PeaPod - Testing Plan and Hazard Analysis and Critical Control Points (HACCP) Plan

NASA/CSA Deep Space Food Challenge Phase 2

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1 Testing Plan

1.1 Acceptability of Outputs

1.1.1 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.

1.1.2 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 ouputs 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 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.

1.2 Safety of Process and Outputs

1.2.1 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, 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 preveniton. By using DfX such as minimal testing and minimal interaction, PeaPod minimizes the introdcution of foreign substances and, in turn, the ingress of potential threats. Interaction will only occur at times of harvest and planting, and double as times of cleaning and sanitaion. 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 DfX regarding prevention, all sourcing of parts and resources has been done with inherent, chemical threats in mind. 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
Aerobic Plate Count (APC) testing to be done with the Conventional Plate Count Method outlined in the FDA's BAM Chapter 3: Aerobic Plate Count. 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. Plate count to be minimized by following !CITE (surface cleaning standards? hard to find).

ATP testing to be done using !CITE (lots of stuff about methods but no standards? look at requirements more)

Food Outputs

APC testing conducted on samples as outlined above to ensure bacterial population below 20 000 CFU/g per STD-3001. Testing for enterobacteriaceae will be performed using the MicroSnap EB rapid test to ensure its population is below 100 CFU/g per STD-3001. Testing for salmonella will be performed using a rapid detection kit to ensure a population of 0 CFU/g. Testing for yeasts and molds will be performed with a testing kit to then be analyzed for a population count below 1000 CFU/g.

Critical pathogens to be tested for individually:

- Enterobacteriaceae: 100 CFU/g
- Salmonella: 0 CFU/g
- Yeast and Molds: 1000 CFU/g
- Escherichia Coli: dep. on tech
- Listeria: dep. on tech

By-Product Outputs

1.2.2 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.

1.3 Resource Outputs

1.3.1 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.

1.3.2 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 this guide from FedEx.

1.4 Reliability and Stability of Outputs

1.4.1 Testing Procedure

PeaPod's outputs 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 slow bacterial growth. 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.(Look into dehydrating processes and shi)

1.4.2 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 each output 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.

1.5 Additional Comments

1.6 Materials

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

1.6.1 System

For a 4x3 extended topology with two control modules:

- 2x Automation (1, 2)
- 12x Housing Shell (3, 4)
- 12x min. Grow Tray (**??**, 6)
- 12x min. Lighting Tray(7, 8)
-

Automation

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 2.54mm	1
SC0510	Raspberry Pi	Raspberry Pi Zero 2 W	1
DMN2005K-7	Diodes Incorporated	MOSFET N-CH 20V 300mA SOT23-3	2
RC0603FR-0710KL	YAGEO	RES 10K OHM 1/10W 0603	5
4484	Adafruit Industries LLC	1.3" TFT Screen	1
5055670271	Molex	Molex Micro-Lock PLUS 2pos 1.25mm	2
5055670471	Molex	Molex Micro-Lock PLUS 4pos 1.25mm	5
5055670871	Molex	Molex Micro-Lock PLUS 8pos 1.25mm	3
5055670681	Molex	Molex Micro-Lock PLUS 6pos 1.25mm	3

Table 1: Automation system electronic components. One per control module.

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

Table 2: Automation subsystem parts. One per control module.

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 components.

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 components.

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.

Index	Manufacturer Part Number	Manufacturer	Description	Quantity
1	SEN0257	DFRobot	Water Pressure Sensor	1
2	GE-2158	Amphenol Thermometrics	Water Temperature Sensor	1
3	996	Adafruit Industries LLC	Solenoid Valve	1
4	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

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

Table 12: Dosage pump electronic components.

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 13: Dosage pump components.

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 14: Dosage pump fabricated components.

Leaf-Zone Thermoregulation

Humidification

Dehumidification

Gas Composition Regulation and Exchange

Lighting

1.6.2 Inputs

Supply Inputs

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

Consumable Inputs

- *Nutrient/pH Adjusment Solutions*: pouches
- *Dehumidification Cartridge*: recharged

1.6.3 Outputs

Food Outputs

By-Products & Waste

1.6.4 Maintenance

Spare Components

Tools

1.6.5 Cleaning

Soaps

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

Disinfectants

Tools

2 Hazard Analysis and Critical Control Point (HACCP) Plan

2.1 Food Production System Description

PeaPod uses automated control systems to generate desired environments. These are air thermoregulation, humidity control, LED lighting, and an aeroponics system. They are automated by an onboard computer and housed in a "control module" at the top of the unit. This lets power be "multiplied" for extended PeaPods by adding more control modules in a controller-follower topology.

PeaPod is an automated plant growth environment, comprised of several control systems regulated by an automation and monitoring system within a modular, cubic housing. It can generate any desired environment while collecting data on plant growth and improving yields. Due to the wide range of actuation for each control system's environment parameter, and the extendable housing topology, the growth environment is adaptable to any plant or mission requirements. In addition, plant growth support platforms (with watering system) and lighting systems are built on modular "trays" mounted to the inside of the housing so the user can position plants and lights to accommodate any plant size.

