PeaPod - Final Report

NASA/CSA Deep Space Food Challenge Phase 2

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1 Technology Description and Progress

PeaPod is an automated plant growth environment, made of control systems and an automation/monitoring system within a modular, cubic housing. It can generate any desired environment while collecting data on plant growth and improving yields.

NOTE: For this submission, only the 4x3 unit **Standard Extended PeaPod** is in consideration. It has one control module, and eight of each tray (grow and lighting).

PeaPod's control systems are made of environmental controls (feedback loops with sensors) and plant inputs (set-states):

- *Lighting*: LEDs, from near-ultraviolet to near-infrared. Dimmable drivers for precision spectrum and intensity control. Efficient, precise emission spectrum, low heat.
- *Aeroponics*: Reverse osmosis (RO) water is pressurized by a pump (with sensor for safety cutoff), brought to temperature, nutrient-dosed and pH-balanced by Venturi siphons with servo-actuated flow control, and forced through nozzles to generate mist. Runoff water is recycled. Water-efficient (98% less than farming), nutrient-efficient (60% less), no pH/nutrient "feedback" (common in reservoir-based hydroponics), increased root oxygenation [1].
- *Air Thermoregulation*: Leaf zone air temperature is regulated by a thermoelectric heat pump. Fans blow air over heat sinks connected to either face of a Peltier tile to circulate air and dissipate heat. A Proportionate-Integral-Derivative (PID) control system is informed by temperature sensors, and controls the direction and magnitude of the heat transfer. Low complexity, high safety/reliability, easy to automate (bidirectional, precisely dimmable, PID tuning).
- *Humidity Regulation*: Leaf zone humidity is regulated by a dead-zone bang-bang control system informed by humidity sensors.
  - *Humidification*: RO water is supplied to a tank with a fine mesh piezoelectric disc. A controllable driver circuit oscillates the disk, producing water vapour. Easy to automate.
  - *Dehumidification*: A dry silica gel bead cartridge is covered by servo-actuated "shutters" to control dehumidification. Fans draw humid air through a HEPA filter into the desiccant and back into the growth environment. The beads change color to indicate water saturation. The crew is then notified to swap and "recharge" in a standard oven.
- *Aeroponic Water Temperature*: Root zone air temperature is regulated in the same way as the leaf zone system. Exceptions include an aluminum water block (vs internal heat sink and fan) and a single temperature sensor after the block for PID feedback in a flowing system.

- *Gas Composition*: Oxygen and carbon dioxide levels are managed by gas exchange. Input and output ports allow fans to draw air into and out of the system. HEPA filters remove microbes and aerosols, and servo-actuated "shutters" prevent unintended exchange. Gas concentration sensors inform a bang-bang control system for port activation.

Once PeaPod has been assembled, the first step is manual sterilization to prevent microbial growth at high growth environment humidities. Any plant- and food-safe means may be employed (i.e. UV, wipe-down with disinfectant followed by distilled water).

Next is the hookup of power, network, and water reservoir inputs, as well as the filling of the water reservoir (reverse osmosis, nutrient-rich and pH-balanced for crop choice).

PeaPod's operation begins at planting. Seeds are removed from vacuum-sealed storage bags and distributed evenly on mesh media, which is then moistened for germination and placed in the grow tray. The front panel is then closed, sealing the internal environment. Once sprouted, plants may be harvested as microgreens or transplanted to neoprene pucks inside grow cups for further growth.

The desired state of the growth environment is encoded via a standardized set of "environment parameters". The specific values of each parameter for each iteration are stored in a "program". The program is set prior to the start of plant growth, and consists of a set of **actions** (e.g. set red LEDs to 63% power) and **control targets** (e.g. hold air temperature at 22°C) as time-series instructions from the start of planting to the point of harvest (or plant death, in the case of multiple-harvest plants) corresponding to the control systems.

When activated, PeaPod's control systems begin to enact the program. PeaPod will notify crew of any required action, including refilling inputs, cleaning components, and harvesting, as well as "End-of-Program", when all inedible plant matter is disposed of. The process can then be repeated (starting at sterilization).

2 Adherence to Constraints

2.1 Volume

Constraint: *Fits through 1.07m x 1.90m doorway; W < 1.820m, D < 2.438m, H < 2.591m; V<= 2m*^{3}

Standard Expanded PeaPod: 4x3x1 units = 194cm x 146cm x 50+20cm (DIN backplane) = 1.98m^3 (< 2)

2.2 Power

Constraint: *Avg < 1500 W, Peak < 3000 W*

Standard Expanded PeaPod: Two Pumps (120W ea.), 4 Solenoids (36W ea.), LEDs at full power (8.4W per strip), 5 LED strips per grow tray = 849W

2.3 Water Consumption

Unconstrained

Standard Expanded PeaPod: Dependent on watering cycle, 5mL/sec per nozzle @100PSI.

For 10sec watering every 30min: CNet = **20L primed + 0.8L per hour** (without recycling).

2.4 Mass

Standard Expanded PeaPod: **90kg**

2.5 Data Connection

Automation: All of PeaPod's operation is automated, save for a select few setup, maintenance, and harvest tasks. This is controlled by a central computer, which uses a "program" to enact the desired environment at each point in time throughout the plant life cycle. *Remote Control*: The program may be changed instantaneously as an **appended instruction set** with immediate effect. *Feedback*: The feedback sensors provide the computer with information that will influence the control it exerts. For example, if the program indicates the leaf zone temperature should be set to 22 degrees C, the computer would apply greater power to the heater if the current temperature was 18 degrees C as opposed to 21 degrees C. This forms a control loop for each parameter, relying on one of many control functions (bang-bang, PID, etc.).

2.6 Crew Time

Constraint: *4 hrs/week*

For calculations and justification, see preliminary calculations Appendix.

Total setup process time (8 trays, 12 units, 1 CM): **17.5 hours** (*one person*) or **4.5 hours** (*crew of 4*)

Total maintenance time per week: **2 hours** (depending on program)

2.7 Operational Constraints

Constraint: *Terrestrial: gravity (9.81 m/s^2), ambient atmospheric pressure (101,325 Pa), ambient atmospheric temperature (22 °C), ambient atmospheric humidity (50 %RH)*

Design operates in terrestrial conditions.

Ambient pressure: tank, bladder, and nozzle are designed to produce indicated outputs at standard air pressure Ambient temperature and humidity: less concern, housing is sealed and insulated

3 Design Approach and Innovation

Control Range and Parameter Independence

Unlike large-scale vertical farming, PeaPod's isolation and parameter independence lets it simulate any climate. Wide LED spectrum can emit both near-infrared and near-ultraviolet light, important for creating hormonal responses and compounds in plants. Combined with insulation, humidification and dehumidification, and thermoelectric heating/cooling, PeaPod can generate extreme environments and even conditions on other planets (minus gravity and atmospheric changes).

These parameters are independent: e.g., lighting heat is countered by thermoregulation cooling. Also, inline nutrient and pH solution injection eliminates drawbacks of reservoir use by taking less space, less solution mixing time, and avoiding a control loop of nutrients/pH (while also being more accurate).

Form Factor and Extendability

The range of output environments is also possible because of the form factor of a single PeaPod unit. Warehouse-scale vertical farming cannot provide wide-spectrum control due to size—poor insulation and air circulation prohibits extreme temperatures. PeaPod solves this with a small, modular design that enables robust lighting, heating, and cooling systems at home and at scale.

Space savings are a benefit of this feature, as the output of an entire farming or hydroponics setup (requiring a flat field or warehouse) can be spread through unused space (corners, under shelves/desks, etc.) via many small PeaPod setups. This means a large yield can be had without construction, zoning, labour, or any of the other issues accompanying large farming or hydroponic setups.

Optimization

Existing approaches to plant optimization are simple and ineffective, relying on a **fixed/unchanging** environment parameter set and only examining **final** plant metrics. This approach is severely limited, in that it does not account for changes over time.

Instead, statistical model is used which takes into account the cumulative property of growth. By monitoring all environment and plant indicators, repeatable and controlled trials with scientific validity are able to be performed. PeaPod counters declining health/quality indicators in real time, and generates tailored programs that to maximize any metric and target further improvement.

Open-Source Design and Data

Since PeaPod is standard and open-source, units can be had in bulk and assembled by anybody. Public contribution to the project (both in design improvement and data) increases the reliability and safety of the solution. Collected data is, ideally, committed to the public, meaning anybody with a PeaPod can run the same iteration with the same program and species to boost scientific validity, or run a different program to expand PeaPod's knowledge base.

