed, the corners began to lift and would lead to the nozzle getting caught on the piece and dragging it off the bed. This occurred using the Bambu Lab A1 mini printer, shown in figure 8 (a), which took about 6 hours to print. A makeshift barrier of cardboard was installed around the printer to limit the airflow, which helped but only marginally.

When the print was done on the Original Prusa MINI printer, the print took just over an hour and did not fail. Due to time constraints, three quarters were printed on the Prusa printer, and the most-usable print from the Bambu printer was also used.

The pieces were assembled by adding glue to the dowel pins and inserting them into the dowel holes. The quarter from the Bambu printer that was used was slightly warped, which led to some misalignment of the faces. The lid was however still usable as it fit over the reservoir and held the fully assembled cups for the duration of the experiment. Figure 8(b) shows three of the quarters of the lid assembled on top of the reservoir.

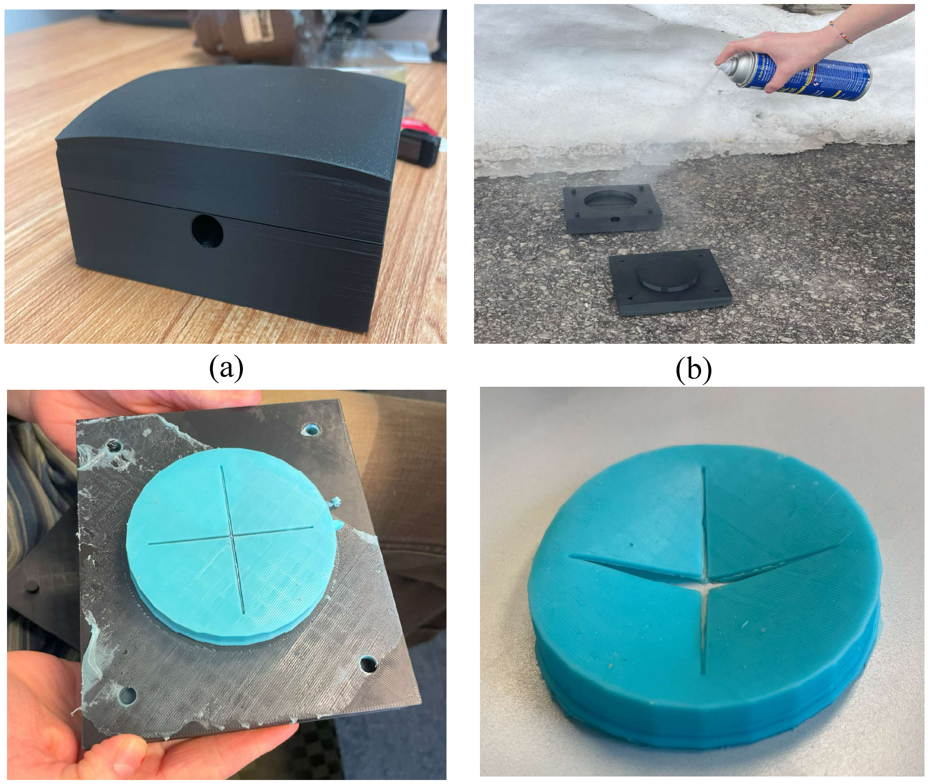


(a) (b)

Figure 8. (a) one of four lid pieces being 3D printed. (b) three out of four lid pieces assembled.

6.2.3. Cup Covers

First, the mold was 3D printed (fig. 9 (a)), and before each cast, the mold was sprayed with a release agent so the silicone could be casted in the mold and removed easily (fig. 9 (b)). The hole to pour the silicone that was designed in the mold did not facilitate the silicone to properly spread throughout the mold (pictures of this failed pour can be found in figure D1 in Appendix D). Instead, the silicone was poured and spread evenly onto one of the mold faces and then both mold faces were clamped together while the silicone set for 30 minutes. This method was successful for the prototype which can be seen in figure 9 (c) and (d), but this method did create some tiny air bubbles to enter the silicone. Therefore, it is recommended that improvements to the pour spout be made for space applications.



(a) (b) (c) (d)

Figure 9. (a) 3D printed mold. (b) Spraying the release agent onto the inner face of the mold. (c) Casted silicone cover prior to removing it from mold. (d) finished cup cover.

6.2.4. Cup

The cups were 3D printed in batches of either 2 or 4. They were printed upright, and tree supports were used on the overhangs. Tree supports were chosen instead of standard ones because they were easier to remove. When tearing standard supports from the cup, it was easy to accidentally break the "window" sections, and it was difficult to remove them from the wick slits. These issues did not arise when using the tree supports because it only touched the bottom of the rim and inside the wick slits. In some cases, the tree supports failed, but the cup structure printed successfully, as shown in figure 10 (a).

6.2.4.1. Cup Assembly

The 3D printed cups were assembled by first weaving medical gauze, which acted as the oxygen permeable membrane, around the "windows" of the cup. The gauze was secured to the edges of the cup with small amounts of super glue to ensure arcillite would not spill out of the cup. Folded paper towel was cut to the wick dimensions and inserted into the designated slits on the cup. Next, arcillite was sieved using a soil sieve to 1-2mm diameter particles and with the wicks evenly spaced in the cup, the arcillite was carefully poured into the cup (fig. 10 (c)). One wick extended higher than the other two, and this was used for germination of the radish seed (fig. 10 (c)). Two seeds were glued to the inside of the fold of the paper towel using guar gum. Once all nine cups were assembled, they were inserted into the nine cup holes in the lid, which was then placed on top of the reservoir. After weighing all 9 cups the average mass per cup was 212 g.

(a) (b) (c)

Figure 10. (a) 3D printed Cup. (b) Fully constructed cup. (c) Top view of cup without cup cover.

7. Testing and Validation

To test our system, radishes were grown in the constructed prototype. Unfortunately, due to time constraints, some parameters of our design had to be altered in order to start the experiment on time. The Nutricote fertilizer was lost in the mail, repurchased, and lost again, and the second time it got lost was just days before the experiment was supposed to commence. Therefore, a liquid nutrient solution was used instead because it was readily available and accessible. Additionally, the synthetic material purchased for the wicks did not work so paper towel was substituted in the system.

