PeaPod - Design Report

Primary Written Deliverable for the Deep Space Food Challenge Phase 1

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1 Design Abstract

PeaPod is a precision-automated plant growth environment, designed as both a low-maintenance food production system and a distributed research tool. PeaPod is able to generate any desired environment, while collecting data on plant growth and improving yields over time.

The growth environment is extendable and modular, featuring a frame-and-panel housing. This extendable topology can be easily adapted to suit the plant selection or mission requirements. The housing is insulated and highly reflective internally for greater efficiency.

Control systems (air thermoregulation, humidification, dehumidification, aeroponics system minus nozzles) and automation systems (central computer) are all housed in a self-contained control module. This allows control power to be multiplied in larger extended PeaPods by adding more control modules in a controller-follower topology.

Both plant support trays and lighting systems are mounted to identical subframes. Subframes are modular, enabling the user to add, remove, or reposition trays at will. This allows for different configurations to accommodate any plant.

Throughout each growth cycle, PeaPod collects data on all environment parameters and plant metrics. This data is then used to train a machine learning surrogate-model to represent the plant's phenology across time. This model aims to fit a function to the plant-environment relationship, which can then be optimized for yield, nutrient concentration, flavour, energy efficiency, water use, or any other metric. Therefore plants grown in PeaPod will be more nutritious, taste better, and yield more as more iterations are performed.

PeaPod provides unrivalled versatility and reliability to food production systems for long duration space missions.

2 Design Report

2.1 Description

Part A

- *Lighting*: A wide spectral range (UV→IR) of powerful LEDs, with dimmable drivers for precision spectrum and intensity control. LEDs chosen for high energy efficiency, precise emission spectrum, low heat production, and low risk of plant tissue damage.
- *Aeroponics*: Reverse osmosis water is pressurized by a pump and tank. Pressurized water flows through a thermoelectric water block to be heated or cooled, with temperature and pressure sensors providing PID feedback and safety cutoffs respectively. This is followed by an injection manifold, where parallel Venturis siphon different nutrient and pH adjustment solutions from containers for inline mixing. Servo-actuated flow-control valves control injection rates. The mixed solution now flows through a solenoid to nozzles mounted beneath the plant support trays, enclosed in a water-tight chamber. Runoff water is pumped from the chamber basin and recycled to the injection manifold. Both runoff and supply lines are quick-disconnect for easy tray removal. This method is chosen for increased water

efficiency (98% less than farming), no pH/nutrient "feedback" loop (common in hydroponics), greater supported crop variety (vs hydroponics).

