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Sustainable Crop Cultivation in Space Analogs: A BRIDGES Methodology Perspective Through SpaCEA Cabinets

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Sustainable crop cultivation in space holds paramount significance for the support of life in future long-duration missions. This research explores the development and integration of innovative low-cost proof-of-concept (LC-POC) plant growth cabinets tailored for use in space analog missions. By outlining past and current efforts in space farming, this study introduces the Space Controlled Environment Agriculture (SpaCEA) Cabinet using the BRIDGES framework, establishing a context for reproducible experiments and innovation in plant growth systems. The SpaCEA cabinets can either be delivered in flat packs or assembled on-site, employing distributed additive and subtractive manufacturing technologies, such as 3D printing and laser cutting. The main objective is to assess how effectively these structures foster crop growth within analog environments while replicating conditions crucial for space exploration. Employing a multi-faceted approach encompassing technical and qualitative dimensions, this project integrates a qualitative investigation where representatives managing analog stations and analog astronauts will partake in interviews

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and questionnaires to discern specific requirements and challenges within these environments. Insights gained from these engagements will significantly define the final design parameters of updated SpaCEA plant growth cabinets. The practical applicability of these cabinets emphasizes ease of assembly and transportation, addressing the inherent spatial and logistical constraints associated with space missions. Furthermore, the BRIDGES framework ensures the standardization of hardware, software, and data-gathering elements within a unified structure that utilizes cutting-edge manufacturing technologies for the prototyping and deployment of these cabinets. The anticipated outcomes of this research include the identification of key design considerations and technical specifications for plant growth cabinets tailored to space farming analog systems. This research is poised to contribute valuable knowledge to sustainable space exploration through the development of interoperable plant growth systems for analog environments, advancing research in space crop cultivation, which will make up part of a larger bioregenerative life support system.

Nomenclature

ECLSS = Environmental Control and Life Support System
BLSS = Bioregenerative Life Support System
CELSS = Closed-Ecological Life Support System
ISS = International Space Station
BRIDGES = Biologically Reliable Integration and Design for Growth Environments in Space
SpaCEA = Space Controlled Environment Agriculture

I. Introduction

Human space exploration requires a reliable source of food for crews, which to date has been formed of largely pre-packaged food sent through regular resupply missions. As humans travel beyond low Earth orbit (LEO), resupply and storage of pre-packaged food become less practical and more costly[1]. In addition to the provision of food, sustainable systems that provide O_2 and clean water and which manage CO_2 released by astronauts and other waste products, such as solid waste and urine, will be critical[2]. Addressing these challenges is of paramount importance as humans plan to return to the Moon with NASA's Artemis Program by the mid-late 2020s[3].

A recognized approach for addressing these challenges is the growth of plants, which, through photosynthesis, could remove CO_2 produced by astronauts and provide O_2, in addition to being a source of nutritious, fresh food[4]. Due to the constraints of the harsh environment of space, this would have to be carried out in fully controlled environments, similar to plant factories on Earth[1]. The authors define this as Space Controlled Environment Agriculture[5]. Several Earth-based large-scale analogs have investigated this concept, including NASA's Biomass Production Chamber[6,7], the Russian Bios-3 project[8], the European Space Agency's MELISSA Pilot Plant[9], the Chinese Lunar Palace 1[10], and the German Space Agency (DLR)[11].

In addition, several smaller-scale systems have been developed for plant growth in the space environment. NASA's Vegetable Production System (Veggie) on board the International Space Station (ISS) was designed for the growth of a range of horticultural crops and consists of a bank of adjustable blue, red, and green Light Emitting Diode (LED) lights, a fan, and flexible and expandable transparent bellows[12,13,14]. Veggie utilizes the ISS cabin environment to control temperature and supply CO_2, with plants commonly grown in 'pillows' containing porous arcillite and providing nutrients through a polymer-coated controlled-release fertilizer[14]. Veggie is a hands-on system with manual watering of plants by astronauts required. It is the primary system used for the development of horticultural practices and testing of candidate space crops for the supplementation of crew diets[15].

In contrast, the Advanced Plant Habitat (APH) was designed for plant physiology research in a microgravity environment. The APH is a fully enclosed, closed-loop system capable of controlling temperature, CO_2, relative humidity, irrigation, and the intensity, quality, and timing of light through a complex bank of red, blue, green, and broad-spectrum white LEDs[16,17]. Additionally, the APH can scrub volatile organic compounds (VOCs) such as ethylene from the growth environment and contains more than 180 sensors and cameras to monitor plant growth, including monitoring of microclimate conditions from the air, growth substrate, plant roots, to the stem and leaf level[16,17].