Due to time constraints, a lunar night phase was not simulated. Rather than following the full lunar cycle—14 Earth days of light (lunar day), followed by 14 days of darkness (lunar night), and another 14 days of light—the radishes were grown under continuous lunar day conditions for 28 days. This approach aligns with the assumption that radishes would not grow during the lunar night. Additionally, simulating the lunar night was not necessary to demonstrate the feasibility of this subsystem. The constraint of the lunar night was considered during the design process, which led to the development of a passive, powerless system capable of functioning without energy input during periods of darkness. As a result, the system is not expected to behave differently under lunar night conditions, and omitting the night phase from testing does not impact the validity of the results.

7.1. Methodology

7.1.1. Experimental Set-Up

A makeshift controlled growth chamber was constructed to keep the system within the temperature and relative humidity range that the OASYS lunar greenhouse will experience (5-30°C and 45%-70%), as seen in figure 11. A large cooler was used to house the plants, and a full spectrum LED grow light was used with a 16 hours on (6:00-22:00), 8 hours off (22:00-6:00) timed cycle using a mechanical timer plugged into the lights. After the lights were set up, the light intensity was measured at 1300 Lux.

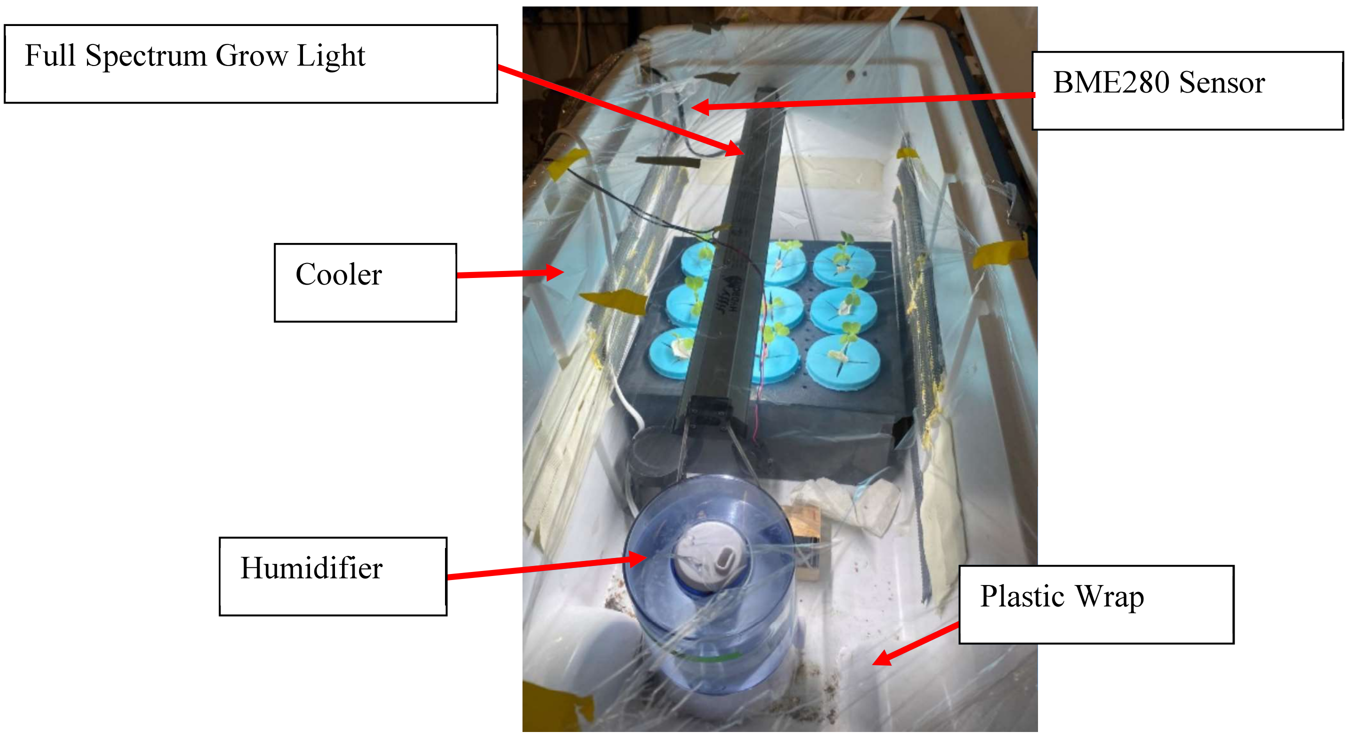


Figure 11. Experimental growth set up.

The liquid nutrients used were a Hoagland A&B solution which is a nutrient solution commonly used in hydroponic experiments that provides plants with a complete set of essential macro and micronutrients. The system was started at a half strength nutrient solution at an electrical conductivity (EC) of 0.7 milliSiemens per centimeter (mS/cm) while the seedlings were small and increased the solution to full strength (EC = 1.4 mS/cm) after 15 days.