4 Scientific and Technical Merit

5 Feasibility of Design

6 Terrestrial Potential

Agriculture-as-a-Service

PeaPod's modularity and ease of storage can turn unused city spaces to PeaPod farms. With fresh produce in local areas, PeaPod can be a direct food system to paying customers. A subscription service would provide patrons with fresh produce without a middle man. By eliminating transport, distribution, and grocery stores, PeaPod creates fresher, better produce for the general public at a lower cost.

Crowd-Sourced Research

PeaPod's automation is unique in the research space, allowing for autonomous, off-site research. Universities save costs related to space and energy usage by subsidizing PeaPods to individuals, schools, or even restaurants. Users receive sets of parameters to grow crops with, sending data back to the institution and using the produce at the cost of space and energy. The result is a massive dataset from identical conditions in different places, verified by comparison with devices conducting the same tests.

This is an effective tool in climate change famine aid. By predicting conditions in at-risk areas, researchers can conduct tests ahead of time to determine what seeds, traits, and care parameters are most effective for certain conditions. This also informs development of seeds specialized for extreme climates, letting areas counteract food scarcity by having a variety of options prepared ahead of time.

De-centralized Production

Many crops are endemic to certain climates, making global transport necessary to for foreign markets. This reduces freshness, necessitates preservatives, and increases the carbon footprint of agriculture. By upscaling PeaPod technology to a farm scale, climate-bound crops can be produced anywhere. This creates regional farms of global variety, making it easier to have a local food diet.

PeaPod's form factor makes it a viable tool for at-home production, either in cities or off-grid. With only a solar power source, water, and a compact supply of nutrient solutions, users can sustain crops even through winter without travelling for nutrients and supplies.

Food Infrastructure Micro-Loans

For many, finding fresh produce is a struggle whilst growing your own is prohibitively expensive. Micro-loan platforms have attempted to solve this by letting donors fund an interest-free loan for technology/infrastructure which then pays the loan as a percentage of its surplus.

Unfortunately, these are only feasible for individuals in rural areas with arable land and climate.

PeaPod brings this solution to low-income urban areas with a platform for donors to micro-loan PeaPod units and inputs. The user feeds themselves and sells surplus, while a percentage of sales go to the interest-free loan. Once paid, PeaPod continues to produce food while sales fund its operation.

This creates permanent, self-sustaining agricultural infrastructure that pays for itself as it grows, requiring little initial capital. This means entire farms throughout high density buildings generating yield with little lost space and almost no labour.

7 Results

7.1 Acceptability of Process

Footprint:

Due to PeaPod's modular construction, the footprint can vary. For a Standard Extended PeaPod, the footprint would be 2m x 0.5m, or about three standing refrigerators. When stowed, volume is reduced to 37% of when assembled. Control module is packed pre-assembled.

The following estimates are for a Standard Extended PeaPod.

Setup Process:

1. Assemble housing - **2 hours**
2. Install control module(s):
   (a) Hook up water, power, and network inputs - **5 min**
   (b) Fill nutrient and pH adjustment solution containers - **10 min**
   (c) Mount CM to housing - **5 min**
3. Assemble all trays - **1 hour**,
4. For each tray, either:
   (a) Mount lighting boards and driver, daisy chain boards to driver, hook up power and signal to driver and CM - **10 min** per tray, **OR**
   (b) Mount aeroponic nozzle mount and arm, hook up water delivery line to nozzles and CM - **10 min** per tray
5. UV sterilization - **20 min**
6. Prepare and plant seeds for desired crop output, seal growth environment - **30 min**
7. Enable primary power supply, and power on automation system, allow to perform self-test and calibrations - **10 min**
8. Open water input shutoff valve
9. Input program for required environments and activate - **5 min**

Total setup process time (Standard: 2 trays per unit, 12 units, 1 CM): **8.5 hours** (*one person*) or **2.5 hours** (*crew of 4*)

Food Production Cycle:

1. Environment is maintained, and environment can be observed live at a computer terminal via sensor data and camera feed
2. Circulation fans enable automated pollination
3. Perform maintenance, including:
   - Cleaning nozzle once a month - **10 min**
   - Swapping and recharging dehumidification cartridges when instructed - **5 min** (active time)
   - Refilling solution containers when instructed - **5 min**
4. Upon End-Of-Program (EOP) notification, the gas exchange system will conduct a "full equalization flush", bringing the internal environment in equilibrium with the surroundings. Users will harvest and store food products (or prepare and consume them immediately, varying time) - **15 min**
5. All organic material remaining in the system is removed and disposed of, presence of residue or algae is determined - **10 min**
6. If algae present, hydrogen peroxide is used to kill the growth - **5 min**
7. (Optional) In event of significant contamination, system can be flushed with an all-purpose surface disenfectant and then rinsed with distilled water - **10 min**
8. Upon End-Of-Life notification (may occur at the same time as EOP), the plant is scrapped (**15 min**), and new plants may be planted

Total maintenance time per week: **1-2 hours** (depending on program)

Process Evaluation:

Setup and maintenance processes are fully documented in a "User Manual", which includes both text instructions (with numerical specifications for different actions) as well as diagrams for reference. Notifications from computer refer users to specific subsections of the Manual for maintenance actions. All processes require no specific expertise, just the ability to operate basic hand tools and follow instructions.

All interactions with the automation system (i.e. program upload, environment/camera monitoring) can be accomplished either via a touchscreen panel on the front of the control module or over the Internet.

7.2 Acceptability of Product

There are several considerations when examining the acceptability of the products of our system:

1. Produce is not only eaten fresh, but also forms the basis for an innumerable variety of combined and prepared foods (i.e. fresh tomatoes vs. tomato sauce);
2. When considering prepared derivatives of the food products, the quality of the preparation is a key factor in acceptability. As such, proper care in training and is to be taken;
3. The products formed by the system (and their properly prepared derivatives) are not exceptional or novel. They are the same plant-based foods grown, consumed, and **accepted** terrestrially, just grown in a more efficient and controlled way. As such, their acceptability is determined to be of **equal or greater value**;

4. Plant-environment optimization can be targeted not only at nutritional value or efficiency, but also at acceptability. The feedback can be gathered either through crew Hedonic rating (i.e. tomatoes grown in environment ABC rate X in appearance, Y in aroma, etc.) or more sophisticated analysis (i.e. computer vision analysis of color/size/shape for appearance, tissue concentrations of various aroma/flavor compounds);

8 Safety

9 Testing Plan

9.1 Acceptability of Outputs

9.1.1 Testing Procedure

Tested via blind studies where participants are divided into two groups and given either control outputs (i.e. established commercial product) or test outputs (i.e. produced by PeaPod). Participants will rate outputs on 4 criteria (appearance, aroma, flavour, and texture) on a 9-point scale.

To simulate acceptability over a long period of time, it will be important to study outputs with consideration for how the subjects will interact with them. This includes varying preparation methods (fresh, cooked, dehydrated, etc.) and preparing combinations of foods both purely with PeaPod outputs and with external foods that would be available in the field.

Blind studies are eminent in consumer testing as they allow researchers to get a completely unbiased dataset. Special care needs to be taken when presenting, preparing, and collecting samples for testing to ensure researchers do not influence results. Ideally, resources will permit a double-blind study where researchers hire an outside entity to conduct the test and return results with generic labels.

The 9-point scale originates from U.S. Army testing, where it was developed using language which has roughly equal psychological distances between points on the scale. While the use of 9 points is otherwise arbitrary, there exists a large history of research validating its analytical use in long-term food production [2].

1382 Characters (Maximum 4000)

9.1.2 Sample Collection Schedule

To test acceptability of a long-term food solution, it is important to test the entire spectrum of output quality at a good-faith approximation of its distribution. This means instead of testing 'good' control outputs against 'good' PeaPod outputs, we will need to test batches of control outputs (at a naturally-arising quality distribution) vs. batches of PeaPod outputs (again, at a quality distribution). This allows for holistic comparison of the technology's performance as well as end user experience as opposed to specific comparison of individual items.

To employ statistical analysis, a sample size of at least $n = 30$ will be collected for each crop, with the collection time dependent on the crop. For initial tests, crops will be collected at a developmental stage roughly equivalent to control crops purchased at a store. For further tests, the crops can be collected at the point PeaPod's analytical tools determine is optimal. Packaging and shipping will be done according to existing best practices, with care to package more than necessary as a factor of safety.

1079 Characters (Maximum 4000)

9.2 Safety of Process and Outputs

9.2.1 Testing Procedure

Given the environment in which PeaPod will operate, process safety will be developed on the foundation of prevention. This is because crisis response and containment is severely limited in the confines of space: identification often requires propagation of the threat (i.e. incubation of potential pathogens for colony count), and quarantine is more difficult and loses a larger proportion of food than it does on Earth.

