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

Davi Souza[1], Sai Tarun Prabhu Bandemegala[2], Luke Fountain[3], Harry Charles Wright[4], Alexis Moschopoulos[5], Stephen Lantin[6], Morgan Kainu[7], Victor Buchli[8]

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 SpaCEA Cabinet using 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 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, which 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
EC = Environmental Control
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

[1] Student of Electrical Engineering, State University of Campinas (Unicamp), Brazil, daviafs15@gmail.com.
[2] PhD Student in Aerospace Engineering, Politecnico di Torino, Italy, mailforstp95@gmail.com.
[3] NASA Postdoctoral Fellow, Kennedy Space Center, Florida, United States, luke.l.fountain@nasa.gov.
[4] Department of Chemistry, The University of Sheffield, United Kingdom, harry.wright@sheffield.ac.uk.
[5] Managing Director, Grobotic Systems Limited, United Kingdom, alexis@groboticsystems.com.
[6] PhD Candidate Agricultural & Biological Engineering Dept., University of Florida, United States, slantin@ufl.edu.
[7] Researcher, Native Sky, United States, morgan.kainu@gmail.com
[8] Professor, University College London, United Kingdom, v.buchli@ucl.ac.uk.

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 becomes less practical and more costly (Wheeler, 2022). 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 (Wheeler, Fitzpatrick and Tibbits, 2019). 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 (NASA, 2020).

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 (Wheeler, 2017). 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 (Wheeler, 2022). Several Earth-based large-scale analogs have investigated this concept, including NASA's Biomass Production Chamber (Wheeler et al., 1996, 2003), the Russian Bios-3 project (Gitelson et al., 1989), the European Space Agency's MELISSA Pilot Plant (Lasseur et al., 2010), the Chinese Lunar Palace 1 (Fu et al., 2016), and the German Space Agency (Zabel et al., 2020).

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 growth of a range of horticultural crops, and consists of a bank of adjustable blue, red and green LED lights, a fan, and flexible and expandable transparent bellows (Morrow et al., 2005, Morrow et al., 2009, Massa et al., 2016). 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 (Massa et al., 2017). Veggie is a hands-on system with manual watering of plants by astronauts required, and is the primary system used for the development of horticultural practices and testing of candidate space crops for the supplementation of crew diets (Bunchek et al., 2024).

In contrast, the Advanced Plant Habitat (APH) was designed for plant physiology research in the 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 (Massa et al., 2016; NASA, 2021). 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 (Massa et al., 2016; NASA, 2021).

A. Past and current efforts on space farming and plant growth systems

a. SpaCEA Cabinet

Description of the proposed design parameters/project requirements for the Plant Growth Cabinets

SpaCEA (Space Controlled Environment Agriculture) 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 (Wright et al 2023, **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 40cm^3, 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 PCB, which together with the chamber chassis can be easily assembled by the end-user on site. The chamber control system and chassis are released under a CC non-commercial license.

