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SIRONA: Sustainable Integration of Regenerative Outer-space Nature and Agriculture. Part 2 — Design Development and Projected Performance

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ABSTRACT

A comprehensive Bioregenerative Life Support System (BLiSS) for human Long-duration Space Exploration Missions (LDSEMs) requires an innovative design philosophy and novel technical solutions. SIRONA: Sustainable Integration of Regenerative Outer-space Nature and Agriculture is a greenhouse design that produces a wide variety of food sources and provides life support functions, including access to nature to improve astronaut restoration, relaxation, and recreation. In a previous paper (Hava et al., 2019), risk analyses, technologies, and system architecture were outlined, while this paper describes the foundational Living Systems Centered Design (LSCD) principles that informed the development of the greenhouse. Analyses on projected performance are also carried out to validate design assumptions and constraints.

1. Introduction

Traditional Bioregenerative Life Support Systems (BLSS without an "i") have primarily focused on air revitalization, waste processing, optimization of edible biomass, and caloric content of growth systems to ensure crew survival. SIRONA is a BLiSS (with an "i") that expands on the idea of the traditional BLSS by helping the crew and the entire living system thrive. Founded on the idea that "Nature is BLiSS" [1], SIRONA values access to nature as a life support function to enhance relaxation, recreation, sensory stimulation, and other restorative factors.

1.1. Context and assumptions

SIRONA design and analysis first began as part of the 2019 NASA BIG (Breakthrough, Innovative, and Game-changing) Idea Challenge [2, 3], where SIRONA received the Most Innovative Concept Award [2]. SIRONA is a greenhouse designed to provision a crew of four during a 600-day mission on an early Mars outpost. The concept relies on the Mars Ice Home [4] as the external support structure and connects to the crew habitat via a pressurized tunnel with an airlock at each end (Fig. 1). The primary shell features an inflatable structure filled with translucent ice, which allows solar light to enter the greenhouse while blocking harmful solar radiation and galactic cosmic rays. The shell is outfitted with additional internal secondary structures and growth systems to form a sustainable greenhouse. The Mars Ice Home [4] was designed by a collaborative team from NASA's Langley Research Center, SEArch+, and CloudsAO and is designed to protect the internal living systems against the harsh Martian environment. A detailed risk assessment of the SIRONA greenhouse, as assembled within a Mars Ice Home, is provided in SIRONA Part-1 [2,3].

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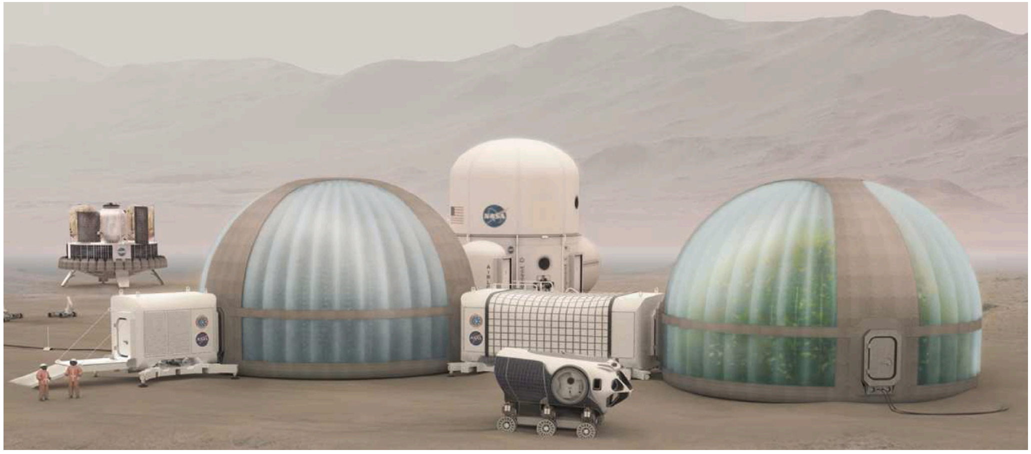

Fig. 1. NASA BIG Idea Mars Ice Home and greenhouse. Image rendered by SEArch+ / CloudsAO/NASA [2].

Acronyms and Abbreviations

AgQ	Agriculture AI (database and statistical analysis)
BLiSS	Bioregenerative Life Support Systems (the *i* in Life indicates access to nature is a primary function)
BVAD	Baseline Values and Assumptions Document
CEA	Controlled Environment Agriculture
CM-DT	Crew Member Diet Target
CM-d, wk, or yr	Crew Member-day, week, or year
CO_2	Carbon Dioxide
CY	Composite Yield
EDL	Entry, Descent, and Landing
FCR	Feed Conversion Ratio
HPI	Human-Plant Interaction
H_2O	Water
HVAC	Heating, Ventilation, and Air Conditioning
IMTA	Integrated Multi-Trophic Aquaponics
IR	Infrared
ISRU	In Situ Resource Utilization
ICE	Isolated Confined Extreme Environment
LDSEM	Long Duration Space Exploration Mission
LED	Light Emitting Diode
O_2	Oxygen
LSCD	Living Systems Centered Design
PAR	Photosynthetically Active Radiation ($\mu mol/m^2/s$)
USDA	United States Department of Agriculture
ROGR	Remotely Operated Gardening Rover
SIRONA	Sustainable Integration of Regenerative Outer-space Nature and Agriculture
UV	Ultraviolet
4XR	Four Root R's: Robust, Resilient, Restorative, and Regenerative

SIRONA Part-1, a prior publication, delves into design philosophy and layout details, living systems functions, greenhouse technologies, concept of operations (CEA controls, lighting, automation, and deployment), and detailed engineering analysis (power, mass, and risk) [5]. Here, SIRONA Part-2 focuses on the development of the Living Systems Centered Design (LSCD) principles, food production and processing, Integrated Multi-Trophic Aquaponics (IMTA), projected performance of the BLiSS functions (CO_2, O_2, water, and access to nature), and a nutritional analysis.

2. SIRONA Part-1 summary

This section provides a brief overview of the SIRONA design; in-depth details and analyses of the architecture and technology topics can be found in SIRONA Part-1 [5]. The major architectural greenhouse sub-systems and technologies of SIRONA are highly integrated and interact in symbiotic relationships (see Fig. 2). These growth sub-systems include the Biowick, a biodigester, herb spirals, photobioreactors, and an Integrated Multi-Trophic Aquaponics (IMTA) system that is paired with ebb and flow grow beds and keyhole wicking beds. For information on grow zones and associated environmental parameters, see Appendix, Tables A.2 and A.3. In addition to the growth systems, SIRONA includes a post-harvest processing and cooking area, dining area, recreational features, a bathroom, and emergency sleeping quarters that allow it to function as a secondary habitat (Fig. 3).

The fruit trees and aerobic microbes in the Biowick passively process grey and blackwater from the bathroom [6–8]. The trees use the nutrient-rich water as a fertilizer. The biodigester turns grey and blackwater from the kitchen into supplemental fertilizer for crops and *Spirulina*.

The Integrated Multi-Trophic Aquaponics (IMTA) system creates a stable aquatic ecosystem consisting of symbiotic relationships between aquatic species to recycle nutrients and increase yields [9]. The IMTA system includes the pond, freshwater mussel tank [10], and juvenile fish tanks. The pond and juvenile fish tanks irrigate the first-floor wicking beds and Biowick. Water from the pond is pumped up to the freshwater mussel tank, then used to water the ebb and flow beds and wicking beds on the second floor, and returns to the pond via the waterfall. The mussel tank's nutrient-rich water refills the photobioreactors after the *Spirulina* is harvested. Once the *Spirulina* culture is separated, the clean water is circulated back into the IMTA system.

Ebb and flow beds are watered through cyclical flooding and draining of the growth media. Wicking beds are sub-irrigated media beds that work similarly to a self-watering pot. Using Growstone® as the aggregate in these media beds provides a highly oxygenated root zone environment with consistent moisture levels between flooding or irrigation cycles to reduce the risk of anaerobic conditions that can lead to root rot and disease. Growstone® reinforces resiliency by allowing crops to survive for several hours in the event of a pump failure, after which they can be hand watered. In comparison, aeroponic system failures can result in crop death in as little as 15–30 min.