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

- *Lighting*: A wide spectrum of LEDs, from IR to UV, with a focus on Photosynthetically Active Radiation (PAR). Dimmable LED drivers enable 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 custom peristaltic pumps (allows for accurate dosing, and prevents backflow under pressure), and forced through nozzles to generate mist. 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. Runoff water is recycled. Water-efficient (98% less water use than farming), nutrient-efficient (60% less use than farming), no pH/nutrient "feedback" loop or waste water (common in hydroponics), increased root oxygenation.
- *Leaf-Zone 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 on demand. The beads change color to indicate water saturation. The crew is then notified to swap and "recharge" via evaporation in a standard oven.

- *Gas Composition Regulation and Exchange*: 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.

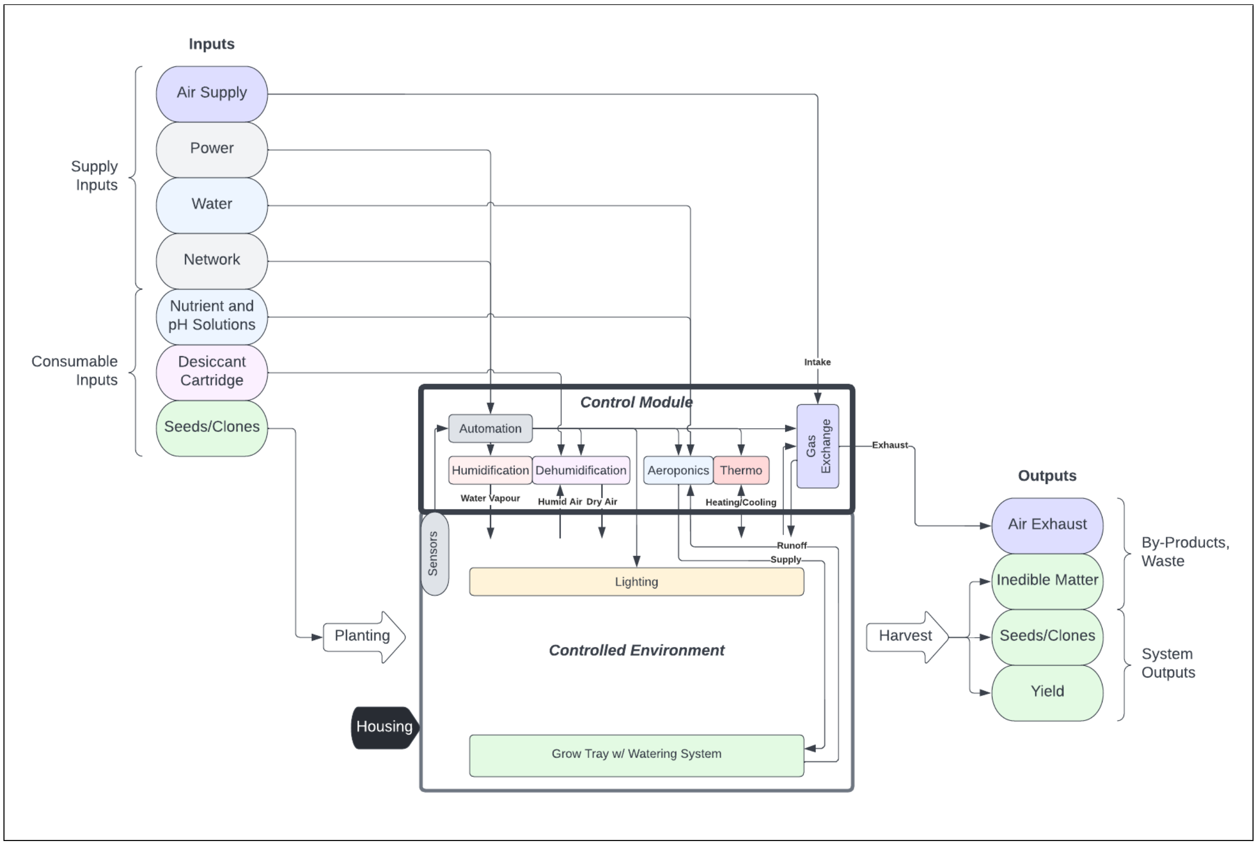

Figure 1: System overview.

2.2 Critical Points

2.2.1 Critical Point A

Hazard Description

Critical Limits

Monitoring Procedures

Deviation Procedures

Associated Documents

2.3 Standard Test Record

2.3.1 Purpose and Summary

2.3.2 Safety and Quality

2.3.3 Test Processes

Preparation of Inputs

Verification

Setup, Maintenance, and Collection Protocols

Storage

Cleanup and Turnover

2.3.4 Closeout

3 Feedback

References