# GAIA (*G*reenhouse *A*ttachment for the *I*ce Home *A*rchitecture)

## NASA's BIG Idea Challenge 2019

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Acronyms

| | |
|---|---|
| AURA | Astronaut Urine Repurposing Apparatus |
| BAS | Building Automated System |
| BSF | Black Soldier Fly |
| EDL | Entry, Descent, and Landing |
| GAIA | Greenhouse Attachment for Ice home Architecture |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IAQ | Indoor Air Quality |
| ISRU | In-Situ Resource Utilization |
| NFT | Nutrient Film Technique |
| PAR | Photosynthetically Available Radiation |
| PPA | Plant Processing Area |
| PtPPGE | Post-touchdown Progressive Plant Growth Escalation |
| PVC | Polyvinyl chloride |
| RH | Relative Humidity |
| SLS | Space Launch System |
| UV-C | Ultraviolet Type C |
| WSN | Wireless Sensor Network |

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# I. INTRODUCTION

The first greenhouse to enable a human presence on Mars is one of the most unique yet fundamental components. It must sustainably produce a variety of crops to provide astronaut nutrition and stimulate morality. At times, Mars is over 400 million kilometers from Earth, so it is imperative this greenhouse symbolizes the biotic familiarity of home. To achieve these goals, we present the Greenhouse Attachment for Ice Home Architecture -- GAIA -- named after the Greek goddess of Earth. As a well-rounded team with expertise in horticulture, biology, and engineering, our design includes a robust greenhouse that sustainably provides a balanced and realistic diet, while creating an enjoyable experience for the crew members.

# II. GREENHOUSE DESIGN

The design of GAIA considers the Martian physical environment and accommodates for activities required for food production, leisurely plant growth interactions, and research. Such considerations include the ability to perform the following:

- Crop production that feeds a 4-astronaut crew for a 600 day mission
- Autonomous operations that compensate for the distance and resupply time from Earth
- Automation and technology that record fundamental data, maintain environmental conditions, and integrate remote interaction
- Crop growth systems that foster a variety of species while accommodating multipurpose or impromptu uses
- Systems and hardware that maintain a habitable environment and minimize resource consumption within the Ice Home Concept (ASHRAE 90.4, 2017)
- Overall design and orientation that incorporate available resources into the ecosystem

This list of primary design requirements contribute to a multifunctional Martian greenhouse that integrates both crew interaction and remote interface. In addition to these considerations, design constraints such as transporting equipment to Mars, presents unique challenges. Assuming GAIA is launched on a Space Launch System (SLS) Block 2 Cargo variant, the maximum greenhouse payload mass is 18,000 kg after safety factor (Big Idea Website, 2018). The maximum dimensional limits when stowed in the Entry, Descent, and Landing (EDL) aeroshell are 6.7 m in diameter and 9.3 m in height (Big Idea Website, 2018). GAIA payload must be compact; light; easily assembled, operated, and maintained; and functional after extended stowage. Acknowledging these considerations and challenges helps successfully merge GAIA with the Ice Home, as discussed in the following sections.

## A. Deployment

GAIA deployment applies the same protocol used for the Ice Home, with slight additions to accommodate crop growth hardware, and applies lessons learned from the Ice Home deployment. After landing in the operational location, robotic assets ensure a proper distance and orientation from the Ice Home habitat. Power and data cables attach to GAIA, and after the Earth-based team confirms nominal performance, air pumps inflate GAIA by bringing filtered Martian atmosphere into the greenhouse. This additional set of air pumps for the greenhouse can be used to inflate either dome, should the Ice Home air pumps ever be inoperable.

After GAIA is fully inflated and confirmed to be holding pressure, water collected through In-Situ Resource Utilization (ISRU) fills the water cells. When enough water collects in these cells, GAIA freezes in the shape of the water cells. The water freezes slowly to produce as large of ice crystals as possible, limiting the amount of surfaces that can scatter light and, therefore, producing ice cells that are more transparent.

Finally, after confirming GAIA is nominally holding weight, robotic assists connect the two airlocks, described below, to GAIA and the Ice Home habitat. In addition, load bearing arms unfold from the center core of the greenhouse to support the floors of the greenhouse and the water system tubing is put in place, with the primary connection tubing surrounding the greenhouse at the base of the plant growth racks.

## B. Outfitting

After the floors are fully deployed, robotic assists unpack the second floor plant racks, shown in Figure 1, into the greenhouse via the airlock. These racks arrive in a folded state in order to fit on the lift within the “Chemistry lab/storage space” area. After arriving on the second floor, the racks are locked into the moving shelving system slots and connected to the water and power systems.

The items and furniture within the “Chemistry lab/storage space” and “Plant Processing Area” (PPA) remain as cargo until placed by the crew members as they prefer.

## C. Layout and Post-Landing Initiation (ConOps)

The layout of GAIA is incorporated into the Ice Home design (NASA Langley, 2017) and considers the aforementioned conditions, constraints, and goals of this system. This layout further accounts for crop production time, volume, inputs, byproducts, and post-harvest processing. A ConOps of GAIA deployment and the support system layout uses a Post-Touchdown Progressive Plant Growth Escalation (PtPPGE) approach. PtPPGE deploys plant growth activities to fulfill dietary needs via a 3-step timeline that begins when humans land on Mars. Step 1 addresses immediate nutritional needs upon arrival as well as serving as a proof that systems are functioning properly, while Step 2 uses the deployed equipment to increase crop variety and yield. Step 3 is the long-term plan that incorporates biomass and oxygen from crops and Martian regolith, while promoting ecological activity and research.

## D. System Support and Equipment

System support in GAIA includes electricity, water, breathable air, network link, wireless fidelity (Wi-Fi), and 3D printing (Table 1). In the time window between initial Ice Home ConOps and human arrival, an oxygen- and moisture-enriched environmental condition is maintained by an AI-incorporated building automated system (BAS). The BAS uses a heating, ventilation, and air conditioning (HVAC) system to control temperature, gas concentrations, and humidity.

Thermodynamics and heat transfer cause heat produced by the support systems and potential sun to raise the temperature in GAIA. Air movement fans located at the top of the structure move the warmer air through heat transfer channels within the the ice layer, prior to feeding air into the HVAC system for heating or cooling. Using ice to cool heated and humid greenhouse air prior to to the HVAC saves energy consumption while maintaining environmental conditions.

Crew members initiate Step 1 of the PtPPGE upon arrival by establishing microgreens, which are available 3-5 days after initiation. Meanwhile, the crew begins Step 2 to address intermediate crop production by establishing the remaining plant, fungus, and insect species. Over time, the crew uses Step 3 to incorporate biomass and photosynthetic oxygen to the system and enjoy the symbolism of Earth that GAIA provides. Under Step 3, the crew also researches the preparation process of Martian regolith as a plant growth substrate.

| Item | Description | Mass (kg) | Power (W) |
|---|---|---|---|
| External Structure | Ice Home inflatable external structure | 988 | - |
| Internal Structure | Internal support structure | 5,250 | - |
| HVAC (Air Handling/Gas Control/IAQ) | AI incorporated BAS/Gas monitoring, multi interface control, sensor and environmental parameter controls | 400 | 1,120 |
| Ice/Environment heat transfer system | Pre-HVAC air circulate heat through ice structure | 80 | 300 |
| Electrical (110 V - 220 V) | NEC Standard and power distribution system | 50 | 500 |
| Communications | Communications to networking systems, Fiber Optic Networking (or latest technology) | 300 | 150 |
| Airlocks | Dual-Chamber Hybrid Inflatable Suitlocks (DCIS) with gas exchange addition (w/ BEAM mass estimation) and robotic deployment | 2,826 | 1,000 |
| Waste Management | Compost/Water Reclamation / Human Waste | 175 | 1,500 |
| Chemistry Lab | Essential Chemicals and Lab Equipment | 150 | 150 |
| Storage and Sterilization | Autoclave/Dehydrator/Refrigerator/Freezer (PPA) | 120 | 2,300 |
| Plant/Black Solider Fly Lighting | Variable Natural Lighting Dependent PAR/BAS paired | 63 | 6,314 |
| Hallway lighting | Any lighting not designated for plant growth | 30 | 953 |
| Plant Monitoring Systems | Electronic systems to monitor plant health and communication system | 50 | 100 |
| Growth Media / Seeds | Primary Hydroponic (NFT) Systems / Plant Growth Containers / Growth Structures / Seeds | 140 | - |
| Greenhouse Fluids and Nutrient Solution | DI water and nutrient solution / pH mixing systems (on tap) | 600 | - |
| Plant Preparation / Harvest Area | 3D printer / Mill / Oil Press / Tresher / Mess area / Sink and wash area | 400 | 3,000 |
| Plant Irrigation Variable Control | Multi-interface nutrient solution and irrigation variable control | 40 | 100 |
| **Total before Margin** | | 11,662 | 17,487 |
| Margin | 25% Added Margin | 2,916 | 4,372 |
| **Total** | | 14,578 | 21,859 |

Table 1: GAIA Systems and equipment, with corresponding mass and power requirements.

Earth-based participants use technology and automation to monitor plant growth and interact to limit required crew time. The automation uses ambient solar lighting levels to manage photosynthetically active radiation (PAR) and conserve energy. Further, a crew member has interaction expectations of crop initiation, periodic monitoring as directed by Earth scientists, harvest, and cleanup. Finally, the crew is alarmed if immediate crop growth needs arise.