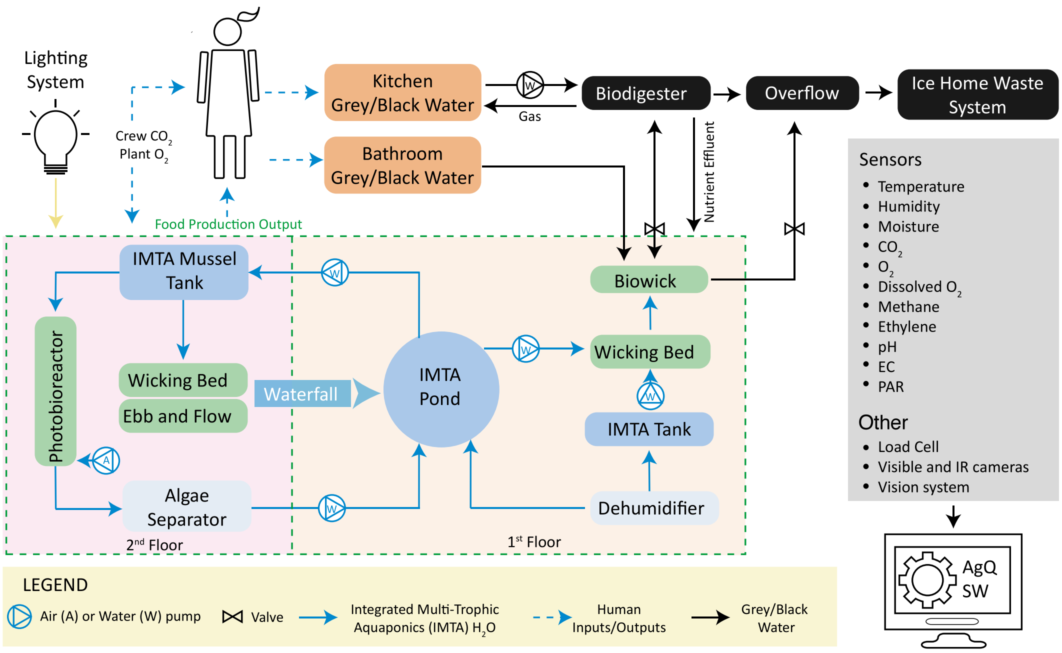

Fig. 2. SIRONA system overview [3].

The photobioreactors produce microalgae *(Spirulina)*, which has a rapid growth cycle and is projected to be one of the first crops harvested during a mission. The genus *Spirulina* was selected for cultivation in the photobioreactors due to its high nutritional density and the alignment of its environmental needs with the greenhouse climate [11]. The *Spirulina*, along with micro-greens and pre-packaged food supplies, fill the nutritional need during the greenhouse's start-up phase, when other growth systems have not yet begun to yield edible biomass. Furthermore, microalgal photobioreactors scrub carbon dioxide from the SIRONA greenhouse during dark periods when land plants are not photosynthesizing. To supplement air revitalization beyond the capacity of plants, it is assumed that a physico-chemical life support system will complement the SIRONA BLiSS to include functions such as removing harmful trace gases and buffering of the carbon dioxide and oxygen levels. However, the design of such a system is beyond the scope of this paper.

The lighting and automation technologies complement SIRONA's other growth technologies. LED lights and a solar fiber optic Himawari system provide lighting for crops. The programmable multi-spectrum LED lights provide 350 μmol/m^2/s of full spectrum Photosynthetically Active Radiation (PAR), as well as infrared (IR) and ultraviolet (UV) radiation; for details on lighting periods, see Appendix, Table A.3. Generally, light periods vary in each zone according to the species of plants and the Earth lighting conditions to which they are adapted. In addition, they also deliver short, high intensity pulses (800–1000 μmol/m^2/s) for five minutes several times per day to increase photoprotective carotenoids in leafy crops without compromising biomass production [12]. The Himawari passive solar collection system concentrates and transmits sunlight into the greenhouse via fiber optic cables, thereby providing half of the total PAR. The automation technology integration is further discussed in Section 5.4.

2.1. Mass, power, and deployment volume summary

The water (*in situ* production of 100 kg/day), power (40 kW provided by the Kilopower system), and launch mass (18,000 kg) constraints were provided by the BIG Idea Challenge [13]. Analyses of power, mass, volume, and water were conducted to evaluate SIRONA's anticipated performance. A summary of the power utilization and system mass is provided in Table 1. The water analysis can be found in Section 5.1, Table 5. Details of these analyses, and a risk analysis, are found in SIRONA Part-1 [5].

Table 1
Mass and power summary.

Summary	Mass Total (kg)	Power Total (W)
Allocation	18,000	40,000
SIRONA total	15,087.2	35,353.9
Total raw margin	2,912.8	4,646.1
[a]Total raw margin %	16.18%	11.62%
50% power use		12,285.6
[b]% power use margin		30.71%

[a]Assumes 100% of all electrical items are running at rated power.
[b]Assumes 100% lighting and 50% non-lighting systems are running at rated power.

A packing factor analysis based on existing Mars Ice Home parameters was conducted to derive SIRONA's features and capabilities. SIRONA can be packed to fit in the 8m-diameter cargo shroud of the Space Launch System vehicle. It also conforms to the volumetric and dimensional constraints of the Launch and Entry, Descent, and Landing (EDL) aeroshell. Like the Ice Home, the SIRONA platform will be transported to the Mars deployment location via robotic transporters that are pre-positioned on the surface [4]. Deployable structures within SIRONA were analyzed for their expansion capacity using a metric called the packing factor (Eq. (1)). A higher packing factor indicates higher expansion capacity.

$$r_{deployment} = \frac{Total\ Deployed\ Volume}{Total\ Stowed\ Volume} \tag{1}$$

A detailed breakdown of stowed and deployed sub-system volumes is reported in Table 2. A packing factor is applied to the deployed volume to estimate the stowed volume for each sub-system. The packing factor of collapsible sub-subsystems is estimated to be equivalent to the packing factor of the SIRONA shell structure (calculated to be 6.06). Non-collapsible sub-systems have a packing factor of 1. The estimated deployed volume takes into account empty interstitial space created during expansion; thus, sub-systems such as the IMTA system undergo a dramatic increase in volume. The estimated sub-system (or component) volumes and dimensions are either derived from the SIRONA architecture or relevant parameters from NASA's Life Support