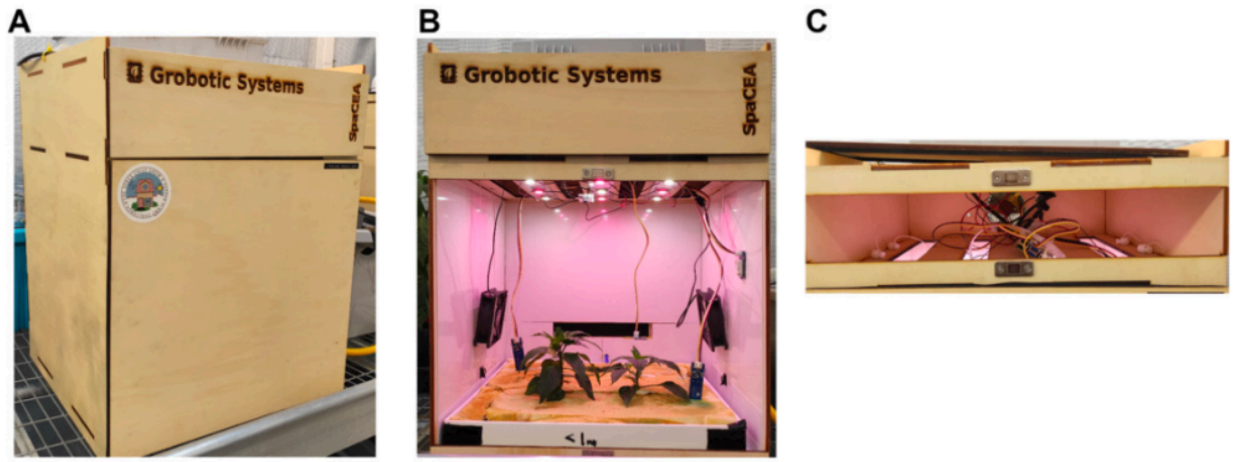

Fig. 1: A) The prototype SpaCEA chamber with the grow area and electronics area doors on, B) the grow area door removed to show grow area C) the shelf for electronic components inside the growth chamber. This version did not have a bespoke PCB.

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 (ICCEG 2004; ICCEG 2008; Both et al 2015) 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. These principles align it well within the BRIDGES framework and will allow for analog astronauts in different locations to more easily share protocols and experimental data and for comparing results between analog stations.

Prototyping/deployment process of Plant Growth Cabinets and details of the manufacturing technologies

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 perspex, and the interior walls of the growth area are laser or 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.

b. BRIDGES

Biologically Reliable Integration and Design for Growth Environments in Space (BRIDGES) emerges as a modular and hybrid methodology based on the integration of biological life with physicochemical processes. The objective of this framework is to deploy a 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 and simulations to small-scale experiments, to optimize system performance, evaluate environmental control dynamics, and validate advanced technologies. The BRIDGES methodology conveys novel perspectives for the establishment of metrics and criteria aiming at unifying SpaCEA 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.

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.

The BRIDGES methodology encompasses a wide range of activities, from software to hardware standardization and improvements, to small-scale experimentation and validation of technologies so as to gradually incorporate self-reliance and independence from Earth based resources. This methodology 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 hardware components, such as growth chambers, lighting systems, nutrient delivery systems, and environmental sensors, tailored to meet the needs of SpaCEA research in various mission scenarios. For data management, it includes developing guidelines for data acquisition, real-time monitoring, and remote control functionalities, as well as integration with existing space mission control systems and data analysis platforms. In addition, BRIDGES also takes into account 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, especially the ones who will be taken to the Moon and Mars. 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 (Golden et al., 2018).

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 and Arnhof (2021). 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 (Souza et al, 2022).

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. The analog missions can help to orientate further research by identifying what areas are in need of more research, new areas for research, and strategies that aid with knowledge accumulation over time (Bell et al., 2019). That's why, there is a need to develop and test new technologies and to conduct experiments aiming at scientific results before its implementation off-Earth.

Despite 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. Differently from what will be required in future space settlements, plant growth is not a critical element for analog missions. Still, the study of plants and space farming systems in these scenarios can lead to important outcomes. Such as: 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 (Heinicke et al.,2021; Rezende and Souza, 2022).

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 looked also into current light treatment as well as the addition of supplemental LED light by measuring their light levels inside the GreenHab [Source: https://www.researchgate.net/publication/289576320].

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. (2016). [Source: http://www.marspapers.org/paper/Merkle_2016_pres.pdf]. 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 much 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 are being reported during the missions, also including 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 to the installation of its second cultivation system. The following activities were proceeded by the implementation of the operational protocols for management, maintenance, cleaning, harvesting, and data collection routines. 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 [Source: https://doi.org/10.34117/bjdv8n3-024].