## E. Airlock System

To pass between the Ice Home habitat and GAIA, there are 2 Dual-Chamber Hybrid Inflatable Suitlocks (DCIS), designed by Scott Howe and Kriss Kennedy (Howe et al., 2011). This airlock, built and proven in the NASA Desert Research and Technology Studies (D-RATS) analog field tests in 2011, is also consistent with the airlock used in the original Ice Home Mars Habitat Concept of Operations (Kempton et al., 2017). This design commonality, as opposed to varying from the airlock used by the Ice Home Mars Habitat, allows for simpler repair of the airlocks and shared replacement parts, as needed. As the DCIS does not yet have a mass estimate, we speculate that the mass is similar to that of the Bigelow Expandable Activity Module (BEAM), being of similar size and material, at 1,413 kg each (Kremer, 2016).

This redundant airlock system provides a risk-mitigating, single-point tolerance that allows crew members to travel between the Ice Home habitat and GAIA even when one airlock is damaged. When both airlocks are nominal, crew members can travel in either airlock regardless of their direction.

This airlock system also maintains a higher $CO_2$ concentration in GAIA. Using a 2 door system, only the air that enters the airlock when a crew member walks in from the departing dome mixes with the destination dome. While this system limits the amount of $CO_2$ that leaves the greenhouse area, there are also 2 air shafts that connect the Ice Home habitat to GAIA. When $O_2$ in GAIA becomes too high due to plants photosynthesizing, when $CO_2$ in the Ice Home habitat becomes too high due to human respiration, or when $CO_2$ GAIA becomes too low due to air exchange in the airlocks, fans kick on in these air shafts. These fans force the air at membrane gas exchange “filters” to allow only $CO_2$ to pass through to GAIA or $O_2$ to pass through to the Ice Home habitat. Retentate gases from this process are rerouted back to their origin dome.

## III. CROP SELECTION

One of the more unique aspects of our concept is its ability to almost fully supply the astronauts diet after the first round of crop cycles are completed. In order to achieve this complete diet, a thorough trade study was conducted regarding which crops (1) would be able to supply the astronauts with the proper nutrients, while also (2) being able to be grown in the GAIA environment and (3) provide for varied palatability. This section describes these three elements that are important for the astronaut diet.

### A. Crop Selection for Feasibility

The following crops are ideal for GAIA based on fitness, nutrition, and palatability (Table 2). Crops considered highly fit have moderate statutes and days to maturity, can produce fruit in the absence of unavailable pollinators, have single-harvest cultivars when possible, require minimal post-harvest processing, and produce limited refuse. Thus, crops requiring large areas and high inputs, such as Cucurbitaceae species, corn (*Zea mays* L.), and tree and shrub fruit, are not ideal. Long-maturing biennials and perennials like kohlrabi (*Brassica oleracea* L.) and asparagus (*Asparagus officinalis* L.), respectively, have been omitted. Further, the selected crops are not recalcitrant species, so seeds can be successfully cold stored without detrimentally affecting viability.

### B. Crop Selection for Nutrition

The selected crops also optimize nutrition to meet crew dietary goals (USDA, 2018). Table 2 includes an example of a day’s menu, including 3 meals, a sweet snack or dessert, and tea. By using the most nutrient-dense ingredients, this menu provides enough nutrition to the crew members without requiring excessive eating. The example menu achieves 100% of the daily energy requirement, approximately 65% of the daily water requirement, high protein, and a moderate amount of carbohydrates (USDA, 2018). In addition, menus can be tailored to fit individual crew members’ nutritional needs and recommended dietary allowances for vitamins and minerals. These customized parameters are calculated via the basal metabolic rate (BMR) equation -- also called the Harris Benedict Equation -- which accounts for gender, weight (W), height (H), and age (A). The BMR equation is used to quantitatively assess if a crew member is obtaining her or his caloric requirements. The gender-specific BMR equations are as follows:

Women:

$$BMR = 655 + (9.6 \times W) + (1.7 \times H) - (4.7 \times A)$$

Men:

$$BMR = 66 + (13.7 \times W) + (5 \times H) - (6.8 \times A)$$

| Latin name | Serving Size | Recipe Inputs (g) | | | | |
|---|---|---|---|---|---|---|
| | | Breakfast Skillet | Baked Sweet Potato Lunch | Stir Fry Dinner | Strawberries & Mint Tea | Daily Crew Amount Needed (g) |
| Chives (*Allium schoenoprasum* L.) | 3 g (1 Tbsp) | | 3 | | | 12 |
| Tarragon (*Artemisia dracunculus* L.) | 3 g (1 Tbsp) | | | 2 | | 8 |
| Swiss chard [*Beta vulgaris* L. ssp. *cicla* (L.) W.D.J. Koch] | 36 g (1 cup; 0.75 leaf) | | | 18 | | 72 |
| Kale (*Brassica oleracea* L. var. *acephala* DC.) "Red Russian" | 67 g (353 mL) | 35 | | 35 | | 280 |
| Broccoli (*Brassica oleracea* L. var. *italica* Plenck) "Happy Rich" | 91 g (260 mL) | 46 | 30 | 46 | | 488 |
| Collards (*Brassica oleracea* var. *viridis* L.) | 36 g (658 mL) | | | 18 | | 72 |
| Peppers (*Capsicum annuum* L.) "Triton" | 45 g (535 mL) | 45 | 23 | | | 272 |
| Strawberries [*Fragaria × ananassa* (Weston) Duchesne ex Rozier] | 144 g (163 mL) | | | | 145 | 580 |
| Sunflower seeds (*Helianthus annuus* L.) "Aurora" | 46 g (168 mL) | 46 | | 46 | | 368 |
| Sunflower oil (*Helianthus annuus* L.) "Aurora" | 14 g (1 Tbsp) | 14 | 7 | 14 | | 140 |
| Black soldier fly (BSF) (*Hermetia illucens* L.) | 100 g (118 mL) | 100 | 90 | | | 760 |
| Sweet potato tubers, with skin [*Ipomoea batatas* (L.) Lam.] | 130 g (182 mL) | | 130 | | | 520 |
| Sweet potato leaves [*Ipomoea batatas* (L.) Lam.] | 35 g (677 mL) | | | 25 | | 100 |
| Lettuce (*Lactuca sativa* var. *crispa* L.) "Outredgeous" | 28 g (845 mL) | | 14 | | | 56 |
| Spearmint (*Mentha spicata* L.) | 0.3 g (2 whole leaves) | | | | 2 | 8 |
| Oregano (*Origanum vulgare* L.) | 3 g (1 Tbsp) | | | | | 0 |
| Rice, long-grain brown (*Oryza sativa* L.) | 195 g (438 mL) | 100 | | | | 400 |
| Tomatoes (*Solanum lycopersicum* L.) "Red Robin" | 149 g (159 mL) | 75 | | 75 | | 600 |
| Potatoes, red with skin (*Solanum tuberosum* L.) | 170 g (140 mL) | 350 | | 360 | | 2,840 |
| Spinach (*Spinacia oleracea* L.) | 30 g (788 mL) | 15 | | 15 | | 120 |
| Thyme (*Thymus vulgaris* L.) | 2.4 g (1 Tbsp) | | | 2 | | 8 |
| | **NASA Daily Requirements** | **Supplied Daily Nutrient Intake** | | | | **Total of Daily Requirements (%)** |
| Energy [kcal/100g] | 2,823 | 1,489 | 579 | 718 | 49 | 100 |
| Protein [g/100g] | 85 | 69 | 40 | 22 | 1 | 156 |
| Fat [g/100g] | 94 | 71 | 33 | 40 | 0 | 153 |
| Fiber [g/100g] | 25 | 25 | 11 | 17 | 3 | 224 |
| Carbohydrates [g/100g] | 353 | 153 | 32 | 80 | 11 | 78 |
| Water Content [g/100g] | 2,000 | 496 | 167 | 507 | 134 | 65 |
| **Mineral Composition (DM)** | | | | | | |
| Calcium [mg/100g] | 1,000 | 1,153 | 905 | 316 | 27 | 240 |
| Potassium [mg/100g] | 3,500 | 3,272 | 1,067 | 2,730 | 231 | 209 |
| Magnesium [mg/100g] | 350 | 569 | 205 | 319 | 20 | 318 |
| Phosphorus [mg/100g] | 1,500 | 1,279 | 419 | 635 | 36 | 158 |
| Sodium [mg/100g] | 2,400 | 214 | 170 | 162 | 2 | 23 |
| Iron [mg/100g] | 10 | 15 | 7 | 8 | 1 | 307 |
| Zinc [mg/100g] | 15 | 12 | 6 | 4 | 0 | 149 |
| Manganese [mg/100g] | 5 | 11 | 6 | 2 | 1 | 401 |
| Copper [mg/100g] | 2 | 2 | 1 | 1 | 0 | 236 |
| Selenium [ug/100g] | 70 | 45 | 2 | 28 | 1 | 109 |
| **Vitamin Content (DM)** | | | | | | |
| Vitamin A (Retinol) [RAE: ug/100g] | 1,000 | 254 | 1,064 | 1,257 | 6 | 258 |
| Vitamin C (Ascorbic acid) [mg/100g] | 100 | 187 | 66 | 138 | 86 | 477 |
| Vitamin B-1 (Thiamin) [mg/100g] | 2 | 2 | 1 | 1 | 0 | 288 |
| Vitamin B-2 (Riboflavin) [mg/100g] | 2 | 2 | 2 | 1 | 0 | 244 |
| Vitamin B-3 (Niacin) [mg/100g] | 20 | 23 | 8 | 10 | 1 | 208 |
| Vitamin B-5 (Pantothenic acid) [mg/100g] | 5 | 7 | 5 | 2 | 0 | 285 |
| Vitamin B-6 (Pyridoxine) [mg/100g] | 2 | 3 | 1 | 2 | 0 | 270 |

Table 2: Selected crops list with sample recipes and corresponding nutrition.

