SIRONA: Sustainable Integration of Regenerative Outer-space Nature and Agriculture. Part 1 – Architecture and Technology

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Plant growth systems are a critical component of a comprehensive Bioregenerative Life Support System (BLiSS) for long-duration human space exploration missions. Previous BLiSS technology development and crop selection have primarily focused on optimization of edible biomass and caloric content. In light of advances in horticulture, human space flight science, technology and nutritional science, these systems can benefit from reexamination. A holistic approach to designing plant growth systems and crop selection for human exploration missions must address how to influence long-term crew health, morale, and performance through multiple modalities. The greenhouse design concept for SIRONA: Sustainable Integration of Regenerative Outer-space Nature and Agriculture is presented. SIRONA is a food production, preparation, and preservation facility that includes: Integrated Multi-Trophic Aquaponics (IMTA), Controlled Environment Agriculture (CEA) systems, automation technologies, food preparation/preservation concepts as well as integration of crew recreation, access to nature, and horticulture therapy. This food production facility has the capability to produce a wide variety of food sources including land crops, algae, aquatic crops and aquatic animals (fish, crustaceans, and mollusks), all of which provide additional health benefits beyond fulfilling basic nutritional needs. SIRONA uses an innovative holistic design approach to integrate the following living systems: astronauts, plants, animals and microbes. Additionally, an updated food selection framework is presented that integrates an expanded set of evaluation criteria including nutritional, medicinal, and psychological value of edible living systems.

Nomenclature

BLiSS	=	Bioregenerative Life Support Systems (the *i* indicates access to nature is a primary function)
CEA	=	Controlled Environment Agriculture
CM	=	Crew Member
CY	=	Composite Yield
DLI	=	Daily Light Integral

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HI	=	Harvest Index
HPI	=	Human-Plant Interaction
IMTA	=	Integrated Multi-Trophic Aquaponics
PAR	=	Photosynthetically Active Radiation (µmol/m2/s)
SIRONA	=	Sustainable Integration of Regenerative Outer-space Nature and Agriculture
VPD	=	Vapor Pressure Deficit

I. Introduction

NASA has been exploring sustainable, regenerative food systems for space exploration missions since the 1950s.[1] However, to date, most of this research has focused on one specific technology area, system, or method instead of designing a fully integrated food production system (i.e., greenhouse) that includes post-harvest processing, a galley/dining system, and basic life support functions.[1, 2] SIRONA (Sustainable Integration of Regenerative Outer-space Nature and Agriculture) is a proposed greenhouse design that fulfills both basic life support needs (food, air revitalization, waste and water processing), while also ensuring that the crew is healthy, happy, and surrounded by familiar Earth-like conditions. The integrated biological systems that are included in SIRONA are modeled after ecologically-robust Earth agricultural systems modified to meet mission-specific challenges. The specific needs SIRONA aims to fulfill include basic life support, enhanced diet, socialization, and the physiological and psychological benefits gained from interaction with nature. Multiple studies suggest tangible benefits of gardening for humans.[2–4] These benefits range from cognitive improvement to increased social cohesion. There are measurable physiological effects, such as reduced cortisol levels and stress, that contribute to a healthy immune system.[5–7] Furthermore, living systems with higher diversity are more resilient in novel conditions and provide more services for humans. In addition to providing nutrition, phytochemicals found in crops treat and prevent medical issues such as radiative damage and micronutrient deficiencies, which astronauts are more likely to experience during long-duration missions. The SIRONA design draws from ecologically-robust agricultural systems that emphasize diversity as a significant contributing factor to increasing human benefits and overall system stability; this is demonstrated in the life support capacity, rich nutrient profile, multi-functionality of yields and enhanced astronaut well-being.

SIRONA provides comprehensive care of humans on Mars through 1) the careful selection of nutrient sources from multiple climate zones and 2) horticultural therapy, which is implemented by promoting passive and active Human-Plant Interaction (HPI). The well-being of astronauts is further enhanced by encouraging activities such as exercise, socialization, and meal preparation in the multi-purpose open space; this space allows the crew to participate in recreation and exercises while surrounded by plants. SIRONA is outfitted with automation technologies and horticulture decision support tools (AgQ, the Brain, and a Remotely Operated Gardening Rover) that help reduce work load and optimize the benefits of horticulture therapy. Gardening tasks that are not time sensitive are assigned when the crew member can benefit the most from taking a restorative break from non-critical stressful tasks.

II. Context and Assumptions

The SIRONA analytical work[8] was first carried out as part of the 2019 NASA BIG (Breakthrough, Innovative, and Game-changing) Idea Challenge,[9] which sought innovations from university teams for the design, deployment, and sustainable operation of a Mars greenhouse. Proposed designs were required to provision a crew of four during a 600-day mission on an early Mars outpost consisting of two structures: a crew habitat and a greenhouse, both of which utilized the same Mars Ice Home as the primary structure. The Mars Ice Home, a concept previously designed through a collaboration between NASA Langley Research Center, Space Exploration Architecture, and Clouds Architecture Office, is a two-story inflatable torus surrounded by a 2m-thick layer of water ice that shields the interior from Galactic Cosmic Rays (GCR).[10] The SIRONA primary shell structure (comprised of an identical Ice Home inflatable shell) is outfitted with additional secondary internal structures and growth systems to create the greenhouse. The same goal of reducing GCR radiation is applicable here, as the crew will be spending a significant amount of time in the greenhouse working, eating, and recreating. The SIRONA greenhouse attaches to the Ice Home–i.e., crew habitat–via a pressurized tunnel with an airlock at each end. The water (in situ production of 100kg/day) and power (40kW provided by the Kilopower system) sources and interfaces for the greenhouse are similar to that of the Ice Home and were prescribed by the NASA BIG Idea Challenge.

Launch and Entry, Descent, and Landing (EDL) parameters were also derived from the conceptual design of the Ice Home. The stowed configuration fits in the 8m-diameter cargo-shroud of the Space Launch System vehicle. SIRONA can be packaged and stowed within the volume and dimension constraints of the EDL aeroshell. As with the Ice Home deployment after landing, the SIRONA package will be transported to the Mars deployment location via robotic transporters already present.[10] The crew is estimated to arrive about 26 months after the launch of the SIRONA package.

III. Design Considerations

This study proposes a complete integration of biological components such that the astronauts, plants, and symbionts (aquatic life, algae, and microbes) remain healthy throughout the entirety of a 600-day mission. Components and technologies are carefully chosen to optimize benefit-to-mass ratios. To support the goal of creating a robust system less prone to failure in a novel, high-risk environment, each element carries out multiple functions and each function is provided by multiple elements (a concept that draws from the stacking functions principle from permaculture). The nature of a regenerative system calls for a design that can continuously process inputs and outputs from various subsystems. The system must be able to produce and/or recycle a portion of food, oxygen, carbon dioxide, greywater, and blackwater as generated by crew members and crops.

A. Design Philosophy

The SIRONA design focuses on creating a highly integrated living system that is resilient, robust, and regenerative. This goal is achieved by drawing upon a unique approach that embraces the concept that the synergistic integration of all organisms is crucial to the well-being of the whole living system. The SIRONA greenhouse integrates proven concepts from the following design methodologies and technologies: permaculture, biophilia, biomimicry, Controlled Environment Agriculture (CEA), vertical farming, and human centered design.

A major goal of this design is to maximize the use cases within the greenhouse volume to improve the habitability and human factors of the outpost beyond satisfying basic nutritional needs. Such use cases include relaxation, recreation, sensory stimulation, meal preparation, and supplemental Bioregenerative Life Support Systems (BLiSS) (e.g., food production, waste management, water reclamation, air revitalization, and access to nature). BLiSS is a specific acronym that embraces the concept that nature improves the health and well-being of the crew, and is a critical function of a bioregenerative life support system.[11–13] It has been said that “Nature is BLiSS,” (Hava, 2016) which embodies the intangible benefits of integrating nature into the habitat.[11–13] Previous BLSS (the acronym without the i) designs focused on crew survival as their primary function; however, a BLiSS design such as that implemented in SIRONA provides support to the additional vital functions of keeping all of the living systems healthy and happy. To fulfill this architectural vision, the layout is designed to mimic the familiarity of Earth parks or gardens that promote well-being, crew cohesion, relaxation, and recreation.[14]

Additionally, SIRONA can be used as an emergency secondary habitat in case of catastrophic failure of the Mars Ice Home primary living quarters. SIRONA includes all of the subsystems necessary to function as a habitat, including a bathroom, kitchen, and emergency deployable sleeping quarters that are stowed during normal greenhouse operations. The Ice Home and SIRONA are connected by a pressurized tunnel and airlocks, allowing the two systems to operate independently. Integration of this functionality into the SIRONA system again demonstrates resiliency even under critically dangerous circumstances.