- *Air Thermoregulation*: Leaf zone air temperature is regulated by a thermoelectric heat pump. Thermoelectric/Peltier tiles heat or cool an internal heat sink (w/ thermal compound). Circulation fans blow air over the heat sinks to distribute heat to homogenously heat or cool the environment. A matching heat sink and fan set on the opposite face of the Peltier tiles conduct heat to/from surroundings, completing the heat pump. A PID control system is informed by temperature sensors distributed throughout the growth environment, and - with the use of a MOSFET H-bridge and dimmable current source - controls the direction and magnitude of the heat transfer. This method is chosen for its low complexity (no liquids, pressurization, etc.) and ease of automation (bidirectional heat pump, precisely dimmable, PID tuning for high accuracy).
- *Humidity Regulation*: Leaf zone humidity is regulated by two complementary systems. A dead-zone bang-bang control system is informed by humidity sensors distributed throughout the growth environment.
  - *Humidification*: Humidity is **increased** by an ultrasonic mesh nebulizer. Reverse osmosis water is supplied to a small container, to which a piezoelectric mesh disc is mounted. A control signal activates a driver circuit which causes the disc to oscillate, producing water vapour. This method is chosen for its ease of automation and consistency of vapour production.
  - *Dehumidification*: Humidity is **decreased** by a rechargeable indicating desiccant cartridge. The cartridge, containing dry silica gel beads, is inserted into a housing. Servo-actuated "shutters" prevent unintended air movement through the cartridge. Fans draw humid air through a HEPA filter into the cartridge, causing dry air to be expelled back into the growth environment. The cartridge changes color to indicate saturation, which is observed by the automation controller. The crew is then notified to swap the saturated cartridge for a dry one, and to "recharge" the cartridge via evaporation in a standard oven.
- *Aeroponic Water Temperature*: Root zone air temperature is regulated in the same way as the leaf zone system. Exceptions include the use of an aluminum water block (as opposed to an internal heat sink and fan) and a single temperature sensor mounted **after** to account for flow direction.
- *Gas Composition*: Oxygen and carbon dioxide concentration imbalances due to photosynthesis are managed by gas exchange with the surroundings. Two ports are covered by servo-actuated "shutters", preventing unintended exchange. Fans draw outside air in via an input port, bringing CO_2 up and O_2 down. Fans also draw inside air out to an onboard filtration and dehumidification system, filtering out aerosols (pollen, seeds, allergens, etc.) and bringing humidity down to acceptable levels. Gas concentration sensors collect data on the concentrations of relevant gasses (CO_2, O_2, etc.), informing a bang-bang control system for the input and output port shutters and fans. This approach allows natural photosynthesis to counteract human carbon dioxide production while remaining safe and minimizing cross-contamination.
- *Optimization and Plant Analysis*: Food products are optimized over time via plant metric analysis and "surrogate model" machine learning. Cameras (birds-eye and horizontal) capture live video for observation as well as time lapse photography for computer vision

analysis. Metrics of both plant health and yield quality (plant "output"), along with data collected on the environment (plant "input"), are used to train a machine learning model to act as a digital representation of the plant. As more iterations of the plant are grown, the dataset becomes generalized across different environmental inputs/programs, and new programs can be selected to intelligently target certain optimization factors (i.e. yield mass, flavour, nutrient concentration, energy/water efficiency).

Part B:

2.2 Innovation

2.3 Adherence to Constraints

2.3.1 Outer Dimensions, Volume

PeaPod is a modular system of "unit cells," each consisting of a .5 x .5 x .5 meter cube frame with insertable insulation walls. This cell is expandable to physically link with neighbouring cells, creating a single frame. An "expanded system" may share a single control module and have no separating wall (thus producing the same environment), or may have multiple control modules operating in either a master-slave topology (again, producing a homogenous system with no separation) or may be linked only physically (having no sharing of environment or control). The adaptibility of PeaPod ensures it meets the constraints of its environment while yielding as much produce as possible.

2.3.2 Power Consumption

Electrical power is consumed by most subsystems. Most are negligible (<100W, i.e. the computer), so only the greatest consuming systems are listed.

Lighting - Highly efficient drivers (up to 96%) were selected to minimize energy waste. 5 LED series x 3 LEDs per series x 9 LED boards = 135 LEDs[1]. The maximum consumption per LED is 3V @1.2A = 3.6W. Max Consumption: **486W**[1]

Air & Water Thermoregulation - Although less energy efficient than compressor- or resistance-based heating/cooling mechanisms, this is offset by both their reduced footprint and complexity, as well as the ability to be directly controlled electrically. This allows us to further tune the efficiency via PID control. The maximum consumption per thermoelectric tile is 8.5A @15.4V = 131W[2]. Max Consumption (2+2 Tiles[1]): **524W**

Overall Max Consumption: 1000-1200W[3]

[1] Per unit (see 2.3.1)

[2] Per-unit, although neighbouring units may be configured to run in a "follow" configuration, where they mimic the environment of the "host" unit, and may omit this system.

[3] *NOTE*: This is running ALL LEDs and both air and water thermoregulation at max power. The system's power output is over-engineered, and will likely never be used this way in most use cases.

2.3.3 Water Consumption

Water is consumed by two systems:

Humidification: By using a mesh nebulizer to produce smaller and more consistent droplets (vapour), a less non-vapour mist was produced, thus resulting in a greater overall water consumption efficiency.