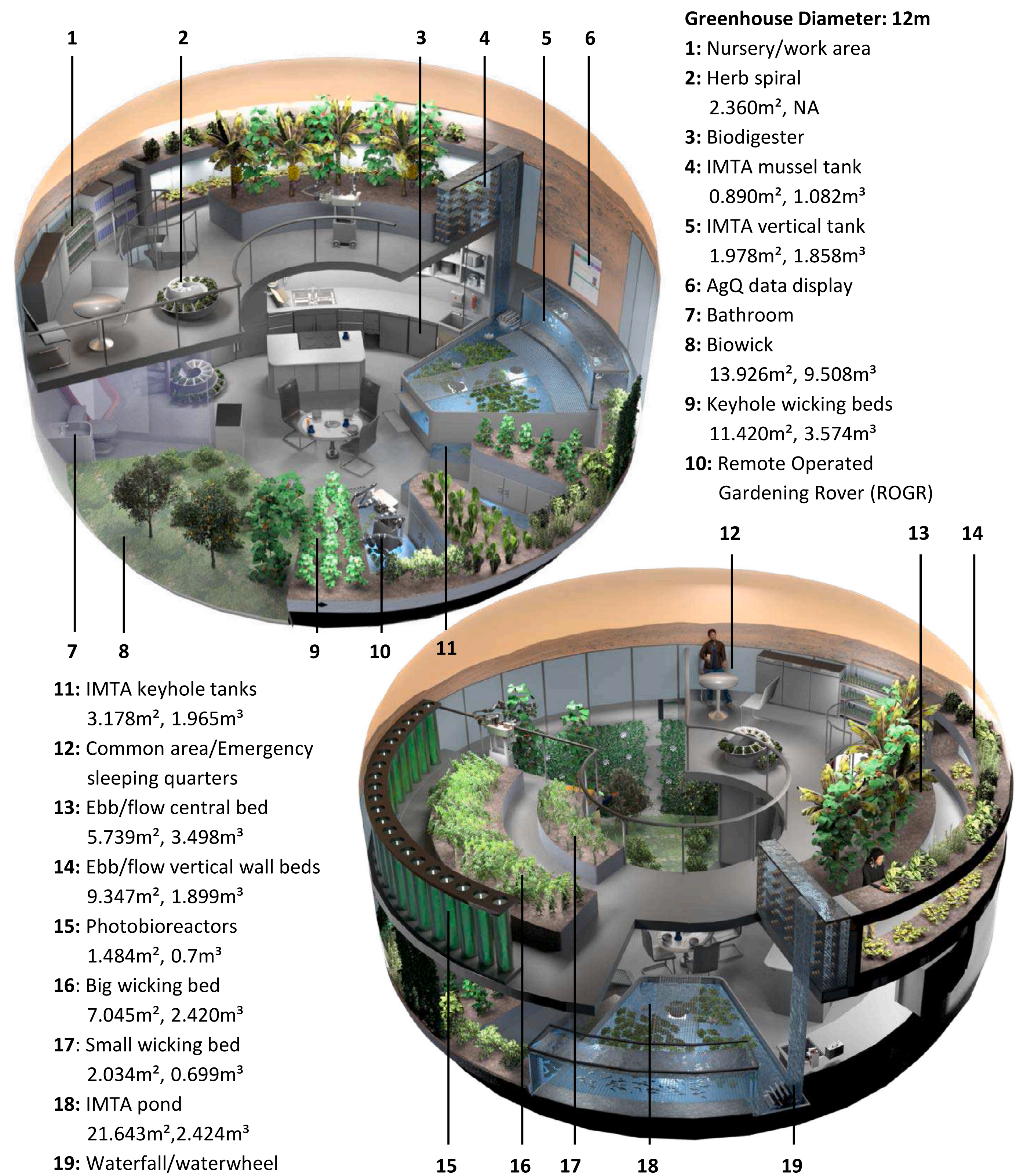

Fig. 3. SIRONA architecture layout (revised from [5]), with sub-system area and volume. Sub-systems located on the first-floor (cutaway view: top) are: the kitchen with a biodigester, herb spiral, food forest including a keyhole wicking bed garden and Biowick, watered by the Integrated Multi-Trophic Aquaponics (IMTA) reservoirs (keyhole juvenile tanks and pond). Second-floor (bottom) sub-systems include: herb spiral, plant nursery, and common area (doubles as area for deployable emergency sleeping quarters) and the IMTA freshwater mussel tank that waters the ebb and flow beds, wicking beds, and photobioreactors. Multi-level features include: high-wire plant trellising, programmable multi-spectrum LEDs, and the Himawari solar lighting system (lighting fixtures and solar collectors not shown).

Table 2
Deployment volumes.

Sub-system (or component)	Stowed Vol. (m^3)	Deployed Vol. (m^3)
First-floor system[a]	6.5	39.3
Second-floor system[a]	6.8	41.2
Photobioreactors[a]	0.1	0.7
Wicking beds[a]	1.1	6.7
Ebb and flow beds[a]	0.9	5.4
IMTA system[a]	1.2	7.3
Misc. (bathroom walls, furnishings, etc.)[a]	10.6	64.0
Biowick[a]	1.6	9.5
Growth media[b]	21.6	21.6
Kitchen equipment[b]	25.4	25.4
Lighting panels[b]	3.1	3.1
Himawari solar collectors[b]	61.1	61.1
Photobioreactor bulbs[b]	0.04	0.04
Total internal payload	140.0	285.3
Available internal payload	175.3	N/A
SIRONA structure	327.9	1986.5
Internal payload margin:	35.32 (20.15%)	

[a]Packing factor of 6.06.
[b]Packing factor of 1.
Launch Configuration: Internal payload volume is contained within the stowed SIRONA structure.

Baseline Values and Assumptions Document (BVAD) [14]. Worst-case volumes suggest an estimated margin of 35.32 m^3 (20.15% of available payload volume) in the launch configuration. For details of the SIRONA deployment plan, timeline, and sub-systems, see SIRONA Part-1 [5].

3. SIRONA architecture development

3.1. Human challenges, architecture gaps, and solutions

SIRONA targets psychological and physiological concerns that originate from LDSEMs in Isolated Confined Extreme (ICE) environments. Some of these concerns include boredom, social isolation, menu fatigue, nutritional deficiencies, oxidative stress, sensory deprivation, and exposure to a sterile, mechanical environment. Current architecture solutions, primarily informed by systems engineering and human factors engineering, do not adequately account for the needs of all the living organisms in a space habitat and greenhouse outpost to provide a truly integrated and optimized living system.

SIRONA sets out to achieve a new vision for space architecture by creating an integrated network of living systems that improve habitability beyond meeting minimum human needs. In the same way that a tree's roots create a foundation for growth and support, four synergistic characteristics that inform SIRONA's BLiSS are called the **Four Root R's (4xR): Robust, Resilient, Restorative, and Regenerative**.

- **Robust:** characterized by low failure rates; easily maintained under a wide range of conditions.
- **Resilient:** the ability to ensure performance under a wide range of conditions:
  - survive: provide basic functionality during a failure;
  - rebound: recover from a failure;
  - thrive: flourish and build system capacity during nominal operations.
- **Restorative:** capable of alleviating system stressors to rejuvenate the vigor of the entire living system, with emphasis on restoring the cognitive capacity and psychological health of human symbionts.
- **Regenerative:** internal capacity to cultivate and enrich the health and well-being of the whole living system with minimal external inputs.

The 4xR outcomes can be achieved through a diverse agroecosystem that provides dietary variety and an environment conducive to crew cohesion, restoration, relaxation, and recreation (Fig. 3 and Fig. 4). The SIRONA BLiSS mimics a park or garden with additional features including: Human-Plant Interaction (HPI), horticulture therapy, meal preparation, and supplemental regenerative life support (e.g., food production, waste management, water reclamation, air revitalization, and access to nature). The 4xR's also lower overall system risk, as discussed in SIRONA Part-1 [5].

3.2. Architecture design development and techniques

This section highlights the most salient design principles, techniques, and technologies implemented in SIRONA. However, it is not an exhaustive list.

3.2.1. Food production systems

The SIRONA food forest is the top-level architecture that is a fusion of the individual food production systems described in Section 2 and the following elements:

A **food forest** is a regenerative agroecosystem that mimics the natural canopy layers, functions, structure, and integrated ecosystem of a forest [15]. Stacked functions are achieved through physical stacking and polyculture guilds of intercropped perennial and annual plants as well as through technology and architecture functions.

Polyculture guilds are groupings of plants, animals, insects, and microbes that work together to ensure the survival and success of the whole living system [16]. Humans are symbionts integral to the guild.

The **keyhole wicking beds** are a technology and design layout adapted from permaculture keyhole beds [17]. The SIRONA design improves access and integrates multiple functions into one greenhouse element.

The **hydroponic herb spiral** mimics a natural pattern to create a space-efficient 3D growing space. The SIRONA herb spiral is a hydroponic version of the permaculture herb spiral [17].

3.2.2. Living systems centered design (LSCD) principles

SIRONA utilizes a unique set of design principles described in this section that build upon classical permaculture theory originated by Mollison and Holmgren [18]. Mollison later wrote the definitive work "Permaculture: A Designer's Manual" [17]; whereas Holmgren formalized the permaculture design principles [19]. While some of the LSCD principles are derived from the foundation of permaculture design, the remainder of the LSCD principles are delineated in the Living System Centered Design theory, which is a novel design theory developed by H. Hava.

A number of the following LSCD principles informed the individual components and systems integration of SIRONA. Each concept is first introduced and then followed by an example of its implementation in SIRONA. Concepts in the SIRONA design are highly interconnected; the order in which they are listed does not indicate importance.

Prioritize biomimicry over non-biologically inspired artificial or mechanical systems when designing living systems. Biomimicry utilizes nature-inspired systems and biological organisms to provide yields, functions, or services in support of human needs and health [20]. Nature has created and evolved well-adapted structures, materials and systems through natural selection, resulting in solutions to many complex challenges. By utilizing biomimicry, efficiency and the 4XR's can be improved in a BLiSS. Ex. The SIRONA food forest mimics the biodiversity of natural ecosystems. Similar to how diverse plants grow in specific climates, SIRONA takes advantage of the environmental variations within the greenhouse to grow a wide variety of crops

Fig. 4. SIRONA cut-away view. Aesthetics and space for recreation and communal living are core to the design concept.

with divergent needs and growing conditions. By utilizing this natural environmental variation, instead of trying to create a homogeneous environment, the energy required for climate control is reduced. SIRONA also recycles resources similarly to natural ecosystems. One technology used is the biodigester, which mimics a cow's digestive tract to digest biomass and produce effluent that can be used as fertilizer; as opposed to using a physico-chemical technology, such as an incinerator to dispose of waste without recycling it.

Prioritize biophilic design [21] to facilitate human connection with nature to support health, well-being, and restoration within the built environment. Ex: The growth systems and waterfall provide sensory stimulation and improve the restorative ambience inside SIRONA. Crew members experience greater passive Human-Plant Interaction (HPI) during work, recreational, and exercise tasks.

Synergistically integrate, do not segregate, systems to improve robustness, resiliency, efficiency, cohesion, and capacity-building. Ex: The integration of the crop production, processing, cooking, dining and recreation zones increases task efficiency and restoration. By including a bathroom and kitchen, the greenhouse serves as an emergency habitat and achieves improved robustness and resiliency and reduced risk.

Stack functions within the integrated system, such that each element provides more than one function, and each function is satisfied by more than one element. Functions can be stacked in: time, space, behaviors, and services to increase robustness and resiliency. Ex: The organisms in the food forest perform a variety of functions, including: cleaning, filtering, fertilizing, and producing food. The first-floor keyhole wicking beds are positioned on top of a storage system for improved ergonomics and space efficiency. The temperate climate crops, such as leafy greens, are located on the same level as the cooking zone to facilitate frequent harvesting of small quantities. The vertical positioning and nesting of the IMTA juvenile tanks within the keyhole beds stack functions by physical location, services, and yields to other systems.