B. Diet Considerations

The total estimated caloric requirements for this mission are approximately seven million calories. Given the prescribed size of the greenhouse, power constraints, and the current state of lighting technology, it is realistic to assume that the mission involves periodic resupplies of high-calorie staple foods from Earth. The role of SIRONA is to provide supplemental fresh crops and seafood that enhance the micro-nutrient profile, palatability, and psychological attributes of the crew’s diet.

The concept of “food as medicine” and the use of functional foods are adopted to guide crop selection. The crops grown on Mars play a critical role in providing micronutrients that address both the physiological deterioration of crew during long-duration spaceflight and the degradation of nutrients in foods stored for long periods. For example, vitamins D and K are key to counteracting the loss of bone mass.[15] Antioxidants such as selenium, Vitamin E, and carotenoids (e.g., zeaxanthin, β-carotene, lutein, and lycopene) may help to mitigate the effects of space radiation.[16] Certain spices and herbs long used in numerous cultures’ traditional medicines have been clinically shown to have measurable positive effects on health,[17] in addition to livening up otherwise bland dishes.

Palatability is a key design driver because it can override all other attributes in influencing food consumption. Thus, a menu is required that not only supplies necessary nutrients but also is highly palatable over the full duration of a Mars exploration space mission. To this end, the design adopts aspects of highly effective techniques utilized by professional chefs in fine dining. Raw ingredients and cooking tools are chosen that create contrasting flavors and textures on the plate. To encourage the crew to engage with and be provoked by their meals, the selection of exotic crops is balanced with fruits and vegetables familiar to a Western diet.[18]

C. Crop Integrated Value

A diverse roster of crops provides nutritional, medical, and psychological benefits to the crew. The SIRONA crop complement was determined through an assessment of functions each plant performs. Rather than exporting the standard Earth agricultural definition of yield as biomass per area[19], the novel metric Composite Yield (CY) is used to guide the crop selection process. In the SIRONA system, CY is the weighted value of all plant functions summed over the percent of usable biomass (i.e., $1 - HI$). By this definition, the system favors those plants with the greatest number of functions and highest harvest index ($HI = \frac{\text{edible biomass}}{\text{inedible biomass}}$) (i.e., high-scoring crops). This equation is flexible and may be adjusted based on mission constraints and priorities by adding, subtracting, or otherwise manipulating the relative weight of each function in the numerator. Selection of robust, high value crops using the CY metric thus reflects the emphasis on optimizing the crop complement for complex and diverse gains. Equation 1 represents this novel metric.

$$CY = \frac{\sum_i v_i}{1 - HI} \tag{1}$$

In the above formula, $v_i = \{0, 1\}$ is a single plant function, and HI is the harvest index such that the CY for each crop is the sum of functions per usable harvestable mass. In this design, three primary crop functions in the numerator were used to evaluate each crop: nutrition, psychological benefit, and medicinal value. Table 1 provides details of each crop.

Table 1. Crop Complement Overview

Crop	Total Area	Edible Biomass	Key Nutrients	Key Functions		
	m^2	kg/yr	Vit=Vitamin; Min=Mineral	Diet	Psych	Med
Zone 1 – Keyhole Wicking Beds						
Lettuce	0.64	30.66	Vit (C), Min (Mn, K, Cu, Fe), fiber	x		
Spinach	1.096	29.2	Vit (A, B, E, K), Min (Mn, Mg, Fe, Cu), folate	x		
Kale	1.965	30.66	Vit (A, B, K), folate, protein, fiber, α-linolenic acid, lutein, zeaxanthin	x		
Ground cherry	0.496	0.477	Vit (A, C), Min (Fe, Ca, P), niacin, thiamin, riboflavin	x	x	
Sorrel	1.381	15.33	Vit (C), Min (P, Fe), fiber, oxalic acid, flavonoids	x	x	x
Green onion	0.165	4.928	Vit (B, C), quercetin, fiber	x		
Bok choy	0.834	21.921	Vit (A, V)	x		
Carrot	1.464	39.986	Vit (K), fiber, lutein, α- and β-carotene, lycopene	x	x	
Radish	0.294	9.837	Vit (A, B, K), Min (P), folate, protein, α-linolenic acid, lutein, zeaxanthin, fiber	x		
Potato	3.229	124.1	Vit (B6, C, K), Min (Mn, P), niacin	x		
Zone 2 – Ebb and Flow Beds						
Strawberry	2.48	130.448	Vit (C), Min (P), folic acid, fiber	x	x	x
Tomato	3.626	229.95	Vit (A, C), lycopene, lutein, α- and β-carotene	x	x	
Pepper	1.665	90.52	Vit (A, C, E, K), fiber	x	x	
Ginger	0.52	6.921	gingerol		x	x

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Crop	Total Area m^2	Edible Biomass kg/yr	Key Nutrients Vit=Vitamin; Min=Mineral	Key Functions Diet	Psych	Med
Turmeric	0.52	4.55	curcumin		x	x
Aloe	0.26	0.139	Vit (C), anthraquinones		x	
Marigolds	0.52	0.064	calendulin, linolenic acid, carotenoids	x	x	x
Banana	2	48.48	Min (P), carbohydrates, fiber	x	x	
Oca	3.229	43.913	antioxidants, starch, fiber	x		
Cilantro	0.52	5.2	lutein, zeaxanthin, β-carotene	x	x	x
Chamomile	0.74	0.37	terpenoids, flavonoids	x	x	x
Basil	0.52	12.199	Vit (A, K), Min (Mn, Mg)	x	x	
Mint	0.39	1.685	Vit (C), rosmarinic acid	x	x	x
Zone 2 – Wicking Bed						
Nasturtium	0.52	1.596	Vit (C), Min (Fe)		x	
Mashua	1.614	21.956	antioxidants, starch, fiber	x		
Sweet potato	6.961	131.4	Vit (A, C), Min (Ca, K)	x		
Zone 2 – Biowick						
Dwarf lemon	1	45	Vit (C), Min (K)	x	x	x
Barbados cherry	3	39.6	Vit (A, C), niacin	x	x	x
Dwarf kumquat	1	45	Vit (C), fiber	x	x	x
Dwarf plum	3	110.1	Vit (C), zeaxanthin	x	x	x
Passion fruit	3	64	Vit (A, C), fiber, β-carotene	x	x	x
Kiwi	3	68.1	Vit (C, K), Min (Ca), fiber	x	x	
Crop Sub-totals	51.65	1715.39	Avg. Edible Biomass Density (kg/m^2): 3.21			
Photobioreactor and Integrated Multi-Trophic Aquaculture (IMTA) Crops						
Spirulina	N/A	3.65 dry mass	Vit (B), Min (Ca, K, Mg, Fe), niacin, amino acids	x		
Duckweed	N/A	3.37	protein, antioxidants	x		
Watercress	N/A	2.56	Vit (C, K), carotenoids	x	x	
Sacred lotus	N/A	8.27	flavonoids, glucosides, triterpenes	x	x	
Crop Sub-totals	N/A	14.21	Avg. Edible Biomass Density (kg/m^2): 0.61			
Integrated Multi-Trophic Aquaculture (IMTA) Seafood Species						
Tilapia	N/A	36.31	Protein	x	x	
Jade perch	N/A	54.46	Protein, omega-3 fatty acids	x	x	x
Barramundi	N/A	54.46	Protein, omega-3 fatty acids	x	x	x
Prawn	N/A	10.14	Protein	x	x	
Crayfish	N/A	24.31	Protein	x	x	
Mussel	N/A	17.64	Protein	x	x	
Seafood Sub-totals	N/A	197.32	Avg. Edible Seafood Biomass Density (kg/m^3): 26.93			
Total Edible Biomass (kg/yr): 1926.91			Avg. Daily (kg/CM-d): 1.32			

D. Food Processing Considerations

Post-harvest processing is another factor that guides crop selection. Previous studies estimate that roughly 5 CM-h/d of active crew time is dedicated to meal preparation and cleanup in a hybrid bulk-commodity, salad-crop food system with an additional 90 minutes per CM-d for consumption.[20] Given the fresh food grown and the processing equipment included in SIRONA, crew time is expected to increase to 6-9 CM-h/d to accommodate post-harvest processing (not including crop tending) and cooking beyond simple rehydration and heating. While some of the highly perishable crops (e.g., salad crops) must be eaten fresh, other selected crops are amenable to long-term storage or preservation in order to compensate for seasonal variations in abundance and scarcity. Inedible plant and fish matter can be incorporated into other stages of the bioregenerative loop, such as serving as fish food in the aquaponics system.