Aeroponics: Aeroponics by design uses far less water than traditional farming (up to 98%). 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 (5-50 micron mean droplet diameter). Finally, by enclosing the root zone in a waterproof bag, no water escapes, and excess/runoff water collected at the bottom of the bag can be removed via an outlet and recycled (RO reclaimer).

2.3.4 Mass

Through the optimization of volume, the mass of PeaPod was indirectly minimized. By using smaller parts, power consumption and complexity was reduced along with volume and mass. PeaPod's mass was also optimized through minimizing density across components. Aluminum was chosen for the framing due to it's high strength to density ratio. For insulation, a less dense foam coated in mylar was used to maintain PeaPod's insulating capabilities while reducing mass.

2.3.5 Data Connection

Automation: All of PeaPod's operation is automated, save for a select few maintenance 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.

This program comprises of a set of **time-series instructions** concerning the various environment parameters (i.e. set leaf zone air temperature to 23 degrees C at 16:30 each day). These parameters include:

- Leaf zone air temperature;
- Leaf zone humidity;
- Aeroponics nozzle activation (on/off);
- Root zone/aeroponics spray temperature;
- Light activation (% per LED series);
- etc.

Remote Control: The program may be changed at any time instantaneously, remotely or on-board. These changes are reflected as an **appended instruction set** to the program, and take effect immediately.

Alongside and fuelling this automation is an array of environment parameter (aka feedback) and plant metric sensors. These include:

- Leaf zone air temperature;
- Leaf zone air humidity;

- Water temperature (pre-aerosolization);
- Root zone air temperature;
- Leaf zone CO_2 ppm;
- Leaf zone top-down and side camera capture/live feed, with computer vision analysis for:
  - Leaf health indicators (i.e. leaf tip burn, leaf curl, chlorosis);
  - Leaf count, size distribution;
  - Leaf density;
  - Canopy dimensions/surface area;
  - Plant height;
  - Fruit/harvest body size, ripeness;
  - etc.

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.).

Data Presentation: This data collection, accompanied by a number of "known" quanities (i.e. aeroponics flow rate, per-LED spectral data) allows for a full quantitative description of each plant's growth environment to be displayed on-board and remotely, instantaneously, with live updates (i.e. real-time data, live video feed).

2.3.6 Crew Time Requirement - Setup & Maintenance

Operational costs for the crew break down into three primary categories.

First, setup: Before plants are grown, crews must make sure resource resevoirs are full. Since PeaPod mixes nutrients via an automated, inline process, they do not need to perform any measuring or mixing—only filling resevoirs to capacity. Then, for some plants such as strawberries, manual pollination must be done during the appropriate period, resulting in a few minutes of extra work per day during this time. Second, harvesting and planting: These take little time, as crew members simply need to remove the plant from its cup and replace it with a seed in the growth material. Finally, output processing and storage. Processing will depend on the produce grown, varying from dehydrating to grinding to freezing in the ISS's freezers. These operations have a sum active time of, at most, 10 minutes per day—but most days will be far less.

2.3.7 Palatability of Crop Output

Hydroponic crops have seen commercial success, suggesting that their output is of sufficient hedonic quality to be desired. Additionally, PeaPod is designed to optimize for edible plant mass, nutrient denisty, and other health indicators—pushing hedonic quality up over time.

2.3.8 Operational Constraints

Gravity informed the use of an aeroponic system, as this allows plants to be placed in a hanging cup secured only on one side. Ambient pressure is critical for component selection regarding the tank, bladder, and nozzle, all of which are designed to produce the outputs we desire at this air pressure. Ambient temperature and humidity allow the use of mylar as an insulator, as it is of sufficient quality to work in these conditions.

2.3.9 Processing Time for Outputs

By creating a solution to "grow plants," PeaPod has been designed from the ground up to produce food that requires no additional processing time. Harvesting is an instantaneous process, and raw produce is immediately consumable, as the user can decide precisely what they wish to grow.