Incorporate and value diversity to increase the 4xR outcomes. Previous BLSS (life support only systems) designs have viewed diversity as an undesirable trait because it adds complexity. Ex: In SIRONA, if one crop fails, the remaining crops in the polyculture guild maintain viability. As a result, just as in a natural ecosystem, diversification lessens the impact of crop failure on the overall system health and dietary variety.

Obtain a yield and produce no waste. Minimize non-usable yields (i.e. outputs). Many yields can be measured directly. However, other types of yields may encompass non-tangible benefits that nevertheless fulfill a function, need, or requirement of the living system. Outputs are not considered to be waste, but rather yields that can be an input to another element of the system. Ex: The Biowick stacks the functions of waste and water processing with plant growth by turning the human output streams into fertilizer, thereby obtaining multiple yields [7,8].

Value beauty and aesthetics as a function. When form and aesthetics are valued as a function, then these attributes can be integrated more broadly into a system; both for the stand-alone purpose of providing beauty in the environment and as a stacked function that an element provides within the system. Restorative environments that support human psychological health and well-being often include subjective traits of beauty and aesthetics. Elements such as art, organic forms, natural materials, sounds, and sights often provide a higher level of restoration than machine and built environments. Ex: The herb spiral exemplifies this design principle.

Build in opportunities to develop system capacity. It is important for living systems to have the capacity to evolve, adapt, and grow. Ex: The SIRONA technology choices allow for expansion using additional IMTA systems or adaptation to a hybrid IMTA/soil-based system over time. See Section 6.2 for further details.

Value and utilize natural environmental variations, processes, and passive systems. The built environment often works against natural systems. In contrast, this approach encourages utilizing the emergent benefits, opportunities, yields, and services these variations provide. Ex: Examples of this design principle are described in the following principle, as they are complementary and have significant overlap.

Capture, store, and recover value created within and available to the system. Energy, renewable resources, and services already within the system can be captured as a yield or from accessible natural or artificial external sources. Identify opportunities to take advantage of natural energy variations. Store energy, when necessary, in anticipation of shortages. The following examples embody this principle and the two preceding principles.

Ex: The Himawari relies on sunlight to provide passive supplemental crop lighting with minimal energy input to the collector tracking system. By placing the temperate crops on the first floor across from the kitchen and the tropical crops above the kitchen on the second floor, the natural heat gradient in the greenhouse reduces the need for active heating and cooling. The waterfall provides humidification and uses kinetic energy to turn the aeration wheel in the IMTA pond. These examples also employ the stacking functions principle to increase resiliency and robustness. The Biowick passively processes grey and blackwater output streams. SIRONA utilizes inedible biomass to make fish pellets for the IMTA system, produce fertilizer from the biodigester, or to build soil using the sheet mulching technique described in Section 6.2. Transpired water is recovered for re-use as drinking water and/or makeup water for the IMTA system and photobioreactors.

Utilize and design artificial, mechanical, and automation systems to support living systems and enhance their survival, well-being, and performance. The built environment and artificial systems shall conform to, enable, and optimize living systems, instead of hindering them. Ex: Automation systems such as AgQ and ROGR support the growth systems and crew members to improve system robustness, resiliency, and productivity.

Implement human factors best practices to ensure system usability, safety and performance, when designing living systems. Special attention to human factors is required to: optimize human well-being, increase safety, reduce human error, enhance the 4xR outcomes, improve system performance, and boost productivity. Ex: Both the layout of SIRONA and the decision support systems (i.e., AgQ and ROGR) employ many human factors principles to improve greenhouse usability, thereby increasing workload efficiency and system productivity. The decision support systems and the user interface of AgQ provides help to reduce human error in crop care, which improves growth system productivity and increases workload efficiency. The kitchen layout is designed to improve food processing efficiency and strengthen crew cohesion through team cooking and dining activities.

To experience a realistic fly-through of the SIRONA greenhouse, watch this video: https://youtu.be/AuPx4YJrQpI.

3.3. Food processing design development

Turning raw edible biomass into a delicious meal satisfies far more than basic caloric and nutritional requirements. On Earth, food has a variety of functions, such as social cohesion, entertainment, cultural identity, pleasure and the like [22]. Once basic requirements of quantity and acceptability are met, humans also expect food to be interesting and delicious [23]. Food's significance to the crew has been shown to be only further magnified in ICE environments, including space [24]. Thoughtful engineering of both food production and processing systems has the potential to increase the likelihood of mission success.

SIRONA is equipped with a full kitchen for rough post-harvest processing and daily cooking tasks. This is an innovative design rarely proposed in previous BLSS scenarios. Processing large amounts of produce at harvest makes operational sense, as certain crops mature all at once and must be quickly trimmed, washed, and stored, with a small portion reserved for immediate use and the majority put away for long-term storage. Cooking is also important to the psychological well-being of the crew. It has been noted that opportunities for physical making decline as machines and automation take over [25]. Spaceflight missions are highly mechanical environments where crewmembers carry out rote tasks according to a pre-determined schedule. Cooking provides a rare break in the day and allows the crew to get in touch with their physical reality in a creative way.

Operational constraints such as hygiene requirements, space limitations, and human factors considerations led to a kitchen design that is partitioned into two zones: (1) along the wall, where bulk processing and long-term storage take place; and (2) at the island, where cooking and short-term cold storage units are located. For a detailed list of kitchen equipment, see SIRONA Part-1 [5]. Along the wall, recently harvested produce is cleaned and processed in one corner, with the inedible biomass directly entering the biodigester under the sink. Deep freezers can hold bulk produce and seafood for long-term storage. Daily cooking tasks are carried out at the island, allowing crew members to face each other, increasing opportunities for group bonding. In order to maximize space and decrease potential injuries, the island is equipped with appliances and small cold storage units within arm's reach of a crew member.

The kitchen is equipped with a suite of tools that delivers precision and versatility as a response to weight and volume limitations. For example, the all-in-one prep station uses a single base with multiple rotary attachments to achieve different culinary effects, such as chopping, whipping, and blending. The multi-cooker can steam, pressure cook, and sauté, among other functions. The temperature-controlled induction stovetop offers precision and lowers the risk of fire from an open flame. The oven, using a closed flame fed by biogas from the biodigester, can roast and broil at high temperatures or dehydrate at lower temperatures. The sous vide bath is a temperature-controlled water bath that cooks packages of food sealed under vacuum.

4. Food production

4.1. Crop complement design development

The Crew Member Diet Target (CM-DT) (Eq. (2)) is a function of edible biomass, diet recommendations (either found in or derived from BVAD), and area, which is the main adjustable variable in SIRONA. These considerations produce a more comprehensive metric than does the commonly used value of edible biomass. The quantity of each crop to be grown was determined through iterative optimization of the dedicated area for each crop across the entire complement. Due to the growth area limitations, not every crop could meet the four crew member diet target. In these cases, the gap can either be filled by supplied foods or by an alternative crop in the complement that is not part of the BVAD menu recommendations.

Crew Member Diet Target Definition: The number of crew members for which SIRONA can meet the dietary recommendation.

$$CM\text{-}DT = \frac{\frac{Edible\ Biomass\ (\mathrm{kg/m^2\,d})}{Growth\ Area\ (\mathrm{m^2})}}{Diet\ Recommendation\ (\mathrm{kg}/CM\text{-}d)} \tag{2}$$

The dietary recommendation is based on the target daily menu mass (kg/CM-d) that each crew member should consume for a given crop (BVAD Table 4-64 [14]). The edible biomass for each crop (kg/(m^2-d)) comes from BVAD Table 4-99 [14] or is derived from the literature cited next to the edible biomass values in Table 3. Each crop is allocated a dedicated SIRONA growth area (m^2). The crop complement (edible biomass, CM-DT and allocated growth area, composite yield analysis; Table 3 and Table A.1), the living systems inputs and outputs analysis (Section 5.1) and the nutritional profile (Section 5.2) have been updated from the SIRONA Part-1 analysis.

The following factors were considered during the iterative process of creating the crop complement and assigning the crop growth area. One concern relates to the quantity of the diet that can be provided by supplied foods without negatively impacting palatability and quality. For example, canned tomatoes can be made into sauce with minimal effect on quality, whereas fresh tomatoes are preferred for salads. Therefore, the total recommended tomatoes in the diet can be divided across fresh and supplied food sources. The crop complement was also optimized by

Table 3
Crop complement overview.