This begins pre-flight, as all materials - especially biological - are sanitized, tested, and packaged in isolation so a breach contaminates as little product as possible. Once everything is installed in the field, the design principles of the entire system take over as methods of prevention. By employing key design principles such as minimal interaction, PeaPod mitigates the introduction of foreign substances and, in turn, the ingress of potential threats. Interaction will only occur at times of harvest and planting, which double as times of cleaning and sanitation.

For testing the UX of the processes, using established space station procedures, subjects will harvest and clean product, clean all surfaces, sanitize all surfaces, and plant surface-sterilized seeds.

As for non-biological threats such as heavy metals or other toxins, careful selection and sourcing of construction materials will eliminate most threats to the system. As a regular maintenance measure, flushing of the water and air supplies through the space station's recycling system will prevent buildup by keeping them up to external standards.

Chemical Hazards
As part of PeaPod's design principle regarding prevention, all sourcing of parts and resources has been done with inherent, chemical threats in mind (lead-free solder and electronic components, food-safe fittings and parts for aeroponics, etc.). As a result, the default construction of the unit poses no threat for chemicals or other toxins to enter the biological system or its surroundings.

The other source of potential threats is during crew interaction steps when they harvest, clean, sanitize, and plant. To protect against hazards, PeaPod's maintenance steps follow carefully designed HACCP protocols and use food-safe cleansers and sanitizers.

Biological Hazards
There are no biological hazards inherent to the PeaPod system. Plant species selection should be performed carefully to ensure safety according to mission requirements.

Aerobic Plate Count (APC) testing to be done with the Conventional Plate Count Method outlined by the FDA [3]. This is selected over the Spiral Plate Method as it is inexpensive and uses many household materials. The goal of APC testing is to indicate the bacterial population in food-adjacent sections of the design. Results to be compared against STD-3001 to ensure a maximum of 3000 colony forming units/square ft. Colony forming units appear as distinct "blobs" of bacteria on a growth material, indicating the relative abundance of viable bacteria on a given surface.

Food Outputs

APC testing conducted on samples as outlined for biological hazards to ensure bacterial population below 20 000 CFU/g per STD-3001. *Enterobacteriaceae* have a population limit of 100 CFU/g per STD-3001, and can be tested via a rapid test such as the MicroSnap EB. Similarly, testing for salmonella will be performed using a rapid detection kit to ensure a population of 0 CFU/g. Finally, testing for yeasts and molds will be performed with a testing kit to to ensure a population count below 1000 CFU/g.

Given the wide use cases for crops (raw/dried, cut/whole, fresh/preserved) it will be important to conduct tests on each use case to see if results remain acceptable. For example, higher surface area crops are intrinsically more susceptible to bacterial growth per gram. So, crops prior to testing will be processed in the same way they would be before consumption in order to validate realistic operating conditions.

By-Product Outputs By-product outputs fall into two cateogries, air exhaust and inedible matter. Air will be filtered and dehumidified to ambient levels by the gas exchange system, ensuring it is safe for the local environment. Inedible matter will be tested in the same way as food outputs to ensure threats are not present in the system at all. Further threats would arise in the processing of by-products should they be used as a nutrient source in successive cycles. If this process is implemented, new testing procedures will be developed for it. Otherwise, threats are mitigated by disposal in the same manner as other biological substances such as human waste.

4036 Characters (Maximum 4000)

9.2.2 Sample Collection Schedule

Safety testing will be conducted in tandem with collection of samples for acceptability, with key metrics being measured as successive rounds of crops are collected. Beyond number and size of samples, it will be critical to follow operating procedures as closely as possible. This is because of its two-fold interaction with crop quality and safety. The only deviation will be the measuring of metrics such as CFU count, as this is safe to do on Earth conditions.

Regardless of test results, crop collection will continue to see if the design's mitigation strategies are effective. For example, if Harvest 2 has allowable but present levels of *Enterobacteriaceae*, it is important to see if it persists to Harvests 3 and 4 or if standard cleaning procedures manage to eliminate it.

Then, over the course of 30 or so harvests, the presence of hazards can be charted as a function of harvest number and cleaning cycles, allowing patterns to emerge and weaknesses to be found for long-duration missions. Testing for these hazards will be in line with the list above: bacteria via APC, organic residue via ATP testing, and chemical hazards via water supply analysis. Water supply testing is straightforward, with an abundance of commercial test strips available to identify any given substance.

1172 Characters (Maximum 4000)

9.3 Resource Outputs

9.3.1 Testing Procedure

Personally testing nutritional makeup of outputs is far beyond the resources and scope of this project. Instead, a variety of outputs will be produced and shipped to an external, ISO-17025 certified lab such as SGS Canada for testing.

While this is useful for validation on Earth, it fails to address the issue of analysis at time of harvest. To tackle this, PeaPod will use data collected on Earth-bound trials in combination with lab analysis and existing datasets to develop a way of predicting crop quality during the growing process. By applying algorthmic prediction, we can optimize resource output efficiency by, for example, marking crops that show early signs of failure for replacement. This helps maximize the output to input ratio by cutting losses earlier and with less labour cost than people would be able to.

826 Characters (Maximum 4000)

9.3.2 Sample Collection Schedule

The number of days required for sample collection is entirely dependent on what sample is being produced. For one-time growth products, such as carrots or lettuce, the days required is exactly the time to harvest of the plant. Size of collection is dependent on how many units are run at the same time. For plants that produce products multiple times, such as beans or tomatoes, samples should be collected after each production cycle. This means the time required to collect n samples is C + n*X, where C is the initial growth period of the plant and X the time between harvests. It is important to collect multiple subsequent harvests in order to see the relationship between this and produce quality.

Packaging and shipping will be done according to freight standards of the carrier being used, such as [4].

824 Characters (Maximum 4000)

9.4 Reliability and Stability of Outputs

9.4.1 Testing Procedure

PeaPod's outputs are fresh produce, and as such are intended for consumption as soon as possible after harvest and preparation. Any product not immediately consumed post preparation should be stored in an airtight package and kept below 12.5°C to prolong shelf life and maintain acceptability. Certain products of PeaPod have the possibility of being dehydrated to further increase their shelf life.

To mitigate the need for long duration food storage, growth cycles should be staggered to periodically supply fresh produce when astronauts are ready to eat.

558 Characters (Maximum 4000)

9.4.2 Sample Collection Schedule

Collection time is not a critical variable for this test, however safe storage time is. To quantify it, a variety of outputs can be compared to their control equivalents to identify any disparities in shelf life—be it raw, dehydrated and cooled, or airtight and cooled.

The number of cycles necessary to complete testing will be equivalent to the number of items tested. Each of these three storage methods should be tested for a variety of plant species and yield types over a number of trials to minimize randomness.

Criteria for shelf life will include acceptability as a function of time, quantity/existence of bacteria, and the relationship between crew time and quality of output.

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9.5 Additional Comments

9.6 Materials

As of May 31st, any false or absent entries are as a result of design and/or prototype incompleteness.

9.6.1 System

For a 4x3 extended topology with two control modules:

- 2x Control Module, each comprises:
  - 1x Automation (Tables 17, 2)
  - 1x Aeroponics Supply (Tables 10, 9)
- 12x Housing, each comprises:
  - 1x Housing Shell (Tables 3, 4)
  - 1x Grow Tray, each with:
    - 1x Grow Tray Frame (Tables **??**, 6)
    - 1x Aeroponics Watering System (Tables 11)
  - 1x Lighting Tray (Tables 7, 8)

Automation

Part	Description	Quantity	Supplier	Part Number
Motherboard PCB	2 Layers, HASL Finish (Lead-Free)	1	JLCPCB	-

Table 1: Automation subsystem parts.

Part Number	Manufacturer	Description	Quantity
A000005	Arduino	Arduino Nano ATMega328	1
S404GSEJ6-U3000-3	Delkin Devices, Inc.	4GB MicroSD	1
61304021121	Würth Elektronik	Male Header Pins 40POS	1
SC0510	Raspberry Pi	Raspberry Pi Zero 2 W	1
DMN2005K-7	Diodes Incorporated	MOSFET N-CH 20V 300mA	2
RC0603FR-0710KL	YAGEO	Res 10K Ohm 1/10W	5
4484	Adafruit Industries LLC	1.3" TFT Screen	1
5055670271	Molex	Molex Micro-Lock PLUS 2pos	2
5055670471	Molex	Molex Micro-Lock PLUS 4pos	5
5055670871	Molex	Molex Micro-Lock PLUS 8pos	3
5055670681	Molex	Molex Micro-Lock PLUS 6pos	3

Table 2: Automation system electronic components.