2.4 Performance Criteria

2.4.1 Acceptability

Acceptability of Process

Footprint:

Due to PeaPod's modular construction, the footprint can vary. For a 3x4x1 expanded PeaPod (3 units = 1.5m tall, 4 units = 2m wide, 1 unit = 0.5m deep), the footprint would be 2m x 0.5m, or three standing refrigerators. This leaves .5 cubic meters for control modules and accessory systems.

When stowed, volume is reduced to 37% of when assembled. Control module is packed pre-assembled.

Setup Process:

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

[4]Per unit
[5]Per control module
[6]Per tray per unit

Total setup process time (2 trays per unit, 12 units, 1 CM): **17.5 hours** (*one person*) or **4.5 hours** (*crew of 4*)

Food Production Cycle:

1. Environment is maintained, and environment is observed live at a computer terminal via sensor data and camera feed;
2. Perform maintenance, including:
    - Cleaning nozzle once a month - **10 min**[3];
    - Swapping and recharging dehumidification cartridges when instructed - **5 min**[2] (active time);
    - Refilling solution containers when instructed - **5 min**[2];
3. Upon End-Of-Program (EOP) notification, users will harvest and store food products (or prepare and consume them immediately, varying time) - **10 min**[1];
4. 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 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.

Acceptability of Food Products

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);

Case Study in Fresh Produce: Acceptability of Fresh Cantaloupe Melon

- Appearance: 7.93/9.00
- Aroma: 7.77/9.00
- Flavor: 6.83/9.00

- Texture: 7.43/9.00
- **Overall**: 7.17/9.00 (>6.00)

2.4.2 Safety

Safety of Process

Being a sustainable isolated unit, PeaPod requires little cleaning. When it does need to be cleaned, PeaPod is easily disassembled due to its modularity. PeaPod uses safe materials in its chassis, insulation and circuitry. The main frame is constructed using aluminum. Although large quantities of aluminum in food are deemed dangerous, the small exposure of aluminum to the plants passes well below the toxicity limit; as healthline says, when using aluminum cookware the, "amounts are very small and deemed safe by researchers" referring to the aluminum captured in the food . The bracketing and mounts of PeaPod are constructed using PETG plastic which has been deemed "food-safe plastic" by AcmePlastics . The insulation used in PeaPod is commonly used for housing and is reported to be safe (another source). To avoid toxins in circuitry, lead-free soldering was used for all electronics. The dehumidification of PeaPod uses silica gel, which is commonly found in food packets and is described by Millenium Waste Inc as "biodegradable and non-toxic" . All voltages of PeaPod are sub 48V DC, avoiding any high-voltage risks. The voltage risk is also mitigated by short-circuit/overcurrent protection. All pressures of the PeaPod experienced by its irrigation system stay below 100 PSI, avoiding dangers with high pressures. The dangers with pressures are also mitigated through the use of PTFE tape, fail-safe solenoids (which primarily stay closed) and a pressure sensor shutoff. Due to the aforementioned mitigation processes, PeaPod avoids the risk of off-gassing. The presence of microbes or other harmful pathogens are mitigated through the use of clean seeds, reverse osmosis water and pure nutrient/pH solutions. Through a nutrient injection manifold, PeaPod also has the ability to administer anti-pathogenic compounds such as fungicides and algicides. To avoid cross-contamination, PeaPod provides plant nutrients directly without the use of fixing bacteria. The production process of PeaPod is fully automated, preventing the risk of human error. In the event of a malfunction, PeaPod also allows the user to override the program for the purposes of editing or shutting down the unit. The produce of PeaPod can be consumed raw after rinsing, or may need to be processed depending on the plant grown.

Safety of Food Products

With PeaPod being a tool rather than an outright solution for interplanetary travel, it provides astronauts the ability to select and grow the produce of their choosing. Before takeoff, the representatives responsible for providing food resources should create a stockpile of seeds that will provide ample food for the astronauts throughout their journey. The variety and quality of crop/seed selection is the primary variable for repeated consumption.

