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# Design Strategies of Greenhouse and Food Production/Preparation Module for Long-Duration Human Exploration Missions

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**Space horticulture has come a long way from germinating a single plant in orbit to producing vegetables for multiple meals. However, one of the main prerequisites of long-duration missions is producing and supporting nutritious food without resupply from the Earth. A single small greenhouse chamber needs to transform into a larger module with both greenhouse and food production/preparation systems to reach this goal. This paper will describe current and novel macronutrient production technologies which transform a harvested plant into edible carbohydrates, protein, and lipids for consumption. Then, micronutrient and flavoring production methods will be considered to ensure the meal is both nutritious and tasty. Earth-independent food support in zero gravity will not be possible without safe food preparation and storage systems. This review will show the timeline and pin the milestones needed to move one step closer to a long-duration mission.**

## Nomenclature

| | | |
|---|---|---|
| BLSS | = | Bioregenerative Life Support System |
| CRL | = | Crop Readiness Level |
| DRM | = | Design Reference Mission |
| ECLSS | = | Environmental Control and Life Support System |
| EXPRESS | = | EXpedite the PRocessing of Experiments to the Space Station |
| FN | = | Food and Nutrition |
| HRR | = | Human Research Roadmap |
| HRP | = | Human Research Program |
| ISS | = | International Space Station |
| LEO | = | Low Earth Orbit |
| MDL | = | MidDeck Locker |
| NASA | = | National Aeronautics and Space Administration's |
| SPP | = | Scientific Passenger Pods |
| TRL | = | Technology Readiness Levels |
| WM | = | Wall Mounted |

## I. Introduction

THIS paper first discusses the greenhouse system's evolution to compare the scale of the plant growth units with future needs. Afterward, food production/ preparation systems' development is discussed based on the two mission scenarios (earth-dependent and earth-independent). It then briefly introduces current knowledge gaps in the space food industry and categorizes them by their affiliations. Then it compares the scale and priority of

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the gaps in relation to the architectural design process. Finally, it provides an update about pioneer approaches in the space food field, suggesting possible systems and milestones for developing a greenhouse and food production/preparation module.

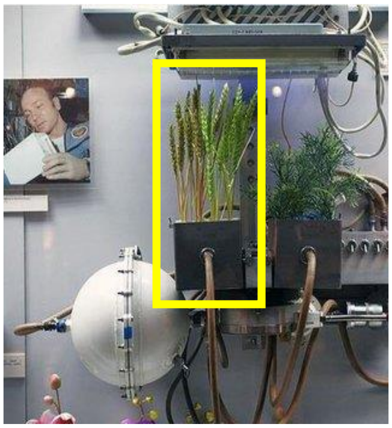
## A. Greenhouse Systems for Space Applications

Greenhouse and bioregenerative life-support systems for space have been investigated for over 60 years. Table 1 briefly outlines the evolution of plant growth units since 1966, and Appendix A provides their photos. The first photosynthesis and plant growth experiments were conducted in satellites during a 3-day trip around the Earth. It was not until Salyut and its Wall Mounted system that the crew had their first interaction with plants.[1] As shown in Figure 1, these pouches are just a few centimeters in dimension and have a growth area of less than 0.01 $m^2$. Then in 1982, and with the larger spacecraft such as a Shuttle, the decking system introduced MidDeck Locker. This 12cm x 43cm x 51cm cube had an automated environmental control system and increased the growth area seven times. However, the growth area was doubled with the ISS's EXPRESS rack. Since 2017, Advanced Plant Habitat has had the largest fully automated plant growth facility with over 0.17 $m^2$.