Housing

Shell

Part	Description	Quantity	Supplier	Part Number
Control Module Housing	5-Sided Enclosure	1	Protocase	-
Frame Front X	20x20mm, Cut to 500mm	2	McMaster-Carr	5537T101
Frame Door Y	20x20mm, Cut to 500mm	2	McMaster-Carr	5537T101
Frame Rear X	20x20mm, Cut to 460mm	2	McMaster-Carr	5537T101
Frame Door X	20x20mm, Cut to 460mm	2	McMaster-Carr	5537T101
Frame Rear Y	20x40mm, Cut to 460mm	2	McMaster-Carr	5537T111
Frame Front Y	20x20mm, Cut to 460mm	2	McMaster-Carr	5537T101
Frame Z	20x20mm, Cut to 460mm	4	McMaster-Carr	5537T101
Foam Insulation	GPS, 4' x 8' x 1"	1	Home Depot	1001211234
Reflective Laminate	27" x 12' x 0.002"	1	McMaster-Carr	7538T11
Adhesive	LePage PL300 Foamboard	2	Home Depot	1000403469
Door Hinges	Plastic, Black	2	McMaster-Carr	5537T85
Feet Bumpers	Adhesive-Back	4	McMaster-Carr	95495K24
M5x0.8 10mm Bolts	Alloy Steel, Socket Head Cap	44	McMaster-Carr	91290A224
M5 T-Nuts	Zinc-Plated Steel	44	McMaster-Carr	5537T651

Table 3: Housing shell parts.

Part	Quantity	Materials	Process
L Bracket	8	PETG Filament	3D Printing
T Bracket	4	PETG Filament	3D Printing
Feet	4	PETG Filament	3D Printing

Table 4: Housing shell fabricated parts.

Grow Tray

Part	Description	Quantity	Supplier	Part Number
Tray X	20x20mm, Cut to 440mm	2	McMaster-Carr	5537T101
Tray Z	20x20mm, Cut to 400mm	3	McMaster-Carr	5537T101
Nozzle Arm	20x20mm, Cut to 150mm	2	McMaster-Carr	5537T101
M5x0.8 10mm Bolts	Alloy Steel, Socket Head Cap	25	McMaster-Carr	91290A224
M5x0.8 16mm Bolts	Alloy Steel, Socket Head Cap	20	McMaster-Carr	91290A232
M4x0.7 16mm Bolts	Alloy Steel, Socket Head Cap	12	McMaster-Carr	91290A154
M4x0.7 Hex Nuts	High-Strength Steel	12	McMaster-Carr	94166A110
M5 T-Nuts	Zinc-Plated Steel	35	McMaster-Carr	5537T651
M5x0.8 Hex Nuts	Alloy Steel	2	McMaster-Carr	94166A120
Grow Cup	2" Diameter	16	Amazon	

Table 5: Grow tray frame parts.

Part	Quantity	Materials	Process
L Bracket (Grow Tray)	4	PETG Filament	3D Printing
Diagonal Bracket	4	PETG Filament	3D Printing
T Bracket	4	PETG Filament	3D Printing
Tray Hook BL	1	PETG Filament	3D Printing
Tray Hook BR	1	PETG Filament	3D Printing
Tray Hook FL	1	PETG Filament	3D Printing
Tray Hook FR	1	PETG Filament	3D Printing
Grow Plate Quarters	4	210x210x5mm PET Sheet	Table Saw
Grow Plate Washer	1	PETG Filament	3D Printing
Nozzle Mount A	2	PETG Filament	3D Printing
Nozzle Mount B	2	PETG Filament	3D Printing

Table 6: Grow tray fabricated parts.

Lighting Tray

Part	Description	Quantity	Supplier	Part Number
Tray X	20x20mm, Cut to 440mm	2	McMaster-Carr	5537T101
Tray Z	20x20mm, Cut to 400mm	3	McMaster-Carr	5537T101
M5x0.8 10mm Bolts	Alloy Steel, Socket Head Cap	24	McMaster-Carr	91290A224
M5x0.8 16mm Bolts	Alloy Steel, Socket Head Cap	12	McMaster-Carr	91290A232
M4x0.7 16mm Bolts	Alloy Steel, Socket Head Cap	12	McMaster-Carr	91290A154
M4x0.7 Hex Nuts	High-Strength Steel	12	McMaster-Carr	94166A110
M5 T-Nuts	Zinc-Plated Steel	36	McMaster-Carr	5537T651

Table 7: Lighting tray frame components.

Part	Quantity	Materials	Process
L Bracket	4	PETG Filament	3D Printing
T Bracket	2	PETG Filament	3D Printing
Tray Hook BL	1	PETG Filament	3D Printing
Tray Hook BR	1	PETG Filament	3D Printing
Tray Hook FL	1	PETG Filament	3D Printing
Tray Hook FR	1	PETG Filament	3D Printing
Lighting LED Board Mount	5	PETG Filament	3D Printing
Lighting Power Board Mount	1	PETG Filament	3D Printing

Table 8: Lighting tray frame fabricated parts.

Aeroponics

All parts are rated for over 100PSI.

Supply

Part	Description	Quantity	Supplier	Part Number
3/8" ID Tubing	1/2" OD, 10', PET	1	McMaster-Carr	1979T3
1/4" OD Tubing	1/8" ID, 25', PET	1	McMaster-Carr	1979T4
PTFE Tape	1/2" x 21' Roll, White	1	McMaster-Carr	4934A14
SAE #6 Hose Clamp (Pack of 10)	7/32" to 5/8", Steel	1	McMaster-Carr	5415K11
Bonded O-Rings for 1/2 BSPP	Nitrile Rubber and Steel	5	McMaster-Carr	50915K816
Grip-Lock Socket to 1/2 MPT	Zinc-Plated Steel	1	McMaster-Carr	6539K37
Grip-Lock Plug to 1/2 MPT	Zinc-Plated Steel	1	McMaster-Carr	6539K67
Shutoff Valve	Brass, 1/2 FPT	2	McMaster-Carr	47865K23
1/2 MPT to 3/8" Barb	Brass	1	McMaster-Carr	2838N23
Diaphragm Pump	4.1L/min @80PSI	1	Amazon	
3/8 MPT to 3/8" Barb	Aluminum	1	McMaster-Carr	5357K37
1/2 FPT to 3x 3/8 FPT Manifold	Aluminum, Heat Block	1	McMaster-Carr	3491N13
3/8 MPT Manifold Plug	Aluminum	2	McMaster-Carr	3867T364
1/2 MPT to 3/8" Barb	Aluminum	1	McMaster-Carr	5357K38
3/8 MPT to 3/8" Barb	Brass	1	McMaster-Carr	2838N22
3/8 FPT Elbow	Brass	2	McMaster-Carr	50785K37
3/8 MPT to 6 1/4" Push Connect	Solution Manifold	2	McMaster-Carr	5203K956
1/4" Push Connect Tee	Plastic	6	McMaster-Carr	5111K528
1/4" Push Connect Plug	Plastic	6	McMaster-Carr	5111K504
3/8 NPT Right-Angle Tee	Brass	1	McMaster-Carr	50785K223
1/2 FPT to 3/8 MPT Adapter	Brass	1	McMaster-Carr	50785K29
Accumulator Tank	0.75L	1	Amazon	
1/2 FPT to 1/2 M BSPP Adapter	Brass	1	McMaster-Carr	1786N138
1/2 BSPP Tee	Brass	1	McMaster-Carr	9151K272
1/2 BSPP Nipple	Brass	1	McMaster-Carr	9151K375
1/2 F BSPP to 1/2 MPT Adapter	Brass	1	McMaster-Carr	50785K608
1/2 FPT to 1/4" OD Compression	Brass	1	McMaster-Carr	51875K14

Table 9: Aeroponics supply parts.

Part Number	Manufacturer	Description	Quantity
SEN0257	DFRobot	Water Pressure Sensor	1
GE-2158	Amphenol Thermometrics	Water Temperature Sensor	1
996	Adafruit Industries LLC	Solenoid Valve	1
114991171	Seeed Technology Co., Ltd	Water Flow Sensor	1

Table 10: Aeroponics supply electronic components.

Watering System

Part	Description	Quantity	Supplier	Part Number
1/4" Compression Quick-Disconnect	Plastic	2	McMaster-Carr	5012K122
1/4" Push Connect 1/8 MPT Inline Tee	Plastic and Brass	1	McMaster-Carr	51235K147
1/4" Push Connect to 1/8 MPT Elbow	Plastic and Brass	1	McMaster-Carr	51235K127
1/8 FPT Straight Coupling	Brass	2	McMaster-Carr	50785K91
80-Degree Full-Cone Misting Nozzle	Brass, 1/8 MPT	2	McMaster-Carr	3178K75
Dyneema Composite	1.43oz, 0.5x1.5yd	3	Ripstop by the Roll	
Dyneema Pressure-Sensitive Adhesive	1/2" x 15’	3	Ripstop by the Roll	
Drawstring	Nylon Cord, 25’	1	McMaster-Carr	3696T38
Drawstring Lock	Slide-Release	1	McMaster-Carr	3734T4

Table 11: Grow tray watering system parts.