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. For the protocols and routines was developed a dynamic aimed at identifying problems to be solved and the search for alternatives or better solutions to be taken. Many of these solutions can be incorporated into: systems management; greenhouse maintenance and cleaning; monitoring water quality; 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 [Source:https://www.researchgate.net/publication/352377156].

c. HortSpace

The HortSpace project, was developed by the Italian National Agency for new technologies, energy, and sustainable economic development (ENEA), with the aim to identify the best-growing conditions for selected plant species to analyze their ability to adapt to extreme environmental conditions, either on Earth or space [Source: https://www.hortspace.enea.it/i-progetti/hortspace.html]. 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 [Source: https://oewf.org/en/portfolio/amadee-18/]. 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 was composed of a multi-level vertical module, with 4 square meters, which allowed a continuous cycle production, 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 [Source: https://www.hortspace.enea.it/la-tecnologia.html].

The crew of 6 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. All the facilities, the scientific instruments, and the experimental procedures were selected to minimize the crew time commitment (in hours per person) necessary for handling, installation and testing [Source: https://www.hortspace.enea.it/images/brochure/enea_ortextreme_borchure.pdf].

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 [Source: https://oewf.org/en/amadee-24/].

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's 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. Based on the previously evaluated scenarios, the standardization of plant growth structures showed as a necessary endeavor. As highlighted by Wolff et al. (2014), 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 [Source: https://doi.org/10.3390/life4020189].

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. (2021), efforts should also focus on reducing the average time per task, which will also perpetuate choices made for plant species, irrigation systems, level of automation, and use of monitoring interfaces. With that, optimized experimental designs with environmental monitoring and control, together with automation capabilities are essential for future research. The development of standardized growth systems can be beneficial in a way that allows the gathering of pieces 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 [Source: https://doi.org/10.1016/j.lssr.2021.08.002].

Finally, due to the multidisciplinary nature of space missions and the different crews' backgrounds, eliminating the social variations on plant growth and prioritizing astronaut well-being are key considerations for successful space agriculture endeavors. To make it 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 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.

B. 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 research for SpaCEA cabinets encompassing several key aspects, summarized below and in **Fig. 6**.

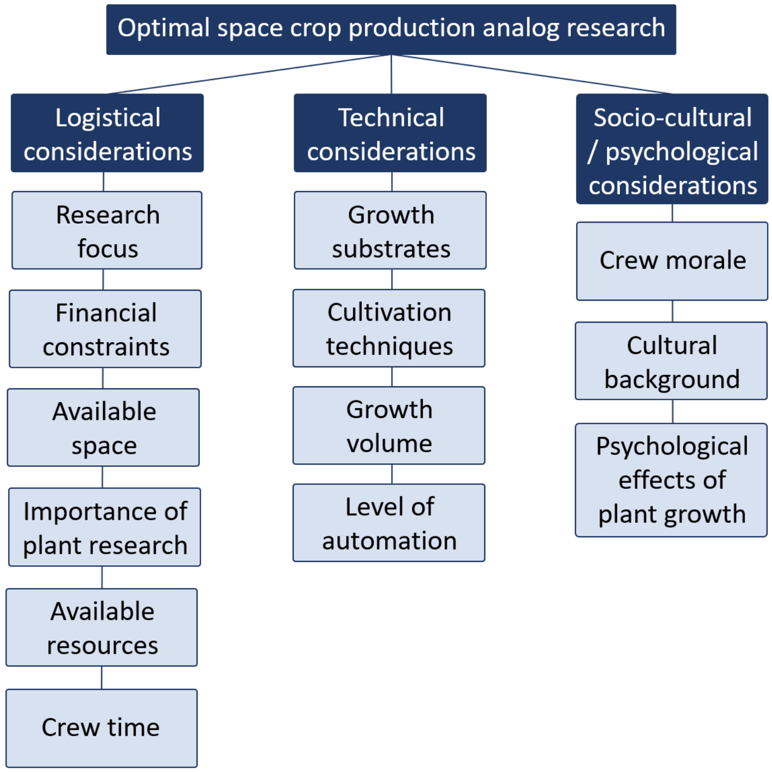

Fig. 6: Summary of key considerations for optimal space crop production research in analog missions.