Crop	Diet target	Edible biomass	Key nutrients	O_2 Out [14]	CO_2 In [14]	H_2O In [14]
Unit	CM	kg/yr	Vit=Vitamin; Min=Mineral	Avg. kg/yr	Avg. kg/yr	Avg. kg/yr
Zone 1 – Keyhole wicking beds						
Bok choy	4	21.92 [26]	Vit (A, K) [27]	12.48	17.16	639.26
Carrot	3	39.99 [14]	Vit (K), fiber, lutein, α - and β -carotene, lycopene [27]	8.74	12.02	945.82
Green onion	3	4.93 [14]	Vit (B, C), quercetin, fiber [27]	0.64	5.87	104.79
Kale	4	30.66 [28]	Vit (A, B, K), folate, protein, fiber, α -linolenic acid, lutein, zeaxanthin [27]	29.41	40.79	1506.47
Lettuce	4	30.66 [14]	Vit (C), Min (Mn, K, Cu, Fe), fiber [29]	1.82	2.50	490.19
Potato	2	124.10 [14]	Vit (B6, C, K), Min (Mn, P), niacin [27]	37.98	53.31	4714.15
Radish	3	9.84 [14]	Vit (A, B, K), Min (P), folate, protein, α -linolenic acid, lutein, zeaxanthin, fiber [27]	1.27	1.75	189.94
Roselle (aka Jamaican Sorrel)	2	19.05 [28]	Vit (C), Min (P, Fe), fiber, oxalic acid, flavonoids [27]	25.69	56.38	1315.69
Spinach	2	29.20 [14]	Vit (A, B, E, K), Min (Mn, Mg, Fe, Cu), folate [27]	3.11	4.28	708.29
Zone 2 – Ebb and flow beds						
Aloe	2	2.08 [30]	Vit (C), anthraquinones [31]	3.89	5.35	474.50
Banana	4	19.98 [32]	Min (P), carbohydrates, fiber [27]	29.93	41.15	7300.00
Basil	4	27.02 [33]	Vit (A, K), Min (Mn, Mg) [33]	7.78	10.70	398.58
Chamomile (flower dry mass)	4	0.24 [34]	terpenoids, flavonoids [27]	11.07	14.05	567.21
Cilantro	4	12.04 [35]	lutein, zeaxanthin, β -carotene [36]	1.95	2.68	99.65
Ginger	4	10.18 [37]	gingerol [27]	38.26	5.26	373.29
Ground cherry	3	28.80 [38]	Vit (A, C), Min (Fe, Ca, P), niacin, thiamin, riboflavin [27]	29.93	41.15	2022
Marigolds (dry mass)	4	3.35 [39]	calendulin, linolenic acid, carotenoids [27,40,41]	7.78	10.70	398.58
Mint	4	43.80 [42]	Vit (C), rosmarinic acid [42]	17.72	24.37	907.70
Oca	3	9.82 [43]	antioxidants, starch, fiber [27,44,45]	30.30	41.67	2956.50
Bell Pepper	4	90.52 [14]	Vit (A, C, E, K), fiber [27]	14.69	20.65	1683.50
Strawberry	4	130.45 [46]	Vit (C), Min (P), folic acid, fiber [27]	37.11	51.03	2507.40
Tomato	3	229.95 [14]	Vit (A, C), lycopene, lutein, α - and β -carotene [27]	34.88	47.96	3665.75
Turmeric (dry mass)	4	3.31 [47]	curcumin [27]	38.31	5.27	373.76
Zone 2 – Wicking bed						
Garden Nasturtium	4	16.01 [48–50]	Vit (C), Min (Fe) [27,51,52]	1.41	1.93	171.38
Mashua	3	21.02 [53]	antioxidants, starch, fiber [27,45,54]	30.30	41.66	2955.58
Sweet potato	2	131.40 [14]	Vit (A, C), Min (Ca, K) [27]	104.47	143.65	7316.94
Zone 2 – Biowick						
Barbados cherry	4	73.00 [55]	Vit (A, C), niacin [27]	25.42	34.95	6199.26
Dwarf kumquat	4	45.00 [56]	Vit (C), fiber [27]	29.93	41.15	7300.00
Dwarf lemon	4	24.32 [57]	Vit (C), Min (K) [27]	14.97	20.58	3650.00
Dwarf plum	2	146.00 [58,59]	Vit (C), zeaxanthin [27]	59.53	81.85	14518.82
Kiwi	3	62.22 [60]	Vit (C, K), Min (Ca), fiber [27]	44.90	61.73	10950.00
Passion fruit	3	16.82 [61]	Vit (A, C), fiber, β -carotene [62]	33.67	46.30	8212.50
Land Crop Sub-totals	3.34	1457.67	Avg. Land Crops Yield (kg/m^2) Per Year: 28.10	766.30	965.42	95461.69

(*continued on next page*)

Table 3 (*continued*).

Crop	Diet target	Edible biomass	Key nutrients	O_2 Out [14]	CO_2 In [14]	H_2O In [14]
Unit	CM	kg/yr	Vit=Vitamin; Min=Mineral	Avg. kg/yr	Avg. kg/yr	Avg. kg/yr
Photobioreactor and Integrated Multi-Trophic Aquaponics (IMTA) crops						
Duckweed (dry mass)	4	29.37 [63]	protein, antioxidants [64]	N/A	N/A	N/A
Sacred lotus	4	262.80 [65]	flavonoids, glucosides, triterpenes [27]	211.43	268.16	N/A
Spirulina (dry mass)	4	14.6	Vit (B), Min (Ca, K, Mg, Fe), niacin, amino acids [66]	21.90	46.72	N/A
Watercress	4	67.60 [67]	Vit (C, K), carotenoids [68]	62.31	79.02	N/A
Aquatic Crop Sub-totals	4	374.37	Avg. Aquatic Crops Yield (kg/m^2) Per Year: 29.17	295.64	393.90	N/A
Integrated Multi-Trophic Aquaponics (IMTA) freshwater seafood species						
Barramundi	N/A	54.46	Protein, omega-3 fatty acids			
Crayfish	N/A	24.31	Protein			
Jade perch	N/A	54.46	Protein, omega-3 fatty acids			
Mussel	N/A	17.64	Protein			
Prawn	N/A	10.14	Protein			
Tilapia	N/A	36.31	Protein			
Seafood Sub-totals	N/A	197.32	Avg. Edible Seafood Yield (kg/m^3) Per Year: 26.93	N/A	N/A	N/A
Total Edible Biomass (kg/yr)		2029.36	Avg. Daily (kg/CM-d): 1.39	1061.94	1359.32	95461.69

See Appendix, Table A.2 and Table A.3 for information about the zones and associated environmental parameters.

increasing diversity within categories of foods. For instance, part of the four CM-DT for spinach can be fulfilled by another leafy green. This was done to increase variety beyond the BVAD recommended menu short of creating a SIRONA-specific menu. In instances where BVAD did not have the edible biomass or dietary recommendation values for a certain crop, the values of a comparable crop in the literature were used. A final factor in the design of the crop complement involved balancing and optimizing the Composite Yield (CY) at the total crop complement level so that considerations such as edible biomass, nutrient profile (Table 3), and dietary, psychological, and medicinal functions (see data in Appendix, Table A.1) were adequately addressed.

4.1.1. Composite yield analysis

Rather than utilizing the standard Earth agricultural definitions of crop yield as edible biomass per area [69] and Harvest Index (HI) as the ratio of edible to total biomass [70] to determine which crops to select; a new metric known as Composite Yield (Eq. (3)) was developed that takes into consideration both food functions and harvest index. Composite Yield is the weighted value of all food functions summed over the Inedible Index (1 - HI), which is best to minimize. Thus, foods with the greatest number of functions and highest harvest index are favored since they will have the highest CY score. Since the CY metric is flexible, it may be adjusted based on mission constraints and priorities by specifying a set of n food functions, each of which is present ($v_i = 1$) or absent ($v_i = 0$), and each weighted with an importance factor w_i.

The Composite Yield was calculated by determining the binary value (presence or absence) of each type of food function (dietary, psychological or medicinal functions) through a review of primary literature and horticultural guides. The SIRONA diet CY analysis was coarse and meant to demonstrate a theoretical framework for comparing holistic, multidimensional functionality across food sources according to the needs in the system. Thus, Composite Yield is a flexible metric that can be adapted to include additional or alternative functions with values that may represent the degree to which the function is present, instead of using binary values. For example, there may be reasons to assign each food different CY function values depending on the threshold and/or the definition of the function or characteristic. To more accurately calculate and compare Composite Yields, experiments with the same production conditions would need to be conducted with clearly defined and biologically meaningful function variables.

$$CY = \frac{\sum_i v_i w_i}{1 - HI} \tag{3}$$

Where,

v_i = 0 is the absence of a single food function; 1 is the presence of a single food function,

w_i = food function importance weight (all assumed 1 herein and in Hava et al., 2019 [3])

HI, Harvest Index = edible biomass/total biomass (i.e., edible+inedible)

(1-HI), Inedible Index = inedible biomass/total biomass (i.e., edible+inedible)

The original Composite Yield equation and analysis was published in Hava et al., 2019 [3]; however, both the CY equation and analysis have been updated and generalized to reflect the following function definitions.