IV. SIRONA Detailed Design Concept

A. Greenhouse Architecture

On Earth, technology and site-specific methods facilitate food production for nutrition and environmental habitability across vastly different ecosystems. Of the many food production approaches, the least resource- and time-intensive systems are agroecosystems, which provide nutrition under even extreme conditions by making use of evolved plant adaptations and mimicry of community-level biological processes.[21] For the mission at hand, the same principles important for stable agroecological systems on Earth (e.g., redundancy, reduction of resource waste, crop diversity)[22] are employed to improve efficiency of both biological and mechanical components. SIRONA is a BLiSS created to optimize system productivity of crops and crew members by mimicking terrestrial agroecological systems with use of permaculture principles and methods.

A key principle in both permaculture and agroecological farming is the importance of perennial plants for stability and resource efficiency of the whole system. Fruit trees, for example, produce edible yields annually for years while simultaneously improving soil stability, habitat, and resource availability for other plants in a terrestrial ecosystem.[23] This concept is implemented in SIRONA by utilizing fruit trees to passively process grey and blackwater via the Biowick. Described in detail in section IV.C.4, the Biowick safely processes human waste to maximize nutrient reclamation while minimizing the risk of exposing edible plant parts to pathogens. This system function, along with high-quality, composite yield of fruit trees, suggests that an adapted food forest[23] will improve the long-term benefits and yields of SIRONA.

To account for time delays associated with perennial crops, successional planting of annuals provides quick and continuous fresh food while trees mature (acting as a carbon sink)[24] and develop fruits in the initial phases of the mission. Individual trees can be transported at approximately age two years to further mature during the cold-temperature transit. Winter simulation through refrigeration during transit induces maturity and fruit production upon planting in SIRONA. Staging and intercropping annuals and perennials creates an artificial ecosystem analogous to agroecosystems, complete with successional resource management and growth media remediation.

B. System Overview

The land crops, trees, algae, aquatic animals, and aquatic crops all produce edible biomass for the crew members (Figure 1 and 2). The biodigester processes all of the kitchen's grey and blackwater, as well as inedible biomass produced by the greenhouse that is not used for other purposes such as creating growth media or fish food. The grey and blackwater from the bathroom (i.e., from human output streams) is used as fertilizer for the Biowick; also, it can handle any overflow from the wicking beds. Bidirectional plumbing between the Biowick and biodigester mitigates the risk of overflow from either, as both are capable of processing grey and blackwater from any source. In the case that both systems are over capacity, the Ice Home waste system serves as the backup overflow system. Furthermore, both the Biowick and biodigester are capable of treating human waste safely through bioremediation and temperature treatment; see Risk Reduction section for more details.

The first-floor keyhole wicking bed is irrigated with IMTA pond water that fertilizes the crops with nutrients from the fish. Pond water is pumped up to the second-floor mussel tank before it is used to irrigate the wicking beds and ebb and flow beds. After irrigating the beds, the water returns to the mussel tank prior to cycling back to the pond via a waterfall that drives a water wheel, both of which serve the function of aerating the water to increase the dissolved oxygen levels. The IMTA water is also used to provide nutrients to the algae photobioreactors. Second-floor systems are interdependent, with various water pumps and a water wheel to facilitate moving the water to and from the pond located on the first floor. The subsystem layout is shown in Figure 1, and Table 2 provides the major system elements' (growth systems and IMTA reservoirs) areas, volumes, and growth zones. These detailed relationships are outlined in Figure 2.

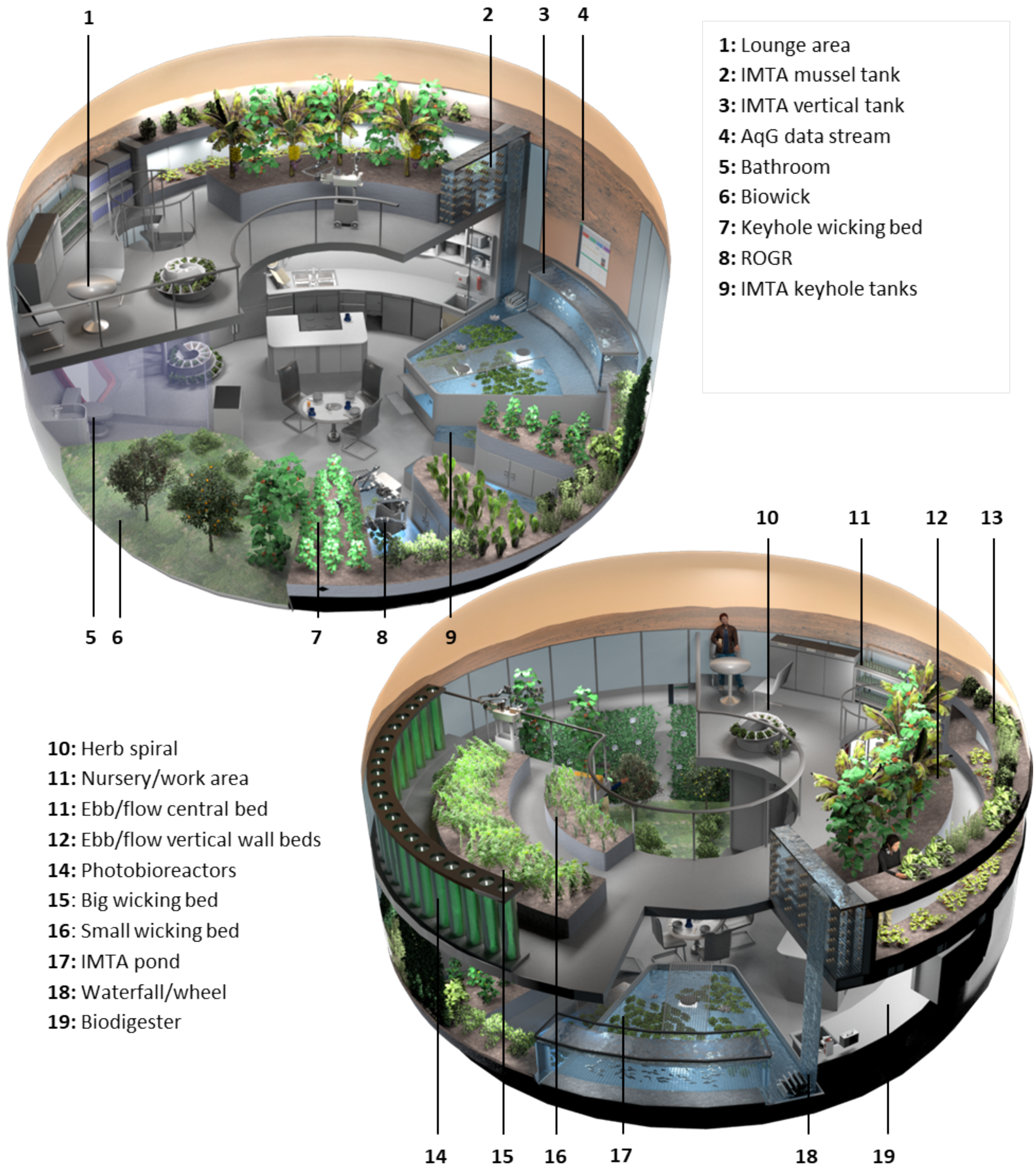

Figure 1. SIRONA Architecture Layout. First-floor subsystems include the Biowick, kitchen with biodigester (bladder located under the kitchen floor), herb spiral, and the Integrated Multi-Trophic Aquaponics (IMTA) system reservoirs (pond and juvenile fish tanks) that water the keyhole garden (wicking beds) and the Biowick. Second-floor subsystems include ebb and flow beds and wicking beds (watered by the IMTA freshwater mussel tank), photobioreactors, herb spiral, plant nursery, and sitting area (or as the area for deployable emergency sleeping quarters). Multi-level features include high-wire trellising, programmable multi-spectrum LEDs, and the Himawari solar fiber optic lighting system. Section C provides detailed descriptions of each subsystem.