In terms of plant growth in space environments, the author's efforts in this field include the design and testing of the Space Controlled Environment Agriculture (SpaCEA) growth cabinets and the development of the Biologically Reliable Integration and Design for Growth Environments in Space (BRIDGES) methodology[18]. These two space endeavors, as follows, represent the alignment of a research framework with practical standards for implementing plant growth systems that can easily share protocols and experimental data. In the presented paper, the principles of these two efforts are merged to synergize their application and validation in different space analog mission scenarios. An overview of space farming research in analog environments will be provided. This will guide the proposed methodology for developing a questionnaire to raise relevant considerations on design, deployment, operations, and usability for the plant growth cabinets. Additionally, this will allow for the direct comparison of results between analog stations while orienting future improvements on both proposals.

a. SpaCEA Cabinet

Space Controlled Environment Agriculture, or 'SpaCEA' cabinets, are small semi-controlled environment plant growth chambers designed to be produced through distributed manufacturing technologies and to be easily assembled by end-users on site. The first prototype chamber [19](**Fig. 1**) is based on the Grobot alpha plant growth chamber developed by Grobotic Systems Ltd., a Sheffield-based startup that has developed a new class of benchtop smart plant growth chambers for plant science research. The prototype chamber has a growth space of approximately 40 x 40 x 40 cm, dimmable broad-spectrum LEDs, exhaust and stirring fans, a camera and environmental sensors for gathering plant growth and environmental data, and an irrigation system all controlled by an ESP32 low-cost microcontroller plugged into a chamber control system. The sensors, lights, irrigation system, fans, and microcontroller plug into a bespoke chamber control system printed circuit board (PCB) which, together with the chamber chassis, can be easily assembled by the end user on site. Distributed manufacturing allows for the digital distribution of component schematics for the local manufacturing of products (reference), reducing shipping costs, facilitating the use of local materials and, if shared under particular licenses, allows for the local modification and improvement of designs. The chamber chassis is laser cut from marine grade plywood or poly(methyl methacrylate) (perspex), and the interior walls of the growth area are laser or computerized numerical control (CNC) cut from perspex or food-grade white PVC, which provides good reflective properties and mimics existing chamber interiors. Chambers can be assembled by non-specialists using common adhesives, and the electronics and electrical components are all off-the-shelf and use standard connectors and components. The bespoke PCB can either be purchased fully assembled from Grobotic Systems or design files can be sent to local or national fabricators.

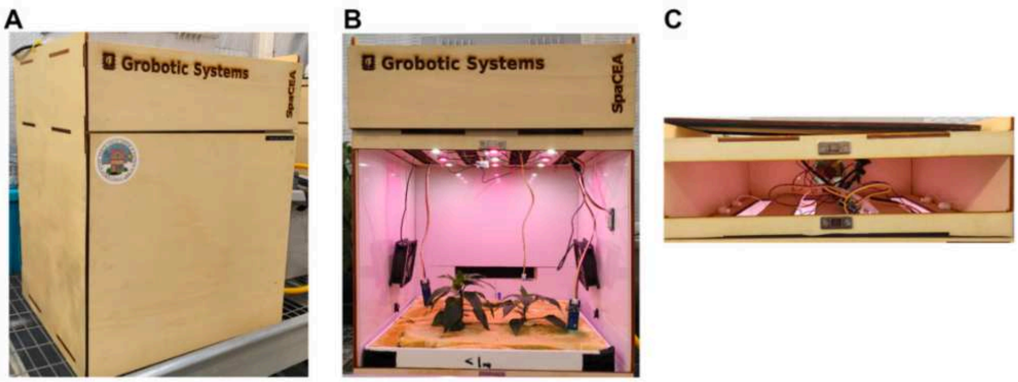

Fig. 1: A) The prototype SpaCEA chamber with the grow area and electronics area doors on; B) the grow area door removed to show the grow area; C) the shelf for electronic components inside the growth chamber. This version did not have a bespoke PCB.

The SpaCEA cabinets will use a proposed open-source plant growth protocol (OSPGP) for controlling plant growth protocols and collecting and storing data during experiments. It is a human- and machine-readable document format designed to improve experimental replicability and reproducibility in plant science. The protocol builds on the guidelines for measuring and reporting parameters in growth rooms, tissue culture, and greenhouses[20,21,22] and allows for more complex growth protocols, including dynamic setpoints over the course of a plant life cycle, radiation information in the form of spectral plots, and a DOI to share the protocol setpoints and actual recorded experimental data through a repository (e.g. fairsharing.org). This protocol can be used for routine plant growth, more formal phenotyping experiments, and in controlled environment agriculture as a “plant growth recipe.” The protocol is open source to allow community development, and extensible, to allow for the evolution of the protocol as technologies and user preferences change over time.

b. BRIDGES

BRIDGES is a modular and hybrid methodology based on the integration of biological life with physicochemical processes[18]. This framework stands for sustainable and scalable system for food production in a variety of environments, including space stations, the Moon, Mars, and extreme environments on Earth. BRIDGES encompasses a wide range of activities, from algorithm design, test of hardware, and simulations to small-scale experiments to assess system’s performance, evaluate environmental control dynamics, and validate new technologies. Based on BRIDGES, a standardized approach is proposed to ensure the implementation of practical testing environments for monitoring, automation, connectivity, and data harvesting of farming activities. The ultimate goal is to integrate both technical and non-technical requirements for the initial system for its upgrade with different technologies, scale and maturity levels. Among the benefits, it is possible to mention risk mitigation, identification of limitations, ability to adapt to changes, flexibility in the use of new technologies, and increased performance. This will not only boost the validation of new solutions for plant cultivation systems but will also allow further analysis of these for applications in diverse mission scenarios. At the same time, it would facilitate the implementation of equipment depending on the mission’s needs, as well as the interpretation and comparison of experimental data generated, based on the technical knowledge of researchers on the topic under study. In addition, BRIDGES also accounts for unified metrics and criteria for evaluating system performance and effectiveness across different applications and environments. These metrics include parameters related to plant growth, resource utilization efficiency, environmental sustainability, and mission objectives.