In the GAIA system, optimal varieties or cultivars have been chosen to further optimize nutrition. For example, red tomatoes are denser in lycopene than orange or yellow tomatoes, so the cropping system includes a high-yielding dwarf red cultivar (*Solanum lycopersicum* L.) "Red Robin" that is also structurally ideal for systems with limited space (USDA, 2018). Further, red potatoes (*Solanum tuberosum* L.) and red leaf lettuce (*Lactuca sativa* var. *crispa* L.) "Outredgeous" have been selected for having higher energy and mineral concentrations than white potatoes and green leaf lettuce, respectively, and while spinach (*Spinacia oleracea* L.) is the most nutrient-dense leafy green, other leafy greens are also included for diet variety (USDA, 2018).

Certain insects can increase nutrient retention within a biological system by converting low-grade organic matter to higher quality edible biomass (Katayama, 2007). In general, insects have high feed-to-biomass ratios, are smaller than other livestock, are more feasible for transport from Earth, and are easier to rear than aquatic species. Silkworms (*Bombyx mori* L.) and crickets (*Acheta domesticus* L.) are common edible insects, but black soldier flies (BSF) (*Hermetia illucens* L.) are the best-suited addition to GAIA, ultimately increasing bioregenerative capacity (Tong et al., 2011; Schlüter & Rumpold, 2012). BSF also provide a source of vitamin B-12, which is not found in plants apart from fortified cereals (Pawlak et al., 2013). In the United States, BSF are gaining recognition for their role in providing sustainable and nutritious livestock feed and for their waste reduction capacity (Wang & Shelomi, 2017; Oonincx et al., 2015). As detritivores, BSF feed solely on decaying organic matter such as food waste, crop residues and refuse, and manure/fecal sludge, while converting 40-60% of the waste biomass into higher quality, edible BSF larvae (Lalander et al., 2015; Wang & Shelomi, 2017). Despite the potential range in diet, BSF in the GAIA cropping system are only raised on substrates approved for livestock like vegetarian food waste and crop residues. BSF are not vectors of disease, and myiasis -- the largest yet rare potential human health risk associated with BSF -- only causes minor diarrhea and can be eliminated via proper sanitation and processing (Wang & Shelomi, 2017; Belluco et al., 2013).

The GAIA cropping system does have two nutrient deficiencies: sodium and vitamin D. The crops grown in GAIA naturally supply approximately 25% of the daily sodium requirement, but adding salt to 2 meals fulfills the remaining sodium needed. For spaceflight, crew members need to maintain a diet rich in vitamin-D to protect muscles and bones (Casaburri, 1999). Mushrooms like shiitake [*Lentinula edodes* (Berk.) Pegler] have been explored as a source of vitamin D; however, mushrooms supply only a fraction of the daily requirement and require inputs and maturation time deemed too great for the GAIA system. Therefore, crew members must obtain vitamin D supplementally. All other nutrients, like vitamin K, are achieved in the GAIA cropping system. Vitamin K is vital for blood clotting and protein development in bones, the latter of which promotes structural support for bone calcium (Casaburri, 1999).

### C. Crop Selection for Palatability

The proposed menu is only one example of a day's meals, and the GAIA cropping system optimizes variety within the limited space. Other recipe ideas include loaded sweet potato fries, salsa, and spicy fried BSF. Meal flexibility aims to provide crew members with ample nutrition while keeping morality high. Hot chili peppers (*Capsicum annuum* L.) "Triton" add spice to meals, while herbs add a variety of flavors to dishes. Although strawberries [*Fragaria* × *ananassa* (Weston) Duchesne ex Rozier] require specialized care in transit to Mars -- as will be discussed below -- providing crew members with a sweet fruit crop can help satisfy sugar cravings. Additionally, sustainably growing a variety of crops like the many leafy greens can give crew members excitement and senses of choice when working with the crops and preparing meals. Broccoli (*Brassica oleracea* L. var. italica) "Happy Rich" has leaner stems than typical cultivars, which is easier to prepare and more tender.

When considering crop selection as a whole, the GAIA cropping system is designed to provide crew members with high nutrition and involved activities, without burdening their schedules. In the case of broccoli, "Happy Rich" is more optimal than other lean-stemmed cultivars like "De Cicco," due to "Happy Rich" being a single-harvest cultivar. Continuous-harvest cultivars such as "De Cicco" require greater crew time.

## IV. FOOD PRODUCTION SYSTEMS DESIGN

After selecting which crops would provide a complete, yet varied diet for the astronauts, we developed a set of plant growth systems that would efficiently grow these crops. This included implementing three different plant growth systems for the various crops in the GAIA greenhouse as well as constructing a plant growth rack that allows for environmental control and efficient space utilization.

### A. Systems Selection

Hydroponic systems are the most suitable option for the Martian environment and GAIA. Martian regolith contains perchlorate salts, which threaten crew health by impairing the thyroid gland and ultimately inhibiting iodine ion uptake and hormone output (Davil et al., 2013). Further research is needed to determine the link between the chemical composition of Martian regolith and human health, as well as the procedures necessary to alter the regolith for suitable plant growth . Thus, hydroponic systems offer a safe plant growth medium that can optimize crop yield and water consumption.

Food production on Mars is not only vital for the crew diet but also for bioregenerative life support processes. Within the closed system of GAIA, plants lessen the reliance on synthetic $O_2$ production and $CO_2$ removal (Wheeler, 2010), while recycling wastewater through the hydroponic systems and reclaiming clean water from humidity condensation (Wheeler, 2004). These bioregenerative benefits can supplement automated processes as available, potentially increasing the lifespan of related equipment. The hydroponic systems provide structural support, vital gases like $O_2$ and $CO_2$, ions, and nutrient solution to the plants. As roots expand, plants receive more support and access to nutrient solution. The hydroponic systems must allow $O_2$ to diffuse into the media and $CO_2$ to diffuse out to avoid root hypoxia . In assessing the growing media for hydroponics, there needs to be close attention to whether the media provides support, appropriate pore size to allow for water retention, and minimal imbalances in the nutrient solution (Stack, 2016). In a hydroponic system, the three main macronutrients that affect plant growth are nitrogen, phosphorus, and potassium. Nitrogen is needed for foliage expansion. Phosphorus aids in root architecture, flower production, and seed production. Potassium increases the chlorophyll concentration in the foliage and regulates the opening and closing of the stomata for gas exchange processes. (Candanosa, 2017). GAIA implements 3 hydroponic system styles: drip, pond, and nutrient film technique (NFT).

Drip systems utilize a micro-irrigation technique via the use of small emitters to drip nutrient solution directly onto crops. This system conserves water by intermittently spraying. Drip system hardware includes drip emitters, thin tubing, polyvinyl chloride (PVC) tubing, a water pump, tray, large bucket, plants pots/containers, pump timer, aquarium grade silicone sealant, hydroponic growing medium, and other power tools to cut the pipes. The PVC tubes carry water and nutrient solution from the reservoir pump to the drip emitters, which fall onto the crops via the thin tubes. Drip pressure can be tailored by modifying the water pump. Plants are grown in individual pots, allowing crew members to control irrigation rates. Since larger plants require more growing media and water, drip systems are ideal to help retain water. Slow draining media like rockwool, peat moss, and coconut coir also provide optimal water delivery for the crops. (Max, 2017). Drip systems are used for sunflower (*Helianthus annuus* L.) “Aurora” and broccoli production.

Pond systems utilize shallow beds and circulating nutrient solution over and around the root zones of the plants. There are two types of pond systems: static and circulating pond systems. In a circulating pond system, the nutrient solution passes through filters before returning to the tanks. In a static pond system, the nutrient solution is replaced before and after each crop cycle. Oxygen content needs to be monitored as there is limited oxygen exchange between the atmosphere and the nutrient solution. (Gill, 2015) Oxygenation of the nutrient solution is facilitated through a pump system to integrate air into the solution. (Purdue, 2018) Pond systems are used to grow the dwarf, brown long-grain rice (*Oryza sativa* L.).

All other crops are produced in NFT systems, which circulate shallow streams of nutrient solution water through channels and supply $O_2$ to plant roots (Purdue, 2016). In a NFT system, there are channels or gutters laid on a slope of an incline between 2-3% upon which nutrient solution is filtered from the supply tank. Filters can be placed in the NFT system to remove debris when the solution returns to the supply tank (Gill, 2015). Seeds are planted into propagation cubes, which structurally support the plants while allowing the roots to rest in the circulating nutrient solution. Pore space within the propagation cubes delivers nutrient solution and aeration to the roots that are long enough to submerge in the solution below (Morgan, 2018). The pH of the nutrient solution can be adjusted with providing an acid such as nitric acid, phosphoric acid, or sulfuric acid to lower the pH. In raising the pH, a base such as potassium hydroxide, sodium hydroxide, or potassium bicarbonate can be added (Gill, 2015).

## B. Greenhouse Layout

The principal structure of plant production areas in GAIA is a multilayered, hydroponic plant growth rack. To conserve space, the plant growth area is consolidated to mobile racks, each separated into multiple shelf sections. The height of each shelf section is based on the depth of the NFT channels and estimated plant height with an additional 20 cm buffer. The height buffer accounts for potential increases in plant height due to reduced gravity and also increases canopy accessibility during harvest. While some of the taller crops, such as sunflowers and rice require fewer numbers of shelf units, smaller crops, such as many of the leafy greens, are placed in 5-shelf racks (Figure 1). Specifically, sunflowers and rice are grown on 2-shelf racks, potatoes, sweet potatoes, broccoli, strawberries, kale, collard, and chard are grown on 4-shelf racks, and tomatoes, peppers, lettuce, and spinach are grown on a 5-shelf rack. Each rack is mobile and fits concentrically with the walls of the greenhouse, using 15° of the greenhouse circumference. The mobile rack system, based on mobile bookshelves in libraries, shifts shelves along a circular track. Racks can rest flush against one another until a specific track must be accessed for harvest, maintenance, etc. GAIA optimizes plant growth space with a total of 11 racks on the first level (Figure 2) and 21 racks on the second level (Figure 3).