Dosage Pump

Part	Description	Quantity	Supplier	Part Number
M4x0.7 16mm Bolts	Alloy Steel, Socket Head Cap	4	McMaster-Carr	91290A154
M4x0.7 4mm Bolts	18-8 Stainless, Socket Head Cap	2	McMaster-Carr	91292A023
Nylon Washer	Lubricated, 15mm x 28mm	2	McMaster-Carr	91545A510
Ball Bearing	Sealed, Stainless Steel	3	McMaster-Carr	6138K65
3/16" OD Tubing	1/16" ID, 10’, Tygon PVC	1	McMaster-Carr	6516T62

Table 12: Dosage pump parts.

Part	Quantity	Materials	Process
Pump Body Lower	1	PETG	3D Printing
Pump Body Upper	1	PETG	3D Printing
Pump Roller Lower	1	PETG	3D Printing
Pump Roller Upper	1	PETG	3D Printing

Table 13: Dosage pump fabricated parts.

Part Number	Manufacturer	Description	Quantity
918	Adafruit	12V Geared Stepper Motor	1

Table 14: Dosage pump electronic components.

Thermoregulation

Leaf-Zone Heat Pump

Incomplete. Missing: heat sink.

Part Number	Manufacturer	Description	Quantity
CP854345H	CUI Devices	77W Peltier, 8.5A	1
2857	Adafruit Industries LLC	Humidity & Temperature Sensor	2
FAD1-12025CBHW12	Qualtek	12VDC Axial Fan	2

Table 15: Leaf-zone heat pump electronic components.

Root-Zone Heat Pump

Incomplete. Missing: heat sinks.

Part Number	Manufacturer	Description	Quantity
CP854345H	CUI Devices	77W Peltier, 8.5A	1
FAD1-12025CBHW12	Qualtek	12VDC Axial Fan	1

Table 16: Root-zone/aeroponics heat pump electronic components.

Driver Board

Part	Description	Quantity	Supplier	Part Number
Thermoelectric Driver PCB	2 Layers, HASL Finish (Lead-Free)	1	JLCPCB	-

Table 17: Thermoelectric driver parts.

Part Number	Manufacturer	Description	Quantity
2N6388G	onsemi	NPN Darlington 80V 10A	1
LM324N	Texas Instruments	OPAMP 4-circuit	1
0436450200	Molex	Molex Micro-Fit 2pos	1
0436500201	Molex	Molex Micro-Fit 2pos	1
0462355002	Molex	20-24AWG Crimp	2
G5LE-14 DC3	Omron Electronics Inc	Relay SPDT 10A 3V	2
MMBT2222A-7-F	Diodes Incorporated	NPN 40V 0.6A	4
5055670681	Molex	Molex Micro-Lock PLUS 6pos	1
KLDX-0202-A-LT	Kycon, Inc.	Barrel Jack	1
KLDX-PA-0202-A-LT	Kycon, Inc.	Barrel Jack	1
RC0402JR-0710KL	YAGEO	Res 10k Ohm 5% 1/16W	5
CL05A104KA5NNNC	Samsung Electro-Mechanics	Cap Cer 0.1uF 25V X5R	1
RC0402JR-071KL	YAGEO	Res 1k Ohm 5% 1/16W	4
RC0402FR-071M6L	YAGEO	Res 1.6M Ohm 1% 1/16W	1
RNCP0805FTD20R0	Stackpole Electronics Inc	Res 20 Ohm 1% 1/4W	2
RC0402FR-07100KL	YAGEO	Res 100k Ohm 1% 1/16W	1
RC0402FR-07200KL	YAGEO	Res 200k Ohm 1% 1/16W	1

Table 18: Thermoelectric driver electronic components.

Humidification
Incomplete. Missing: Humidification driver PCB, driver components, piezoelectric mesh nebulizer disc, water tank.

Dehumidification
Incomplete. Missing: Housing parts, shutters and servos, cartridge parts.

Part Number	Manufacturer	Description	Quantity
FAD1-12025CBHW12	Qualtek	12VDC Axial Fan	2
1334	Adafruit Industries LLC	Color Sensor	1

Table 19: Dehumidification electronic components.

Part	Description	Quantity	Supplier	Part Number
Indicating Desiccant	Silica Gel, 6%, Blue to Pink, 1lb	1	McMaster-Carr	2181K93
Air Filter	PET, MERV 13, 0.3 micron, 10" x 10"	2	McMaster-Carr	3881T101

Table 20: Dehumidification parts.

Gas Composition Regulation and Exchange
Incomplete. Missing: Housing parts, shutters and servos.

Part Number	Manufacturer	Description	Quantity
FAD1-12025CBHW12	Qualtek	12VDC Axial Fan	2

Table 21: Gas exchange electronic components.

Part	Description	Quantity	Supplier	Part Number
Air Filter	PET, MERV 13, 0.3 micron, 10" x 10"	2	McMaster-Carr	3881T101

Table 22: Gas exchange parts.

Lighting

Part Number	Name	Description	Quantity
0451110600	Molex	MicroLock PLUS Cable 6pos 50mm	2
0451110605	Molex	MicroLock PLUS Cable 6pos 450mm	4

Table 23: Lighting subsystem cables.

Part	Description	Quantity	Supplier	Part Number
Lighting LED PCB	2 Layers, HASL Finish (Lead-Free)"	5	JLCPCB	-
Lighting Driver PCB	2 Layers, HASL Finish (Lead-Free)"	1	JLCPCB	-

Table 24: Lighting subsystem PCBs.

Driver Board

Part Number	Manufacturer	Description	Quantity
LDD-500HS	MEAN WELL USA Inc.	0-500mA Constant-Current LED Driver	5
5055670681	Molex	Micro-Lock PLUS 6pos	3
KLDX-PA-0202-A-LT	"Kycon, Inc."	Barrel Plug	1
KLDX-0202-A-LT	"Kycon, Inc."	Barrel Jack	1
RC0402JR-0710KL	YAGEO	Res 10k Ohm 1/16W	5

Table 25: LED driver electronic components.

LED Board

Incomplete. Missing: UV LEDs.

Part Number	Manufacturer	Description	Quantity
XPGDRY-L1-0000-00501	CreeLED, Inc.	Royal Blue LED (451nm)	3
XPGDWT-01-0000-00ME2	CreeLED, Inc.	Cool White LED (5700K)	3
XPGDWT-H1-0000-00GE8	CreeLED, Inc.	Warm White LED (2700K)	3
XPGDPR-L1-0000-00F01	CreeLED, Inc.	Photo Red LED (645nm)	3
XPEBFR-L1-0000-00701	CreeLED, Inc.	Infrared LED (730nm)	3
5055670681	Molex	Molex Micro-Lock PLUS 6pos	2

Table 26: LED board electronic components.

9.6.2 Inputs

Supply Inputs

- *Water*: reverse-osmosis, ambient
- *Power*: 120V 60Hz AC[1]
- *Network*: ethernet or wireless, optional
- *Air Intake*: cabin air, filtered

Consumable Inputs

- *Nutrient/pH Adjusment Solutions*: powder form, vacuum-sealed pouches, specific compound makeup is variable to suit mission requirements
- *Desiccant Cartridge*: recharged
- *Seeds*: cleaned and disinfected, vacuum-sealed

9.6.3 Outputs

Food Outputs
All food outputs are plant matter (leaves, fruits, roots, seeds, etc. dependent on species/preparation method). Species selection is variable to suit mission requirements.

By-Products & Waste

- *Air Exhaust*: filtered, vented to onboard dehumidification and recirculation
- *Seeds/Clones*: harvested, cleaned, and stored for replanting
- *Inedible Plant Matter*: disposed of

9.6.4 Maintenance

Spare Components
Spares for each component (parts, fabricated parts, assembled PCBs) should be included.

Tools
For part replacement, a basic hand tool set (hex keys, screwdrivers, adjustable wrench, pipe wrench, utility knife) should be included. For automation debugging, a USB keyboard and mouse should be included. For all electronics, basic rework tools (soldering iron, lead-free solder, wire strippers, etc.) can be included.

9.6.5 Cleaning

Soaps
Single-use sterile polyester wipes soaked in a dilute solution of food-safe mild soap (such as SunSmile Fruit & Vegetable Rinse from Sunrider [5]) and used.