By maintaining optimal growth cycles, PeaPod ensures that the food produced is clean, varied, and fresh. However, program/environment selection (especially those with chemical components, i.e. nutrient and pH solutions) also play a role, as these directly influence the composition of the food products.

The selection of proper crops and solutions, along with proper harvesting and processing techniques (i.e. only harvesting edible bodies, cooking for long enough), are the only concerns when it comes to product safety.

2.4.3 Resource Inputs and Outputs

Resource Inputs

- *Reverse Osmosis Water*: constant supply, positive pressure (i.e. supply line)
- *120VAC Power*: Standard.
- *Plant Seeds*: Housed in seed bank, 16 plants per grow tray
- *Nutrient Solutions* - one cartridge each, with refill tank
- *pH Adjustment Solutions* - one cartridge up, one cartridge down, with refill tanks
- *Network connection* (optional) - For remote control, live video/data transmission
- *Environment Parameter Program* - Set of time-series instructions defining the growth environment across the full growth cycle (one per plant species).

System Outputs

Product:

- *Edible plant mass*: fruits/vegetables/seeds/etc.
- *Plant seeds*: for seed bank replenishing

Waste, Functional:

- *Aeroponics runoff water*: minimized by optimizing aeroponics spray duration, can be recycled to aeroponics system post-mixing (more efficient) or fed back to external RO system (more precise environment)
- *Inedible plant mass*: stems/roots/leaves/etc.[7]
- *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
- *Sensible Heat*: **Bidirectional** - as a result of leaf zone and aeroponics spray heating/cooling systems.

[7] NOTE: Plant crops may be chosen such that this is minimized (i.e. microgreens)

Optimization

- *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, alongside being used for optimization via data collection, can be used to diagnose program inneffectualities and accelerate the optimization routine. For example, if the computer vision process notes declining plant health over time, the system can take preventative measures to recover yields.
- *Data Collection and Yield Optimization*: By collecting data via computer vision and post-harvest evaluation (dependent on available technology) on the plant's response to the induced environment ("plant metrics"), 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.). The relationship is then represented by a machine learning model via a method known as "surrogate modelling". This analysis is performed by the following method extracted from the Solution Overview (see attached PDF documents):

Assume a plant's growth rate (or state change) is related to its current internal state $\vec{P} \in \mathbb{R}^n$ (for n plant metrics) and the environment conditions $\vec{E} \in \mathbb{R}^m$ (for m environment parameters). Let these both be functions $\vec{P}(t), \vec{E}(t)$ defined at each t, where $t = 0$ indicates the time of planting. Assume that this relationship is constant for all members of a given species.

Define plant state change $\vec{P}'$:

$$\vec{P}'(t) = \frac{d}{dt}\vec{P}(t)$$

Define the plant-environment behaviour function Q:

$$Q(\vec{P}(t), \vec{E}(t), t) = \vec{P}'(t)$$

Given the current internal and external states, determine the plant's state change.

1. Set $\vec{E}_{set}(t)\ \forall\ t$, aka the program;
2. Record $\vec{P}(t)\ \forall\ t$ (plant metrics) and $\vec{E}(t) \approx \vec{E}_{set}(t)\ \forall\ t$ (environment sensors);
3. Calculate $\vec{P}'(t)\ \forall\ t$;
4. Fit $\vec{Q}$ to our data (machine learning model);

By fitting $\vec{Q}$, we can predict $\vec{P}$ at any $\vec{E}$ and t. For example:

$$\vec{P}(t + \Delta t) = P(t) + \Delta t \cdot Q(\vec{P}(t), \vec{E}(t))$$

Food Output Quality

Given the system can induce a wide and continuous range of environments, it can produce the environment suitable for any aeroponically-growable crop. Within the 2 square meters allotted to the solution, 16 PeaPods can be placed, resulting in a maximum of 16 different environments. The sum of the plants grown can be any combination of any number of suitable plant species (grouped into the same environment if suitable, i.e. different microgreens together), and as such, can be selected to meet all macro and micro nutrient requirements (with fortification or supplementation of those not found in plants). (https://www.healthline.com/nutrition/7-nutrients-you-cant-get-from-plants)