Each shelf of each rack can be a closed off to all other shelves through walls on each side of the plant rack. This not only allows for each plant shelf to have independent lighting, temperature, and fan speeds but it also reduces risk the risk of a pathogen spreading through the greenhouse. If it is detected that a pathogen is present in a crop, the respective fan vents can be closed in order to isolate the pathogen until it is contained and removed.

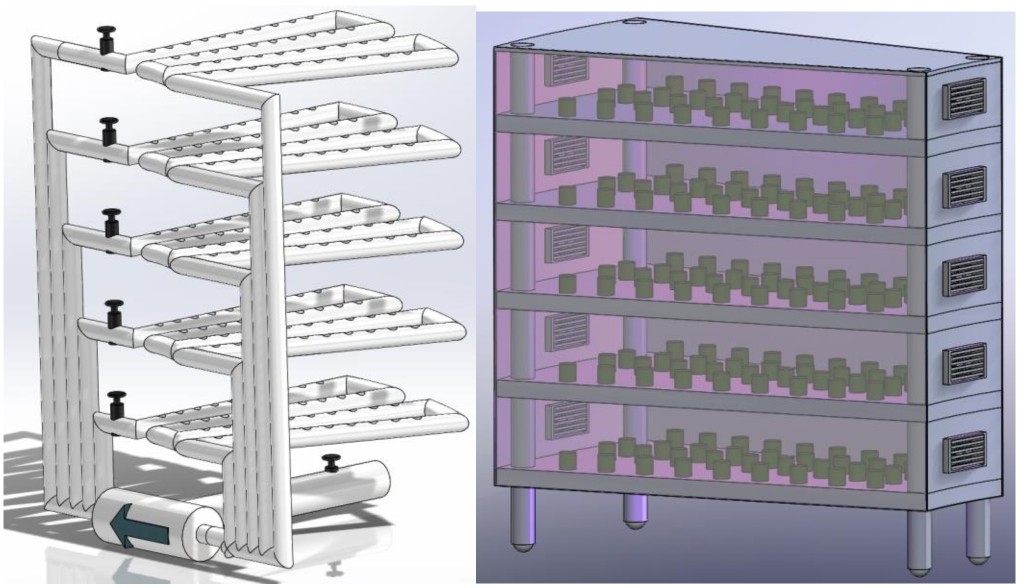

Figure 1. Example of a 5-shelf NFT hydroponic system (left) with water system valves used to produce smaller crops like leafy greens. The system is housed within a mobile rack (right), which includes ventilation and high-gloss walls. The walls, shown as partially transparent in this rendering, enclose the system for customizable environmental plant growth parameters.

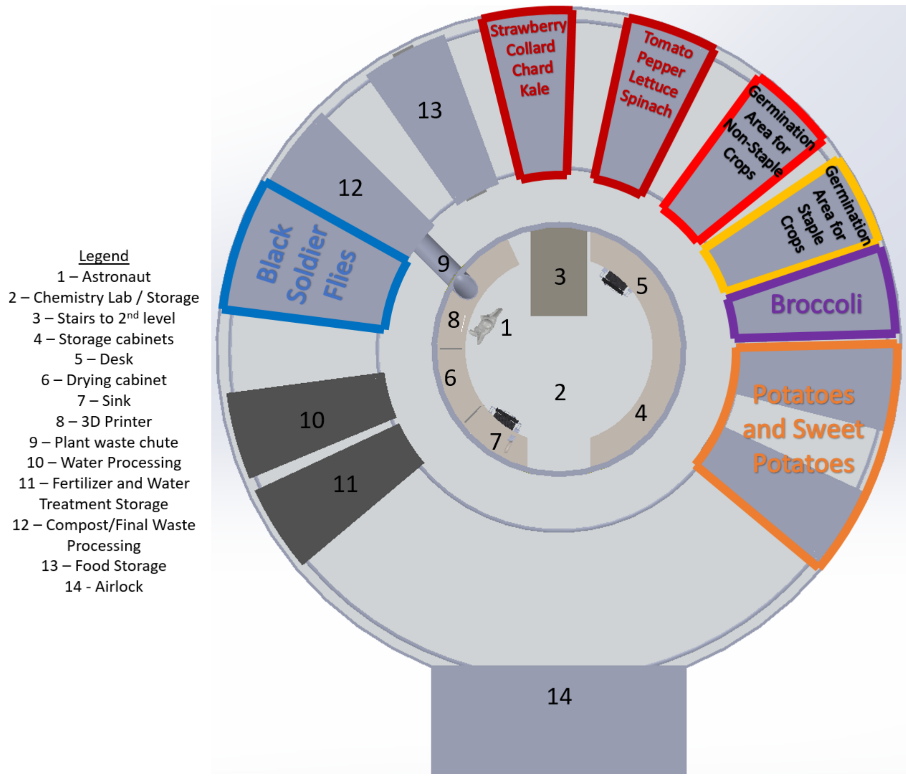


Figure 2. The first level of GAIA, with 9 mobile plant growth racks and 2 stationary racks, being the black soldier fly rack and the Compost/Final Waste Processing (12) rack.

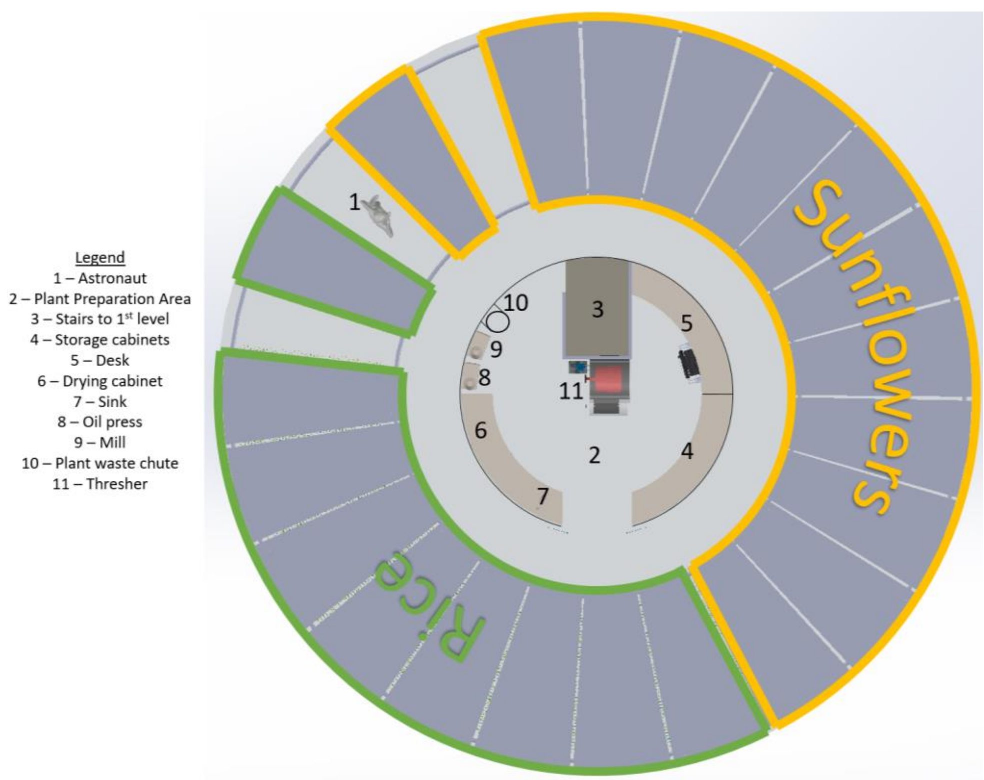


Figure 3. The second level of GAIA, with 21 mobile plant growth racks.

For all three hydroponic system styles, water valves can stop circulation at interim points if ever needed. The overall modular design allows an entire rack to detach from the greenhouse water system via a valve under the rack, as seen in Figure 1. This main valve is most often utilized when the rack is moving along the track rails. When a rack is in motion, the main valve automatically detaches from the larger water system. Once the rack stops at one of the designated attachment positions along the track system, the valve aligns with the water system output and reattaches. This automatic system prevents crew members from manually switching the valves, ultimately keeping crew members safe while limiting crew member procedure time. However, not all racks are mobile. The BSF rack is static to prevent stressing the insects, and the Compost/Final Waste Processing cannot be moved due to its connection to the BSF system and the Plant Waste Chute.

The lighting system uses triple-band LED bars, similar to those currently produced by Agrivolution LLC. Ultraviolet type C (UV-C) lights are also included for post-harvest cleaning, as discussed in section 6, Post-Harvest & Safety. Each bar is 1.2 m long and uses 23 W. To sufficiently illuminate the plants of each shelf, 6 bars are needed per shelf, aligned as 3 rows of 2 end-to-end bars. With a total of 67 plant shelves, the GAIA system uses a total of 402 bars, requiring 9,246 W. Staggering the diurnal cycles of the crops across 3 cycles helps optimize energy consumption, using a constant 6,164 W (Figure 4).

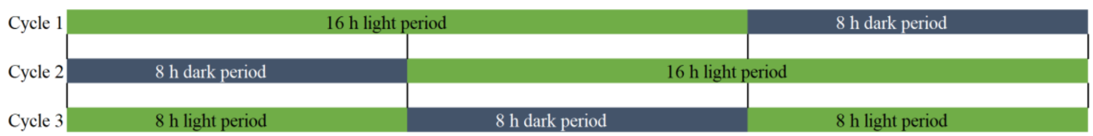

Figure 4. Off-set diurnal crop cycles, which help lower hourly energy consumption.