Table 2. Area, Volume, and Zone of Major Growth and IMTA Systems

Label	Floor (Zone)	Element	Area (m^2)	Vol (m^3)
Growth Systems for Land Crops				
6	1 (2)	Biowick	13.926	9.508
7	1 (1)	Keyhole wicking bed	11.420	3.574
12	2 (2)	Ebb/flow vertical wall beds	9.347	1.899
11	2 (2)	Ebb/flow central bed	5.739	3.498
16	2 (2)	Small wicking bed	2.034	0.699
15	2 (2)	Big wicking bed	7.045	2.420
10	1&2 (1&2)	Herb spirals, both	2.36	N/A
		Subtotal	51.870	21.599
Integrated Multi-Trophic Aquaculture (IMTA) Reservoirs				
9	1 (3)	IMTA keyhole tanks	3.178	1.965
17	1 (3)	IMTA pond	21.643	2.424
3	1 (3)	IMTA vertical tank	1.978	1.858
2	2 (3)	IMTA mussel tank	0.890	1.082
		Subtotal	27.689	7.328
14	1 (4)	Photobioreactors	1.484	0.7

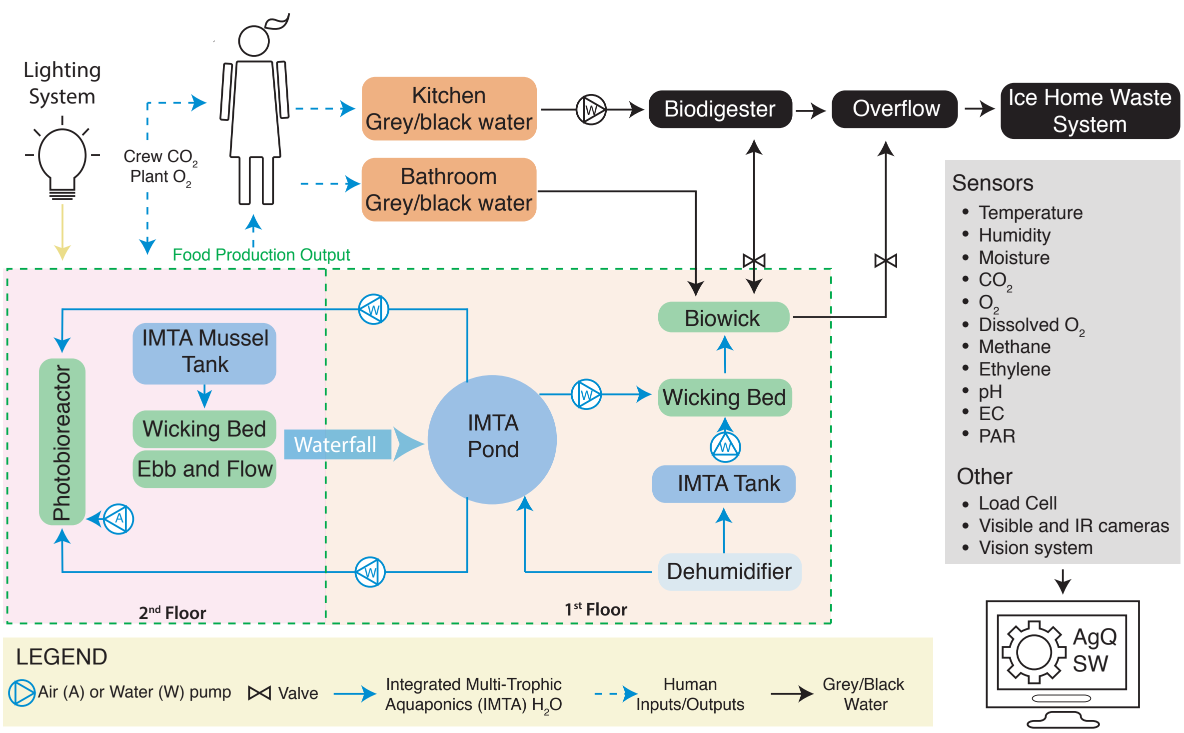

Figure 2. SIRONA System Overview

C. Greenhouse Technologies

1. Integrated Multi-Trophic Aquaponics

Aquaponics make up one of four grow zones in the SIRONA greenhouse. The aquatic aspect of the design is based on the Integrated Multi-Trophic Aquaculture (IMTA) system (Figure 3), which relies on aquatic organisms occupying different levels in the food chain to synergistically recycle nutrients, increase output, and achieve an overall stable ecosystem.[25] Ebb and flow media beds are paired with the IMT-Aquaculture to create an IMT-Aquaponics (IMTA) system.[25, 26] These beds use Growstone®, a lightweight, reusable, off-the-shelf growth media. The integration of hydroponics with aquaculture further increases the harvestable biomass and reduces the need for hydroponic nutrients to be resupplied in the long term. Aquatic species and crop selection for the IMTA system is guided by symbiotic compatibility, capacity for ecological remediation, and consumer palatability. For example, all aquatic species (Table 1) selected must be able to thrive in environments with a temperature and pH that matches the growing environment of the crops grown in the aquaponics system. Three species of fish (barramundi, jade perch, and tilapia) have been selected along with freshwater shellfish (giant prawn, red claw crayfish, and mussels) and three aquatic crops (duckweed, watercress, and sacred lotus). The mussels are powerful filter feeders that ingest uneaten fish pellets and feces,[27] preventing particulates from accumulating in the ebb and flow grow beds. Prawns and crayfish carry out a function in the IMTA ecosystem similar to how the mussels work, further increasing the utilization of nutrient inputs. The acceptability of the aquatic crops for human consumption is another key factor. Selected crops are featured in familiar seafood dishes from a variety of cuisines.

Figure 3. Integrated Multi-Trophic Aquaponics (IMTA) system with the AgQ display above the pond. Remotely Operated Gardening Rover (ROGR) and crew members tend keyhole wicking beds and fruit trees in the Biowick.

2. Grow Beds

SIRONA uses ebb and flow beds (Figure 1) as well as wicking beds (Figures 1 and 3). Ebb and flow beds rely on the periodic flooding and draining of the grow bed to distribute nutrients and oxygen throughout the system. Wicking beds act like a passive self-watering pot, operating on the principles of sub-irrigation and capillary action to deliver water and nutrients to the crops. Both types of beds utilize the highly porous Growstone® (lightweight, recycled foamed glass) as reusable growth media that serves as the water reservoir; the wicking beds and Biowick also have a layer of soilless media that covers the Growstone®. The grow beds receive nutrient-rich water from the aquaponics system and effluent from the biodigester as fertilizer.

Both the ebb and flow bed and wicking bed technologies are selected for their resilience against pump failures. In case of pump failure, there is a long lag time (a couple to several hours) before crop death occurs in either of these media beds. In comparison, a pump or nozzle failure in the nutrient-film technique or aeroponic systems can lead to crop death in as little as 15-30 minutes. In cases where pumps cannot be repaired, both types of media beds can be hand watered. Resiliency is reinforced by the use of Growstone® as the aggregate media. At saturation (i.e., after all free water has drained away), Growstone® maintains a unique balance between moisture (30% of its volume through capillary action) and air (50% by volume), which reduces the chances of developing anaerobic conditions that can lead to root rot. An initial cache of organic soilless media (such as coco coir) is to be supplied for the start-up phase and replenished via *in situ* production of growth media from inedible biomass and biodigester effluent. To minimize launch volume and mass, grow beds and fish tanks are constructed from a deployable carbon fiber frame structure that is covered by Dura Skrim®, a food-safe, flexible, reinforced, high-strength polyethylene film.

3. Photobioreactor

The photobioreactors (Figure 1) produce algae as a nutritional supplement. Since the time between algal harvests is the shortest of any of the selected crops in this greenhouse, algae serves as a fresh food substitute when other crops have yet to reach maturity. Algae-based photobioreactors can simultaneously revitalize air (by consuming carbon dioxide i.e., CO_2 and producing oxygen i.e., O_2) and manage waste (by consuming nitrogen and phosphorus byproduct streams from biological systems), in addition to producing edible biomass.

The genus *Spirulina* is selected for its high nutrient density, acceptability amongst consumers, and designation as food safe by the US Food and Drug Administration and the UN Food and Agricultural Organization. Spirulina occurs naturally in warm, tropical waters (approximately 30 °C) with relatively high pH (pH 7-10); these conditions make it ideal for use in greenhouse systems.[28] The photobioreactor and the rest of the tropical zone are deliberately located on the second floor to take advantage of the natural heat gradient. Nutrients required for the algal culture is sourced from the fish tanks and/or biodigester.

The reactors are comprised of two concentric cylinders in an annulus configuration. A bank of LED tubes is inserted in the center cylinder, and algae surrounds the light in the annulus. The configuration allows for maximum utilization of light by algae and reduces stagnant flow and biomass buildup by minimizing corners. Pumps sparge CO_2-enriched cabin air (or biodigester biogas) through the bottoms of the reactors to mix and feed the culture. Non-reactive plastics, stainless steel, and carbon fiber are used as building materials. In the SIRONA design, reactors are primarily intended for the greenhouse, although there is potential for their installation in the Ice Home habitat.