Composite Yield definitions (for CY data and references see Appendix, Table A.1):

- Dietary function: foods with sufficient quantity in the SIRONA diet to provide a nutritional (macronutrients and/or micronutrients) contribution.
- Psychological benefit function: food sources provide a psychological benefit if they have at least one of the following characteristics: companion animal interaction (i.e., human-aquatic animal interaction) or sensory stimulations (i.e., flavor enhancement, olfactory stimulation, tactile stimulation or visual interest (e.g., flowering, motion, bright colors beyond green)).
- Medicinal function: functional foods characterized by secondary metabolites that support human health outcomes beyond basic nutrient requirements, which includes at least one of the following properties: radiation protection (including eye health/protection), bone health/osteoporosis prevention, improves sleep or has anti-inflammatory properties; included foods may also provide other medicinal functions beyond this list. These foods were identified in "Edible Medicinal and Non-Medicinal Plants" [27] and/or cross-referenced in the primary literature. Evidence of additional medicinal functions that was located during the literature search may also be included in the references. The lack of evidence in the literature does not necessarily mean an

excluded food does not possess these or other medicinal functions; alternatively, evidence may not have been located due to search methods or research may not have been conducted on these specific properties. Once a medicinal property was identified for a given food, other properties may or may not have been investigated in the literature and therefore should not be considered an exhaustive review.

4.2. Integrated Multi-Trophic Aquaponics (IMTA) design development

Integrated Multi-Trophic Aquaponics plays a key role in SIRONA by providing on-site food production and nutrient recycling. Fish have lower energy input costs than other animal proteins typically farmed for human food. The successful cryopreservation of fish eggs – that is, the process of freezing eggs and sperm and transporting them in "suspended animation" – has significant potential to improve logistics management, lower labor costs, and ensure greater control of the livestock within the ecosystem [71].

Table 4
Freshwater seafood production.

Fish	# of Fish	Farmed kg/yr	Edible %	Edible kg/yr	Edible g/CM-d	kCal /100 g	kCal /CM-wk
Tilapia	100	90.76	0.4	36.31	24.87	96	167.57
Barramundi	100	90.76	0.6	54.46	37.30	91	238.26
Jade Perch	100	90.76	0.6	54.46	37.30	91	238.26
Prawn	22	20.28	0.5	10.14	6.94	85	41.43
Mussel	107	44.09	0.4	17.64	12.08	86	72.92
Crayfish	134	121.56	0.2	24.31	16.65	72	84.16
Total	563	1010.2	–	197.32	135.14	521	842.59

Total calories for mission: 288,095.43
(175,258.05 kcal/yr = 120.04 kcal/CM-d from seafood, 3.96% of crew diet)

The pond and tanks are stocked with three freshwater fish species (tilapia, barramundi, and jade perch) and three freshwater shellfish species (prawns, mussels, and crayfish). The six aquatic species (Table 4) were chosen based on a variety of factors. Each species was first considered individually for system compatibility and then further evaluated for viability as part of a polyculture guild. Tilapia is one of the most studied species for life support systems, making it a prime candidate [72]. The other selected species have been commercially produced in recirculating IMTA systems on Earth and, therefore, readily lend themselves to inclusion. They are also known to have low Feed Conversion Ratios (FCRs), and tolerate higher stocking densities and greater variations in water quality, which improve robustness and resiliency. Palatability, menu versatility, and overall acceptability to astronauts are other factors that guided species selection. Barramundi, for example, is widely considered to be a delicious protein source in its native Australia and has gained attention around the world for its flavor and the relatively low environmental impact associated with its farming [73].

In the SIRONA ecosystem, fish, shellfish, and crops work together symbiotically. Prawn and crayfish are bottom feeders that reduce waste by readily consuming uneaten fish pellets, while mussels filter the particulates. In fact, thoughtful engineering of a polyculture guild allows for a composite feed conversion ratio that is lower than the FCRs of any individual species.

5. Projected performance analysis

5.1. Living systems inputs and outputs: O_2, CO_2, H_2O

Loop closure for crew inputs and outputs are summarized in Table 5. The SIRONA crop complement (land, aquatic crops–not including duckweed–and spirulina) produce a total of 2.91 kg/day of O_2 (88.70% of target) and consumes 3.72 kg/day of CO_2 (89.52% of projected output) for a four-person crew. Of this total, the photobioreactors produce 60 g of O_2 per day (assuming a photosynthetic efficiency of 67%) and consume 128 g of CO_2 per day (based on a conservative temperature assumption of 30°C). The remainder of the total is produced by the land crops and aquatic crops (not including duckweed). No projections are currently available for the duckweed; however, this crop would contribute to further closing the gap of the remaining air revitalization requirements.

The biodigester would be sized to process 100% of the grey and blackwater produced in the kitchen. These output streams can also be diverted to the Biowick for processing, if needed. The total water uptake by the entire land crops growth system is 261.5 L/day. Of this total, the Biowick has an uptake capacity of 139.26 L/day, which is 253% additional capacity of the expected grey and blackwater production (39.412 L/day) in the bathroom (including hygiene, laundry, and toilet output water). In periods when the water output from the bathroom is not able to fulfill the total Biowick capacity, the gap is met by either the kitchen water output or the IMTA system. The drinking water input requirement is assumed to be primarily provided through In Situ Resource Utilization (ISRU). The dehumidification system recovers transpired water to provide a secondary source of drinking water that can also be returned to the IMTA system or Photobioreactors as makeup water. The total yearly rates of oxygen production, carbon dioxide consumption, and water uptake for each crop were found using Eq. (4). When values for a particular crop were not provided by BVAD (Table 4-98) [14], values of a comparable crop were used or the following generic values were used for oxygen production (41.0 g/m^2 per day) and carbon dioxide uptake (56.375 g/m^2 per day). The system's total values were calculated by summing individual crop values (Table 3) and are summarized in Table 5.

$$Daily\ Rate \frac{g}{m^2 - d} * Area * 365 \text{ days} = Yearly\ Production \text{ (kg/yr)} \quad (4)$$

5.2. Nutritional profile

A summary of the food production system is provided in Table 6. SIRONA provides approximately 51.871 m^2 of land crop production, divided into a 40.45 m^2 sub-tropical zone and a 11.42 m^2 temperate zone. The land crops provide an overall average yield (i.e., total edible biomass/total growth area) of 28.10 kg/m^2. The total annual biomass production for land crops is 1457.67 kg/yr; 374.37 kg/yr for the aquatic crops and *Spirulina*, and 197.32 kg/yr for seafood. The total annual edible biomass of the entire ecosystem is 2029.36 kg/yr, or 1.39 kg/CM-d.

Table 6 presents the nutrient breakdown of the SIRONA food production system. The target quantities are nutritional goals set forth by NASA in BVAD [14]. The total amount of a nutrient supplied by SIRONA ("SIRONA Total" column) is calculated by first multiplying the expected edible mass for a given crop (Table 3) with the quantity of a given nutrient found in a typical specimen of the crop, provided by either the US Department of Agriculture's (USDA) FoodData Central database [68], or when the crop was not listed in the USDA database, one of the following alternative crop nutrient reference [40,41,44,45,51,52,54] was used; then the values across the entire crop complement were summed.

The entire ecosystem provides 92.05% of the total dietary mass (Table 5), or 24.29% of the total metabolic energy for a crew of four during a 600-day surface stay (Table 6). The high dietary mass is mostly attributed to fruits and vegetables, which have high fiber and water content.

Carbohydrate crops and seafood contribute the majority of the metabolic energy provided by SIRONA. Seafood provides approximately 4% of the total caloric needs. The yield is the equivalent of four 8-oz meals of seafood per crew member per week (Table 4) and presents a readily available source of fresh protein and omega-3 fatty acids. The photobioreactor produces 10 g/CM-d of dry edible Spirulina biomass, which is included in the total edible biomass reported above.

Table 5
Living systems inputs and outputs.

	O_2	H_2O	CO_2	Food	Metabolic energy	Bathroom wastewater	Kitchen wastewater
Units	kg/d	kg/d	kg/d	kg/d	MJ/d	kg/d	kg/d
Human (Inputs & Outputs)	In	In	Out	In	In	Out	Out
Required (CM)	0.82	2.50	1.04	1.51	12.71	9.85	5.41
Total Required (4 CM)	3.28	10	4.16	6.04	50.84	39.412	21.64
SIRONA (Inputs & Outputs)	Out	In	In	Out	Out	In	In
Total Inputs & Outputs (4 CM)	2.91	10	3.72	5.56	12.35	139.26	21.64
% Provided by SIRONA	88.70	100	89.52	92.05	24.29	353.35	100

These estimates are based on Earth values and could change under spaceflight conditions.

Table 6
Total dietary nutrient profile.