Plant growth racks are shielded from potential light pollution during dark periods with high-gloss walls. These partitions also allow individual rack to be programmed with environmental settings optimal for each crop. On average, nutrient solution pH ranges from 5.8 to 6.5, nutrient solution EC ranges from 1.8 to 3.5 mS $cm^{-2}$, air temperature ranges from 14 to 27 C, and RH ranges from 50 to 70% (Philipsen et al., 1985). However, further focusing these ranges, as well as plant spacing, to best fit each crop can help select for the best possible yields. Cool season crops such as like lettuce, spinach, kale (*Brassica oleracea* L. var. *acephala* DC.) "Red Russian," Swiss chard [*Beta vulgaris ssp. cicla* (L.) W.D.J. Koch], and broccoli should not be grown at above 21 C, which is preferred for warm season crops like tomatoes, peppers, and sweet potatoes [*Ipomoea batatas* (L.) Lam.] (Northeast Nursery, 2015). These specific cool season crops also prefer lower RH (50-70%) than the abovementioned warm season counterparts (75-85%) (Mattson, 2016; Northeast Nursery, 2015).

The plant growth racks also include ventilation, as shown in Figure 1, to promote air circulation. The vents contain carbon filter, which absorb volatile organic compounds (VOCs) not filtered out by the plants themselves (Hoehn et al., 1998).

## C. Nutrient Recycling

In lieu of transporting salt from Earth, a saline solution produced via the Water Processing facility (Figure 2) provides a source of salt on Mars (Subbarao et al., 1999). This wastewater recycling system is similar to the Astronaut Urine Repurposing Apparatus (AURA) created for the NASA X-HAB Challenge (Siceloff, 2008).

In the Fertilizer and Water Treatment Storage facility, nutrients are recycled through the end product of the bioreactor, further stabilized, and inserted into the hydroponic systems as a nutrient-rich amendment. The stabilization process allows for the decrease in inhibitory soluble carbonaceous compounds (Gilrain et al., 1999). Stabilizing the nutrient solution requires monitoring plant macronutrients, micronutrients, and pH.

## V. CROP CULTIVATION & FOOD PRODUCTION

With our crops selected and plant growth systems designed, we then conceptualized a manner in which to grow the crops that would prioritize (1) ensuring plants are properly sterilized for growth, (2) harvests of plants are staggered to ensure a constant food supply (3) and ensuring crops and insects properly reproduce to create a sustainable food system to last the entire Mars mission.

### A. Crop Preparation for Flight

Crops are packed for flight as seeds, except strawberries, sweet potatoes, and potatoes. Strawberry runners, sweet potato slips and potato tubers increase flight mass but produce truer to the desired genetics and faster than seeds. Prior to flight, all seeds and propagules are surface sterilized with *Muscodor albus*.

*M. albus* is a sterile endophytic fungus that produces a cocktail of 28 VOCs that synergistically work as a powerful yet selective mycofumigation biocontrol measure (Strobel, 2001; Strobel et al., 2018). Composed of short-chain alcohols, organic acids, esters, ketones, and multiple aromatic hydrocarbons, the VOCs are produced at low concentrations (150 ppb) and effectively kill or inhibit a selective but wide range potential human and plant pathogens (Alpha et al., 2015; Hutchings, et al., 2017). The unique combination of VOCs has a complex mode of action with multiple targeted pathways, allowing *M. albus* to be broadly effective against gram-negative bacteria like *Escherichia coli*, gram-positive bacteria like *Staphylococcus aureus*, other fungi like *Aspergillus fumigatus*, nematodes, and arthropods (Alpha, et al., 2015; Strobel, 2006). The use of *M. albus* has been USDA and EPA approved for use on all food crops and seeds/propagules, and in EPA tests, no toxic, infective, or pathogenic effects were observed in mammals (Barsoum, et al., 2005). Likewise, the VOCs have not been reported to injure plant tissue or leave measurable residue upon the surface of plants/produce (Barsoum, et al., 2005).

*M. albus* is ideal for GAIA not only because it has comparably lower toxicity rates and efficacy than other sanitization methods but also because its use increases the bioregenerative nature of the GAIA system. By using VOCs, microbial levels can be reduced across the entire surface area without impacting the organoleptic quality of produce, and using *M. albus* requires minimal crew time. Lacking reproductive structures, the fungus grows vegetatively, and if supplied with moist media, rich in carbon and nitrogen, populations of the fungus can be grown and harvested as needed (Ezra & Strobel, 2003; Strobel, 2006).

Once harvested, M. albus is inoculated onto grain by incubating it in a sealed container with a sterilized rice grain ratio of 12 water : 10 heat (Ezra & Strobel, 2003). After 2-3 weeks, the inoculated grain can be used immediately or desiccated for long-term storage (Mercier & Jimenez, 2003; Stinson, et al., 2003). To revitalize desiccated grain, one previous study placed the grain in tea bags, soaked them in water for 4 hours, and placed them near seeds and propagules (Mercier & Schnabel, 2006). For seed sterilization, other studies have mixed the inoculated rice into growth media, along with the seeds, or within close proximity to seedlings (Stinson, et al., 2003). For pre-harvest sanitization, as the VOCs require at least 24 hours to reach full effectiveness, the reactivated inoculated grain would be placed in proximity of the plants at least 1 day prior to harvest (Alpha et al., 2015). For this duration, the ventilation would be turned down, to allow the VOCs to reach effective levels (Braun et al., 2012).

The grain itself acts as a limiting factor to the life duration of *M. albus*, and once the nutrients are depleted, the mycelia die, and VOC production is halted. This characteristic prevents *M. albus* from becoming a pest. At this point, the teabag is removed, and samples are surface sterilized and ready to use (Mercier & Schnabel, 2006; Strobel 2006).

Since seeds and propagules are surface sterilized prior to being packed for flight, crew members are ready to initiate crop production. *M. albus* will also be sent to Mars to surface sterilize at later increments, which will be described in part 6, Post-Harvest & Safety. For transport, the *M. albus* mycelia can be grown on sterile paper strips, desiccated, and either stored at -20 C for over a year or stored on potato dextrose plugs in sterile distilled water at 4 C for over 4 years (Ezra & Strobel, 2003; Strobel et al., 2001). Due to the long mission duration, the latter storage option is better suited for this scenario.

For flight, seeds, propagules, and *M. albus* are cold stowed in a facility based off the Polar system currently used aboard the International Space Station, the Space-X Dragon Capsule, and the Orbital Cygnus Capsule (NASA, 2019). The divided system freezes seeds to -80 C while maintaining propagules at 2 C and *M. albus* at 4 C. Strawberry runners present a unique challenge in that the delicate propagules must be kept moist. Runners are stored in media that has been treated with *M. albus* prior to packing. An automatic slow drip irrigation pump will periodically add small amounts of water to the media. The BSF are be cool-transported to Mars as eggs. When stored at cool temperatures around 6 C, the eggs remain preserved and viable viable until ready to hatch in the GAIA system. Upon arrival on Mars, the crop payload is stored in similar conditions until initiation in GAIA.

### B. Plant Cultivation

Growth parameters determine the cycles and timelines of the GAIA cropping system (Table 3). These parameters include dietary requirements, standard planting densities, average yield/plant, germination time, maturation time, shelf life, storage availability, and labor intensity. Further, enough shelf stable crop quantities are grown to allow for leftover from each harvest, which insures caloric needs are met in the event of poor yield or crop failure.

In Table 3 & Figure 5, the parameters were taken into consideration and condensed into a chart detailing the crop area required, the amount of yield expected, the amount of days that that cycle will feed (indicated by the black lines). The cycles were also intentionally staggered to evenly spread the harvesting dates so that crew members time will not be overly expended in a short time period.

To preserve crew morale via crop variety, there will be alternating cycles of kale/collards and lettuce/chard. These crops had similar nutrition and as leafy greens have generally low storage rates, this alternation also serves to not overwhelm the crew with salad crops and spreads out harvesting dates. Spinach will be continuously provided, due to high crop nutrient density.