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/Questionnaire

Our research questions will be a mix of open-ended questions and ranking qualitative and quantitative questions and will be designed to explore their backgrounds, experience with, challenges, and insights into space farming research. Collected data can include habitat sizes, habitat geographical locations, proposed crew routines, participants' backgrounds, and previous experience in farming operations.

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 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 involve the cabinet's usability for integrating food cultivation routines, psychological assessment, test of technologies, and relevant scalability factors, during long-term space analog missions

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/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.

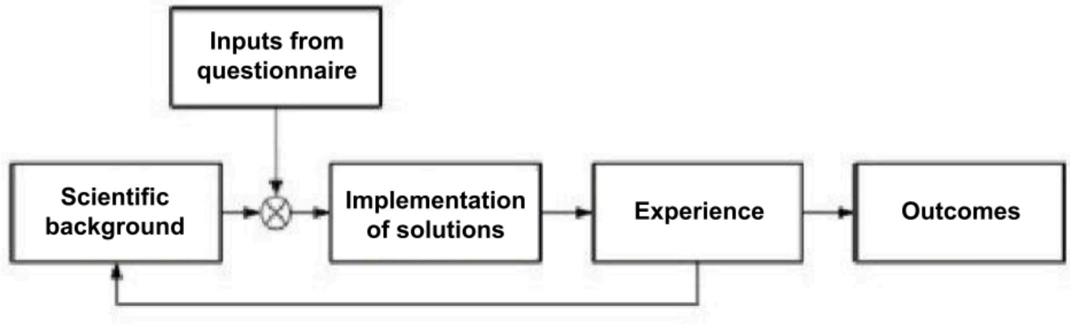

Fig. 7: Workflow for the study. Source: Adapted from https://www.researchgate.net/publication/352377156

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. Results and Discussion

A. Insights gained from interviews/questionnaires

The insights gained from the interviews/questionnaires of the participants in the analog missions will help to further understand the existing challenges faced. 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 BRIDGES methodology respectively which can then guide future research and development efforts. The questionnaires can also specifically aid in integration of these cabinets for space farming research in actual space missions by helping improve the 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 can 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 the 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, and ensure compatibility with existing infrastructure and can 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 the 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 be benefitted.

D. Interpretation of qualitative data and technical findings

The interpretation of qualitative datasets and technical findings would involve synthesizing the insights gleaned from interviews, surveys, experiments, and simulations to provide a comprehensive understanding of the challenges, opportunities, and implications for space farming research at large. Integrating qualitative insights from interviews and surveys with 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 collection of quantifiable data that 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

BRIDGES framework is inherently based on 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 space farming research. 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.

V. Future Work

The World's Biggest Analog (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 of one week to one month in the Sept-Oct time frame in 2025. This team will be testing the developed methodology at various analogs during the WBA to simultaneously gather the results from multiple stakeholders. These results will then be analyzed for improving the methodologies.

VI. Conclusion

In conclusion, the presented study paves the way to promote significant insights into the development and integration of 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 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. Moreover, once exploring the nuances of the human-plant-system interface, it was highlighted the need for user-friendly systems that empower astronauts, regardless of their agricultural background, to effectively engage in farming activities. The application of SpaCEA cabinets aimed at facilitating crop growth within analog environments, replicating conditions critical for space exploration. The BRIDGES framework ensures standardization across hardware, software, and data-gathering elements. Anticipated outcomes include identifying key design considerations and technical specifications to deliver interoperable plant growth cabinets to be applied to 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.

References

Bandemegala, Sai Tarun Prabhu & Souza, Davi & Shileikis, Eran. (2022). Biologically Reliable Integration and Design for Growth Environments in Space (BRIDGES).