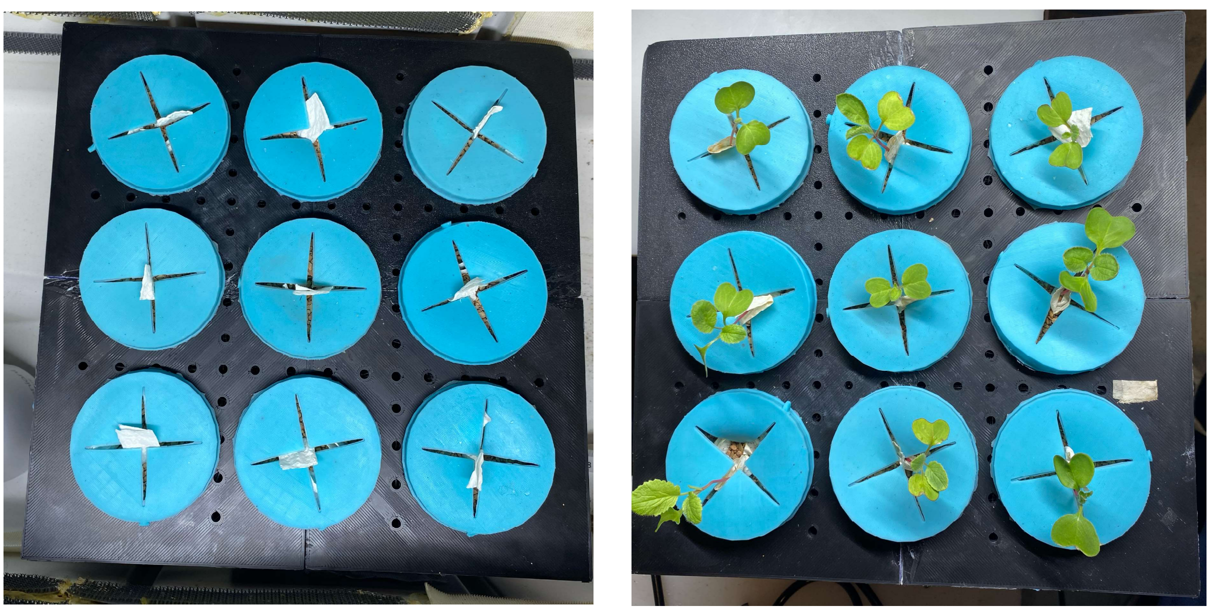
7.1.2. Data Collection and Monitoring

A number of parameters and aspects of the system were observed and monitored on a daily basis. Firstly, because we switched to using liquid nutrients, this meant having to check the pH and EC daily. Radishes grow optimally when the nutrient solution is maintained between 6-7 (Wildrose Heritage Seed Company, n.d.). The pH would often go above 7, in which case drops of 3M sulfuric acid were added to the solution until the pH was within range.
The space that we were allocated to conduct our experiment in had very low humidity and was quite warm so a small fan and humidifier were added. A BME280 temperature and relative humidity sensor was coded using an ESP8266 NodeMCU V3 board to log the temperature and humidity of the growth chamber. This sensor took measurements every 30 seconds. Using InfluxDB to track the sensor output, we were able to monitor the temperature and humidity and make adjustments with the fan and intensity of the humidifier to either increase or decrease these two parameters. Additionally, plastic wrap was used to cover the cooler, and this was partially opened and closed if the temperature and or humidity became too high. Table E2 in Appendix E shows the daily average relative humidity and temperature logged by the sensors.

The heights of the leaves were also measured once they started germinating, and observations were noted everyday about the plants and the environment.

7.2. Results

The experiment ran for 18 days. A side-by-side comparison of the system from day one to day fifteen is shown in figure 12.



(a) (b)

Figure 12. (a) System on day one of experiment (b) System on day fifteen of experiment

Observations made during the growth of the radishes are as follows in Table 10:

Table 10. Key dates and observations made during the experiment.

Day	Observation
3	First signs of germination
4	First leaves emerge from paper towel wicks
5	8 out of 9 of the cups germinated. The seedlings on either side of the light started leaning slightly towards the light over the middle row.
7	All 9 cups have germinated. 8 out of 9 cups have 2 seedlings that have sprouted. All seedlings emerged without being obstructed by the silicone cup cover.
10	All seedlings reach an average height of 4.5 cm measured from the where the seedling emerged from the arcillite
12	Mold buildup was first observed on wicks.
13	Seedlings thinned by cutting the base of the weaker seedlings.
16	Emptied and cleaned reservoir and replaced the capillary matting lining the bottom. The nutrients were replaced with a full-strength nutrient solution. To kill the mold on the wicks, they were sprayed with a 50% ethanol solution, as suggested by our mentor.
18	Mold was no longer growing on the wicks, but the paper towels were no longer wicking water. The experiment was terminated at this point.

Unfortunately, as stated in table 10, the experiment was terminated before the radishes grew to maturity due to the appearance of mold on the paper towel wicks as seen in figure 13. The mold began to break down the paper towels and until they became frail and started to break off. It was attempted to kill the mold with an ethanol spray, but instead this led to the wicks losing function. Because the paper towel wicks were imbedded in the arcillite it was not possible to replace the wicks without disturbing the root network of the seedlings.

Figure 13. Mold on the wicks.

It is hypothesized that the use of liquid nutrients created favorable conditions for mold growth. The original design was not made for the use of liquid nutrients, and the airholes in the lid design allowed light to penetrate to the nutrient solution and contribute to the optimal growing conditions for microbes. In the original design, light penetration into the reservoir from the holes was believed to not lead to significant microbial growth since the nutrients would be contained in the cups. The experiment was ended after the ethanol treatment because it was assumed that the issues that arose were because of critical changes that were made during prototyping, namely the use of liquid nutrients and paper towel wicks.

Due to the short-term nature of the capstone project, there was not enough time to repeat the experiment. Nonetheless, several successes were observed during the 18 days the radishes grew, and key takeaways emerged that can inform the next iteration of the OASYS project. Notably, the radish seeds germinated successfully when glued to the wicks with guar gum, and the silicone cup covers did not obstruct germination or seedling emergence through the slit. In some cases, seeds germinated underneath the hole cover but were still able to emerge without assistance. Overall, the hole covers performed well, effectively containing the arcillite while allowing the seedlings to grow unobstructed.

7.2.1. Post experiment test

Initially, a key result we were hoping to obtain from the experiment was to see how much water a full-grown radish would consume in our system. This was going to be measured by measuring the wet and dry mass of the radish. Since the radishes did not grow to maturity, this result was not obtained. Alternatively, one measurement we were able to obtain was the amount of water absorbed by the wicks and the arcillite in a single cup. This was done by conducting a side experiment to determine the water holding capacity of the arcillite. First, a cup was assembled with the gauze, wicks, arcillite, and cup cover and weighed. Then, the cup was placed above a jar of water, with the wicks in contact with the water, simulating the water delivery of the system. The cup was allowed to sit for two weeks, and then the mass was taken again.
The dry mass was found to be 183.76 g, and the wet mass was 251.3 g. Therefore, 220cm^3 of arcillite with 3 wicks can hold 67.5 g, or 67.5 cm^3 of water, equal to about 31% of its weight.