II. Space Farming Research in Analogs

In the scenario of space exploration, the space agencies, together with researchers from various scientific disciplines, seek to optimize the performance of astronauts. This is relevant when the aim is to minimize the risk of mission failure and to accomplish the expected goals. With that, research on teams in isolated, confined, and extreme (ICE) environments (e.g., Antarctic expeditions, space analog habitats, and space chamber simulations) is conducted to anticipate the dynamics of future long-term space missions[23]. That said, an analog habitat, or station, can be defined as an environment aimed at training individuals, also called analog astronauts, where the complexities of a crewed space mission are replicated. Besides that, each analog has its unique specificities, given that not all of the environmental factors and structural capabilities may be present in a particular ICE environment. Examples are listed by Heinicke *et al.*[24]. In these locations, field tests, or analog missions, are carried out to simulate the working and living conditions in the space environment. During the missions, the crew is encouraged to seek alternative methods to understand the critical aspects of operating a space habitat and present satisfactory results that can be applied in future space missions. Furthermore, each team member has their respective duties, which define their responsibilities and activities that will be developed throughout the mission period, while considering a restricted scenario of water, food, and energy consumption[25].

Another feature is the guidance for future research, which is particularly important due to the expenses and time required to achieve relevant outcomes to be applied in space. Analog missions can help to orientate further research by identifying what areas are in need of more research, new areas to pursue, and strategies that aid with knowledge accumulation over time[26]. This is why there is a need to develop and test new technologies and to conduct experiments aimed at scientific results before its implementation off-Earth. In addition to the range of explored areas in analogs, spanning extravehicular activities (EVAs), resource management, human factors, as well as medicine and engineering, another vital aspect for space missions must be addressed: local food production. Despite its requirement in future space settlements, plant growth is often not considered a critical element for analog missions. Nevertheless, the study of plants and space agriculture systems in these scenarios can lead to important outcomes, including facilitating new systems' deployment; increasing the operational efficiency of current solutions; promoting a better understanding of available technologies; and understanding plants' robustness in habitat conditions and their effect on the crew's mental well-being[27,28].

A. Plant growth in analog environments

Considering the opportunities associated with space farming research in analog environments, this section will evaluate examples of food cultivation systems and plant growth experiments in different space analog scenarios. The objective is to provide an overview of efforts in the space farming domain, including relevant inputs from previous experiences, together with their strengths and weaknesses, to better guide the implementation of future solutions.

a. GreenHab

The GreenHab greenhouse is one of the six structures at the Mars Desert Research Station (MDRS), located in the desert region of Utah, United States. The facility has the goal to grow plants and support the food demand of up to seven members on a 2-3 week mission simulating life on the Martian surface. Activities at the GreenHab range from crop growth, plant science studies, crew well-being, and determining the necessary food resources that future Mars explorers will require during a long-term mission on the red planet. The initial horizontal cylindrical structure was built in 2003, and had an experimental water recycling system, together with a heat and ventilation air conditioning system, used for vegetable growth over the season, which was harvested and consumed by the latest crews in rotation at the station. By upgrading the facility, a hydroponic system was installed to feed the crew with fresh lettuce, carrot, pea, and herb plants. In February 2014, Crew 135 conducted studies in terms of illumination and automation of the GreenHab. These studies also looked into current light treatment as well as the addition of supplemental LED light by measuring their light levels inside the GreenHab[29].

After an incident occurred in 2015, during the mission with Crew 146, the greenhouse was severely damaged and a temporary grow tent was built with discrete, low-power indoor gardens for the continuation of research. This motivated the researchers to rebuild the greenhouse structure with a new hybrid system, designed and fabricated from recycled parts of the previously existing system, as proposed by Merkle *et al.*[30]. The proposed Hydroponic-Aquaponic Food Production System was composed of 54 growth sites in a floating raft—deep water culture (DWC) system, with the use of aquaponic technique for the growth of fish and plants. Eighteen additional growth sites were also available in tanks if used solely for hydroponic plant production. After several missions, it was realized that the GreenHab required a prohibitive amount of crew time for maintenance and daily operations. This led to a change in the operations for more lean production, utilizing soil-based cultivation.