| Crop | Cycle | Seeded (day) | Growth Period (days) | First Harvest (day) | Yield (kg) | Cycle Length/Days Supplied | Excess Yield/ Storage (days) | Area (m^2) |
|---|---|---|---|---|---|---|---|---|
| Sunflower | 1 | 0 | 110 | 110 | 16.56 | 36 | 9 | 16.72 |
| | 2 | 36 | 110 | 146 | 16.56 | 36 | 9 | 16.72 |
| | 3 | 72 | 110 | 182 | 16.56 | 36 | 9 | 16.72 |
| SF (oil) | 1 | 0 | 110 | 110 | 9.64 | 55 | 13.8 | 14.61 |
| | 2 | 55 | 110 | 165 | 9.64 | 55 | 13.8 | 14.61 |
| Rice | 1 | 0 | 90 | 90 | 15 | 30 | 7.5 | 19.69 |
| | 2 | 30 | 90 | 120 | 15 | 30 | 7.5 | 19.69 |
| | 3 | 60 | 90 | 150 | 15 | 30 | 7.5 | 19.69 |
| Potato | 1 | 0 | 90 | 90 | 63 | 18 | 4.5 | 2.16 |
| | 2 | 18 | 90 | 108 | 63 | 18 | 4.5 | 2.16 |
| | 3 | 36 | 90 | 126 | 63 | 18 | 4.5 | 2.16 |
| | 4 | 54 | 90 | 144 | 63 | 18 | 4.5 | 2.16 |
| | 5 | 72 | 90 | 162 | 63 | 18 | 4.5 | 2.16 |
| Sweet Potato | 1 | 0 | 90 | 90 | 19.5 | 30 | 7.5 | 1.24 |
| | 2 | 30 | 90 | 120 | 19.5 | 30 | 7.5 | 1.24 |
| | 3 | 60 | 90 | 150 | 19.5 | 30 | 7.5 | 1.24 |
| Strawberry | 1 | 0 | 64 | 64 | 10.21 | 16 | 1.6 | 0.35 |
| | 2 | 16 | 64 | 80 | 10.21 | 16 | 1.6 | 0.35 |
| | 3 | 32 | 64 | 96 | 10.21 | 16 | 1.6 | 0.35 |
| | 4 | 48 | 64 | 112 | 10.21 | 16 | 1.6 | 0.35 |
| Tomato | 1 | 0 | 60 | 60 | 7.92 | 12 | 1.2 | 1.08 |
| | 2 | 12 | 60 | 72 | 7.92 | 12 | 1.2 | 1.08 |
| | 3 | 24 | 60 | 84 | 7.92 | 12 | 1.2 | 1.08 |
| | 4 | 36 | 60 | 96 | 7.92 | 12 | 1.2 | 1.08 |
| | 5 | 48 | 60 | 108 | 7.92 | 12 | 1.2 | 1.08 |
| Pepper | 1 | 0 | 60 | 60 | 8.98 | 30 | 3 | 0.62 |
| | 2 | 30 | 60 | 90 | 8.98 | 30 | 3 | 0.62 |
| Broccoli | 1 | 0 | 27 | 27 | 4.85 | 9 | 1 | 4.74 |
| | 2 | 9 | 27 | 36 | 4.85 | 9 | 1 | 4.74 |
| | 3 | 18 | 27 | 45 | 4.85 | 9 | 1 | 4.74 |
| Kale | 1 | 0 | 36 | 36 | 2.52 | 9 | - | 1.29 |
| | 2 | 18 | 36 | 54 | 2.52 | 9 | - | 1.29 |
| Collard | 1 | 9 | 36 | 45 | 0.65 | 9 | - | 0.25 |
| | 2 | 27 | 36 | 63 | 0.65 | 9 | - | 0.25 |
| Lettuce | 1 | 0 | 28 | 28 | 0.39 | 7 | - | 0.14 |
| | 2 | 14 | 28 | 42 | 0.39 | 7 | - | 0.14 |
| Chard | 1 | 7 | 28 | 35 | 0.5 | 7 | - | 0.32 |
| | 2 | 21 | 28 | 49 | 0.5 | 7 | - | 0.32 |
| Spinach | 1 | 0 | 28 | 28 | 0.84 | 7 | - | 0.32 |
| | 2 | 7 | 28 | 35 | 0.84 | 7 | - | 0.36 |
| | 3 | 14 | 28 | 42 | 0.84 | 7 | - | 0.36 |
| | 4 | 21 | 28 | 49 | 0.84 | 7 | - | 0.36 |
| BSF | 1 | 60 | 20 | 80 | 8 | 10 | 0.5 | 2.5 |
| | 2 | 70 | 20 | 90 | 8 | 10 | 0.5 | 2.5 |
| | 3 | 80 | 20 | 100 | 8 | 10 | 0.5 | 2.5 |
| | 4 | 90 | 20 | 110 | 8 | 10 | 0.5 | 2.5 |
| Herbs | | | | | | | | 0.5 |
| Totals | | | | | 643.9 kg | | | 191.13 |

Table 3. Crop growth timeline with required area and yield.

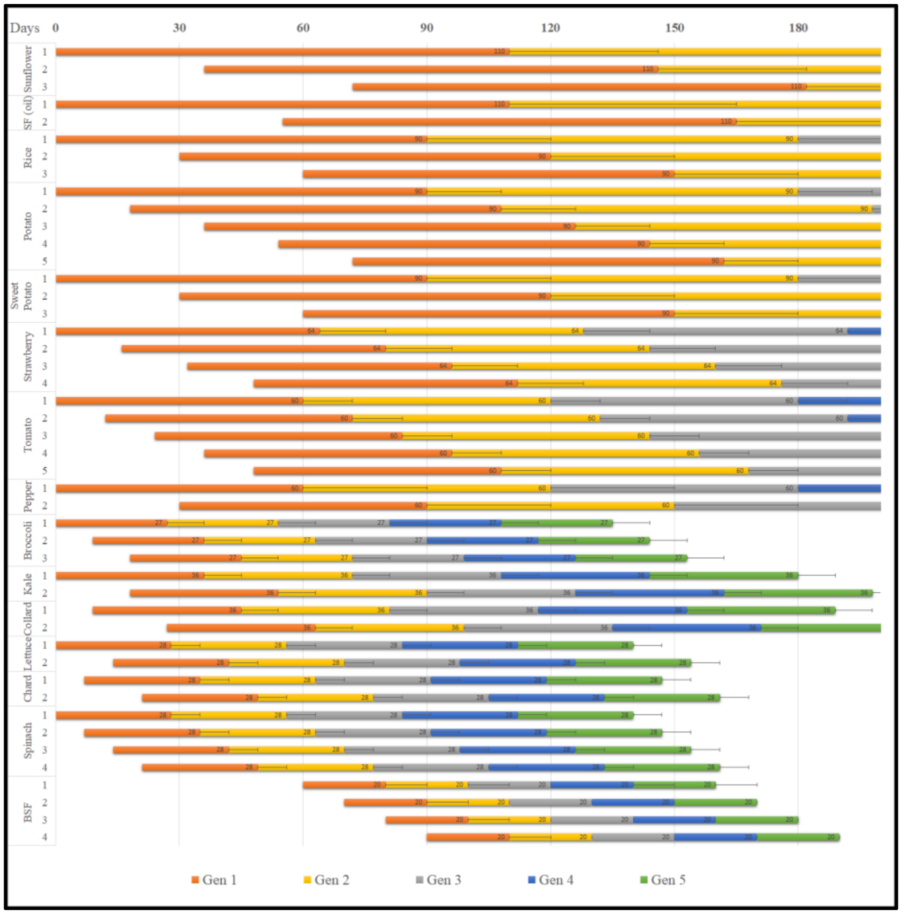


Figure 5: Crop growth timeline with required area and yield.

## C. Crop reproduction

Ample amounts of seeds are available in the event of a catastrophic event that warrants entirely restarting all crops. However, most selected crops are open pollinated, such as the "Red Robin" tomato cultivar, so new batches of seeds can be collected, cleaned with *M. albus*, and stored for future use. Roughly 3-5% of open pollinated crops are designated to go to seed production, including inhibiting bolting in leafy green crops. The crops are pollinated via air movement, as the plants are touched by crew members, and when racks are moved. Hybrid (F1) crops like broccoli and peppers will have to be planted with seed brought from Earth; using seed from yield produced in GAIA could result in genetics that differ from the desired F1 generation. Other hybrid crops like strawberries and sweet potatoes, as well as potatoes, are harvested and propagated as propagules.

## D. Insect Cultivation

BSF larvae are cultivated around 27 C and 70% RH for optimal survival rates and growth (Oonincx et al., 2015). As long as these environmental parameters are met, BSF larvae are extraordinarily resilient as they can moderate their metabolism and development time in response to food availability and tend to prefer high population densities (Diener et al., 2009). This ability to regulate their development also means that the quality, amount, and timing of the larval diet can be customized to shorten BSF development time (Figure 6), increase waste reduction capacity, increase body mass, and even play a role in their nutritional content (Diener et al., 2009). GAIA's BSF larval cultivation system is designed to maximize these positive effects, with insects raised at roughly 40,000 larvae $m^{-2}$(4 BSF larvae cm$^{-2}$). Prior to adding BSF eggs to the system, a crew member will add between 12-14 kg per tray(.0.3-0.35 g per BSF larvae) to the BSF rack system after the wasteflow steadies ~ day 120. (Barragan-Fonseca et al., 2018). The larvae consume a slurry of crop residue and food waste (~70% moisture content) that, once spread across their growth chamber, does not exceed 8 cm depth (Diener et al., 2009). After oviposition, the larvae consume large amounts of organic biomass for 12-14 days, before entering the prepupae stage. At this stage, the larvae exit the substrate and seek higher ground (Figure 7). Through a process dubbed "self-harvesting," the BSF instinctively crawl out of the substrate, climb the strategically placed ramps, and fall into a collection bin for further processing. Once harvested and dried, each collected BSF weighs about 0.08 g, producing roughly 8 kg m$^{-2}$ consumable BSF yield per harvest (Oonincx et al., 2015).