7.3. Experimental Challenges

Challenges arose throughout the experiment. To simulate the lunar greenhouse and reduce variability of growth conditions, the radishes were grown in the cooler with lights and a humidifier. However, regulating the temperature and humidity proved challenging. With the lid open on the cooler but the top fully sealed with clear plastic wrap, the humidity became too high, and water droplets condensed on the lid and hole covers. Also, the lights used produced more heat than expected, and, since the cooler is a very effective insulator, it became very hot in the cooler. Openings were created in the plastic wrap to allow excess humidity and heat to escape. the size and placement of them had to be adjusted throughout the experiment to keep the cooler within the desired temperature and humidity range. Additionally, the lab that the experiment took place in had poor insulation, and the temperature in the cooler fluctuated with the fluctuating outdoor temperatures.
Additionally, as stated in previous sections, the solid nutrients in the design did not arrive, so the prototype used a liquid nutrient solution instead. This proved challenging because it was an unexpected adjustment that was not accounted for in our design.

8. Recommendations

This iteration is part of a continuous project that will be elaborated on in subsequent years by other capstone groups. Lessons learned from this iteration and suggestions for improvement can be used to refine the design.

Firstly, it has been shown in this experiment that liquid nutrients are high maintenance and lead to microbial growth on the wicks. The next group should experiment using solid nutrients to validate that this does not occur with solid nutrients as hypothesized. Also, it is hypothesized that the Nutricote fertilizer may be able to supply adequate nutrients for more than one growth cycle because they are slow-release. If this is the case, then that would mean that less nutrients would need to be required, which would reduce the cost and mass of the system. This should therefore be tested in future iterations.

Additionally, paper towel wicks should not be used in subsequent iterations or on the lunar design because of how fragile they are and their potential for microbial growth. Other materials of synthetic wicks should be evaluated and judged for their use based on their wicking ability, durability, and resistance to microbial growth. Some experiments at the CSA have found success with a capillary mat made of a "polypropylene, polyester, viscose material" (Sustainable Village, n.d.).

The hole cover design fabricated in this design proved successful and should be used in subsequent iterations. The silicone material contained the growth medium while allowing for successful germination. In the next experiment, radishes should be grown to maturity to assess if the hole cover exerts any mechanical stress on the hypocotyl.

Also, the hole in the mold into which to pour the silicone was too small, so the casting was done by pouring the silicone onto one side of the open mold and then sandwiching the two halves together. This is not proper casting technique, so the mold design should be revised so the silicone can be poured into the already-closed mold.

In this prototype, the oxygen-permeable membrane, or medical gauze, was adhered to the cup using hot glue. When the cup was filled with arcillite, however, duct tape had to be wrapped around the top and bottom of the gauze to prevent arcillite from spilling out. The cup design should also be updated to make the gauze easier to attach, like small hooks around the inside wall of the cup, for example. Also, the gauze that was used was easily stretched and led to bulging of arcillite as it settled. This made the cups difficult to remove from the lid. Other materials for the oxygen-permeable membrane should be considered that are less flexible and keep the arcillite in place.

In future iterations when radishes are grown to maturity, the fresh and dried mass of the radishes should be taken. This will help update the current assumption that the radishes are 100% water with a more accurate estimation of necessary water intake, which will help refine the mass of water needed for a growth cycle.

9. Conclusion

This project supports the Canadian Space Agency's OASYS initiative to assess the feasibility of a miniature lunar greenhouse for growing radishes. The nutrient delivery system was designed to reliably supply water, nutrients, and aeration to the root zone using a passive, power-free mechanism.

In this system, radishes are grown in individual cups filled with arcillite, a clay-based growth medium. Each cup is suspended above a water reservoir, with wicks drawing moisture upward to the plant roots. Solid, slow-release fertilizer delivers nutrients over time, while an oxygen-permeable membrane around the root zone and silicone hole cover over the top keep the growth medium in place and allow the plant to grow unobstructed.

The design was developed with compatibility in mind. The cups feature a raised lip that allows manipulation by the Robotic Harvesting Arm without resistance from the hole cover. Collected humidity from the Humidity Control subsystem can be recycled directly into the water reservoir via tubing. The entire growth system would interface with the pressure vessel using aluminum rails for secure transport and deployment on the Moon.

A prototype was tested using alternate materials for accessibility and convenience. However, the solid nutrients did not arrive in time, so liquid nutrients were used instead. Additionally, the purchased synthetic wicks were ineffective, and paper towel wicks were substituted. While radish seeds germinated and began growing successfully, mold developed on the wicks by Day 12, and the experiment was terminated on Day 17. Despite these challenges, the experiment validated many aspects of the original design. Solid nutrients appear to significantly reduce microbial risks and require less maintenance than liquid alternatives, which needed frequent pH and EC adjustments. Synthetic fiber wicks are also expected to minimize microbial growth. Although the radishes did not reach maturity, the prototype offered valuable insights for future development. Recommendations include testing with solid nutrients and effective synthetic wicks, and refining the mold used to create the hole covers for improved usability. This report will hopefully serve as a starting point for the next capstone group to take on this project.

Ultimately, this project contributes to the broader efforts of space agencies to produce fresh food for long-duration missions. Findings from space-based agriculture—such as this passive nutrient delivery system—advance the vision of biological life support systems that enable astronauts to live in closed-loop environments with gas exchange, waste recycling, and fresh food production. These technologies are key to supporting sustainable human presence on the Moon and beyond.

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11. Appendices

Appendix A

Table A1. OASYS requirements provided by the Canadian Space Agency.