In summary, several approaches and options for the GreenHab automation, illumination, and capacity expansion were evaluated based on various research, production, and operations interests. The use of LED supplemental lighting greatly improved light conditions inside the greenhouse, therefore enhancing crop growth and yield. Current activities that are being reported during the missions, include the collection of data on environmental conditions, temperature, hours of supplemental light, daily water usage, available water in the tank, and irrigation times.

b. BioHabitat

Located in Habitat Marte Space Analog Station, in the Brazilian semiarid region, the BioHabitat greenhouse is a circular environment that contributes to forming an analog space ecosystem or laboratory conditions focused on food production. Chronology of the stages of deployment and operating actions of the BioHabitat greenhouse were reported from mission 3 (April 2018) to mission 40 (June 2020). It started with the installation of the greenhouse structure and its first cultivation system, followed by the expansion of the structure and installation of its second cultivation system. The implementation of the operational protocols for management, maintenance, cleaning, harvesting, and data collection routines followed construction. BioHabitat's cultivation systems utilize aquaponic techniques to cultivate crops (e.g. lettuce, cherry tomato, spinach, basil, scallion, and bell pepper) and fish (e.g. tilapia), with both Ebb-and-Flow and DWC decoupled modules. The systems are composed of a fish tank, water and oxygen pumps, along the cultivation beds, and a ventilator to increase the air movement inside the structure and reduce the internal temperature[25].

Experimental activities within BioHabitat encompass the application of sustainable practices in the agricultural processes through food routines and operational protocols. During the missions, the analog astronauts are responsible for conducting activities related to the protocols, including observation, diagnosis, and referrals about food production in both aquaponic systems under the same environmental conditions. The protocols and routines were developed to be dynamic and iterative, allowing for the incorporation of solutions to identified problems directly into the workflows. These solutions can be incorporated into: systems management; greenhouse maintenance and cleaning; water quality monitoring; planning and establishing the cultivation and harvesting schedule; analysis of environmental data; and other operational procedures. These practical experiences showed the importance of the correct management of space greenhouses as a solution to increase astronauts' performance, reduce interventions, and optimize the time spent on farming operations[28].

c. HortSpace

The HortSpace project was developed by the Italian National Agency for new technologies, energy, and sustainable economic development (ENEA), with the aim of identifying the best growing conditions for selected plant species to analyze their ability to adapt to extreme environmental conditions, either on Earth or space[31]. HortSpace's growth system was first implemented during the AMADEE-18 field mission, in February 2018, held by the Austrian Space Forum in the desert of Oman[32]. The cultivation modules were installed by the researchers within the mobile and inflatable greenhouse connected to the main habitat.

The structure was designed to cultivate microgreens in a controlled environment and it is composed of a multi-level vertical module, with 4 square meters of growth space, which allowed a continuous production cycle, ensuring a constant supply of food during the mission. HortSpace was equipped with computerized systems for real-time management and control; sensors to monitor chemical-physical-environmental parameters and growth conditions of the plants; LED lighting; filtration and sterilization systems; and fully automated hydroponic setup, using ebb-and-flow and nutrient film technique (NFT) systems[33].

The crew of six analog astronauts was responsible for the production of high-quality microgreens while studying the effects of two different photoperiods on their growth, morphology, and nutritional characteristics. The facilities, scientific instruments, and experimental procedures were selected to minimize crew time commitment (in hours per person) for handling, installation, and testing[34].

For the period between the 5th of March to the 8th of April, 2024, the updated version of HortSpace is expected to be utilized during the AMADEE-24 mission, which will be managed by the Austrian Space Forum and hosted by the Armenia Aerospace Agency. Along the mission, a crew composed of six analog astronauts will be responsible for conducting life sciences experiments with the Hort3Space "space garden". The system will be equipped with full-spectrum LED lights and an integrated robotic arm, which will be set up inside a sterile grow room in an inflatable self-erecting tent to evaluate cultivation performances, supporting the diet of the crew with the growth of different species of microgreens[35].

B. Identified requirements and challenges

Efficient food production in space demands more than just advanced tools and technologies; it also requires understanding human capabilities and other structural limitations. Simplifying activities like plant growth is crucial for long-term missions. Addressing limitations in current space farming investigations, such as irregular structural requirements and the lack of standards, is vital for maintaining balanced space ecosystems over extended periods.

To lay the groundwork for space analogs, it is essential to understand their specific needs and demands. Modular assembly and deployment processes, along with considerations for space, energy, and resource constraints, are crucial for plant growth systems in analog environments. Evaluating previous analog scenarios it becomes clear that standardization of plant growth structures is an important factor and research gap. As highlighted by Wolff *et al.*[36], this would not only facilitate the data collection and centralized access to the research outcomes, but it would also prioritize research on fundamental processes, such as photosynthesis, gas exchange, transport of water and solutes, and stability of the plant genome, to ensure sustainable plant production in space. Experiments should also, whenever feasible, include an assessment of a plant's complete growth cycle, while taking into consideration the amount of biomass produced, as a function of the crew's food demand[36].

On the other hand, crew time needs to be accounted for as a decisive factor in designing space cultivation modules. Based on the list of tasks established by Poulet *et al.*[37], efforts should also focus on reducing the average time per task, which will also guide choices made for plant species, irrigation systems, level of automation, and use of monitoring interfaces. The development of standardized growth systems beneficially allows for the centralization of information from multiple locations, taking advantage of international collaboration to share results and experiences, and enhancing experimental outcomes. This would allow astronauts to dedicate more time to accomplish mission objectives and focus on personal well-being[35].