**Table 1 Evolution of Plant Growth Units and Chambers**

| | Plant Growth Units and Chambers | First Launch | Platform | Growth Area ($m^2$) | Notes |
|---|---|---|---|---|---|
| Satellite | Orbital Vehicle (OV-1) | 1966 | SPP | n.a. | The first satellite with photosynthetic and respiratory gas exchange. [2] |
| | Biosatellite Program (1,2, and3) | 1966-1969 | | n.a. | The first plants, animals, and microorganisms are grown in zero-g. [3] |
| Salyut | Oasis Series | 1971 | WM | 0.001 | The first plant system in a crewed spacecraft.[4] |
| | Vazon | 1973 | | n.a. | The first ornamental plants.[5] |
| | Malachite | 1973 | | n.a. | The first psychological human-plant interactions.[5] |
| | Oasis Series | 1974 | | 0.010 | The First space-grown crops were eaten by humans.[5] |
| | Biogravistat/Magnetobiostst‌ | 1976 | | n.a. | The first magnetic centrifuge gravity simulator.[5] |
| | Svetoblok | 1982 | | n.a. | The first flowering of plants in space.[6] |
| | Phyton | 1982 | | n.a. | The first successful seed-to-seed experiment.[6] |
| | SVET | 1990 | | 0.100 | The first automated controlled environmental conditions greenhouse.[7] |
| | SVET-GEMS | 1995 | | 0.100 | The first implanted IBM notebook with daily reports to Earth.[4] |
| Shuttle | Plant Growth Unit (PGU) | 1982 | MDL | 0.050 | The first plant growth unit in the Mid Deck Locker (MDL).[6] |
| | Astroculture (ASC) | 1992 | | 0.021 | The First active trace gas control system.[5] |
| | Plant Generic Bioprocessing Apparatus (PGBA) | 1996 | | 0.075 | The first 2 MDL units.[5] |
| | Plant Growth Facility (PGF) | 1997 | | 0.055 | The first system with an ethylene filter, humidity, CO2, and temperature control.[5] |
| ISS | Advanced Astroculture (ADVASC) | 2001 | MDL & EXPRESS | 0.052 | The first plant growth chamber in the EXPRESS Rack.[5] |
| | Biomass production system (BPS) | 2002 | | 0.104 | The first four individual plant growth chambers.[5] |
| | Lada | 2002 | | 0.050 | The First hazard analysis and critical control point.[4] |
| | European modular cultivation system (EMCS) | 2006 | | 0.077 | The first two rotors for multiple and different gravity levels. [4] |
| | Plant experiment unit (PEU) | 2009 | | 0.027 | The first seed to seed chamber. [4] |
| | Advanced biological research system (ABRS) | 2009 | | 0.053 | The green fluorescent protein imaging system |
| | VEGGIE | 2014 | | 0.160 | The first food production system in space |
| | Advanced Plant Habitat (APH) | 2017 | | 0.171 | The first fully automated plant growth facility |
| | Habitation and Logistics Outpost (HALO) | ~2024 | Module | n.a. | The first module |

Plants and other photosynthetic organisms such as algae are critical components of biogenerative models for their ability to produce food and oxygen, remove carbon dioxide, and help to recycle wastewater. Since there are no cooking or refrigeration facilities available in the ISS[8], bio chambers only produce salad greens as a supplement to the crew's diet[9]. Meanwhile, ECLSS studies show that 40 to 50 $m^2$ (with a minimum of 25 $m^2$) of crop growing area is required to support oxygen production for one person. [2 10] Comparing the current growth area (APH with 0.171 $m^2$) with these requirements shows a wide gap in knowledge and technical capabilities in this field.



Wall-Mounted at Salyut[11]

MidDeck Locker at Shuttle[12]

EXPRESS Rack at ISS[13]

**Figure 1 Plants Platforms Size Comparison**

## B. Food Systems Supplies Analysis

Space food systems have evolved significantly throughout the past years, contributing to the success of space exploration initiatives. While adequate to support spaceflight within LEO, the current food system should continue its evolution following space agencies' move toward extended deep space missions such as Mars[14]. Food packaging strategies have also evolved and modified since the dawn of human spaceflight (Figure 2). Alan Shepard ate bite-sized cubes, freeze-dried powders, and used tubes with semi-liquids during the first US space flight – the Mercury mission. In 1969 during Apollo 10 mission, astronauts used the first "spoon bowl," a plastic container that could be opened to eat the food with a spoon to improve the sense of eating. In July 1969, Neil Armstrong and Buzz Aldrin ate the historical first meal on the moon, which consisted of bacon squares, peaches, sugar cookie cubes, pineapple grapefruit drinks, and coffee. To this day, there are no refrigerators or freezers for food storage in the ISS[8]. All the food is processed and prepackaged in one of the methods shown in Figure 2.