Nutrient	Target Qty. per CM-d	SIRONA Total	Target % Met
Water	825 g	1121.89 g	135.99
Energy	3033 kcal	737.59 kcal	24.32
Protein	125 g	54.63 g	43.70
Fat	104 g	7.20 g	6.92
Carbohydrate	400 g	138.37 g	34.59
Dietary fiber	42 g	32.53 g	77.46
Calcium	1000 mg	580.59 mg	58.06
Iron	10 mg	14.92 mg	149.25
Magnesium	350 mg	309.11 mg	88.32
Phosphorus	1000 mg	727.90 mg	72.79
Potassium	3500 mg	4142.05 mg	118.34
Sodium	2400 g	455.33 g	18.97
Zinc	15 mg	4.26 mg	28.43
Vitamin C	100 mg	1253.67 mg	1253.67
Thiamin	1.5 mg	1.10 mg	73.26
Riboflavin	2 mg	1.48 mg	73.82
Niacin	20 mg	10.92 mg	54.59
Vitamin B-6	2 mg	1.82 mg	91.01
Folate, DFE	400 µg	304.32 µg	76.08
Vitamin B-12	2 µg	2.96 µg	148.12
Vitamin A	5000 IU	5080.51 IU	101.61
Vitamin E	30 IU	5.36 IU	17.87
Vitamin D	400 IU	74.85 IU	18.71
Vitamin K	80 µg	490.27 µg	612.84

For fifteen of the eighteen key vitamins and minerals designated by the USDA, the SIRONA diet provides greater than 50% of the daily target quantity recommended by NASA [14]. This is a notional supplemental diet, and both crop types and quantities can be adjusted to meet a specific nutritional profile once a detailed diet has been developed based on crew preference and mission constraints. The diet would also consider factors such as growing conditions, cooking, processing, and nutrient pairings during consumption, all of which affect the nutrient content and bioavailability of the food [12,74,75].

These calculations validate the design assumption that a feasible first-generation food production system involves production of perishable crops with high levels of micronutrients and high palatability. The SIRONA crops are supplemented by resupplies of high-calorie, shelf-stable bulk foods (grains, legumes, fats and oils, etc.) from Earth to create a well-rounded diet. As surface capabilities expand, later versions of SIRONA may be developed to grow and process more calorically-dense foods.

5.3. Food production timeline

The following timeline (Fig. 5) estimate the crop output (based on Earth data) over the entire duration of the mission; some variation in production schedule for individual species is expected.

Phase 0: Transit from Earth to Mars Crops with a dormant stage are transported as seeds in an airtight, dark, and cool container to preserve seed viability. Dwarf woody fruit trees/vines are transported as two-year-old grafted plants. Young trees are wrapped in wicking material and kept in cold, climate-controlled areas to minimize the risk of tree damage. Tuber crops are transported as roots, to be split for clonal reproduction upon arrival. Fish and shellfish will be transported as cryopreserved fertilized eggs that can be thawed as needed [71].

Phase 1 (0-6 months): fast-growing and continuous harvest crops

After deployment, the keyhole and mussel tanks are transferred into SIRONA and filled with water produced (by ISRU) before crew arrival. The water is pre-positioned within the deployed habitat and is sufficient for the initial phase of crop and fish production. The remaining IMTA tanks are filled with water produced after crew arrival via ISRU; assuming a water extraction rate of 4.2 kg/hr (roughly 100 kg/day), the remaining tanks will take 1.4 months to fill.

Land crops and *Spirulina*, which continuously produce edible yield, along with other crops that quickly reach harvestable maturity, are the primary sources of fresh food during the first six months of the mission. There is an expected delay of 21 days to first harvest of any crop, due to the time lag between planting and harvest.

Phase 2 (6-12 months): mid-mission harvestable foods

Crops that are continuously producing and quick to mature (Phase 1 crops) continue to be planted and harvested. The first seafood harvest occurs during this phase when the fish population reaches full capacity. Table 4 provides a detailed analysis of seafood yield.

Phase 3 (12-48 months): woody crops

In addition to crops harvested during Phases 1 and 2, which will continuously produce after the initial harvest, mature trees will yield fruits throughout Phase 3. Trees will continue to provide fruit for subsequent missions assuming that crews overlap (i.e., there is continuous care provided by a crew or automation).

5.4. Automation and crew time

The automation and robotic technologies used in SIRONA include AgQ, the Brain, and the Remotely Operated Gardening Rover (ROGR). The AgQ (Agriculture AI) software utilizes machine learning and data from the multi-sensor and vision system called the Brain. The Brain uses sensors to collect data on pH, electrical conductivity, dissolved oxygen, water and air temperature, ethylene, methane, and other trace gases to monitor plant health. AgQ uses the data collected by the Brain to provide plant care decision support through monitoring, alerts, diagnostics, and prediction. ROGR is a rover with two arms and end-effectors that have embedded finger sensors for performing manipulation tasks requiring fine motor skills. ROGR automates repetitive, monotonous, and time-consuming gardening tasks to lower the demand on precious crew time. These automation technologies also provide care task scheduling guidance.

Table 7 summarizes the average daily time the crew spends on land crop care (it does not include the time for aquatic crops or fish care) and the time savings from automation. The estimates are based on a previous study in the EDEN ISS project that tracked task timing inside a greenhouse [76]. The care task times are derived by first obtaining the task time per unit area per day and then scaling the values by the SIRONA area factor of 3.53 or by the individual crop area. Tasks are then allocated as either a crew task or automation task.

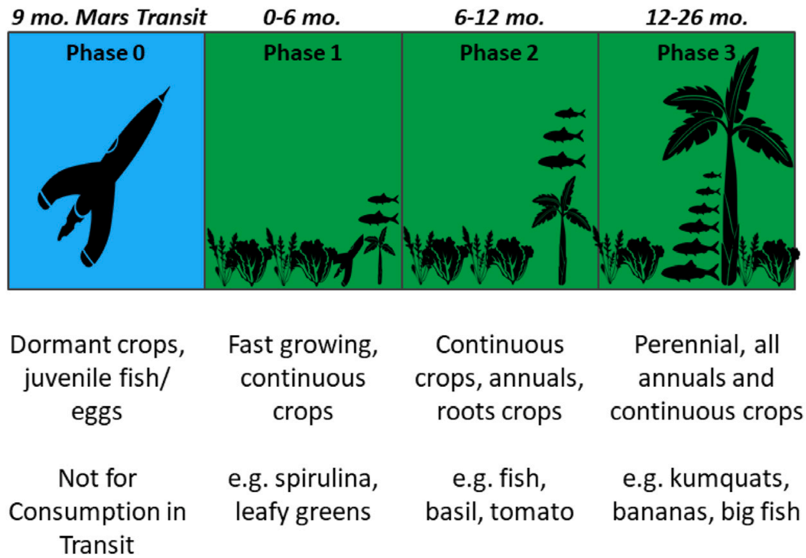

Fig. 5. The timeline summarizes the projected time to harvest for crops and aquatic organisms based on averaged phenological data. When Earth-adapted organisms are grown on Mars, the assumption that the rate of plant and fish maturation will not vary significantly will require validation and further research.

Table 7
Crew and robotic care tasks.

Tasks	Crew time min/day	ROGR min/day
Crop-specific tasks	72.9	109.3
Preparation tasks	38	0
General horticulture tasks	10	148.2
Daily Nutrient management tasks	0	6
Infrequent tasks daily avg.	7.4	0.6
Total	128.2	264[a]

[a]Daily crew time saved by robotic care systems.

Daily Care Tasks

• Crop-specific care tasks done by the crew: thinning, pruning, training, harvesting, quality check of plants, and cleaning.

• Crop-specific care tasks done by ROGR: seeding germination trays, transplanting, and pollinating.

• Preparation tasks: gathering tools, cleaning work area, and disposing of trash or inedible biomass.

• General horticultural tasks: verifying sensor readings and minor crop management, ex. removing damaged leaves.

• IMTA nutrient management system tasks: verifying water pH and measuring PAR of lights.

Infrequent maintenance tasks happen on a 30–180 day cycle. The estimated task times were divided by the cycle length to obtain an equivalent daily average of 7.4 minutes, though the actual amount may vary day to day. Conversely, certain tasks may not be completed in 7.4-minute increments but instead can be accommodated in larger increments that equate to 51.5 minutes per week. Such tasks include changing and cleaning air filters, calibrating sensors, cleaning IMTA tanks, and cleaning/disinfecting HVAC and dehumidification systems.

The estimated crew time required in the greenhouse is 128.2 minutes/day, or just about 32.1 minute per crew member. The automation systems provide total equivalent crew time savings of 264 CM-minutes/day, though these systems will likely spend much longer on a given task than the associated crew time savings.

6. Future development and conclusion

6.1. Martian crop science and adaptive breeding

A participatory breeding program built on collaborative research by both astronaut farmers and horticulturalist advisors will develop site-adapted cultivars suitable to Martian greenhouse conditions. Crops that have been previously selected for spaceflight studies, such as Outredgeous lettuce and Seascape strawberry, will be the first generation crops used for *in situ* experimental breeding. Genomic and phenotypic data will be collected from all plants. Astronaut farmers will cross and propagate the best performing ten percent of each breeding population for multiple generations. The objective is to develop palatable and robust crop varieties adapted to the novel conditions of a space greenhouse. Seeds adapted to SIRONA may be reciprocally transplanted back to Earth for further research and application in terrestrial biological contexts.