Finally, due to the multidisciplinary nature of space missions and the differences in crews' backgrounds, eliminating the variability of regional/social plant growth methodologies is a key consideration for successful space agriculture endeavors. To make this feasible, developing a standardized methodology for accurately reporting and analyzing farming operations is vital. This would include a detailed description of expected climatic conditions, defining data collection periods, and precise reporting of plant handling and analysis to further increase the comparability between studies. In an optimal scenario, implementing these considerations into mission planning could lead to the development of a user-friendly system that optimizes crew time on farming activities. At the same time, it would promote scenarios where astronauts, regardless of agricultural expertise, can successfully grow produce and troubleshoot the system.

III. Methodology

A. *Overview of Proposed Investigation*

This research will allow development of a comprehensive methodology to gather qualitative and quantitative data through surveys aimed at analog astronauts, space analog habitat directors or managers, and plant researchers participating in the World's Biggest Analog (WBA) mission scheduled for 2025. The research methodology is designed to explore their experiences, challenges, and insights into space farming research, with a focus on the development and integration of SpaCEA cabinets under the BRIDGES framework.

B. *Application of BRIDGES*

The BRIDGES methodology conveys for the establishment of metrics and criteria aiming at unifying cabinet's applications in space analog mission scenarios. The methodology provides a holistic evaluation of the plant-human-system interface, ranging from systems' deployment and configuration to mission objectives, analog astronauts' backgrounds, and other relevant logistical factors.

C. *Goals and Description of Surveys*

The primary goal of the surveys is to elicit detailed information regarding space farming research in analog environments. These surveys will include open-ended questions to delve into the nuanced perspectives of analog astronauts and managers and will be distributed to all analog astronaut crew members and relevant habitat directors or managers participating in the WBA.

Survey results will be used to facilitate the delineation of potential research avenues and focal points concerning the implementation and optimization of space farming systems within analog environments. We foresee a number of major areas of consideration for optimization and integration of SpaCEA cabinets in future analog missions, encompassing several key aspects, summarized below and in **Fig. 2**.

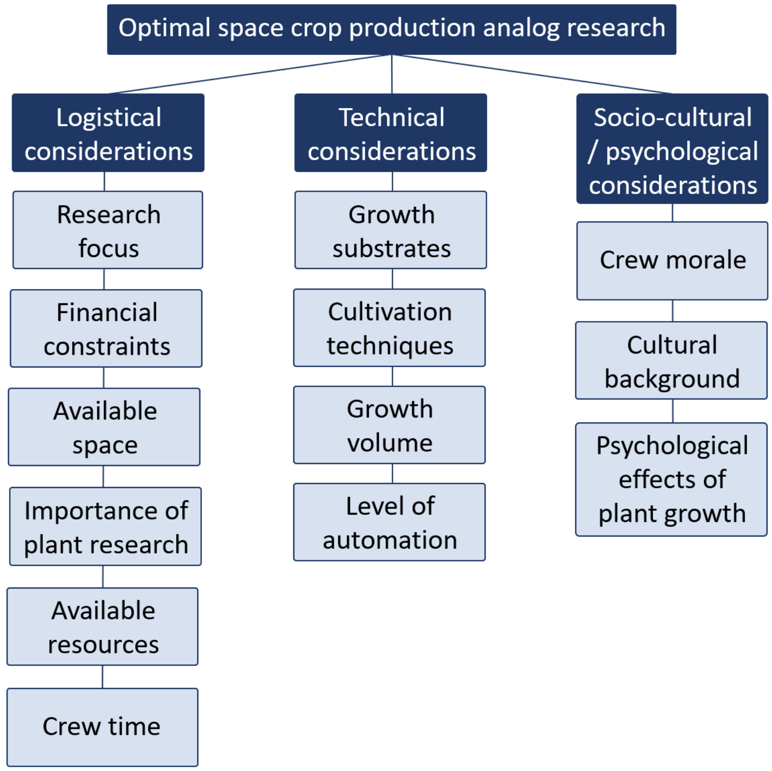

Fig. 2: Summary of key considerations for optimal space crop production research in analog missions.

a. Participant Groups

Participants in the survey will include analog astronaut crew members actively involved in the World's Biggest Analog 2025 mission and analog habitat directors or managers responsible for overseeing their respective analog environments. The inclusion of diverse perspectives is essential to comprehensively understand the challenges and opportunities associated with space farming in analog habitats.

b. Description of Interviews and Questionnaire

Our proposed research questions will include a mix of open-ended questions and ranking qualitative and quantitative questions designed to explore participants' backgrounds, experience with, challenges, and insights into space farming research. Collected data will include habitat sizes, habitat geographical locations, proposed crew routines, participants' backgrounds, and previous experience in farming operations, in addition to technical information detailing logistical and operational requirements for analog space crop production systems.

The collected data will assist us in evaluating the logistics, involved costs, technical, and functional requirements for conducting on-site assembly of SpaCEA cabinets and inform us of practical engineering considerations for the design of the next generation of SpaCEA cabinets. It is also expected to provide a proper understanding of the operational needs based on what is desired versus what can be offered to researchers who are not trained or experienced with farming activities.

The analysis will follow the workflow presented in **Fig. 3**, which involves the cabinet's usability for implementing solutions and generating novel outcomes regarding food cultivation routines, psychological assessment, test of technologies, and relevant scalability factors, during long-term space analog missions.