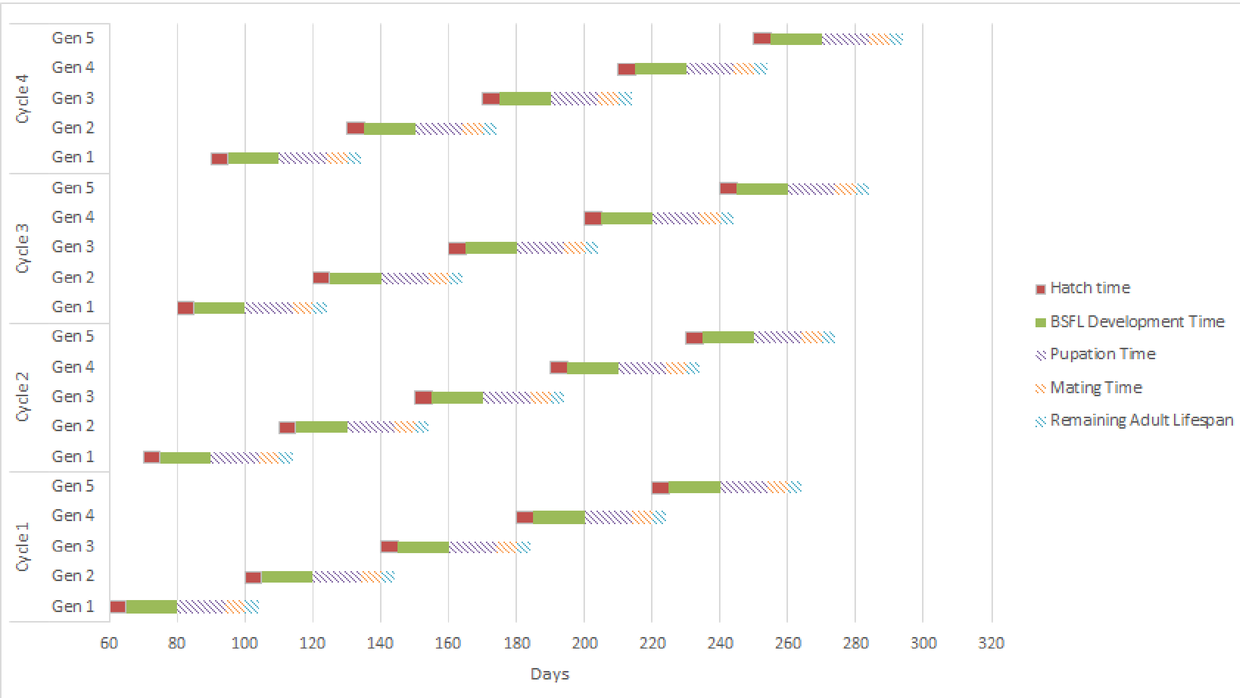


Figure 6. BSF generation cycle timeline. Cycles are staggered to continuously supply BSF yield to crew members.

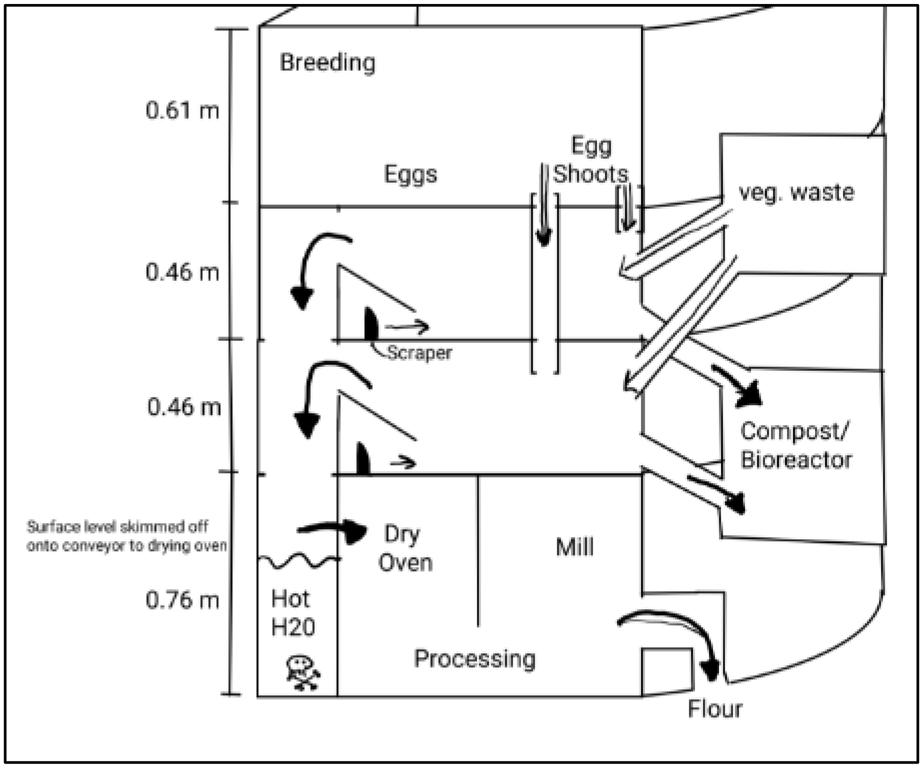


Figure 7. The BSF production rack. As BSF progress through life stages, insects progress downward from level to level. Post-processing is completed in the adjacent Vegetable Waste System and Compost/Bioreactor.

### E. BSF Reproduction

To support the dietary needs of the crew, sizeable breeding populations must be developed and maintained. Portions of each prepupae harvest are set aside and transferred to smaller containment systems where they pupate and develop into adults. Adult BSF require only water and 3 (50 W) LED lights to sustain their 10-day lifespan (Nakamura et al., 2015). BSF are aerial breeders, so the adults are provided spacious mesh-sealed enclosures at approximately 1370 breeding flies $m^{-2}$ (Nakamura et al., 2015). Each female produces at least 80-100 eggs, and assuming half the breeding flies are female, each $m^2$ of breeding area produces around 60,000 larvae (Nakamura et al., 2015). As the system is arranged vertically, oviposition tubes feed directly into the BSF larvae cultivation areas. With these considerations, 10 $m^2$ of larvae raising area and 5 $m^2$ breeding area produce around 24 kg BSF larvae every 20 days.

### F. Packaged Meals to Fresh Crop Transition

In addition to the crops planted as part of Phase 1, microgreens are also established as part of PtPPGE Step 1, including broccoli, kale, collards, chard, and spinach. Microgreens can be used to garnish packaged meals to improve organoleptic quality and to add vitamins and minerals to the diet; however, the microgreens do not constitute a significant portion of the crew member diet. Growing microgreens also serve to quickly improve crew morale after the long journey and to quickly test if the greenhouse system is exhibiting issues. Microgreens are phased out as broccoli and leafy green crops begin yielding at day 28. Crew members continue to rely on packaged meals through day 90, with supplemental fresh food from tomatoes, peppers, broccoli and leafy greens. Staple crops start yielding at day 90, allowing crew members to phase away from packaged meals. Following this transition, remaining packaged meals are kept in the event of a catastrophic failure in GAIA.

## VI. GREENHOUSE MONITORING

In order ensure crops are successfully grown and required crew time is minimized, a system of sensors and cameras are utilized to allow for the constant monitoring of all plant and insect systems.

### A. Biological Components

In order to monitor crop health in GAIA, a WSN is set up to places sensor packages within each shelf of each crop rack. Sensors in this network include light intensity, water flow rate, shelf temperature, ethylene, ammonia, $O_2$ and $CO_2$ levels, and humidity. In addition, hyperspectral cameras are capable of monitoring plant health by taking images that quantify light within a 400-1930 nm range. This allows for documentation of pathogen infection, nutrient content, abiotic stress, heat stress, biotic stress, plant biomass, yield of the crops, and growth media properties.

### B. Earth Monitoring Team

By using the hyperspectral cameras and sensors positioned in each plant rack, Earth-based botanists and engineers monitor the telemetry sent from the sensors in the WSN. The Earth-based team adjusts these levels as needed and uses this technology to capture more detailed information about a crop or nutrient solution. Having a team remotely monitor GAIA reduces the required crew activity time; crew members are only needed for certain initial setups, harvesting, and interactions requested by the Earth-based team or by any unexpected alarms.

One potential drawback to hydroponic systems is that plants can be sensitive to imbalances in the nutrient solution. Plants can exhibit deficiency symptoms and toxicity symptoms that must be monitored over the growth period (Philipsen et al.,1985). The plants in GAIA are monitored for deficiencies like nitrogen, which causes stunted growth and chlorotic foliage (Philipsen et al., 1985).

## VII. POST-HARVEST & SAFETY

After crops have been properly grown and harvested, it is important to ensure that collected food is properly sanitized for consumption. Food safety is an issue NASA takes very seriously, as the entire scope of their VEG-01A was to prove the food safety of the Veggie plant growth chamber (Massa et al., 2017). In addition, GAIA has a three-tiered storage system that allows for food to be safely stored for both short term and long-term consumption.

### A. Crop Sanitation and Processing

The post-harvest crop process in GAIA varies by species. Some crops, like sunflower seeds, require moderate treatment, including drying, dehulling, and pressing for oil (Myers, 2002). Conversely, leafy greens, tubers, and fruit only require cleaning after harvesting to be fit for consumption. To prevent the occurrence of foodborne illness, plant crops are sanitized with *M. albus*. 2 days before harvest, *M. albus* is added to the specified rack system, and the sanitation process will conclude on the day of harvest. Warm water is used as needed in the Plant Preparation Area to rinse debris off harvested crops (Figure 2).

As mentioned, certain crops require processing after harvest in order to be consumed. For this reason, a thresher, oil press, and mill are located in the 2nd floor Plant Preparation Area. The thresher is used to remove the sunflower seeds from the sunflowers as well as to remove the rice grain from the husk. The mill is then used in the rice post harvest process in order to ensure the rice can be eaten by the crew. Finally, in order to create sunflower oil, the sunflower seeds are broken down by the oil press in the Plant Preparation Area.

## B. Insect Sanitation and Processing

The first 5% of the prepupae to accumulate within the collection area are collected and transferred to the breeding area to pupate and eventually produce future generations. The remaining 95% begin automated processing, where scalding hot water (95 C) flushes over the insects for 5-10 minutes (EFSA, 2015; Schlüter & Rumpold, 2012). Not only are the BSF killed almost instantly, but the hot water also minimizes the BSF distinct flavor and provides an initial round of sanitation (Rumpold & Schlüter, 2013; Kouřimská & Adámková, 2016). Then, the BSF are skimmed off the water onto a conveyor to a drying oven, which heats beyond the survival thresholds of most potential microbial contaminants (Wang & Shelomi, 2017). Once dried to about 5% moisture content, the BSF remains are milled into a powder, which a crew member collects and adds to meals (Wang & Shelomi, 2017). Aside from this final collection and the transfer of the next breeding generation, the ideal is for crew members to remain uninvolved with BSF cultivation, which helps limit the potentially negative organoleptic bias that often results from the popular culture perceptions of entomophagy (Van Huis et al., 2013; Wang & Shelomi, 2017).