Disinfectants
Single-use sterile polyester wipes soaked in a dilute solution of food-safe disinfectant (such as those used currently on the ISS, see below) are used.

[1] The power supply can be altered to suit a variety of power inputs (i.e. DC)

Compound	Composition
Octyl Decyl Dimethyl Ammonium Chloride	0.0399%
Dioctyl Dimethyl Ammonium Chloride	0.01995%
Didecyl Dimethyl Ammonium Chloride	0.01995%
Alkyl Dimethyl Benzyl Ammonium Chloride	50% C14, 40% C12, 10% C16
Dimethyl Benzyl Ammonium Chloride	0.0532%

Table 27: Disinfectant solution compound breakdown [6].

10 Hazard Analysis and Critical Control Point (HACCP) Plan

10.1 Food Production System Description

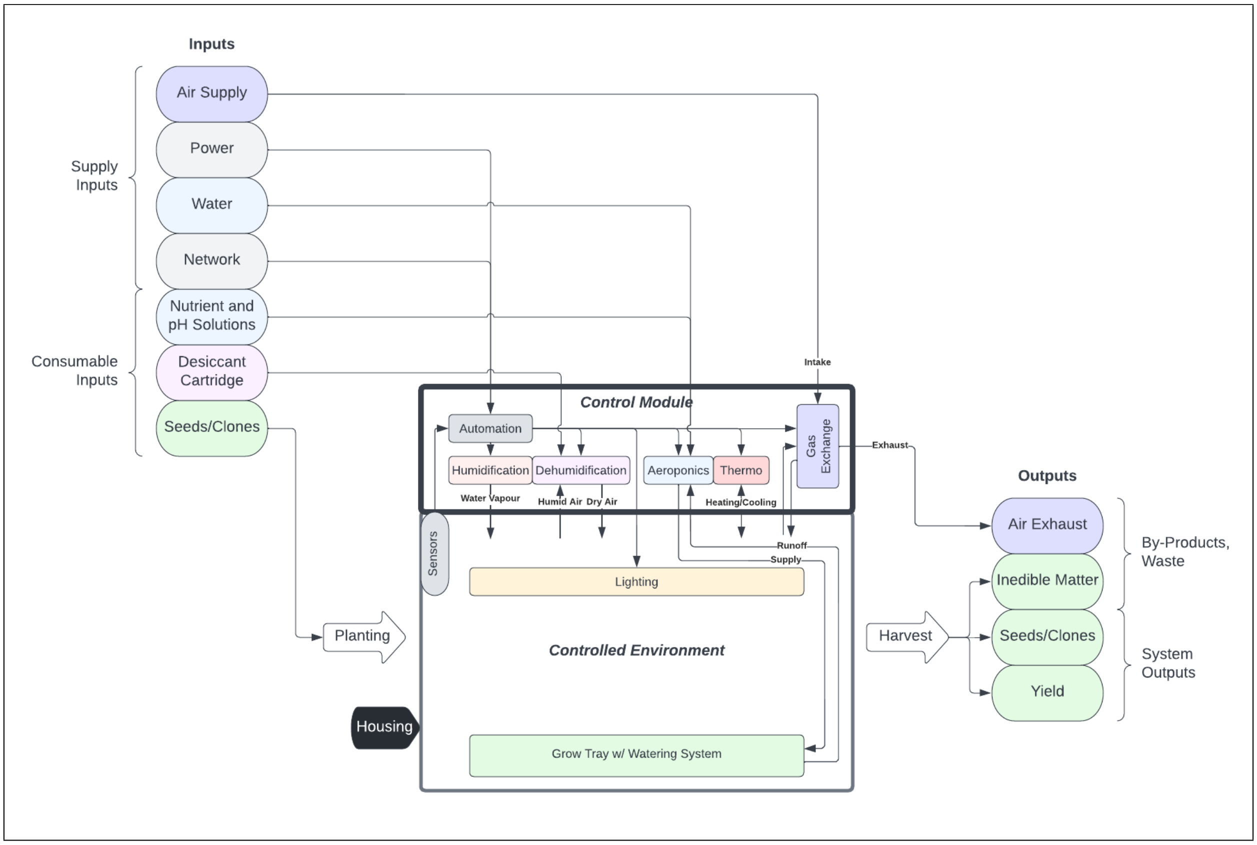

Figure 1: System overview.

10.1.1 Hazard Analysis: Crew Contact (Harvesting, Cleaning, Maintenance)

Source		Crew contact with system during harvesting, cleaning, and maintenance
Identification		Pathogens (bacteria, fungi, viruses) transferred from crew to system
Evaluation	*Severity*	Transfer of biological pathogens onto system surfaces has the potential to infect crops, posing a hazard to crew health during harvesting and ingestion.
	Likelihood	Fungi and viruses are of very low probability, as they cannot live on surfaces. Human gut bacteria (i.e. E. coli) is of low probability, as crew sanitation procedures are well-established.
	CCP?	The HACCP team determines that the risks of cross-contamination or infection are very low. Crew sanitation practices (especially prior to system interaction), practices that minimize system interaction, and sanitizing food outputs prior to consumption are adequate to control this potential hazard.

Table 28: Hazard analysis: pathogens transferred from crew to system.

Source		Crew contact with system during harvesting, cleaning, and maintenance
Identification		Pathogens (bacteria, fungi, viruses) transferred from system to crew
Evaluation	*Severity*	Biological pathogens present in system materials have the potential to infect crew during interaction.
	Likelihood	All pathogens are of moderate probability, as they can be present in infected seeds (and thus food products at the time of ingestion). However, there are no known instances of plant-borne pathogens infecting humans. Bacteria can also be present on all surfaces.
	CCP?	The HACCP team determines that the risks of infection are low. However, for the sake of maximizing yield acceptability and consistency, care should be taken in seed sanitization. This, along with system sanitation practices (both pre-flight and during harvest) and practices that minimize system interaction, are adequate to control this potential hazard.

Table 29: Hazard analysis: pathogens transferred from system to crew.

<table>
<tr><td colspan="2">Source</td><td>Crew contact with system during harvesting, cleaning, and maintenance</td></tr>
<tr><td colspan="2">Identification</td><td>Chemical hazards to crew (i.e. heavy metals, process chemicals) introduced by system</td></tr>
<tr><td rowspan="3">Evaluation</td><td>Severity</td><td>Heavy metals (i.e. lead) and chemicals introduced during manufacturing pose a threat to crew health, either during system interaction or food product ingestion. In addition, process chemicals (i.e. acidic/ basic solutions) can pose a hazard either through physical contact or accidental ingestion.</td></tr>
<tr><td>Likelihood</td><td>Heavy metals are of low probability, but may be present in trace amounts in components (i.e. plumbing, electronics) and thus may come either in direct physical contact with crew(i.e. during maintenance) or be present in food products (i.e. uptake via water supply).</td></tr>
<tr><td>CCP?</td><td>The HACCP team determines that the risks of heavy metal ingestion are low. All electronics, circuit boards, solder, plumbing fittings, are certified lead-free. All soldered surfaces are cleaned of flux residue. In addition, the aeroponic system is flushed of all process chemicals prior to crew interaction. Practices that include cleaning system surfaces after manufacturing, wearing gloves during handling and interaction, and cleaning food outputs of residue prior to consumption, are adequate to control this potential hazard.</td></tr>
</table>

Table 30: Hazard analysis: chemical hazards to system introduced by crew.

<table>
<tr><td colspan="2">Source</td><td>Crew contact with system during harvesting, cleaning, and maintenance</td></tr>
<tr><td colspan="2">Identification</td><td>Chemical hazards to system (i.e. disinfectants) introduced by crew</td></tr>
<tr><td rowspan="3">Evaluation</td><td>Severity</td><td>Chemicals can remain on system surfaces, and may be present in food product, posing a hazard either through physical contact with surfaces or through ingestion.</td></tr>
<tr><td>Likelihood</td><td>Disinfectants are of moderate probability. In addition, process chemicals used during maintenance (i.e. descaling agents for the aeroponics system) may be present on food product surfaces (i.e. root vegetables).</td></tr>
<tr><td>CCP?</td><td>The HACCP team determines that the risks of chemical ingestion are low. Disinfectants are food-safe and dilute. In addition, the aeroponic system is flushed of all process chemicals prior to crew interaction. Practices that include wearing gloves during handling and interaction, wiping surfaces and food products with pure water prior to physical contact and ingestion, and practices that minimize system interaction are adequate to control this potential hazard.</td></tr>
</table>

Table 31: Hazard analysis: chemical hazards to crew introduced by system.