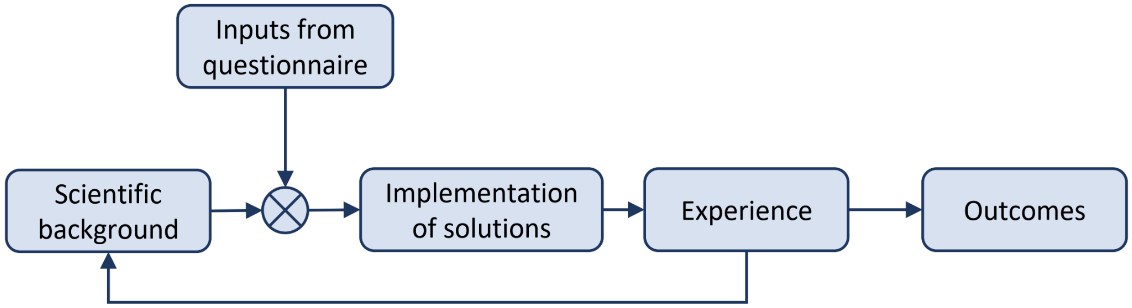

Fig. 3: Workflow for the study. Source: Adapted from Souza *et al*[28].

The surveys may include questions regarding various aspects such as:

- *Station Sizes and Geographical Locations*: Obtain information on the physical attributes and geographic locations of the space analog stations involved in the World's Biggest Analog, providing context for the spatial constraints faced during space analog missions and understanding available capacity for setting our agricultural system and its requirements.

- *Logistical, Technical, and Functional Requirements*: Evaluate the logistical, technical, and functional requirements for on-site assembly of SpaCEA cabinets, considering the practical engineering aspects involved.

- *Operational Needs*: Understand the operational needs from the perspective of participants, differentiating between desired outcomes and what can realistically be offered to researchers who may lack training or experience in farming activities.

- *Proposed Routines*: Investigate the routines and operational processes proposed or currently in place within the involved space analog habitats, contributing to an understanding of the daily activities and requirements related to space farming and overall allotment of time to our systems maintenance and tending to.

- *Participants' Backgrounds*: Gather insights into the backgrounds of the participants, including their training, expertise, experiences relevant to space farming or agriculture, educational background, and other demographic data.

- *Previous Experience in Farming Operations*: Explore any prior experience the participants may have in farming operations, contributing to a nuanced understanding of their capabilities and potential challenges.

- *Cultural Perspectives on Space Farming*: How do analog astronauts perceive and integrate space farming practices into their daily routines within the confined spaces of analog habitats?

- *Social Dynamics in Analog Environments*: What social dynamics emerge among analog astronauts and station managers during the collaborative process of cultivating crops in space analog missions?

- *Perceptions of Bioregenerative Life Support Systems*: How do analog astronauts conceptualize the integration of bioregenerative life support systems, specifically focusing on plant growth cabinets, within the broader context of sustainable space exploration?

- *Impact of Spatial Constraints on Social Interaction*: How do spatial and logistical constraints inherent in space missions influence the social interactions and cooperation among analog astronauts engaged in the assembly and operation of SpaCEA cabinets?

- Innovation and Adaptation: What innovative practices and adaptive strategies do analog astronauts employ when faced with challenges in the assembly and operation of SpaCEA cabinets during space analog missions?

- *Human-Plant Interaction in Analog Environments:* How do analog astronauts perceive the psychological and emotional aspects of interacting with plants within confined spaces, and what impact does this interaction have on their overall well-being?

- *Collaboration and Communication in Space Farming:* How do communication patterns and collaborative efforts unfold between representatives managing analog stations and analog astronauts during the development and deployment of SpaCEA cabinets?

- *Cultural and Individual Variances in Plant Cultivation Practices:* Are there cultural or individual variations in the approaches and attitudes toward plant cultivation within analog environments, and how do these variances impact the success of space farming initiatives?

- *Ethical Considerations in Space Farming*: What ethical considerations and values emerge among analog astronauts and station managers in the context of sustainable crop cultivation for long-duration space missions?

- *Perceived Benefits and Challenges of Space Farming*: What are the perceived benefits and challenges of space farming as articulated by both analog astronauts and representatives managing analog stations, and how do these perceptions shape the ongoing development of plant growth systems?

c. Data collection Methodology
Methods for conducting interviews and distributing questionnaire:
We will incorporate a mixed-methods approach combining quantitative and qualitative surveys and questionnaires with qualitative interviews to ensure a comprehensive understanding of user needs, challenges, and preferences. We will use a purposive sampling technique to select participants who have direct experience with analog environments and plant growth systems, as well as participants who have no direct experience with analog environments and plant growth systems in order to gain a comprehensive understanding of the user experience from various user groups.

d. Selection criteria for interviewees:
All participating analog astronaut crew members and their respective habitat manager or director that are selected by and participating in the World's Biggest Analog in 2025.

e. Data Analysis of Usability and Integration
The analysis of collected data will extend beyond descriptive statistics and thematic analysis. It will specifically focus on the usability of SpaCEA cabinets concerning:
    a. Food Cultivation Routines: Assess the potential integration of SpaCEA cabinets into existing food cultivation routines within analog habitats.
    b. Psychological Assessment: Explore the psychological aspects associated with the presence of plant growth in confined spaces, aiming to understand the impact on analog astronauts.
    c. Testing of Technologies: Examine the suitability of SpaCEA cabinets for testing new technologies relevant to space farming.
    d. Scalability Factors: Investigate the scalability of SpaCEA cabinets for long-term space analog missions, considering factors such as resource availability and crew-time allocations.