Tube Food
Since 1961


Cube Food
Since 1963


Beverage

Spoon Bowl Food
Since 1969


Intermediate Moisture Food
Since 1985


Thermostabilized Food
Since 1985


Rehydratable Food
Since 1985


Natural Form Food
Since 1985

**Figure 2 Development of Food Packaging in Space Missions** [15]

Today, crewmembers can choose from about 200 different items for their standard menu that can be augmented with some personal choices from commercial off-the-shelf items. Without any dedicated refrigerators or freezers for food storage other than a chiller to cool beverages and condiments, all food items on the ISS are stored at ambient temperature and must remain stable under those conditions. Although the current food system works well for ISS missions, many of the current space menu items do not maintain acceptability and/or nutritive value beyond two years. More extended space missions will require food systems that sustain crew health and nutrition for 3 to 5 years without necessary replenishments. [16]

Obviously, the primary purpose of food is to provide required nutritional support for the crew to perform work activities and fulfill mission goals. Macronutrients have the most prominent portions and are usually measured in grams depending on the daily intake amount. Micronutrients, on the other hand, are measured in milligrams or micrograms. Table 2 shows that macronutrients are carbohydrates, protein, and lipids (fats) and micronutrients are vitamins and minerals. The current food system is designed to prioritize macronutrients in food and support the micronutrients with supplement pills.

**Table 2 Nutrients**

| Nutrients | | | | | |
|---|---|---|---|---|---|
| Macronutrients | | | Micronutrients | | |
| Carbohydrates | Protein | Lipids | Vitamins | Minerals | Phytochemicals |
| Sugar | Essential Amino Acids | Saturated | Water-Soluble Vitamins | Macrominerals | Polyphenols |
| Starch | Non-Essential Amino Acids | Mono-Unsaturated | Fat-Soluble Vitamins | Microminerals | Terpenoids |
| Fiber | | Polyunsaturated | | | Alkaloids |
| | | Trans Fats | | | Phytosterols |
| | | | | | Organosulfur Compounds |

Generally speaking, two food support options for long-duration missions that can fulfill nutritional requirements throughout the whole mission can be categorized as 1) Earth-Dependent Food Resupply Systems; and 2) Earth-Independent Food Supply Systems. Specifics that characterize these two options and their trade-off studies help select a proper approach for a specific mission and therefore develop sufficient habitat and greenhouse design strategies.

### 1. *Earth-Dependent Food Resupply System*

The current Earth-dependent Resupply system ships all the foods monthly from Earth to the ISS. Except for the rehydrator and heater, there is no cooking or preparation equipment. The onboard grown plants are mainly on a small scale and for bioregenerative research purposes. However, occasionally plant consumption offers fresh treats and improves the psychological aspect of the eating through advancements in meal quality. This option can also be used for shorter mission durations, including early lunar surface missions.

Although the ISS does not have a dedicated freezer for food, freezers designated for science sample return are frequently launched on cargo vehicles such as SpaceX Dragon or Northrup Grumman Cygnus spacecraft. Since freezers often are launched empty, they may carry items such as ice cream or other frozen treats for crewmembers' enjoyment.[15]

Studies show that resupplying essential nutrients for astronauts in transit to Mars and long-duration Martian surface missions might not be achievable with the current technologies. The mass requirement for 3000 kcal per crewmember per day is 1.83 kg, and the total mass for a Mars scenario (6 crewmembers, 1095 days) is 12,023 kg[17]. This number is more than 70% of the SpaceX Falcon Heavy payload capacity. Additionally to mass limitations, 5-year shelf life is required for food supplies. Now, just 7 out of 65 thermostabilized foods are expected to be palatable after five years of storage, and therefore the current food system would become unacceptable for the crew before the mission ends [18].

### 2. *Earth-Independent Food Supply System*

This production method supports food resources with maximum in-situ resource utilization and a minimum of resupply. Current proposals portray this system as a greenhouse module processing plants into palatable food.

The first step in these proposals is improving techniques for crop preparation for space and increasing the Crops Readiness Level (CRL is a maturation scale analogous to TRL but for crops and BLSS).[19] For example, short or dwarf growth, high harvest index, high yields, organoleptic acceptance, good nutrient content, and ability to control microbial contaminants are desirable traits for the selection and maturation of CRL for space. Similar to applying TRLs for aerospace hardware, a CRL's approach provides a logical methodology for testing and evaluating space crops. The current scale is focused on the ISS and Mars transit needs. Still, surface settings with larger BLSS crop systems may call for different criteria or factors appropriate for specific settings, such as higher macronutrient content, ability to grow in multispecies plantings, and radiation tolerance. [20]

The second step is acknowledging that even a combination of diverse plant species in a space-based agro-ecosystem does not meet all nutritional requirements. Common characteristic problems of plant-based diets, such as lack of animal-origin vitamins and fat, especially B12 and cholesterols, and unbalanced amino acid content, will happen along with lack of some minerals (e.g., sodium). [21]

## II. Current Knowledge Gaps

Various space agencies are working on identifying knowledge gaps in the space food industry. Chinese and Russian space officials have revealed their plans for lunar stations, and as said, it cannot happen without solving significant obstacles along the way. This paper focuses on NASA's roadmap due to ease of access to more detailed sources.