## C. Storage

The shelf life of various crops in part dictates the designation of harvest times. Leafy greens and fruit crops with shorter shelf lives are harvested more frequently and in smaller amounts than rice, oil, powdered BSF, and tuber crops with longer shelf lives (Eat By Date, 2018). The estimated yields of one harvest of each crop is nearly 200 kg, which requires 0.5 $m^3$ for storage. 0.2 $m^3$ of this area is refrigerated for leafy greens and fruit, while the remaining space is cool, dry, and airtight for crops with longer shelf lives.

A single rack is designated for all post-harvest food storage (Figure 8). The rack can be opened from either side and has a “in” and “out” side, in order to ensure ample food cycling and that no food is unintentionally left in storage past its shelf life.

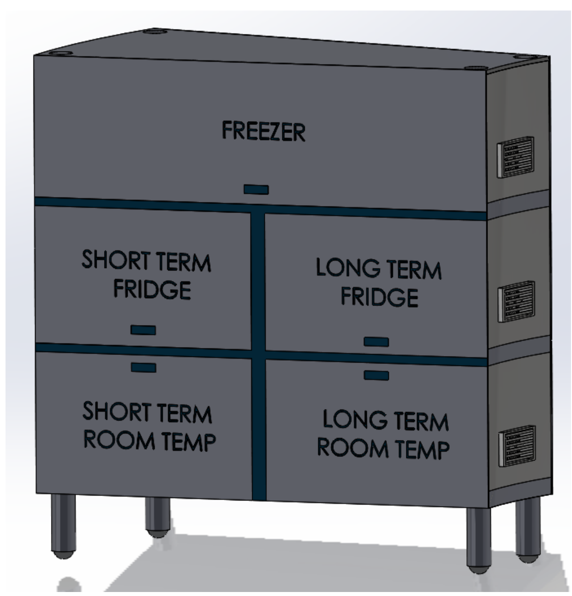


Figure 8: Storage Rack

The rack is separated into 5 sections. The upper-most section, being a 2.73 $m^3$ freezer, holds the stock of broccoli, tomatoes, peppers, and strawberries that is designated for “long-term, emergency” use. The second level is divided into two separate 1.37 $m^3$ refrigerated sections. The “Short-Term Fridge” holds the broccoli, strawberries, tomatoes, peppers, kale, collards, lettuce, chard, spinach, and black soldier flies until they are consumed within their typical shelf life. The “Long-Term Fridge” holds potatoes and sweet potatoes that are designated for "long-term, emergency" use. Finally, the 1.37 $m^3$ "Short-Term Room Temp" section holds sunflower seeds, sunflower oil, rice, potatoes, and sweet potatoes for short term consumption while the 1.37 $m^3$ "Short-Term Room Temp" section holds up to 60 days worth of sunflower seeds, sunflower oil, and rice for emergency consumption.

## VIII. CLEANUP & WASTE MANAGEMENT

Between crop cycles, systems are cleaned with a 3-tier process. First, water flushes the system to remove debris. Crew members can wipe down the rack structure as needed with water and cloths. Second, UV-C lights are turned on for a minimum of 24 h to kill microbes. Third, vents are closed, and racks are heat-treated for a minimum of 24 h. Because racks are separated from another and regularly cleaned out, it is unlikely that a pathogen contamination can occur. However, in the event of a contamination, affected racks can be cleaned out, sealed by closing the vents, and quarantined with the aforementioned steps.

Finally, while the GAIA system minimized the amount of waste produced during the process of crop growth, harvest, and consumption, some waste is unavoidably produced. Fortunately, GAIA has a developed waste management system that looks to utilize the created waste and recycle the crop nutrients. Based off of kilograms of yield per crop, estimations were made concerning how much vegetable and food waste would be produced each harvest (Figure 9). Then, based off these numbers BSFL feeding rates were established, and the amount of leftover unprocessed waste that would be leftover was estimated. Due to their resilient metabolisms, BSF larvae can be fed different amounts without making a significant impact on their prepupal harvest biomass, thus as the amount of waste fluctuates, the BSF will fluctuate their metabolisms to match. However, the quality and quantity of the waste will have an impact on how much the BSF consume, and broad estimates that the BSF will be able to consume 40% to 60% of the waste. BSF at the aforementioned rate of 50-70 kg $m^{-2}$ every 20 days, and with 10 $m^{-2}$ allotted for BSF production, 30-40 kg total waste are eliminated each BSF cycle (Figure 6). In addition to converting inedible biomass to food, BSF also reduce the microbial populations within the substrate, including species like *E. coli* and *Salmonella spp.* (Wang & Shelomi, 2017). After the BSF reach the pupae stage and leave what is left of the substrate, the remaining nitrogen-rich frass and other biomass move to a bioreactor along with human excrements and other excess waste. Bioreactors rely on microorganisms to oxidize organic carbonaceous and nitrogenous materials in solid wastes. (Hu et al. 2009). The microorganisms capable of breaking down the biomass exist freely, they do not have to be brought separately.

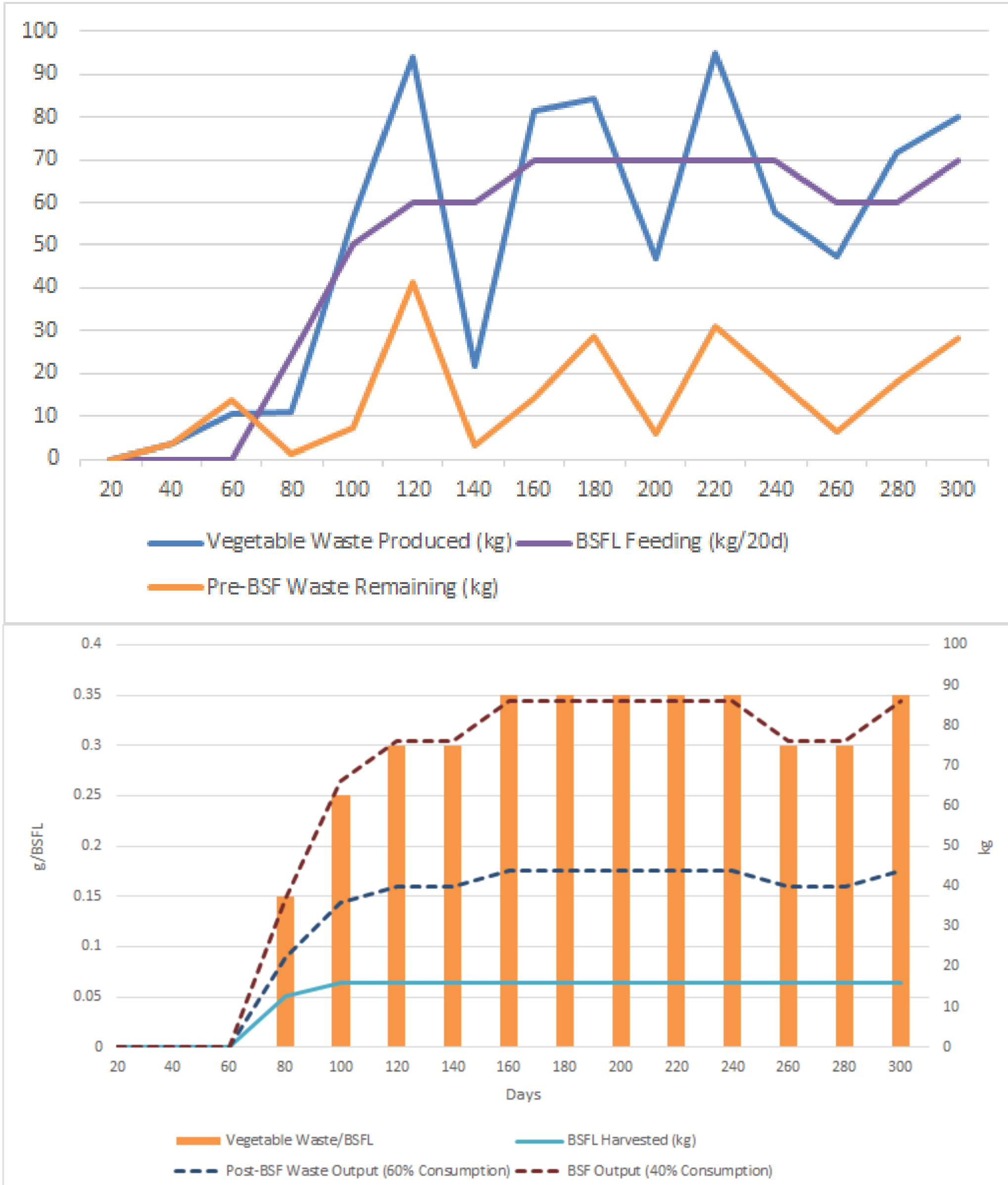


Figure 9. Waste management in the GAIA system.

## IX. CONCLUSION

By combining a realistic and complete astronaut diet with innovative technology for plant production, proper waste processing, and efficient energy and space use, GAIA is an effective addition to the Ice Home mission architecture. After the first round of crop cycles are completed, our proposed concept completely eliminates the need for supplemental food brought from Earth for a Mars surface mission, therefore significantly reducing launch mass and mission risk. By utilizing advanced technology and optimizing plant growth volume, GAIA merges innovative and creative methods to successfully supply food, serve as a reminder of home, and aide in scientific exploration.

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