Qualitative analysis:

- Thematic analysis will be performed to identify recurring themes and patterns in the qualitative data gathered from interviews. Insights from analog astronauts and station managers will inform the refinement of SpaCEA design parameters and other research opportunities.

Quantitative analysis:

- Quantitative data will focus on common challenges and technological preferences in space farming research. The questionnaire will undergo statistical analysis to extract insights into the effectiveness of cabinets' application to meet the requirements of space analog missions.

Deployment phase:

- Future work aims at the deployment of the cabinets in selected space analog stations. The deployment process will be documented to assess the ease of assembly and integration into the analog environment.

Monitoring interface:

- The growth of crops within the cabinets will be closely monitored. Data loggers and sensors will be employed to capture relevant environmental variables. Protocols focused on gathering key parameters such as yield, growth rate, and overall plant health will also be developed.

IV. Potential Results

A. Insights gained from interviews/questionnaires

The insights gained from the interviews and questionnaires of the participants in the analog missions will help to further understand existing challenges in analog plant production. These may include resource management, system control, plant growth, etc. Insights into these specific pain points will help identify areas for improvement. In addition, these will help in assessing the effectiveness, reliability, and scalability of the SpaCEA cabinet and the BRIDGES methodology, respectively, guiding future research and development. The questionnaires can also specifically aid in incorporation of these cabinets' in space missions by reducing integration challenges. This can inform strategies for enhancing the relevance and applicability of research findings.

B. Influence of qualitative data on design parameters, together with the spatial and logistical constraints

Qualitative data gathered from interviews, surveys, and observations will be used to provide insights into the specific needs and preferences of users (analog system managers, researchers, astronauts, etc.). By understanding user requirements, designers can tailor the design parameters of plant growth systems to better meet the needs of end-users within the available spatial and logistical constraints. Analysis of this data can also help identify key priorities and considerations for designing analog systems for space farming research, with logistical constraints expected to drive technical constraints. This includes factors such as optimizing space utilization, ensuring ease of operation, maximizing resource efficiency, and minimizing environmental impact. Design parameters can be adjusted to optimize space utilization, minimize footprint, ensure compatibility with existing infrastructure, and inform decisions regarding the layout, arrangement, and scaling of components within the analog system.

C. Potential application for space analogs in different mission scenarios (short-, mid-, and long-term)

Questionnaire responses and interviews can quickly highlight pressing issues and challenges faced by analog system managers in short-term mission scenarios. This can facilitate rapid iteration and improvement of analog systems to better support these missions by adjusting design parameters to address immediate needs and enhance the efficiency, reliability, and safety of space farming research within constrained timeframes. For mid-term mission scenarios, this methodology can help in integrated mission planning - by collecting data from both station coordinators and analog astronauts, future longer missions can benefit.

D. Interpretation of qualitative data and technical findings

The interpretation integration of qualitative insights from interviews and surveys with the technical findings from experiments and simulations ensures a holistic understanding of the data and enables the identification of key themes and patterns - thereby highlighting key challenges faced in deploying sustainable and scalable systems as well as opportunities for innovation and improvement.

E. Comparison with existing systems and technologies

The current systems in place at analog stations differ from location to location, rendering the collection of quantifiable data, that which is also useful, very difficult. Having such a standardized methodology that would analyze stakeholder perspectives gathered from interviews, including analog system managers, researchers, astronauts, and other relevant stakeholders, will provide valuable insights into the needs, preferences, and priorities of all the stakeholders involved. This will, in turn, benefit SpaCEA research significantly.

F. Evaluation of the technical challenges and success

By documenting experiences, identifying areas for improvement, and developing strategies to address challenges encountered during implementation, the team intends to assess the scalability and adaptability of the developed methodology and evaluate its performance across different scales, from small-scale experiments to large-scale implementations. In the proposed study, BRIDGES will help in improving the standardization of hardware use, software use, and data management of plant growth systems. The results would include detailed specifications for standardized components, guidelines for data acquisition, real-time monitoring, and remote functionalities, tailored to meet the needs of SpaCEA research in various mission scenarios.

V. Discussion and Future Work

The impact of the implementation of the SpaCEA cabinet will be assessed primarily through surveys filled out by analog astronauts, during the World's Biggest Analog (WBA) mission, in pre- and post-mission scenarios. The WBA is an international collaboration of researchers, scientists, educators, and entrepreneurs that aims to bring together most analog stations on the planet in a unique mission. The mission is set to take place for a duration between one week and one month in the September-October time frame of 2025. This team will be testing the developed methodology at various participating analogs during the WBA to simultaneously gather the results from multiple stakeholders.