10.1.2 Hazard Analysis: Water Supply

Source		Water supply as a medium for accumulation and distribution of hazards
Identification		Chemical hazards (i.e. heavy metals, process chemicals) build up in water supply and transfer to produce and, in turn, crew
Evaluation	*Severity*	Heavy metals (i.e. lead) and chemicals introduced during manufacturing and process pose a threat to crew health when ingested via food products. In addition, buildup can compromise other systems (i.e. flow rate) and reduce resistance to other threats.
	Likelihood	Heavy metals are of low probability, but may be present in trace amounts in water supply and components (i.e. plumbing) and thus may be present in water supply for periods of time. However, regular flushing and cleansing of the supply will provide an upper bound on possible concentrations both in the supply and in any given produce.
	CCP?	The HACCP team determines that the risks of chemical accumulation are low. All plumbing fittings are certified lead-free. In addition, the aeroponic system is flushed of all process chemicals prior to crew interaction. Existing water supply standards for space missions are adequate to control this potential hazard.

Table 32: Hazard analysis: chemical hazards in water system.

Source		Water supply as a medium for accumulation and distribution of hazards
Identification		Bacteria present in water supply thrive, transfer to produce and, in turn, crew
Evaluation	*Severity*	Bacteria in/on produce, surfaces, or suspended in mist can infect crew.
	Likelihood	Probability of human-borne bacteria (i.e. *E. coli*) is unlikely given stringent crew sanitation procedures. Other sources are infected seeds, however there are no known instances of plant-borne pathogens infecting humans.
	CCP?	The HACCP team determines that the risks of bacteria accumulation are low. GAPs that include removing all organic material during cleaning, disinfecting system surfaces after interaction, wearing gloves during handling, and flushing the water system regularly are adequate to control this potential hazard.

Table 33: Hazard analysis: bacteria grow in water system.

Source		Water as a medium for growth and propagation of algae
Identification		Biological hazards (algae) establish in damp, nutrient rich conditions (i.e. growth tray)
Evaluation	*Severity*	Introduces unnecessary organic material into growth areas, absorbs nutrients and emits waste products. No direct risk to humans.
	Likelihood	Given damp, nutrient-rich conditions and a plant-optimized light source, algae growth is highly likely, and should be monitored as a utility organism for general hygiene purposes. Can be reduced by ensuring GAPs are followed when during cleaning (no organic material is left behind).
	CCP?	The HACCP team determines that the likelihood of algae growth is moderate, given that the conditions present in growth areas are inherently suitable for algae. However, regular presence/absence testing (swabbing and visual inspection for residue) and counter-measures (3 wt% hydrogen peroxide solution) minimizes risk.

Table 34: Hazard analysis: algae in growth environment.

10.1.3 Hazard Analysis: Nutrient Supply

<table>
<tr><td colspan="2">Source</td><td>Nutrient supply as a medium for accumulation and distribution of hazards</td></tr>
<tr><td colspan="2">Identification</td><td>Bacteria in nutrient supply thrive, transfer to water and, in turn, crew</td></tr>
<tr><td rowspan="3">Evaluation</td><td>Severity</td><td>Bacteria from nutrient supply can be distributed throughout the system and infect crew.</td></tr>
<tr><td>Likelihood</td><td>Nutrient supply is kept in pre-sealed packets of individual doses, meaning control on earth will eliminate introduction of threats via nutrient supply. Once in use, any bacteria will have come from the system, so presence in the nutrient supply is non-additive.</td></tr>
<tr><td>CCP?</td><td>The HACCP team determines that the risks of biological threats in the nutrient supply are low. Given purity of nutrients, as well as proper care in pre-flight steps and standard operating procedures when interacting with nutrient supply, enough practices are in place to control this hazard.</td></tr>
</table>

Table 35: Hazard analysis: pathogens in nutrient supply.

10.1.4 Hazard Analysis: Seeds

<table>
<tr><td colspan="2">Source</td><td>Seed supply as a medium for introduction of hazards</td></tr>
<tr><td colspan="2">Identification</td><td>Pathogens (bacteria, fungi, viruses) present in seed supply are introduced to system</td></tr>
<tr><td rowspan="3">Evaluation</td><td>Severity</td><td>Minimal, there are no known occurences of plant-borne pathogens infecting humans.</td></tr>
<tr><td>Likelihood</td><td>Moderate, however introduction of a pathogen will have occured pre-flight. But, they are sanitized and stored in isolated pouches which also minimize likelihood of bacteria on their surfaces.</td></tr>
<tr><td>CCP?</td><td>The HACCP team determines that the risks of biological threats in the seed supply are low. Given proper care in pre-flight steps and standard operating procedures when planting seeds, enough practices are in place to control this minimally risky hazard.</td></tr>
</table>

Table 36: Hazard analysis: pathogens introduced via seed supply.

10.1.5 Hazard Analysis: Testing

Source		Testing as a method for propagation or introduction of threats
Identification		Chemical hazards (i.e. process chemicals) introduced by testing apparatus
Evaluation	*Severity*	Minimal, testing substances are either buffer solution in small quantities or trace amounts of indicators on paper strips.
	Likelihood	Minimal, as any testing would be conducted outside of the unit using a sample collected by crew contact (see 30, 31).
	CCP?	The HACCP team determines that the risks of testing introducing chemical hazards into the system are minimal. This is given the mundane, external nature of the substances at play as well as the process design of PeaPod which intentionally limits the frequency of testing.

Table 37: Hazard analysis: chemical hazards introduced via testing.

Source		Testing as a method for propagation or introduction of threats
Identification		Bacteria propagated by testing apparatus and procedures
Evaluation	*Severity*	Severe, can inflate bacterial populations from negligible to significant, widespread, systemic threats.
	Likelihood	Minimal, as bacterial testing is limited if not eliminated by the process design of PeaPod and the lack of resources in the field.
	CCP?	The HACCP team determines that the risks of testing propagating bacterial hazards are minimal. This is given the process design of the system which avoids bacterial testing and the stringent system controls which are designed for elimination of bacteria in the first place.

Table 38: Hazard analysis: bacterial propagation induced via testing.

10.2 Critical Points

No critical points were identified in hazard analysis.

10.3 Standard Test Record

No critical points were identified in hazard analysis.

11 Inputs and Outputs

11.1 Inputs

Infrastructural Inputs: Reverse osmosis water (constant supply at positive pressure from onboard RODI system), nutrient solutions (stored, one container each plus refill tanks), pH solutions (one container pH up, one container pH down, plus refill tanks, stored), power (onboard power, standard 120V AC 60Hz), network connection (onboard network, for remote control, live video/data transmission), plant seeds (stored in vacuum-sealed seed bank, selected for variety and acceptability), input air (HEPA filtered, carbon dioxide-rich)

Process Inputs: Plant species identifiers, environment program (for entire growth cycle, one per plant species), nutrient and pH-adjustment solution identifiers (compounds and molarities, i.e. solution A is 0.6M $NaNO_3$)

Common nutrient solutions target specific ions, including bioavailable nonmetals (nitrates/nitrites, ammonia/ammonium, phosphates, sulphates), metals (potassium, calcium, magnesium, iron) and other trace elements.

Products: Edible plant matter, recorded environment data, plant metric data, live video feed, time-lapse capture

Byproducts: Inedible plant matter (stems/roots/leaves/etc., waste), sensible heat (from thermoregulation pumping, managed by onboard heating/cooling), exhaust air (via HEPA filter, sterilized and dehumidified by onboard life support, oxygen-rich), minimal water vapour (as a result of higher air humidity, minimized by housing seal), latent heat (as a result of higher leaf zone temperature, minimized by insulation)

Humidification: By using a mesh nebulizer to produce smaller and more consistent vapour, greater overall water consumption efficiency was achieved.

Aeroponics: Aeroponics by design uses far less water than traditional farming. In addition, higher quality nozzles with adjustable directionality allow for more of the water to be sprayed directly at the root zone and with better and more consistent droplet sizes for better uptake. Finally, by enclosing the root zone in a watertight container, no water escapes, and runoff water collected at the bottom of the container can be recycled. 5mL/sec/nozzle @80PSI x 2 nozzles per unit x 12 units x 10 seconds misting per hour

In calculation, it is assumed that all aeroponic water is consumed, as all runoff water is recycled.

High Success Rates: Complete automation and environmental control ensures high crop success rates and yield predictability.

Repeatability: Once optimal conditions are found for a given crop species, they can be repeated ad infinitum.

Immediate Sensor Feedback and Response: Immediate feedback from both environment sensors and plant metric analysis empowers the system to respond to unpredictable or otherwise uncontrolled factors (i.e. poor seed health, outside interference). Plant metric analysis can be used to diagnose program ineffectualities, accelerate optimization, and preventatively mitigate plant health decline.