NASA's Human Research Program (HRP) has developed a web-based Human Research Roadmap (HRR) with the risks-gaps-tasks-deliverables, and strategies. Table 3 shows the HRR's risk ratings and dispositions per design reference mission categories. Currently, the green sections with accepted or optimized categories only cover short missions in LEO, lunar orbit, and the lunar surface, plus up to a year of living in LEO. Other scenarios will require the development of mitigation strategies.

**Table 3 Risk Ratings and Dispositions per Design Reference Mission (DRM) Category**[22]

| DRM Categories | Mission Type and Duration | Operations | | Long-Term Health | |
|---|---|---|---|---|---|
| | | LxC | Risk Disposition * | LxC | Risk Disposition * |
| Low Earth Orbit | Short (<30 days) | 3x1 | Accepted/Optimize | 2x1 | Accepted |
| | Long (30 days-1 year) | 3x1 | Accepted/Optimize | 3x1 | Accepted |
| Lunar Orbital | Short (<30 days) | 3x1 | Accepted/Optimize | 3x1 | Accepted/Optimize |
| | Long (30 days-1 year) | 3x3 | Requires Mitigation | 3x2 | Requires Mitigation |
| Lunar Orbital + Surface | Short (<30 days) | 3x1 | Accepted/Optimize | 3x1 | Accepted/Optimize |
| | Long (30 days-1 year) | 3x3 | Requires Mitigation | 3x2 | Requires Mitigation |
| Mars | Preparatory (<1 year) | 3x4 | Requires Mitigation | 3x4 | Requires Mitigation |
| | Mars Planetary (730-1224 days) | 3x4 | Requires Mitigation | 3x4 | Requires Mitigation |
| Note: LxC is the likelihood and consequence rating. The information above was last approved by the Human System Risk Board in 2/2020. | | | | | |

In HRR's Gaps section under the Food and Nutrition (FN), the roadmap lists 15 gaps from FN-101 to FN-702. Each has a description of the present state of knowledge, the research approach, and the target for closure. Since space architects' responsibility is to ensure and support safety, sustainability, habitability, reliability, crew efficiency, productivity, and comfort in extreme environments, they need to recognize these gaps and design space habitats and bases accordingly. Here are the 12 FN gaps that influence design requirements:

### 1. *FN-102*[23]

"Determine what techniques, technologies, or processes can be used to extend the stability of nutrients in spaceflight food (examples of areas that can be investigated include bulk components for 3D printing or cooking)—formulation, processing, packaging, and storage all impact the nutrition and shelf life of food products. Identification and development of novel food formulations, food matrices, food preservation processes, packaging, and storage solutions would support extended essential nutrients' stability for 5-7 years."

### 2. *FN-103*[24]

"Identify … the best crops for spaceflight (based on their growth, nutrition, acceptability, safety, reliability, yield, resource requirements, etc.), the resource requirements, the hardware infrastructure (may change with gravity and mission profile), and shelf-life requirements of fresh-grown components (e.g., seeds). Identification of optimal crops to grow (may include GMOs), optimal hardware to use, optimal environmental conditions (light, water, growth media, atmosphere/CO2), risk and benefits of different systems."

3. *FN-202*[25]

"Product Palatability -Determine if there are sensory changes due to changes in the food products (prepackaged or fresh-grown): formulation, processing, packaging, and storage impact food products' quality and shelf life. … Evaluate and understand formulation, processing, packaging, and storage that can contribute to quality stability in the food products."

4. *FN-203*[26]

"Prevent menu fatigue by providing optimal variety and strategies to manage limited variety. Consider trade space of prepackaged, fresh, cell-biology and bulk ingredients used for in-situ food creation, meta-analyses of military data and data from other populations, develop a "best practice" standard, and then validate it."