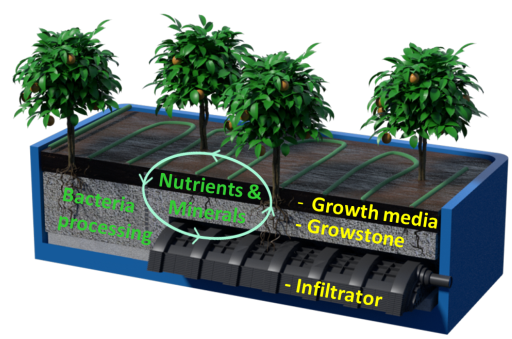

Figure 4. Biowick cut-away view

4. Nutrient Recycling Technologies

A unique passive aerobic Biowick system (Figures 1, 3 and 4) optimizes the growth of fruit-bearing trees and vines in SIRONA. The closed-loop Biowick is adapted for space from the Watson Wick,[29] an Earth-based aerobic pumice wick invented by Tom Watson. The Biowick relies on the symbiosis between microbes and woody plants to passively process grey and blackwater from human waste streams into nutrients for plants.[30, 31] A half-cylinder infiltrator creates an open-air volume buried under a layer of Growstone® aggregate, which itself is buried under a layer of growth media.

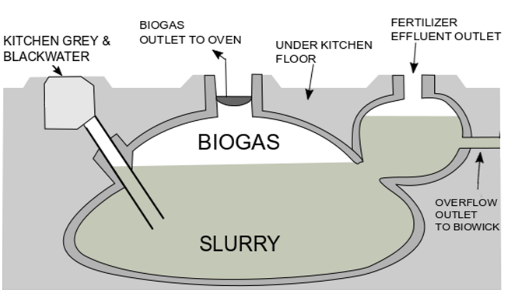

Figure 5. Biodigester

The infiltrator allows water and human waste to surge into the system from an inlet, while providing an open space for air to infiltrate the media bed. The highly porous Growstone® houses primarily aerobic (and some anaerobic) bacteria that process incoming waste, and acts as a medium through which air, liquids, and particulates percolate. Once processed by the bacteria, nutrients and minerals are then drawn up through the tree roots as moisture and fertilizer. Potentially hazardous blackwater never comes into contact with edible fruits, thereby preventing transfer of pathogens via direct contact. Plant roots easily infiltrate the porous media bed, drawing water and nutrients up from the Growstone® into the woody tissue of the tree or vine. About 1-5% of the water is consumed by the tree in metabolic processes and growth, while the rest is returned to the atmosphere through transpiration. The purified water vapor produced by transpiration is then recaptured by dehumidification.

Biodigesters (Figure 5) are highly effective sources of renewable energy and fertilizer production that are easy to maintain and simple. Methanogenic bacteria anaerobically process a mixture of organic waste, such as food scraps, inedible biomass, human/fish manure, and greywater.[32] The process produces a biogas composed of 50-70% methane and 30-40% carbon dioxide, as well as a nutrient-rich effluent that can be used as fertilizer for crops and algae, providing additional nutrient loop closure. The biogas product can be used for cooking, heating, methane extraction, and carbon dioxide enrichment of plants.[32]

5. Post-harvest Processing

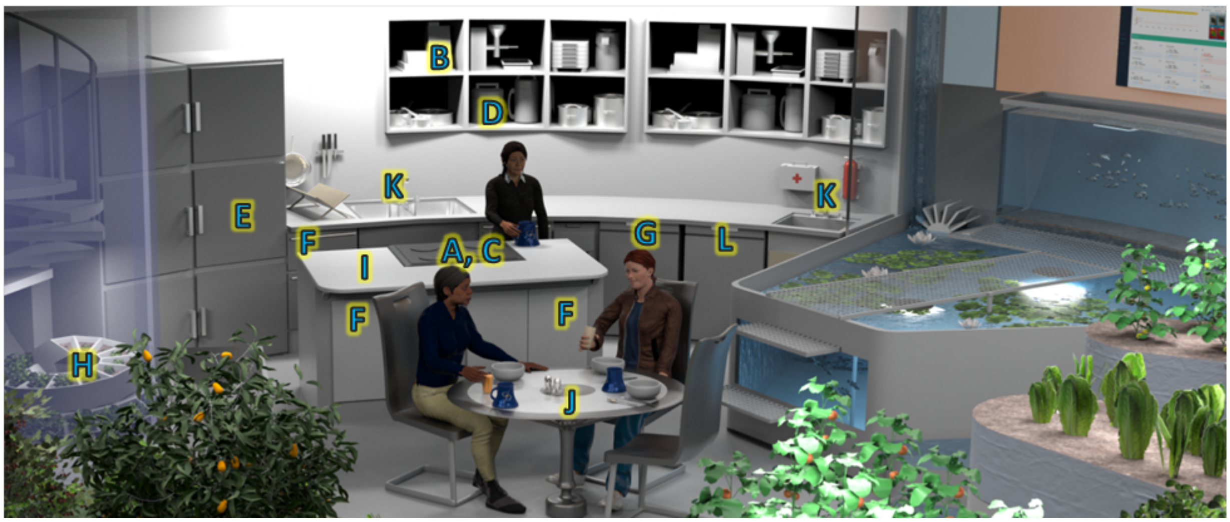

Figure 6. Kitchen Overview

Table 3. Kitchen Equipment

Label	Equipment	Mass (kg)	Power (W)	Comments
A	Induction burner sous vide bath	7.5	1500	Used together or separately; ideal for cooking fish and large vegetables
B	All-in-1 prep station	2.6	240	With attachments for blender, food processor, whisk
C	Oven/broiler/dehydrator	10.2	15 w/ biogas	Contains fan for forced convection; runs off of gas from biodigester
D	Multi-cooker	11.7	1400	frying, searing, pressure/slow cooking, etc.
E	Pantry	11	0	Stores grains, potatoes, etc.
F	Cold storage	352.4	486	Deep freezer (long-term storage); 2x freezers (short-term storage); 2x refrigerators
G	Dishwasher	32.7	1300	Greywater goes to biodigester
H	Herb spiral	5.0	60	Easily accessible for garnishes
I	Island	15.0	0	.8 m x 1.5 m x .9 m (height)
J	Dining table	15.0	0	.7 m x 1.4 m x .7 m (height)
K	Sinks	7.8	0	Food prep/dish sink; crop utility
L	Biodigester w/ macerator	10	540	Biogas connected to oven

The primary galley is moved from the crew quarters to the greenhouse (Figure 6) and expanded into a fully functional kitchen (Table 3) adjacent to a dining/recreation area. Consequently, post-harvest processing, preservation, and cooking all take place in close proximity to the growing and harvesting sites.

The kitchen relocation not only enhances crew efficiency, but also has the potential to improve physical and psychological well-being by increasing the amount of crewtime spent amidst nature. The layout of the kitchen maximizes both functionality and aesthetics. Equipment associated with long-term food storage (deep freezer and pantry) are located along the wall, with those for immediate post-harvest processing (a utility sink for initial cleaning of crops and fish, and a biodigester equipped with a macerator for breaking down inedible materials) located closest to the grow areas. Food residue on dirty dishes can be also discharged into the biodigester before being cleaned in the dishwasher or sink.

V. Concept of Operations

The concept of operations details how the greenhouse will be deployed and ran while on the surface. The basic operational processes of all the major subsystems are listed below.

A. Control and Operations

1. Environmental Control

Four climate zones (Table 4) are outlined according to analogous terrestrial climate zones and standard CEA methods. While no single crop necessarily experiences optimal environmental conditions at all times, the polyculture guilds planned in each zone are productive and resilient under slightly variable conditions.[21] In permaculture, plant guilds are groupings of different plants, animals, and other components that create a symbiotic relationship to help them grow and stay healthy, while providing useful resources to humans.

The selected crop complement is expected to uptake roughly 258 L of water/day, 96-99% of which is transpired. Humidity is maintained around 50-80%, depending on the grow zone temperature and the desired Vapor Pressure Deficit (VPD) to support plant growth at all stages (vegetative, flowering, and fruiting simultaneously). In order to maintain the desired VPD, the dehumidification system recaptures the transpired water and recycles it back into the IMTA system.

The IMTA system's dissolved oxygen level is maintained above 5 ppm[?] through aeration provided by the waterfall and waterwheel. The waterfall also serves the function of humidification in the early startup phase before the crops reach their full transpiration rate. Since the wicking beds in the temperate climate Zone-1 require cooler temperatures, they are enclosed by a clear CO_2/O_2 permeable membrane curtain system that creates a microclimate for that zone. Multiple V-FloFans create airflow in the greenhouse and redistribute heat and humidity. By using a vertical airflow system, constant airspeed and desired microclimates can be achieved at the plant level.