Data Collection, Yield Optimization: By collecting data via computer vision and post-harvest yield evaluation (GCMS, weighing, etc.) on the plant's response to the induced environment, the relationship between the species behaviour and the surrounding environment can be analyzed. Plant metrics include plant health indicators (chlorophyll concentrations/chlorosis, leaf count/size distribution/density, plant height/canopy dimensions leaf tip burn, leaf curl, wilting, etc.) and crop yield (edible matter net mass/percent mass of plant, total plant mass, chemical/nutritional composition, caloric measurement, etc.). Data is filtered/smoothed across time to account for noise. The relationship is then represented by a statistical/machine learning model via a method known as "surrogate modelling". The method for this analysis can be found in the preliminary calculations Appendix **??**.

12 Reliability and Stability

12.1 Process Description

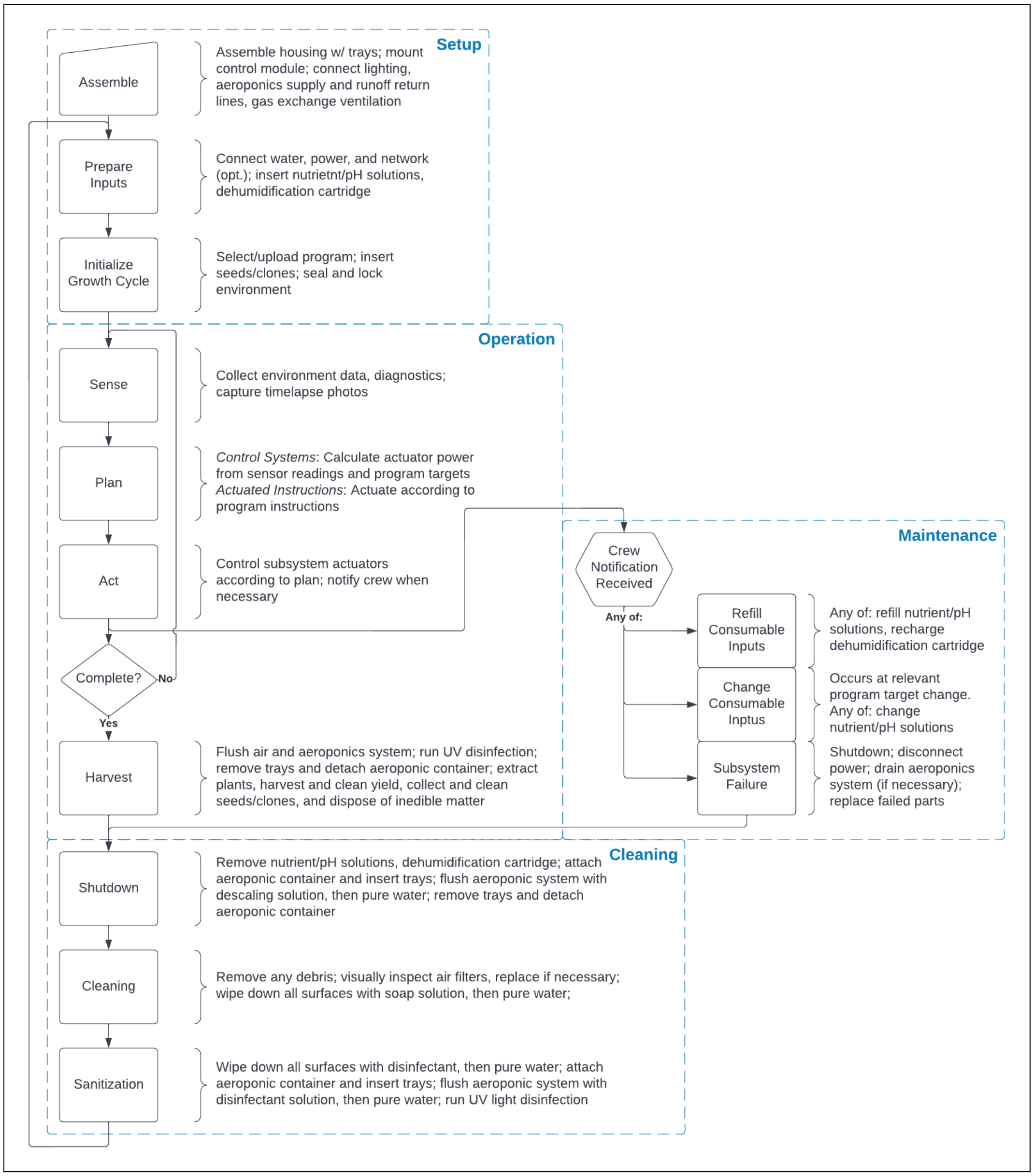

Figure 2: Process diagram.

12.1.1 Setup

Assembly:

1. Assemble housing, trays (see **??**);
2. Mount control module, trays (see **??**);
3. Connect subsystems to control module:
   - *Housing Solenoid Lock*: relay (see **??**)
   - *Aeroponics Supply & Runoff Collection Lines*: quick-disconnect (see **??**)
   - *Lighting Driver Board*: power, control signal (see **??**)
4. Connect gas exchange exhaust to ventilation (see **??**);

Prepare Inputs:

1. Connect supply inputs:
   - *Power*: 120V 60Hz AC (see **??**)
   - *Network*: ethernet or wireless, optional (see **??**)
   - *Water*: reverse-osmosis, ambient (see **??**)
2. Insert consumable inputs:
   - *Nutrient/pH Adjusment Solutions*: pouches (see **??**)
   - *Dehumidification Cartridge*: recharged (see **??**)

Initialize Growth Cycle:

1. Select or upload program;
2. Insert seeds/clones;
3. Seal and lock environment;
4. Start growth cycle;

Proceed to Operation (see 12.1.2).

12.1.2 Operation

Sense, Plan, Act represents the three simultaneous automatic processes of the program's execution (see **??**).

- **Sense**: Environment data, diagnostic information, and timelapse photos are captured and stored at regular intervals.
- **Plan**:
  - *Control Systems*: Actuator controls are calculated from sensor readings and program targets.
  - *Actuated Instructions*: Actuator controls are derived from program instructions.
- **Act**: Subsystem actuators are controlled according to plan. Crew is notified to refill consumable inputs when low, change consumable inputs on program target change, and on any subsystem failure (see 12.1.3), as well as when to harvest and on End of Program (EoP).

Harvest and/or EoP:

1. Exhaust all air (automatic, see **??**);
2. Flush aeroponics system with pure water (automatic, see **??**);
3. Run UV disinfection (automatic, see **??**);
4. Unlock and open environment;
5. Remove trays (see **??**) and detach aeroponic container (see **??**);
6. **If EoP**: Extract plants;
7. Harvest and clean yield;
8. Collect, clean, and store seeds/clones;
9. **If EoP**: Dispose of inedible matter;
10. Inspect unit for remaining organic matter, including but not limited to debris, residue, and algae, particularly in the root zone and water system;
11. Remove all matter and residue;
12. Clean algae with hydrogen peroxide solution.

If EoP, proceed to Cleaning (see 12.1.4)**. Otherwise, seal and lock environment and resume program.**

12.1.3 Maintenance

Notification Handling:

- *Refill Consumable Inputs*: includes refilling nutrient/pH adjustment solutions (see **??**), recharging the dehumidification cartridge (see **??**)
- *Change Consumable Inputs*: includes changing nutrient/pH adjustment solutions (see **??**)
- *Subsystem Failure*: all operation stopped, proceed to *Shutdown* (see 12.1.4), disconnect power (see **??**), then drain aeroponics system if necessary (see **??**) and replace failed components

12.1.4 Cleaning

Shutdown:

1. Remove nutrient/pH solutions (see **??**), dehumidification cartridge (see **??**);
2. Attach aeroponic container (see **??**) and insert trays (see **??**);
3. Flush aeroponic system with descaling solution (see **??**);
4. Flush aeroponic system with pure water (see **??**);
5. Remove trays (see **??**) and detach aeroponic container (see **??**);

Cleaning:

1. Visually inspect all surfaces for debris (remove) and components for damage (replace);
2. Visually inspect all air filters (see **??**, **??**), replace if necessary;
3. Wipe down all surfaces with soap solution;
4. Wipe down all surfaces with pure water;

Sanitization:

1. Wipe down all surfaces with disinfectant solution;

2. Presence/absence test for algae, wipe down surface with hydrogen peroxide if needed;
3. Wipe down all surfaces with pure water;
4. Dry all surfaces;
5. Attach aeroponic container (see **??**) and insert trays (see **??**);
6. Flush aeroponic system with disinfectant solution (see **??**);
7. Flush aeroponic system with pure water (see **??**);
8. Seal and lock environment;
9. Run UV sanitization (**??**);

Proceed to Prepare Inputs (see 12.1.1).

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