5. *FN-204*[27]

"Evaluate quality metrics (baseline and stability of taste, texture, color, rancidity, hardness, etc.) in prepackaged food and fresh-grown crops. … more work is required to determine the produce candidates and growth methods that produce the best crops for spaceflight."

6. *FN-401*[28]

"Understand and develop strategies for using food as a physiological countermeasure for radiation/oxidative stress, cardiovascular health, bone, SANS, exercise, immune, and MicroHost. … We need to understand how to optimize the space food system to benefit crew health and mission success."

7. *FN-501*[29]

"Understand and develop strategies for using food as a psychological countermeasure. The food system's psychosocial factors (variety, choice, preparation, mealtime and crew interactions, etc.) and nutrients provided (includes thousands of phytochemicals in whole foods) impact mood, cognition, performance, and sleep. … Optimize agriculture as part of meaningful food preparation, cooking, and work research."

8. *FN-601*[30]

"Trade-space modeling. Develop a computerized model that will allow a trade-space analysis for different DRMS to guide optimal food system design per mission parameters and constraints. Making technology trades earlier in the design process can lead us to focus on alternate food system designs."

9. *FN-602*[31]

"Develop mass and volume reduction strategies. Future missions cannot support the mass and volume requirements of the current food system. Meal replacements may reduce the mass and volume of the food system and reduce choice and caloric intake, impacting crew health and performance. The extent to which other potential solutions may also reduce choice and affect nutritional status, health, and performance needs to be determined per defined mission profile to assess the feasibility of reducing mass and volume on exploration missions.

Research Approach:

Evaluation of mass and volume reduction options for prepackaged food (meal-replacement food bars, increased caloric density/fat content, packaging strategies, storage strategies), fresh crop growth, cell-biology-based foods, and in-situ food production/preparation considerations."

10. *FN-603*[32]

"Novel Food Production/Preparation Infrastructure - Develop in-flight and planetary surface new/novel food production/preparation infrastructure; evaluate their impact on dietary intake and nutritional status in an analog and/or flight environment. Based on current processing, packaging, and storage (room temperature), the prepackaged food system will not meet nutrition and acceptability requirements for exploration mission lengths (5 years). Develop food preparation infrastructure such as options for refrigeration, freezing, heating, cooking, fresh food processing (cutting, peeling), novel molecular synthesizing devices (e.g., Star Trek type replicators), composting, 3D printing."

*11. FN-701*[33]

"Validate the selected food system in a ground analog before the flight. There is no information on the impact of exploration of realistic food systems on crew health and performance over extended durations to date."

*12. FN-702*[34]

"Validate the selected food system in the flight environment before the Mars mission. Implement the finalized version of the selected food system with all its components in a flight demo, followed by full deployment."

In this research, the presented gaps are sorted into five categories, as shown in Figure 3. Selecting the best crops (103) and using more stable packaging (102) improves palatability (202), variety (203), and quality (204) of the food and nutrition. This impacts the crew's health physiologically(401) and psychologically(501). The first orbital module can be launched shortly after trade studies (601), mass reduction (602), and validation of the systems and infrastructures (701) are complete. Then proposed surface infrastructures (603) will be revalidated in preparation for the first surface module landing.