Requirement Code	Title	Description
RQMT-0001	Greenhouse Dimensions	The overall inside dimensions of the container shall not exceed **TBD.**
RQMT-0002	Greenhouse Dimensions	The greenhouse dimensions of growth shall not exceed 30 cm × 30 cm × 30 cm.
RQMT-0003	Greenhouse Mass	The total mass of the greenhouse and all its subsystems shall not exceed **TBD**.
RQMT-0004	Atmospheric Pressure	The atmospheric pressure inside the lunar greenhouse shall be 0.5 atmosphere (50.663 kPa).
RQMT-0005	Outgassing	All materials used shall have a Total Mass Loss (TML) of less than 1% and less than 0.1% Collected Volatile Condensable Material (CVCM).
RQMT-0006	Environmental Conditions	The proposed greenhouse concept shall be operable in a vacuum environment of 2×10^{-12} Torr.
RQMT-0007	Depressurization and Venting	Internal volumes intended to depressurize shall have vent openings with area at least 2 cm^2 per 1000 cm^3 of enclosed air.
RQMT-0008	Lunar Dust Resilience	The lunar greenhouse shall be unaffected by abrasive lunar dust and, where required, protect sensitive areas from lunar dust ingress.
RQMT-0009	Thermal Operating Range	The thermal control system of the greenhouse shall maintain an operable temperature while environmental temperature varies between - 200°C to +100°C.
RQMT-0010	Internal Temperature Operating Range	The internal average air temperature of the greenhouse shall be maintained between 5 to 30°C.
RQMT-0011	Humidity	The humidity in the greenhouse shall be maintained in the range 45% to 70% and should optimally be maintained in the range of **TBD**
RQMT-0012	Internal Atmospheric Composition	**TBD**
RQMT-0013	Solar Panel Area	The proposed greenhouse concept shall ensure enough external area is devoted for solar arrays to generate an average 50 W (**TBC**) during the lunar day.
RQMT-0014	Keep Alive	The greenhouse shall have a designated Keep Alive (KA) state to survive the lunar night.
RQMT-0015	Power System	The greenhouse power generation system shall consist of solar arrays and batteries and shall meet the power needs for operation during a lunar day (such as for mobility, sensing, and communications) and a KA state throughout a lunar night.
RQMT-0016	Power System	The greenhouse power system must be able to supply a peak power of **TBC** W to the **TBD**.
RQMT-0017	Greenhouse Assembly	The greenhouse shall not require any in-situ assembly.
RQMT-0018	Structure	The greenhouse structure shall support the mechanical static and dynamic loads encountered during its entire lifetime with a minimum factor of safety of 1.4.
RQMT-0019	Greenhouse Recharge	The greenhouse shall begin the lunar night with a fully charged battery.

Requirement Code	Title	Description
RQMT-0020	Lifespan	The greenhouse shall remain operable for a minimum of 6 weeks **TBC** (two lunar days and one lunar night).
RQMT-0021	Radioactivity	The greenhouse shall not contain any radioactive material to avoid potential contamination during a launch failure.

Appendix B: Design Dimensions and Calculations

Water height in water reservoir

Assumptions:

- 450 ml of water in the reservoir
- Thickness of reservoir walls are 0.5cm, and an epoxy coating of 0.2cm coat the inside of the reservoir
- The base of reservoir contains a capillary mat at the bottom which is 0.3 cm thick.

$$area\ of\ base\ of\ reservoir = (inner\ length\ )^2 = (26.6)^2 = 708\ cm^2$$

$$height\ of\ water = \frac{volume\ of\ water}{area\ of\ water} = \frac{450\ cm^3}{708\ cm^2} = 0.64\ cm = 0.7cm\ (rounding\ up)$$

Maximum Suggested Slope

Assumptions:

- the maximum of water that will be in the reservoir is 450 ml, and therefore the maximum height that the water will be in the reservoir is 1.6 cm high.
- The water cannot come into contact with the bottom of the cup.
- The cups sit 3.8 cm above the bottom of the reservoir.

With a tolerance of 1cm we assume that the maximum height that would be desired for the water to rise on any side is to a height of 3cm so it doesn't splash or come into contact with the cups. Therefore when the reservoir is full, the water should only rise an additional 1.2 cm.
With the inner length of the base of the reservoir being 26.6 cm and 1.4 being the maximum height that the water should rise trigonometry calculation can be done to find the angle between this rise and run and then find the slope:

$$\frac{1.4}{27} \times 100 = 4.5\%$$

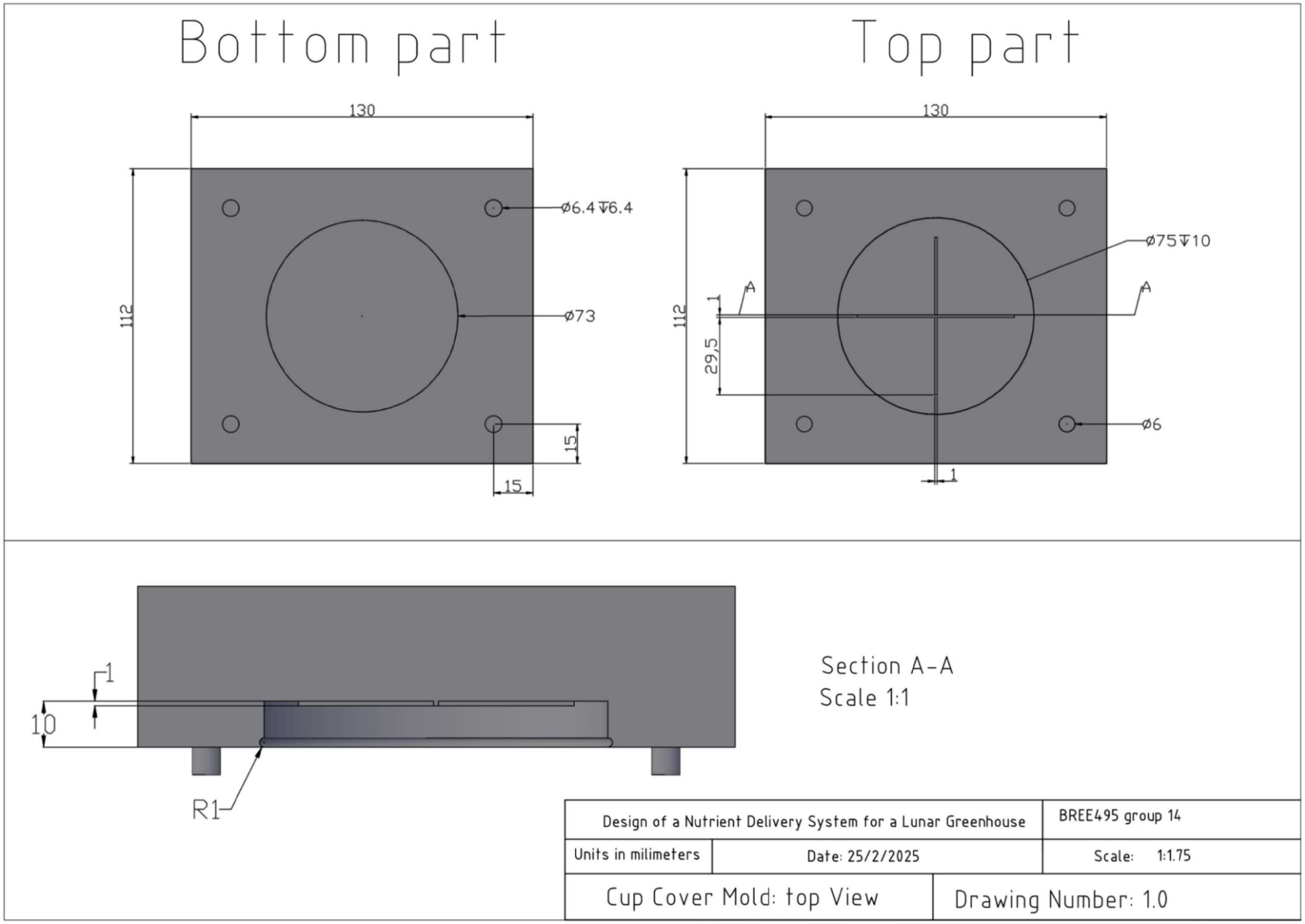


Figure B1. Top view drawing of the cup cover mold.

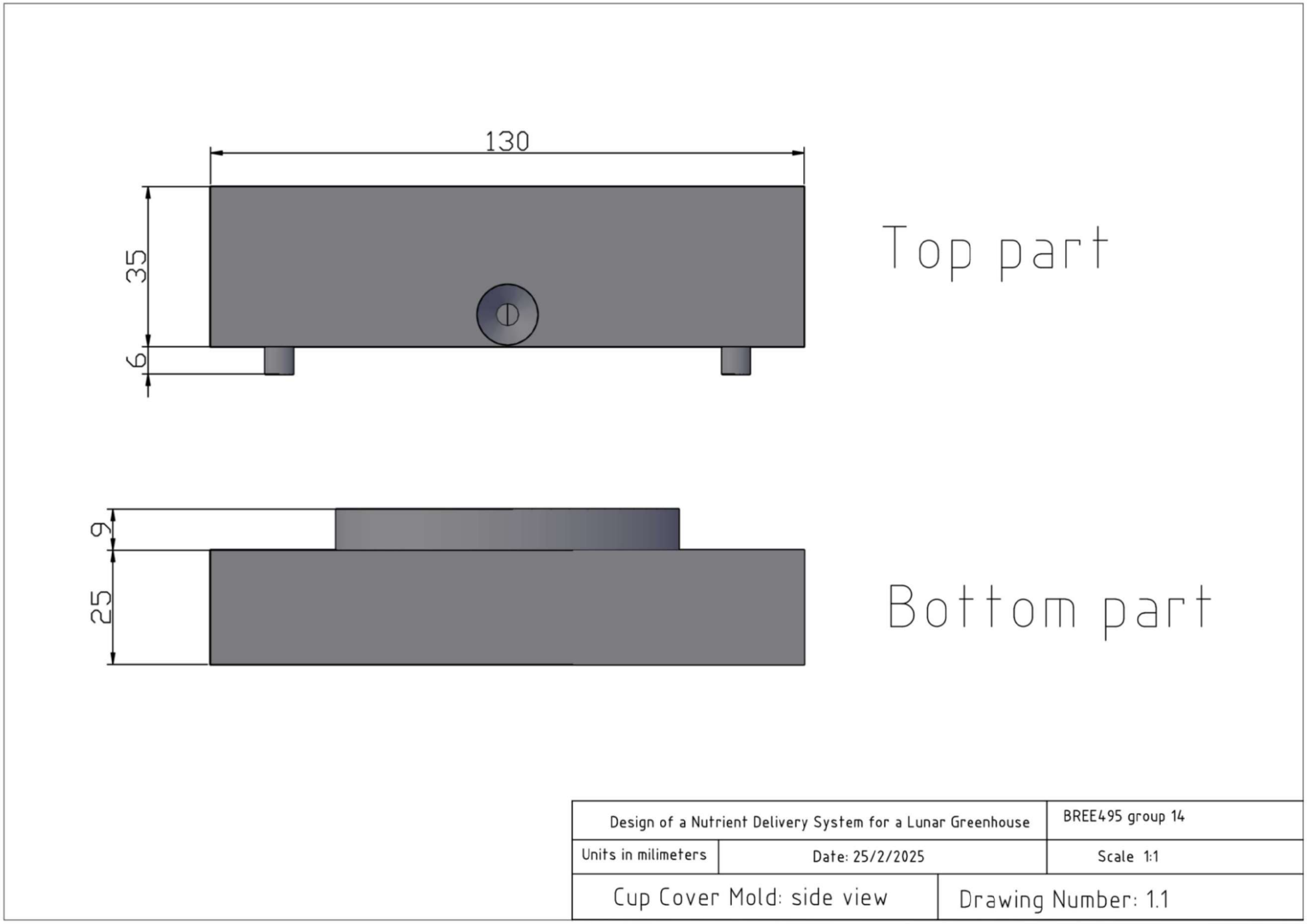


Figure B2. Side view drawing of the cup cover mold.

Appendix C : Mass Calculations

Mass of Reservoir:

According to the British Plastics Federation, the ρ_{ABS} varies between 1.00 and 1.05 g/cm^3. Take 1.05 as the value.