Table 4. Environmental Parameters

Zone	Hydroponic System	Earth Analog	Day Temp. °C (°F)	Night Temp. °C (°F)	Light (hrs/d)	DLI (mol· m^{-2}·d^{-1})	pH	Day RH (%)	Day VPD (kPa)
1	Wicking Beds	Temperate	12.8-21.1 (55-70)	7.2-12.8 (45-55)	12	15.12	5.8 - 6.8	15 - 55	.8 - 1.08
2	Ebb/Flow, Wicking Beds, Biowick	Sub/Tropical	21.1 -26.7 (70-80)	15.6-21.1 (60-70)	16-18	20.16 - 22.68	5.7 - 6.8	55 - 65	.83- 1.12
3	Aquaponics Tanks	Freshwater	25.6-30 (78-86)	25.6-30 (78-86)	16-18	20.16 - 22.68	6.8 - 7.5	53 - 70	.83 - 1.13
4	Algae	Freshwater	30 (86)	30 (86)	24	30.24	7.0 - 10.0	N/A	N/A

2. Lighting Systems

Lighting for crops comes from two sources: LED lights and a solar fiber optic Himawari ("sunflower" in Japanese) system. Programmable multi-spectrum LED lights made by AcroOptics provide the full Photosynthetically Active Radiation (PAR) spectrum as well as infrared (IR) and ultraviolet (UV) radiation. LED lights will be programmed to deliver short 'pulses' of 800-1000 µmol/m^2/s for five minutes five to six times daily, which will increase photoprotective carotenoid content of leafy crops without compromising biomass production.[16] The Himawari solar lighting system provides half the total PAR input to the greenhouse, though it is subject to variability due to Mars weather conditions such as sand storms. The Himawari system is a mature commercial technology that operates as follows: a solar collection system utilizes fresnel lenses to concentrate and transmit sunlight into the greenhouse via thin optical fibers. The optical fibers enter the SIRONA structure through the same utility pass-through as the power system electric wires. Advantages to the Himawari lighting system include minimal energy usage required to power the automatic tracking system that aims the lenses continuously at the sun, and colors that mimic natural lighting. The lighting panels from both systems are spaced such that the plants receive 350 $\mu mol/m^2/s$, which is sufficient for consistent carbon fixation.[33] The total Daily Light Integral (DLI) provided by the lighting system ranges from 15.12-30.24, depending on the zone, which is optimal for vegetable production. The combination of these two systems optimizes power, mass, and control resulting in a robust lighting system. Natural light that filters through the translucent shell of SIRONA helps to illuminate crew tasks and to train circadian rhythms.

3. AgQ, the Brain and System Displays

The AgQ (Agriculture AI) software carries out monitoring, alerting, diagnostics, and prediction functionality to provide plant care decision support.[11] AgQ has a data processing pipeline that utilizes machine learning and aggregated data from the Brain (i.e., a multiple sensor and vision system described below). The Brain provides data real-time streams from the following sensors: pH, EC (electric conductivity), dissolved oxygen, water, air temperature, CO_2, O_2, ethylene, methane, and other trace gases. It also provides the interface for wearable human health monitors. By pairing the plant care needs with the humans' physiological stress state and psychological need for contact with nature, the system provides alerts for plant care tasks at the optimal time when crew members can benefit from HPI. This is possible through the use of a dynamic pairing reinforcement learning algorithm which is fed the stress response from the astronaut before and after being assigned a care task to monitor the change. Additionally, a virtual extension service (plant telemedicine) is implemented to provide astronauts with plant care troubleshooting. The AgQ monitoring tool is displayed on SIRONA's wall above the IMTA pond, as shown in Figures 1 and 3.

Organic Light-Emitting Diode (OLED) microdisplays are used on sections of the ceiling and walls in SIRONA.[34] These low-power displays have advantageous features (e.g., high-resolution display of the color black and long lifetime) that make them a viable display technology. They will be used to display data from the AgQ system, views of Mars (shown in Figure 1), or scenes of clouds and birds from Earth to invoke a connection with nature.

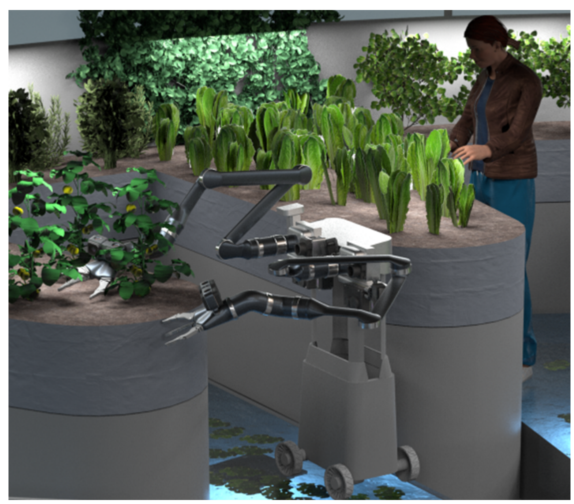

Figure 7. ROGR: Remotely Operated Gardening Rover performs plant care tasks alongside the astronaut and is able to assist automatically or via remote operation.

4. Robotics and Vision Systems

Robots are tasked with repetitive, time-consuming tasks, while activities that bring psychological and physical benefits resulting from HPI, such as harvesting, and tasks that are not appropriate to robots are left to the crew. Daily and weekly plant health monitoring involve a program of robotic manipulation, stereoscopic and multi-spectrum image analyses, as well as using sensors embedded in the growth systems. In addition to health monitoring tasks, the robotics and automation system perform: pollination, nutrient management, and crop performance alerts (e.g., crew notification of harvest readiness, nutrient deficiencies, disease states, and suggestions for corrective actions). All of these functions are integrated between the AgQ decision support and telemedicine modules, the Brain and the Remotely Operated Gardening Rover (ROGR) (Figure 7), with two robotic arms, allowing for complete access to the crops.[11] The Kinova JACO[35] or a similar arm is outfitted with specialized custom end-effectors currently under development at CU Boulder's Correll Lab.[36] Embedded finger sensors in the robotic hands provide sensitivity to textures and proximity, enabling fine motor skills crucial to manipulating delicate living systems.[36] The teleoperator and arm rely on visual input from four separate cameras:

- A basic overview camera displaying the inside of the growth chamber.
- An IR camera to monitor plant health and help diagnose problems.
- A LIDAR sensor that maps plant positions and projects the chamber environment in virtual reality.
- Two cameras on the end of the arm to provide stereo vision for AI or a teleoperator to accurately manipulate the arm and interact with the plants.

Autonomous operations of the robotic system and teleoperators care for the system in between crewed missions.

B. SIRONA Deployment

Figure 8 summarizes the deployment sequence after the greenhouse lands on the Martian surface. Phase-1 of deployment refers to the time after the greenhouse landing, but before crew arrival. Phase-2 of deployment refers to the one week set-up period post-crew arrival. Due to the constraints of the Mars launch window, Phase-2 occurs 25-26 months after Phase-1 of deployment.

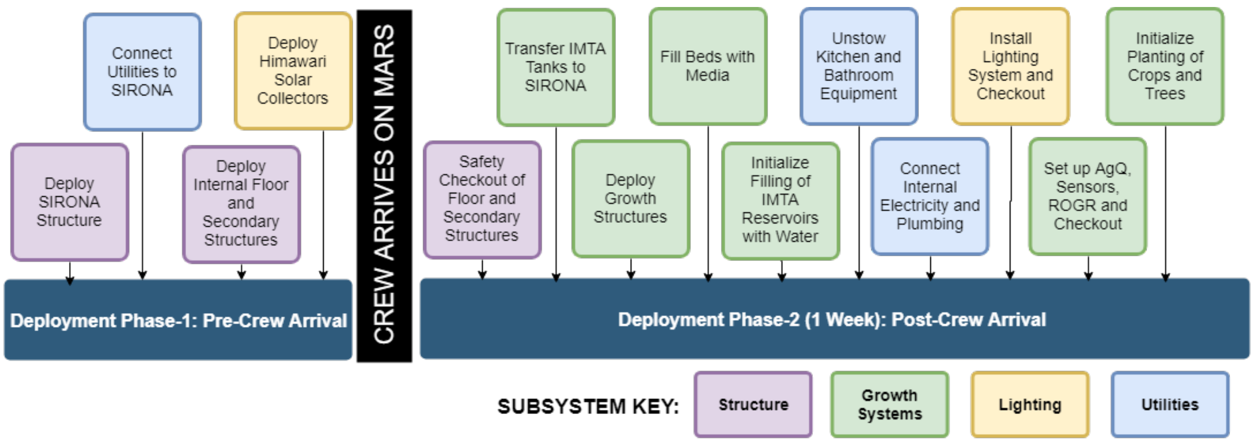

Figure 8. Deployment Timeline

1. SIRONA - Inflatable Deployment

Phase-1 involves deploying the greenhouse and other major systems before the crew arrives on Mars. The robotic transporters that move SIRONA from the landing site to the deployment site deploy the external Himawari solar collectors and connect the utilities to SIRONA. The airlock connecting SIRONA to the Ice Home habitat is deployed before the internal secondary structure deployment is complete. SIRONA utilizes an inflatable system for the internal secondary structural components, including the floors and bathroom walls with vertical and horizontal tensioning cables or webbing for additional support. The bio-inspired flooring system imitates the opening of a flower such that the inflatable floors unfurl from the central hubs. Therefore, the flooring modules are referred to as petals. This design decision was made by considering past studies on inflatable support structures.[10, 37, 38] The inflatable beam components are rigidized with foam or Martian regolith for additional strength.