Crews will first assemble SpaCEA cabinets following detailed instructions. Microgreens such as radish and broccoli will be grown by crews across habitats within assembled cabinets following the pre-established methods for microgreen cultivation. Environmental and plant growth data will be recorded both by cabinets, and crews during crop growth, with standard harvest metrics collected at the end of each growth cycle. Surveys will be distributed to crews throughout the mission, and to habitat managers, particularly focusing on logistical, technical, and socio-cultural and psychological aspects of SpaCEA. Both quantitative, and qualitative results will be used to compare the performance of cabinets and to assess the feasibility of the cabinets' use in space. In summary, through analysis of questionnaires, insights will be extracted focusing on addressing common challenges and technological preferences regarding the effectiveness of SpaCEA cabinets in meeting the requirements of space analog missions.

Ultimately, the evaluation of the questionnaire is envisioned for the development of novel tools based on BRIDGES. The proposed framework is an iterative process with continuous refinement and optimization based on feedback, experimentation, and validation. This iterative approach ensures that technical challenges are addressed and successes are maximized over time, leading to continuous improvement in SpaCEA research. Moreover, the use of reproducible structures adaptable to the context of space analog research enables to predict complex behaviors on how the cultivated plants, once incorporated into a life support system (LSS), interact with the habitat environment. This will lead to the development of operational and technical models to provide a breakdown of costs and resource needs throughout the life cycle of a BLSS while building large-scale crop growth systems. These efforts are expected to guide a phased SpaCEA capable of predicting mass and energy requirements, evaluating potential failure modes, and transforming physicochemical processes into regenerative ones with minimal risks.

VI. Conclusion

In conclusion, the presented study paves the way to promote significant insights into the development and integration of standardized and innovative plant growth modules tailored for space analog missions. By addressing the complexities and challenges inherent in food production in space, we have underscored the importance of understanding not only the technological aspects but also the human dynamics involved. The findings will emphasize the critical role of establishing a foundation for reproducible experiments to streamline operations and maximize the efficiency of systems. By standardizing the technologies and incorporating modular designs, we can enhance data collection, promote international collaboration, and facilitate knowledge sharing across different stakeholders. Furthermore, we highlight the need for user-friendly systems that empower astronauts, regardless of their agricultural background, to effectively engage in farming activities, vital for the success of any plant growth system. The use of SpaCEA cabinets as plant growth systems within the BRIDGES framework provides an exciting opportunity to ensure standardization across hardware, software, and data-gathering elements while using rapid design iteration to address any challenges identified with the systems. This synergistic approach allows for outcomes including the identification of key design considerations and technical specifications, delivering interoperable plant growth cabinets with application in space farming research during analog missions.

Moving forward, the next steps involve interdisciplinary collaboration and international cooperation bolstered by feedback from analog station managers and astronauts, together with the refinement of design parameters for future space farming systems. Key priorities include further research on the human-plant-system interface, building upon the multi-faceted approach that integrates technical and qualitative dimensions. Future contributions should concentrate on translating the practical outcomes of this study into tangible solutions, with particular attention to optimizing assembly and transportation processes to address the spatial and logistical constraints inherent in space missions. These initiatives pave the way for future long-duration space missions and the establishment of interplanetary habitats, ensuring the viability of food production in space environments.

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Appendix A

Table A-1. Categories and leading questions for the questionnaire

Question I.D.	Question category	Question subcategory	Leading question
LC-001	Logistical considerations	Research focus	What are the primary requirements for plant growth systems during the mission?
LC-002	Logistical considerations	Financial constraints	How much investment or budget is available for the cabinet deployment?
LC-003	Logistical considerations	Available space	What are the preferences for the assembly and deployment process of the cabinets?
LC-004	Logistical considerations	Importance of plant research	What areas of research are envisioned and how high a mission priority is crop research?
LC-005	Logistical considerations	Available resources	Which resources and/or materials (seeds, substrates, trays/buckets, gardening tools) are most needed and/or required?
LC-006	Logistical considerations	Crew time	What is the time basis for the cabinet's use based on the length of the mission?
TC-001	Technical considerations	Growth substrates	Which crops will be grown in the cabinet and in which growth substrates?
TC-002	Technical considerations	Cultivation techniques	What design features (e.g. modularity) would optimize plant growth and ease of assembly within analog environments?
TC-003	Technical considerations	Growth volume	What is the required or available space (area and volume) for the cabinet use at the station?
TC-004	Technical considerations	Level of automation	Which parameters must be monitored and what levels of automation, or how much control of tasks, should the system have?
SC-001	Socio-cultural/psycho logical considerations	Crew morale	How does having the plant growth system contribute to individual and overall crew morale throughout the mission duration?
SC-002	Socio-cultural/psycho logical considerations	Cultural background	How do cultural backgrounds inform crew member’s interactions with the plant growth system?

SC-003	Socio-cultural/psychological considerations	Psychological effects of plant growth	How does exposure to plant growth within space analog habitats affect astronauts' mood, stress levels, and overall psychological well-being during extended missions?; What are the cognitive and emotional impacts of interacting with plants in confined, artificial environments? How does this vary, if at all, between different cultures and socio-economic backgrounds?