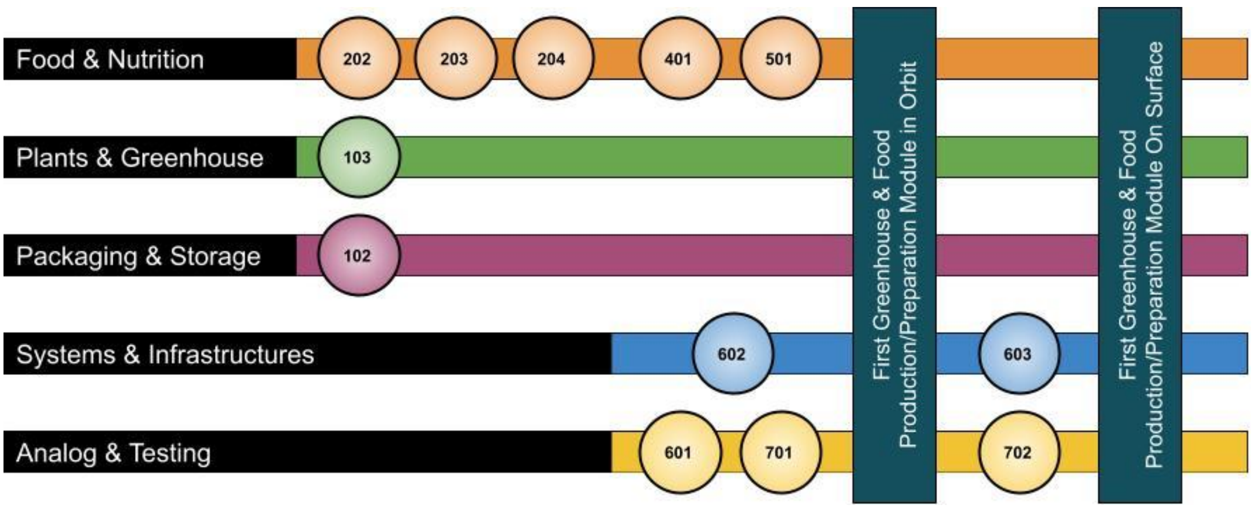



**Figure 3 NASA's Knowledge Gaps Categories and Priorities**

The primary purpose of identifying and categorizing space food systems knowledge gaps is to define design strategies for optimizing the integration of plant growth and food processing systems into habitat and base architectures without compromising habitability and their environmental and structural integrity.

Design Strategies

Surface habitat and base architectures have to address existing and potential design strategy gaps, including the need to specify the scale and level of support for identified knowledge gaps. Figure 4 shows that some mentioned knowledge gaps are the essential requirements and should be resolved even for earth-dependent food systems and smaller-scale missions.

For example, palatability (202), variety (203), and quality (204) that affect physiological (401) and psychological (501) aspects of crew health and packaging (102) should be developed at the early stages of the development of surface architectures. On the other hand, comparing the scale of the gaps in Figure 4 to their priority in Figure 3 shows that allocating the best plant list (103) is only meaningful at a modular scale – the same applies to systems, infrastructure, and testing analogs.

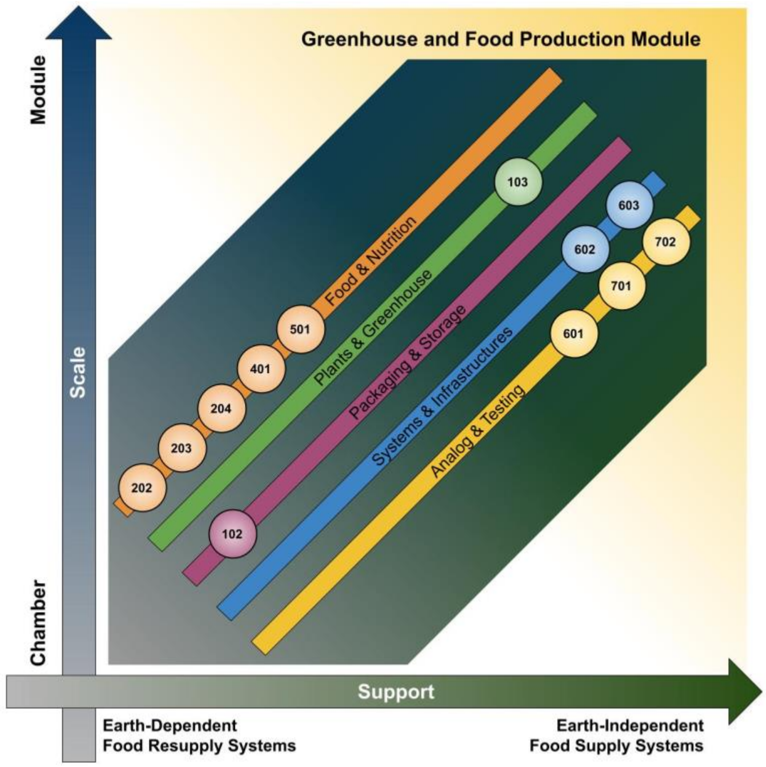



**Figure 4 NASA's HRP Knowledge Gap Scale and Support**

## III. Proposed Pioneer Approaches

NASA's Deep Space Food Challenge is the most creative and recent event dedicated to space food challenges and strategies. The winners of phase 1 were announced in October 2021 for their novel proposals for food production/preparation technologies or systems. The aim was to develop solutions built upon minimal inputs while maximizing safe, nutritious, and palatable food outputs for long-duration space missions. The 18 winning teams or companies used technologies in 4 different categories:

### A. Bio Cultured Cells

Cultured proteins, fat or carbohydrate, are made using stem cells collected from living animals. The cells brought from the Earth are immersed in a nutrient bath. They multiply and eventually form strips of tissue that can be processed into products that have a consistency similar to that of canned meat, finely ground hamburgers, and chicken nuggets[35].