For example, quinoa - a crop already highly dense in nutrients (protein values 12-18%, unique amino acid composition high in lysine) - has shown excellent potential for hydroponic/aeroponic growth in controlled environments (https://ntrs.nasa.gov/citations/19940015664) with increases in nutrient density and yield (up to 37% harvest index aka edible yield mass percent). "Initial results indicate that quinoa could be an excellent crop for [controlled-environment agriculture] because of high contentration of protein ... and potential for greatly increased yields in controlled environments." *NOTE*: Despite promising results, the experiment cited was performed with "no attempt to maximize productivity". When combined with the optimization routine, yields could be maximized even further.

Other crops suitable to aeroponics are listed here alongside their benefits and some examples of nutrient analysis:

- *Microgreens* (sunflower sprouts, beansprouts, etc.) - Fast growth, edibility raw (minimal processing), more concentrated nutrients (9-40x higher than mature greens). High in

  a variety of vitamins and minerals. (https://www.healthline.com/nutrition/microgreens, https://www.webmd.com/diet/news/20120831/tiny-microgreens-packed-nutrients)
- *Legumes* (soybeans, chickpeas, etc.) - High caloric density. *For 100g boiled soybeans*: 173 Calories. High in protein (16.6g), carbohydrates (9.9g) which are mostly fiber (6.0g), polyunsaturated fats (5.1g) and Omega-6 fatty acids (4.5g). (https://www.healthline.com/nutrition/foods/soybeans)
- *Leafy Greens* (lettuce, spinach, cabbage, kale, etc.) - Fast growth (more bulk output, more filling), edibility raw (minimal processing), versatility. *For 100g raw spinach*: 23 Calories. Contains protein (2.9g) and carbs (3.6g) which are mostly fiber (2.2g), as well as a variety of vitamins (A, C, K1, Bfolic acid) and minerals (iron, calcium). (https://www.healthline.com/nutrition/foods/spinac
- *Herbs* (basil, mint, etc.) - Fast growth, utility in cuisine.
- *Berries* (strawberries, etc.) - Edibility raw (minimal processing), high palatability (sweet and delicious)
- *Garden Vegetables* (tomatoes, cucumbers, peppers, etc.)[8] - Edibility raw (minimal processing)
- *Root Vegetables* (potatoes, carrots, radishes)
- *Grains* (quinoa, oats, corn, rice, etc.) - High caloric density

Let it be noted that the primary goal of this design is not to satisfy the nutrient constraints. It is of the opinion of the submission team after extensive study that there is no way to produce 10,000 Calories in a 2 cubic meter environment via crop growth. The closest we got was a method for the production of microtuber potatoes as described in (https://doi.org/10.1007/BF02869609), which produces an estimated 2,000 Calories per day in a 2 cubic meter space.

Instead, this system caters to the human aspects - palatability and enjoyability, versatility of products for different cuisine, diversity of outputs, and the positive effects of growing plants on human emotional health, to name a few.

[8] I know they're technically fruits ok shut up

2.4.4 Reliability and/or Stability

Process Reliability

By nature of its design, PeaPod will last three years at near 100% functionality on minimal maintenance. This is achieved by self-monitoring component health, using servicable materials, and providing smart notifications to the user when maintenance is needed. For one, PeaPod is designed to be assembled by a single user with readily available tools. This means it can be disassembled, cleaned, and put back together by one person in a non-restrictive amount of time. For another, the sensors used to monitor plant health and growing conditions allow PeaPod to notify the user when a part needs to be fixed or replaced. For example, if humidity readings fall below historical levels for current water output, PeaPod will notify the user to replace the insulating material in the nozzle area. If light intensity begins to drop in a certain sector, PeaPod will tell the user to replace a certain bulb.