Figure 9 shows the deployment of the floors within the SIRONA structure. Vertical tension cables allow the second-floor central hub to be suspended between the toroid's ceiling and floor hubs. Stage (a) of the figure displays the petals in the stowed position. In Stage (b), as the inflation process proceeds, each petal pivots at the central hub as it is lowered into position and unfolds like a fan. Upon unfolding, the floor petals are secured to the SIRONA shell. Additional horizontal

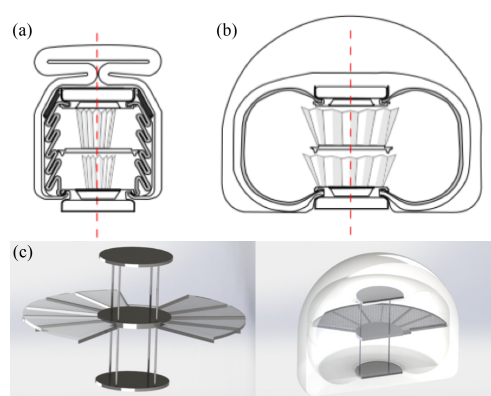

Figure 9. Schematic of the inflatable structure's deployment. (a) Collapsed structure at launch. The collapsed configuration allows for more usable empty space in the payload area. (b) Early stages of inflation and the unfolding of the multiple flooring petals. (c) Fully expanded floor petals.

support webbing is attached at the central hub and is pre-strung along
the inflatable beams that support the petal floor surface. Once the petals are deployed, these horizontal stabilization straps (which are attached to the toroidal shell) are tensioned to provide additional structural support. A similar process happens for the first floor. For example, collapsible growth system components such as the Biowick and IMTA pond are also stowed and unfolded in a similar process as the floor petals; as the flooring expands, these components are pulled into place and deployed. Other heavy items such as the kitchen island with refrigerators are stowed on the first floor central hub on castors and can easily be moved into place when the crew arrives.

2. Deployable Structures within SIRONA

The deployment timeline (Figure 8) details the order of the major steps taken to reconfigure and start the systems in SIRONA. After a safety checkout of the systems that were deployed in Phase-1, small equipment, hardware (e.g., light panels, cooking equipment and tools), and growth systems are unstowed from the launch configuration to the deployed SIRONA location by the crew in Phase-2. Hardware (e.g., furniture, equipment, and growth systems) is designed to be both easily stowed and deployed. For example, tables, chairs, storage areas (shelves and cabinets), growth systems, plant nursery equipment, photobioreactors, and the staircase can all be collapsed for transport. Once all of the systems are reconfigured, the initialization process can occur; this includes connecting the utilities to the internal systems, a system checkout process and planting of the living organisms (seeds, trees, tubers and aquatic species).

Living systems deployment begins with transit from Earth to Mars. Non-perennial plants (e.g., lettuce, tomatoes) will be transported to Mars as dormant seeds and are planted upon arrival. Perennial plants (e.g., dwarf kumquat, banana) will be aged on Earth to approximately two years of age prior to launch and stored in dark refrigeration during transit to simulate a third winter period. Tuber crops (e.g., sweet potatoes, mashua) will also be stored in dark refrigeration during transit and will be split and propagated vegetatively upon arrival. Aquatic animals will be cryopreserved as eggs and gametes to decrease equipment load and will be hatched or fertilized and incubated upon arrival.

VI. System Summary

A. System Nutrition, Power, and Mass Summary

The overall biomass yield for land crops is 1408.29 kg/yr, 17.86 kg/yr for the aquatic crops and spirulina, and 197.32 kg/yr for seafood (e.g., fish, mollusks, crustaceans). The total biomass yield of the entire ecosystem is 1930.56 kg/yr, or 1.32 kg/CM-d. The entire ecosystem provides 77.81% of the total dietary mass containing 18.59% of the 50.84MJ/d metabolic energy target[20] for a crew of four (or approximately one crew member's provisions) over the course of the 600-day surface stay. The greenhouse design achieves the goal, previously stated in Section III Design Considerations, of providing a moderate amount of metabolic energy and a high quantity of micronutrients, phytonutrients, and antioxidants. For more details on loop closure (input/output recycling) and crop performance (including: a full nutritional profile, water usage, CO_2/O2 exchange analysis, and crop phasing information), see Hava *et al.*, 2019a[8] and Hava *et al.*, 2019b[39].

Figure 10 and Table 5 present a first-order mass and power analysis based on values derived from a combination of commercial hardware and past space flight systems. Of the 40 kW allotted to the greenhouse, SIRONA uses 35.35 kW when 100% of the equipment is running, leaving a raw power margin of 11.62%. However, this is generally unrealistic and represents a maximum estimate. A more realistic scenario is one in which 50% of the equipment runs simultaneously along with the crop lighting system; in this case, the 50% power use margin is 12.29 kW, or 30.71%.

The total mass of the greenhouse system is 15,087 kg. This leaves a 16.18% margin of the budgeted 18,000 kg. The food production system, excluding crop lighting, is the component with the highest mass, accounting for 48.5% of the total system mass and utilizing 4.8% of the total power to run pumps and heaters.

LEDs have a high degree of controllability and are power intensive (50% of total power) but mass efficient (0.8% of total mass). The Himawari solar tracking system accounts for only 0.2% of the entire greenhouse power consumption, which makes it an excellent power-saving light source. The result is the ability to provide double the crop area with very little additional power. However, the Himawari accounts for 8.7% of the total greenhouse mass, as compared to the 0.8% taken up by the LEDs. Thus, pairing the LED system with the low-power Himawari optimizes total PAR, controllability, power, and mass. The photobioreactors consume an additional 7.6% of the power, of which the majority is used by LED lighting. The total lighting for the food production systems accounts for 57.8% of the total power consumption.

Appliances in the kitchen subsystem consume 5% of the total power (assuming only one third of the non-refrigeration equipment runs simultaneously and refrigerators/freezers are running continuously) and take up 2.7% of the total mass.