Both, A.J., Benjamin, L., Franklin, J. *et al.* Guidelines for measuring and reporting environmental parameters for experiments in greenhouses. *Plant Methods* 11, 43 (2015). https://doi.org/10.1186/s13007-015-0083-5

Bunchek, J.M., Hummerick, M.E., Spencer, L.E., Romeyn, M.W., Young, M., Morrow, R.C., Mitchell, C.A., Douglas, G.L., Wheeler, R.M., and Massa, G.D. (2024). Pick-and-eat space crop production flight testing on the International Space Station. Journal of Plant Interactions **19**(1). https://doi.org/10.1080/17429145.2023.2292220

Fu, Y., Li, L., Xie, B., Dong, C., Wang, M., Jia, B., Shao, L., Dong, Y., Deng, S., Liu, H., et al. (2016). How to establish a bioregenerative life support system for long-term crewed missions to the Moon and Mars. Astrobiology *16* (*12*), 925–936 https://doi.org/10.1089/ast.2016.1477. PubMed

Gitelson, I.I., Terskov, I.A., Kovrov, B.G., Lisovskii, G.M., Okladnikov YuN, Sid'ko FYa, Trubachev, I.N., Shilenko, M.P., Alekseev, S.S., Pan'kova, I.M., and Tirranen, L.S. (1989). Long-term experiments on man's stay in biological life-support system. Adv. Space Res. *9* (*8*), 65–71 https://doi.org/10.1016/0273-1177(89)90030-6.

International Committee for Controlled Environment Guidelines (2008) *Guidelines for Measuring and Reporting Environmental Parameters for Experiments in Plant Tissue Culture Facilities.*

International Committee for Controlled Environment Guidelines (2004) *Minimum Guidelines for Measuring and Reporting Environmental Parameters for Experiments on Plants in Growth Rooms and Chambers.*

Lasseur, C., Brunet, J.D., De Weever, H., Dixon, M., Dussap, C.G., Godia, F., Mergeay, M., Van Der Straeten, D., and Verstraete, W. (2010). MELISSA: the European project of a closed life support system. Gravitational and Space Biology *23* (*2*), 3–12.

Lucibello, S. (n.d.). La Tecnologia. Hortspace. https://www.hortspace.enea.it/la-tecnologia.html

Massa GD, Wheeler RM, Morrow RC, Levine HG. (2016). Growth chambers on the International Space Station for large plants. Acta Hortic. 1134:215–222. doi:10.17660/ActaHortic.2016.1134.29.

Massa GD, Newsham G, Hummerick ME, Morrow RC, Wheeler RM. (2017). Plant pillow preparation for the veggie plant growth system on the International Space Station. Gravit Space Res. 5(1):24–34. doi:10.2478/gsr-2017-0002

Merkle, P., Cuneo, C., Asce, M., & Maccarrrone, M. (2016). Hydroponic-Aquaponic Food Production System for the Mars Desert Research Station Acknowledgments of Support. https://marspapers.org/paper/Merkle_2016_pres.pdf

Morrow RC, Remiker RW, Mischnick MJ, Tuominen LK, Lee MC, Crabb TM. (2005). A low equivalent system mass plant growth unit for space exploration. SAE Tech. Paper 2005-01-2843.

Morrow RC, Remiker RW. (2009). A deployable salad crop production system for lunar habitats. SAE Tech. Paper 2009-01-2382.

NASA (2020). NASA's Lunar Exploration Program Overview. https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

NASA (2021). Advanced Plant Habitat Factsheet. https://www.nasa.gov/wp-content/uploads/2021/07/advanced-plant-habitat.pdf

OEWF. (n.d.). AMADEE-18 Mars Analog Field Simulation, February 2018, Oman | OeWF. Austrian Space Forum (OeWF). Retrieved February 13, 2024, from https://oewf.org/en/portfolio/amadee-18/

OEWF. (n.d.-b). AMADEE-24 Mars Simulation. Austrian Space Forum (OeWF). https://oewf.org/en/amadee-24/

Piccirillo, S., Nardi, L., Metelli, G., Corallo, G., Potenza, M., Cavaliere, F., Mascetti, G., & Benvenuto, E. (n.d.). HORTEXTREME Protected HORTiculture in inflatable facilities, resistant to EXTREME conditions, for the production of high nutritional value plants: a field experiment in the AMADEE-18 mission Hortextreme projectRetrieved https://www.hortspace.enea.it/images/brochure/enea_ortextreme_borchure.pdf

Poulet, Lucie & Doule, Ondrej. (2014). Greenhouse automation, Illumination and Expansion study for mars desert research station. 13. 9714-9724.