Volume of Reservoir:

$V_{reservoir} = V_{bottom} + V_{walls} = 28cm * 28cm * 0.5cm + 2 * 0.5cm * [28cm * 13cm + 27cm * 13cm = 1107.0\ cm^3$.

The heights of the sidewalls are 13 because the other 0.5 cm is accounted for in the volume of the bottom. Assuming 100% infill,

$$m_{reservoir\_ABS} = \rho_{ABS} * V_{reservoir} = 1.05\frac{g}{cm^3} * 1107cm^3 = 1162.4\ g$$

There is also a layer of resin that will be applied to the inside walls of the reservoir to increase smoothness. Assuming $\rho_{resin} = 1.68\ g/cm^3$ based on this source, and assuming the thickness of the layer is to be $t = 0.25\ cm$ and applied to the whole inside surface area, then

$$V_{resin} = t * [A_{bottom} + A_{inside\_walls}] = 0.25cm * [(27cm * 27cm) + 4 * (13cm * 27cm)] = 533.3cm^3$$

$$m_{resin} = \rho_{resin} * V_{resin} = 1.3\frac{g}{cm^3} * 533.3cm^3 = 693.2\ g$$

Then the mass of the entire reservoir including the resin layer is

$$m_{reservoir} = m_{reservoir\_ABS} + m_{resin} = 1162.4\ g + 693.2\ g = 1855.6\ g$$

Mass of Lid:

The lid will be made of ABS plastic, and as stated before, $\rho_{ABS} = 1.05\ g/cm^3$. The lid has nine holes of $D_{plant\_hole} = 6.7\ cm$ (allowing 0.2 cm tolerance for the cups) and 52 holes of $D_{air\_hole} = 0.5\ cm$, and the thickness is 0.5 cm. There is a lip that extends down 1 cm from top of lid and is 1 cm wide. The volume is

$$V_{lid\ without\ holes} = 1cm(28cm)^2 - 0.5\ cm(26\ cm)^2 = 446.0cm^3$$

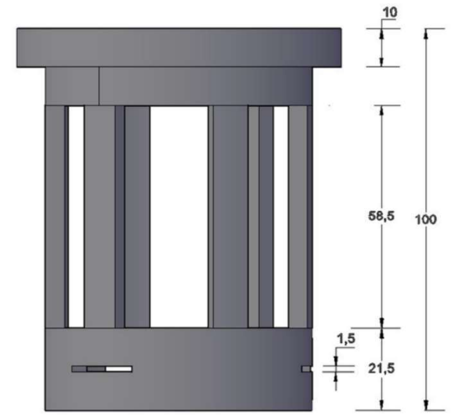
The Volume of the holes is

$$V_{holes} = V_{plant\_hole} + V_{air\_hole} = \frac{\pi}{4} * [9 * (6.7cm)^2 + 52 * (0.5cm)^2] = 327.5cm^3$$

Therefore, the mass of the whole lid is

$$m_{lid} = \rho_{ABS} * (V_{lid\ without\ holes} - V_{holes}) = 1.05\frac{g}{cm^3} * [446.0cm^3 - 327.5cm^3] = 124.4\ g$$

Mass of Cups:
The inner and outer radii of the cups are $r_i = 3\ cm$ and $r_o = 3.25\ cm$.



The volume of the bottom of the cup up is $V_{bottom} = \pi(3.25cm)^2 * 0.5cm = 16.6\ cm^3$. Since the bottom is 0.5 cm thick.

The slits are 2 cm long and there are three, equaling a total of 6 cm of open space. This translates to 29.4% of the circumference being removed due to the slits.
The volume of the area from the top of the bottom of the cup to the bottom of the window is

$V_{slit\ area} = \pi[(3.25cm)^2 - (3cm)^2\ ] * (0.15cm)(1 - .294) = 0.520\ cm^3$ and
$V_{area\ around\ slits} = \pi[(3.25cm)^2 - (3cm)^2\ ][2.15cm - .15cm - .5cm] = 7.36cm^3$

Between the windows there are six vertical pieces that are each 1 cm thick = 6 cm of material in this section. So 70.6% of the material is removed from the windows being there.

$V_{window\ area} = \pi[(3.25cm)^2 - (3cm)^2\ ] * (5.85\ cm)(1 - .706) = 8.44\ cm^3$

The volume from the top of the windows to the top of the cup is:

$$V_{above\ windows} = \pi[(3.25cm)^2 - (3cm)^2\ ] * (1cm) + \pi[(4.25cm)^2 - (3cm)^2\ ](1\ cm) = 33.38\ cm^3$$

Assuming $\rho_{ABS} = 1.05\ g/cm^3$, then the total mass of all nine cups is

$$m_{cups} = 9 * 1.05\frac{g}{cm^3} * (16.59cm^3 + 0.520cm^3 + 7.36cm^3 + 8.44cm^3 + 33.38cm^3) = 626.4\ g$$

Mass of water:
Assuming 450 mL of water will be used in the reservoir, and $\rho_{water} = 1\frac{g}{cm^3}$, then

$$m_{water} = 450cm^3 * \frac{1g}{cm^3} = 450\ g$$

Mass of growth medium (arcillite):

The volume of arcillite that will be added to the cups is $V_{arcillite} = 220cm^3$. The maximum bulk density of arcillite sieved to 1-2 mm particles is $\rho_{arcillite} = 0.64 \frac{g}{cm^3}$ (Steinberg, et al, 2005). Therefore the mass of arcillite for all nine cups is

$m_{arcillite} = 9 * \rho_{arcillite} * V_{arcillite} = 9 * 0.64 \frac{g}{cm^3} * 220cm^3 = 1267.2g.$

Mass of nutrients (Nutricote):

Since the dosage of fertilizer is 7.5g/L growth medium, the mass of Nutricote is

$$m_{Nutricote} = 9 * V_{arcillite} * 7.5 \frac{g}{L} = 9 * 220cm^3 * 7.5 \frac{g}{L} * \frac{1L}{1000cm^3} = 14.85\ g$$

Mass of Wicks:

For polyester wicks, assume the density is $\rho_{wick} = 0.1\ g/cm^3$ (Porous Polyester Wick, n.d.). Each cup will have 3 wicks that will be 2 cm wide, 2 mm= 0.2cm thick. Assuming the wicks are placed 1 cm from the bottom of the cup, and the bottom of the cup is 2.5 cm from the bottom of the reservoir, then the length outside the cup will be 3.5 cm. The wicks will extend to the top of the cup, so the length of wick inside the cup is 8 cm.

$$L_{wick_{total,one\ cup}} = 3 * ((1cm + 2.5cm) + 8cm) = 34.5\ cm$$

$$V_{wick_{total_{onecup}}} = 2cm * 34.5cm * 0.2\ cm = 13.8\ cm^3$$

$$m_{wick_{total}} = 9 * \rho_{wick} * V_{wick_{total_{onecup}}} = 9 * 0.1 \frac{g}{cm^3} * 13.8cm^3 = 12.42\ g$$

Mass of Seeds:

One gram of radish seeds includes 90-140 seeds (Seeds per Gram, n.d.). From this, one seed weighs between 0.011 g -0.007 g, out of safety will assume the higher value. If two seeds are sown per cup, then there are 18 seeds total per growth cycle.

$m_{seeds\ total} = m_{seed} * n = 0.011\ g * 18 = 0.2\ g.$

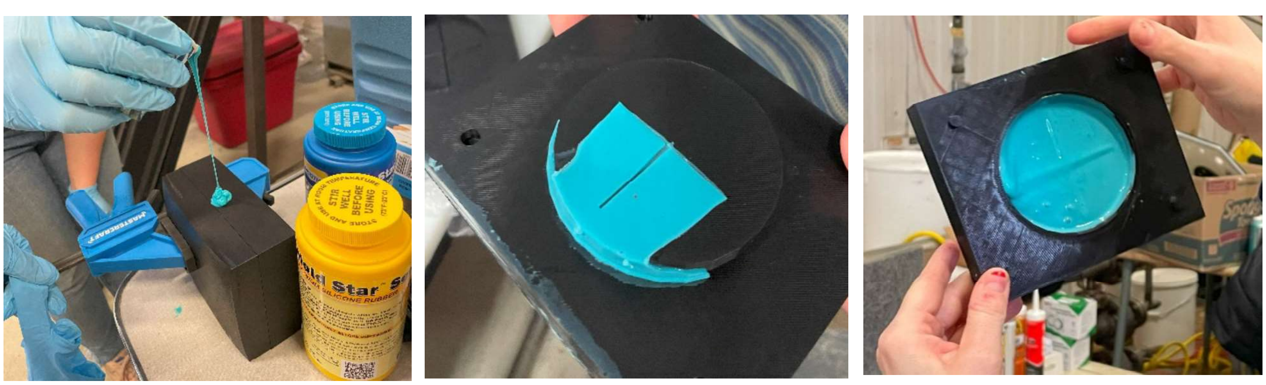
Total mass of the system is the sum of the individual components:

$$m_{total} = m_{water} = 450g$$

Appendix D : Prototyping

Table D1: Budget breakdown.

Item	Component(s)	Actual price
Arcillite (9 liters)	Growing Medium	$131.23
Arduino board	Validation	$268.86
Wires (for sensors)	Validation	
Capillary matting	Wicks	
Guar gum	glue for seeds	
Moisture Sensors	Validation	
3D printing filament	Lid, cups, container	
Silicone Rubber (20.46oz)	Plant hole cover	
Silicone Rubber (pint unit)	Plant hole cover	$91.96
Silicone & release agent	Plant hole cover	$84.71
Capillary matting	Wicks	$40.23
Soil Sieve	Growing medium preparation	$42.30
Nutricote fertilizer	fertilizer	$95.12
Epoxy Resin (32 oz)	Container	$34.44
Gauze	Oxygen-permeable membrane	$35.74
Radish seeds	Radishes!	$26.20
Equipment for experimental set up	Humidifier, LEDs, cooler, temp and RH sensor, timer	Borrowed! = 0$
	TOTAL (after tax & shipping)	$850.79



(a) (b) (c)

Figure D1. Methods used for pouring silicone. (a) original method for pouring the silicone using the pour spout that was designed in the 3D printed mold. (b) The result of casting the silicone with the method shown in part (a) of this figure. (c) the alternative method used to cast the silicone by spreading the silicone across one face of the mold and then closing both faces of the mold while it sets. This method was successful and was used to cast all the cup covers.

Appendix E : Testing

Table E1. Composition of liquid nutrient solution used in growth experiment.

Hoagland A (macronutrients)					
	KH2PO4	KNO3	Ca(NO3)2*4H2O	MgSO4*(7H2O)	
stock (g/L)	136.1	101.1	236.2	246.5	
strength (ml/L of water)	1	5	5	2	
Hoagland B (micronutrients)					
	H3BO3	MnCL2*4H2O	ZnSO4*7H2O	CuSO4*5H2O	NaMoO4*2H2O
stock (g/L)	2.86	1.81	0.22	0.08	0.12
strength (ml/L water)	1				
Additions					
day	**Hoagland A (ml)**	**hoagland B (ml)**	**water (ml)**		
1 (half strength)	10	10	1250		
15 (full strength	20	20	1250		

Temperature and Relative Humidity Monitoring

Figure E1. Screenshot of InfluxDB, the website used to track and monitor the sensor output data.

Table E2. Daily average relative humidity and average temperature for each day of the growth experiment.

Date	Average Relative Humidity (%)	Average Temperature (Degrees C)
March 10	No data available	No data available
March 11	49.9	25.3
March 12	No data available	No data available
March 13	44.7	26.2
March 14	34.3	25.9
March 15	40.1	25.5
March 16	41.6	27.3
March 17	40.4	26.9
March 18	35.5	24.9
March 19	55.0	23.5
March 20	56.0	25.0
March 21	64.5	23.6
March 22	71.8	21.9
March 23	68.1	19.7
March 24	66.8	23.7
March 25	62.8	23.5
March 26	58.2	23.2
March 27	35.6	26.5
March 28	44.7	25.2