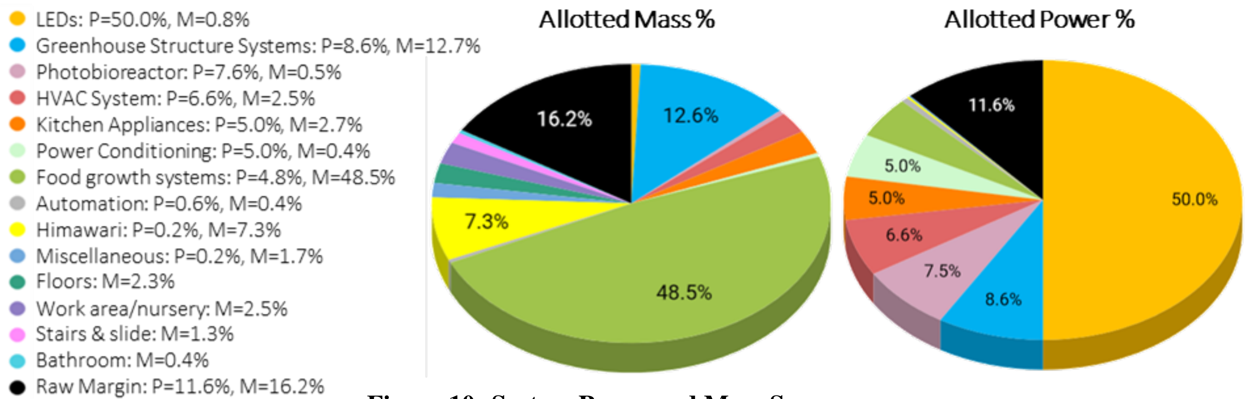

Figure 10. System Power and Mass Summary

Table 5. System Mass and Power Summary

Subsystem	Power (W)	Mass (kg)	Qty	Total (W)	Total (kg)	Comments
Allotted	40,000	18,000	1	40,000	18,000	Starting power and mass budget
Power conditioning	500	20	4	2000	80	Assumes power goes to SIRONA at 95% efficiency
SIRONA Greenhouse - Assumes the greenhouse structure requires the same systems as the Ice Home Habitat						
Greenhouse structure	0	1887	1	0	1887	Total value from Ice Home ConOps Table 5
Air pumps	75	10	4	300	40	Same as Ice Home air circulation
H_2O pumps/heaters	880	80	1	880	80	Same as Ice Home water pumps/heaters
Data, controls, sensors	2255	269.2	1	2255	269.2	Assumes same data collection, control system, and deployment sensor as Ice Home
Internal SIRONA Greenhouse Systems						
Biowick	0	581.4	1	0	581.4	Structure and infiltrator (excluding media)
Aquaponics	1920	2432	1	1920	2432	Tanks/structure, pumps, heaters (excluding lights)
Wicking beds	0	709.6	1	0	709.6	Structure only
Ebb/flow beds	0	500	1	0	500	Structure only
Growth media	0	4141	1	0	4141	Growstone®/growth media for Biowick & beds
Start-up nutrients	0	90	4	0	360	1 yr/CM of nutrients supplied prior to aquaponics/biodigester supply availability
Photobioreactor	3019	84.4	1	3019	84.4	Algae system pumps and 21 LED tube lights
Work area/nursery/displays	0	454.2	1	0	454.2	Work benches, germination racks, tools, supplies, 3D-printer, OLED displays
LED grow lights	400	2.7	50	20000	135	AcroOptics; 400W Grow lights: multispectral LED w/ 6 controllable channels
Himawari	5	88	15	75	1320	Equivalent to a 400W LED Light = 350 PPFD
Robotics/vision	55	13.6	4	220	54.4	JACO arm and vision/sensing systems
Controls	0.3	1	8	2.4	8	Based AgQ/Brain system developed at CU
Grow system fans	205	13	4	820	52	VFlo vertical ventilation fans for grow systems, 1 per grow area
Air temp	360	80	2	720	160	Two climate zones w/ separate control
Humidity control	360	80	3	1080	240	Two climate zones humidity control; an extra unit to handle transpiration load
Kitchen (all appliances)	5055	462.6	0.3	1516.5	138.78	Total power assume only 1/3 of appliances are running simultaneously
Refrigerators/freezers	486	352.4	1	486	352.4	Freezers, refrigerators
Bathroom	0	68.2	1	0	68.2	Plumbing fixtures and storage
Misc. plumbing & equipment	60	300	1	60	300	Bath/kitchen pumps & plumbing, small equipment
Stairs & slide	0	227.3	1	0	227.3	Slide is a secondary exit and recreational
Floors	0	412.3	1	0.0	412.3	1st and 2nd inflatable floor structures
Total				35,353.9	15,087.2	
Total Raw Margin				4,646.1	2,912.8	Remaining power and mass from allocation
Total Raw Margin %				11.62%	16.18%	Assumes 100% of electrical items are running
50% Power Use				12,285.6		Assumes only 50% of non-lighting systems
Margin				30.71%		are running simultaneously

Table 6. Risk Matrix: blue (initial); black (final)

Risk Matrix						
Likelihood	5	11	11			
	4					
	3	5,10	5,6,10	1,3		
	2	2,6,7,8,12,19	2,7,8,16,18,19	4,12, 19, 20		
	1	1,3,18,20	4,9,15,16	13,14,9,15	17,13	14,17
		1	2	3	4	5
Consequences						

Table 7. Risk Reduction and Mitigation

System	#	Risk	Likelihood: Consequence Start	Likelihood: Consequence Result	Mitigation
Biowick	1	Overflow	3 : 3	1 : 1	Overflow goes to biodigester.
Biowick	2	Tree loss	2 : 2	2 : 1	Plant alternate crops from seed.
Biodigester	3	Overflow	3 : 3	1 : 1	Divert to Ice Home waste collection system.
Biodigester	4	Microbe failure	2 : 3	1 : 2	Pre-mission: select microbes to digest cellulose; test radiation exposure. During mission: Use macerator to help breakdown waste.
All systems	5	Pump failure	3 : 2	3 : 1	Provide multiple spares. Design parts w/ high probability of failure to be 3D printed. In case of catastrophic failure, hand water.
Aquaponics	6	Fish loss	3 : 2	2 : 1	Hydroponic nutrients & biodigester fertilizer replace fish-based fertilizer; test fish on Deep Space Gateway to ensure transit survival.
Food system	7	Cold storage failure	2 : 2	2 : 1	Utilize dissimilar cooling technologies. Store food in outside storage box in the Martian environment if catastrophic failure occurs. Utilize other food preservation (ex. dehydration freeze-drying) methods
All systems	8	Parts failure	2 : 2	2 : 1	Spare parts are provided or designed for on-site 3D printing.
Robotics	9	Catastrophic failure	1 : 3	1 : 2	In case of failure, the crew will complete robotic tasks, which will be restructured for crew time considerations.
LED Lighting	10	Light failure	3 : 2	3 : 1	LEDs are in parallel and can be repaired individually. Replacement LEDs, ballasts, and lighting arrays are supplied.
Himawari	11	Dust on collectors	5 : 2	5 : 1	Collectors include a cleaning mechanism to remove dust. As needed, EVA can be conducted for cleaning & maintenance post dust storms.
Oven Burner	12	Methane supply and storage	2 : 3	2 : 1	Biodigester methane is stored at low-pressure outside of SIRONA. Gas is scrubbed for contaminants before use. The Martian atmosphere is a secondary source in case of inadequate supply.
Oven Burner	13	Fire	1 : 4	1 : 2	Smoke detectors, fire extinguishers, & suppression systems (pond is a fire suppression backup) are installed. Flammable objects are stowed away from oven. Cooking equipment w/o an open flame is provided.
Crop Systems	14	Crop loss	1 : 5	1 : 3	Stored food provide bulk calories. Supplements provide key nutrients to maintain adequate health for the remainder of mission.
Crop Systems	15	Crop disease	1 : 3	1 : 2	Cultivar selection for disease resistance. Increased biodiversity of crops and visual monitoring decrease chance of crop loss.
Crop Systems	16	Crop nutrient deficiency	2 : 2	1 : 2	Continuous monitoring with sensors and visual inspection are used for early detection and to trigger corrective actions.
Power Systems	17	Power failure	1 : 5	1 : 4	A backup power system can power the Himawari to provide crop lighting & run pumps. The oven is functional without power.
Growth Systems	18	Sensor failure	2 : 2	1 : 1	Spare sensors are provided. In case of failure, frequent visual inspection is utilized.
Biowick	19	Clog	2 : 2	2 : 1	A manual port allows the crew to remove the clog.
Sinks	20	Hygiene	3 : 2	1 : 1	Separate sinks are provided for cooking and pre-processing of crops.

B. Risk Reduction

The SIRONA Greenhouse should be one-fault tolerant for catastrophic failure of any system. This can be seen in the design choices of SIRONA, such as: dissimilar lighting technologies, the Biowick and biodigester act as redundant systems and provide overflow capacity for each other, a secondary bathroom and full kitchen in case of airlock failure, to name a few of the design fail-safes. Passive systems were implemented wherever possible to reduce the possibility of mechanical failures, thereby increasing the robustness and resiliency of SIRONA. When selecting technologies and growth medias, systems with low risk and low failure were prioritized. Additionally, multiple spare replacement parts for every system will be provisioned and the majority of the parts that may experience failure or will need routine replacement shall be designed for 3-D printing in space. All of the technologies can be maintained *in situ*. The likelihood and consequence definitions from Peeters *et al.* 2015[40] were used to develop the risk matrix (Tables 6 and 7).

Of particular consideration is the treatment of raw human manure for use as fertilizer. Numerous studies have shown that biosolids from human waste can be safely used as nutrition for plants,[41–43] and there is no empirical evidence that suggests human pathogens are transmitted from roots to edible fruits through plant vascular tissue. Also, Biowick system are being used to grow fruit trees on Earth. That said, the Biowick food safety needs to be validated through experimental methods during the future development of SIRONA to fully address this concern. If experimentation suggests that pathogens may be transferred to the fruit from roots or soilless media, then there are two mitigation options: 1) re-route bathroom blackwater to be processed only by the biodigester or 2) add a pre-treatment sterilization step before the blackwater enters the infiltrator of the Biowick.

VII. Conclusion

SIRONA is a multi-functional design that enhances physiological and psychological well-being of the crew while minimizing subsystem mass and power. It draws upon principles of bioregenerative ecosystem design to naturally recycle inputs and outputs between the integrated living systems. This can be seen in the selection of crops as well as their integration with systems such as the Biowick, the Integrated Multi-Trophic Aquaponics system, and the biodigester. Future development of the SIRONA system technologies will include design iteration, prototyping, and deep space testing. SIRONA is capable of producing a wide variety of food sources that provide health benefits beyond fulfilling basic nutritional needs. Versatile and powerful kitchen tools allow for effective post-harvest processing and cooking to improve nutritional intake, crew well-being, and group cohesion. SIRONA provides the full benefits of a bioregenerative life support system including: nutrient and water recycling, air revitalization, nutritious food and access to nature.

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