Poulet, L., Zeidler, C., Bunchek, J., Zabel, P., Vrakking, V., Schubert, D., Massa, G., & Wheeler, R. (2021). Crew time in a space greenhouse using data from analog missions and Veggie. Life Sciences in Space Research, 31, 101–112. https://doi.org/10.1016/j.lssr.2021.08.002

Rezende, J. F. D., & Souza, D. A. F. (2022). Produção de alimentos em habitats espaciais: aprendizados da operação do habitat Marte / Food production in space habitats: learnings from the Mars habitat operation. Brazilian Journal of Development, 8(3), 15873–15886. https://doi.org/10.34117/bjdv8n3-024

Souza, Davi & Rezende, Julio & Santos, Dalmo. (2020). Agriculture in Mars: Habitat Marte findings.

Wheeler, R.M., Mackowiak, C.L., Stutte, G.W., Sager, J.C., Yorio, N.C., Ruffe, L.M., Fortson, R.E., Dreschel, T.W., Knott, W.M., and Corey, K.A. (1996). NASA's Biomass Production Chamber: a testbed for bioregenerative life support studies. Adv. Space Res. *18* (*4-5*), 215–224 https://doi.org/10.1016/0273-1177(95)00880-N. PubMed

Wheeler, R.M., Mackowiak, C.L., Stutte, G.S., Yorio, N.C., Ruffe, L.M., Sager, J.C., Prince, R.P., Peterson, B.V., Goins, G.D., Berry, W.L., et al. (2003). Crop production for Advanced Life Support Systems. Observations from the Kennedy Space Center Breadboard Project. NASA Technical Memorandum 2003–211184.

Wheeler, R.M. (2017). Agriculture for space: people and places paving the way. Open Agric. *2* (*2*), 14–32 https://doi.org/10.1515/opag-2017-0002.

Wheeler, R.M., Fitzpatrick, A.H., and Tibbitts, T.W. (2019). Potatoes as a Crop for Space Life Support: Effect of CO2, Irradiance, and Photoperiod on Leaf Photosynthesis and Stomatal Conductance. Front. Plant Sci. **10**. https://doi.org/10.3389/fpls.2019.01632

Wheeler, R.M. (2023). NASA's contributions to vertical farming. Acta Hortic. 1369, 1-14
DOI: 10.17660/ActaHortic.2023.1369.1
https://doi.org/10.17660/ActaHortic.2023.1369.1

Wolff, S. A., Coelho, L. H., Karoliussen, I., & Jost, A.-I. K. (2014). Effects of the Extraterrestrial Environment on Plants: Recommendations for Future Space Experiments for the MELiSSA Higher Plant Compartment. Life, 4(2), 189–204. https://doi.org/10.3390/life4020189

Wright, H.C., Moschopoulos, A. and Fountain, L. (2023). Design of low cost, open-source prototype plant growth chambers for evaluating crop suitability for space environments. Acta Hortic. 1369, 141-148
DOI: 10.17660/ActaHortic.2023.1369.17
https://doi.org/10.17660/ActaHortic.2023.1369.17

Zabel, P., Zeidler, C., Vrakking, V., Dorn, M., and Schubert, D. (2020). Biomass production of the EDEN ISS space greenhouse in Antarctica during the 2018 experiment phase. Front. Plant Sci. *11*, 656 https://doi.org/10.3389/fpls.2020.00656. PubMed