This said, every component in PeaPod has an expected lifespan over three years. From the LEDs (rated for 5 years) to the nozzle (only needs periodic cleaning) to the bonding agents (tested for materials used), replacement monitoring is only needed as a backup.

Scheduled maintenance breaks down to three primary tasks: refilling nutrients, cleaning spray nozzle, and harvesting/replacing plants. Since PeaPod mixes the nutrient solution automatically, the only required maintenance is replenshing stores of water and individual nutrients. By tracking consumption rates and using past trends, PeaPod can schedule the most efficient refill time in advance and notify the user. The spray nozzle, by way of its fine mesh, will build fine amounts of sediment over time. This can be easily cleaned by the user at either pre-determined times or, as mentioned above, when the unit detects an issue. Finally, plant harvesting is a quick task that simply constitues opening the unit and removing the plant. Replacing it only requires the user to open the unit, place the seed in the grow cup, and digitally set the grow conditions for PeaPod to follow.

Input and Output Stability

PeaPod's input stability is maximized by a variety of design choices, the sum of which give them a shelf life above the three-year mark of a mission. Since the system doses nutrients automatically and at a high-degree of precision, nutrient solution can be stored at a much greater density than would be possible with manual mixing. This minimizes degradation and loss of quality while reducing the space needed to store the solutions. Since the solutions can be stored in such a compact manner, it is feasible to store them in an insulated, opaque container that minimizes fluctuations in environment that could stimulate degredation. And, by utilizing the electrical infrastructure of PeaPod itself, it is trivial to maintain a set temperature within this container that further hampers deterioration.

Outputs will have a shelf life that is, in worst case, comparable to fresh produce grown outdoors. More realistically, crops are expected to last longer as a result of a lack of pests, disease, and optimization of characteristics for ambient conditions nearby. These are the result of PeaPod's isolated enivornment and data collection capabilities. For example, the same sensors used to optimize growth conditions can then be used to optimze traits for the given storage conditions, letting researchers select for crops and characteristics that will last the longest. Finally, PeaPod can let users grow crops on a rotation, providing a steady supply of fresh produce that will not need to be stored for particularly long periods of time, thus circumventing some of the restrictions posed by growing fresh crops.

2.5 Terrestrial Potential

Customer-facing Food Service

At present, a restaurant requires either a local supplier or a substantial amount of outdoor space (and labour) to serve fresh produce. Both of these are cost-prohibitive, and the latter is entirely impossible in many situations. Local suppliers' high costs are the result of a few things:

- Limited seasonal availability
- Frequent transport need
- High costs with little demand

PeaPod has the potential to reduce these barriers in a cyclic way. Partnerships between local suppliers and restaurants will provide these restuarants with space- and time-efficient PeaPod units with the purpose of generating both produce and data. The increase in produce will reduce the frequency at which suppliers need to make deliveries, while the data produced will let suppliers maximize output. Over time, this can increase efficiency to the point where local suppliers can provide produce at a lower price.

Crowdsourced Research

Due to PeaPod's automated nature, off-site research is a feasibile method of collecting data. As a result, universities and other institutions can save costs related to space and energy usage by subsidizing PeaPods to consumers, schools, or even restaurants. Users would receive sets of paramters within which to grow crops, and the data would be sent back to the institution. The user can use the produce, at the cost of space and energy, while the institution continues to provide parameters with which to grow. The end result is a massive set of data, conducted in identical conditions in different places, verified by comparison with the myriad devices conducting the same tests.

De-centralized Production

Many crops are only feasible in certain climates, making global transport a necessity to sell them worldwide. This reduces freshness, necessitates various preservatives, and increases carbon consumption. By upscaling PeaPod technology to a farm scale, it becomes possible to produce climate-bound crops in any location. This creates region-based farms that can produce a tremendous variety of crops, vastly reducing transport needs and making it easier to have a local food diet.