6.2. Soil expansion phase

As the Martian outpost expands, a scalable regolith remediation system can be developed to create additional growth media for the Biowick and media beds. However, perchlorates in Martian regolith prevent the growth of many crops. Perchlorates are also a human hazard and can cause goiter, thyroid hypoplasia, and a decreased metabolism, if ingested [77]. A possible solution involves using enzymes to reduce the concentration of perchlorates in Martian regolith [77]. The reduction of perchlorate to chlorite is catalyzed by the enzyme perchlorate reductase [77]. The chlorite is then reduced to chlorine and oxygen in a reduction reaction catalyzed by the enzyme chlorite dismutase [77]. Once both reactions are complete, the regolith is free of perchlorates and can be used to grow crops. The perchlorate removal procedure is environmentally safe and can also produce supplemental oxygen.

Regolith and sheet mulching of inedible biomass in combination with biodigester effluent can be used to create growth media and/or soil for expanded production capacity. Sheet mulching is a cold composting technique for improving or building soil by layering organic materials such as inedible biomass, food scraps and manure, carbon, nitrogen, oxygen, and water. It can be done in place, on a large or small scale as materials become available, and with minimum equipment and time. During the transition to a soil-based system, adding worms can improve soil health by removing plant detritus (e.g., dead roots), fertilizing, and improving drainage. Worms can also process food scraps directly. Sheet mulching can further support soil building *in situ*. Pruned materials from woody crops can be used in combination with sheet mulching in a hügelkultur method [78,79], modified for spaceflight, can be chipped and added into the sheet mulching layers or as the final top layer of mulch to improve water retention.

6.3. Concluding discussion

The Sustainable Integration of Regenerative Outer-space Nature and Agriculture (SIRONA) architecture mimics and integrates natural systems to provide a synergistic, resilient, robust, regenerative, and restorative living system. This greenhouse design provides bioregenerative life support through waste management, water reclamation, air revitalization, and food production with unique features including: meal preparation, access to nature and horticulture therapy. These integrated stacked functions within the growth systems, food processing zone, and output processing sub-systems provide yields and services that support each other to maximize SIRONA's composite yield.

SIRONA uses the living systems centered design principles to balance: (1) fresh crops with high-calorie re-supplied foods to improve diet; (2) crew time with automation to support plant and human health; and (3) renewable/regenerative systems with consumables shipped from Earth to improve mission sustainability and supportability. SIRONA counteracts the psychological and physiological concerns that originate from long duration exploration missions by using a four root R's (4xR) agroecosystem, which provides dietary variety and an environment conducive to crew cohesion, recreation, relaxation, and restoration. By achieving this improved habitability and new vision for space architecture, SIRONA will sustainably support human space exploration.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A.1
Crop complement overview: fresh mass unless otherwise noted.

Crop	Total area	Edible biomass	Key nutrients	Food functions: v_i=0 if blank		
	m^2	kg/yr	Vit=Vitamin; Min=Mineral	Diet	Psych.	Med.
Zone 1 – Keyhole Wicking Beds						
Bok choy	0.83	21.92	Vit (A, V)	1		
Carrot	1.46	39.99	Vit (K), fiber, lutein, α - and β -carotene, lycopene	1		
Green onion	0.17	4.93	Vit (B, C), quercetin, fiber	1		
Kale	1.98	30.66	Vit (A, B, K), folate, protein, fiber, α -linolenic acid, lutein, zeaxanthin	1		
Lettuce	0.64	30.66	Vit (C), Min (Mn, K, Cu, Fe), fiber	1		
Potato	3.23	124.10	Vit (B6, C, K), Min (Mn, P), niacin	1		
Radish	0.29	9.84	Vit (A, B, K), Min (P), folate, protein, α -linolenic acid, lutein, zeaxanthin, fiber	1		
Roselle (aka Jamaican Sorrel)	1.72	19.05	Vit (C), Min (P, Fe), fiber, oxalic acid, flavonoids	1	1	1 [80]
Spinach	1.10	29.20	Vit (A, B, E, K), Min (Mn, Mg, Fe, Cu), folate	1		1 [81–83]
Zone 2 – Ebb and Flow Beds						
Aloe	0.26	2.08	Vit (C), anthraquinones		1	1 [84–87,87–96]
Banana	2	19.98	Min (P), carbohydrates, fiber	1	1	
Basil	0.52	27.02	Vit (A, K), Min (Mn, Mg)	1	1	1 [97–102]
Chamomile (flower dry mass)	0.52	0.24	terpenoids, flavonoids	1	1	1 [103–108]
Cilantro	0.13	12.04	lutein, zeaxanthin, β-carotene	1	1	1 [36,109,110]
Ginger	0.26	10.18	gingerol	1	1	1 [111–133]
Ground cherry	2	28.80	Vit (A, C), Min (Fe, Ca, P), niacin, thiamin, riboflavin	1	1	
Marigolds (dry mass)	0.52	3.35	calendulin, linolenic acid, carotenoids	1	1	1 [134,135]
Mint	1.18	43.80	Vit (C), rosmarinic acid	1	1	1 [42,102,136–149]
Oca	2.03	9.82	antioxidants, starch, fiber	1		

(*continued on next page*)

Table A.1 (*continued*).

Crop	Total area	Edible biomass	Key nutrients	Food functions: v_i=0 if blank		
	m^2	kg/yr	Vit=Vitamin; Min=Mineral	Diet	Psych.	Med.
Bell Pepper	1.67	90.52	Vit (A, C, E, K), fiber	1	1	1 [150–156]
Strawberry	2.48	130.45	Vit (C), Min (P), folic acid, fiber	1	1	1 [81,83,157]
Tomato	3.63	229.95	Vit (A, C), lycopene, lutein, α- and β-carotene	1	1	
Turmeric (dry mass)	0.26	3.31	curcumin	1	1	1 [158–164,164–179]
Zone 2 – Wicking Bed						
Mashua	2.02	21.02	antioxidants, starch, fiber	1		
Garden Nasturtium	0.09	16.01	Vit (C), Min (Fe)	1	1	
Sweet potato	6.96	131.40	Vit (A, C), Min (Ca, K)	1		
Zone 2 – Biowick						
Barbados cherry	1.7	73	Vit (A, C), niacin	1	1	1 [180–184]
Dwarf kumquat	2	45	Vit (C), fiber	1	1	1 [102,185–189]
Dwarf lemon	1	24.32	Vit (C), Min (K)	1	1	1 [190–197]
Dwarf plum	3.98	146	Vit (C), zeaxanthin	1	1	1 [198–208,208–212]
Kiwi	3	62.22	Vit (C, K), Min (Ca), fiber	1	1	
Passion fruit	2.25	16.82	Vit (A, C), fiber, β-carotene	1	1	1 [106,213–218]
Land Crop Sub-totals	51.87	1457.67	Avg. Land Crops Yield (kg/m^2) Per Year: 28.10			
Photobioreactor and Integrated Multi-Trophic Aquaculture (IMTA) Crops						
Duckweed (dry mass)	9.40	29.37	protein, antioxidants	1		
Sacred lotus	14.13	262.80	flavonoids, glucosides, triterpenes	1	1	
Spirulina (dry mass)	1.48	14.60	Vit (B), Min (Ca, K, Mg, Fe), niacin, amino acids	1		
Watercress	4.16	67.60	Vit (C, K), carotenoids	1	1	
Aquatic Crop Sub-totals	29.17	374.37	Avg. Aquatic Crops Yield (kg/m^2) Per Year: 29.17			
Integrated Multi-Trophic Aquaculture (IMTA) Seafood Species						
Barramundi	N/A	54.46	Protein, omega-3 fatty acids	1	1	1 [219–229]
Crayfish	N/A	24.31	Protein	1	1	
Jade perch	N/A	54.46	Protein, omega-3 fatty acids	1	1	1 [220–231]
Mussel	N/A	17.64	Protein	1	1	
Prawn	N/A	10.14	Protein	1	1	
Tilapia	N/A	36.31	Protein	1	1	
Seafood Sub-totals	N/A	197.32	Avg. Edible Seafood Yield (kg/m^3) Per Year: 26.93			
Total Edible Biomass (kg/yr):		2029.36	Avg. Daily Yield (kg/CM-d): 1.39			

Table A.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	51.871	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

Table A.3
Environmental parameters.

Zone	Hydroponic system	Earth analog	Day Temp. °C (°F)	Night Temp. °C (°F)	Light (h/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	Spirulina	Freshwater	30 (86)	30 (86)	24	30.24	7.0–10.0	N/A	N/A

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