This technology needs biological laboratory tools and equipment such as a cell culture hood, incubator, water bath, centrifuge, sterilizer, refrigerator, and freezer.

### B. Protein-Rich Superfoods

Sustainable future foods like microalgae (spirulina and chlorella), macroalgae (sugar kelp and mussels), insect larvae (the black soldier fly, the house fly, and the mealworm beetle) can be produced at large scales to provide highly nutritious meals [36]. In anticipation of public reluctance to eat these foods, the researchers propose that they can be used as ingredients in popular foods rather than eaten whole like energy bars, pasta, and burgers.

This lab-based technology relies on the greenhouse's green waste to feed the insects.

### C. Plant Growth

Our previous studies show that the cultural diversity of the crew demands an expanded plant list to prevent menu fatigue [37]. Plus, evidence of biophilia indicates that the greenhouse supports the crew's psychological health by acting as an indoor garden during the missions. To achieve this human-centered design without exceeding launching mass capacity, the greenhouse systems should use the higher CRL plants [38 39] and apply optimized shapes to maximize the plant cultivation area[40]. We also have proposed that the greenhouse system on a larger scale will not work without post-harvesting, food production, food preparation, and storage sytems[41].

### D. 3D Printed Food

The novel technology of 3D printing food has the potential to benefit human space exploration by allowing meal customization reflecting the astronauts' needs and eating preferences. Benefits may include precise delivery of nutrients in response to biometrics data, adjustments in nutrient and caloric density to allow variation in the meal size consumed, and alterations in texture and flavor to meet the sensory preference of each astronaut. Additionally, 3D printing may provide attractive presentations to increase appetite[42].

Ready-to-eat freeze-dried ingredients (starch, gelatin), food components (hummus, almond butter, tofu, mozzarella, brussels sprouts), and food matrices (vegetable quiche, spaghetti with meat sauce, and chicken pineapple salad) were successfully 3D printed. Chemical and physical approaches were explored to introduce texture complexity[42].

Other studies showed that the texture of a crunchy vegetable could be perceived within the 0.094" -0.132" particle size range, which fits in the nozzle extruder of a 3D printer. Based on these findings, 'Hummus Crunch,' 'Asian Salad Bar,' 'Cheese Sandwich,' and 'Space Jello' were prepared as final prototypes providing precise nutrition, meal customization, and individualized palatability[42].

The primary constraint of the 3D printing food system is the filaments supply because bringing the ingredients from Earth would be massive and costly. Therefore, using in-situ resources and producing them in the place is the only long-term solution. The macronutrients (carbohydrates, protein, and lipids) can be printed using the previously mentioned biology laboratory products like cultured cells, future foods, and greenhouse products. Plus, a chemical laboratory can produce minerals, vitamins, pigments, and flavors to enhance the taste of 3D-printed food.

## IV. Discussion and Conclusions

Reaching an earth-independent food system would not be possible without having a greenhouse, biology, and chemistry laboratory in the food production/preparation module. Having multiple sources of protein, replacing the time and energy-consuming processes of producing vegetable fat with lab-grown lipids, creating pigments and flavors to increase the palatability of the food, and above all, reducing the launch mass through in-situ production are the goals to achieve the functional and successful design of not only a food production/preparation module but the whole infrastructure of a base or settlement. Figure 5 presents considerations for allocations of nutrients production, and associated food and nutrition gaps are addressed within multi-phased scalable architectures.

By reverse-engineering this concept, the timeline and milestones unwrap. Figure 6 shows that the systems should have been validated before the flight to have the first greenhouse and food production/preparation module in orbit (701). To reach this TRL, trade studies should analyze (601) and pick the optimum mass reduced model (602). All the knowledge gaps related to food, nutrients, plants, packaging, and storage should have been solved by this point. Then, the only barrier for the first surface module is testing in orbit. With this strategy, all the knowledge gaps can be covered, and we will get one step closer to pursuing long-duration missions.

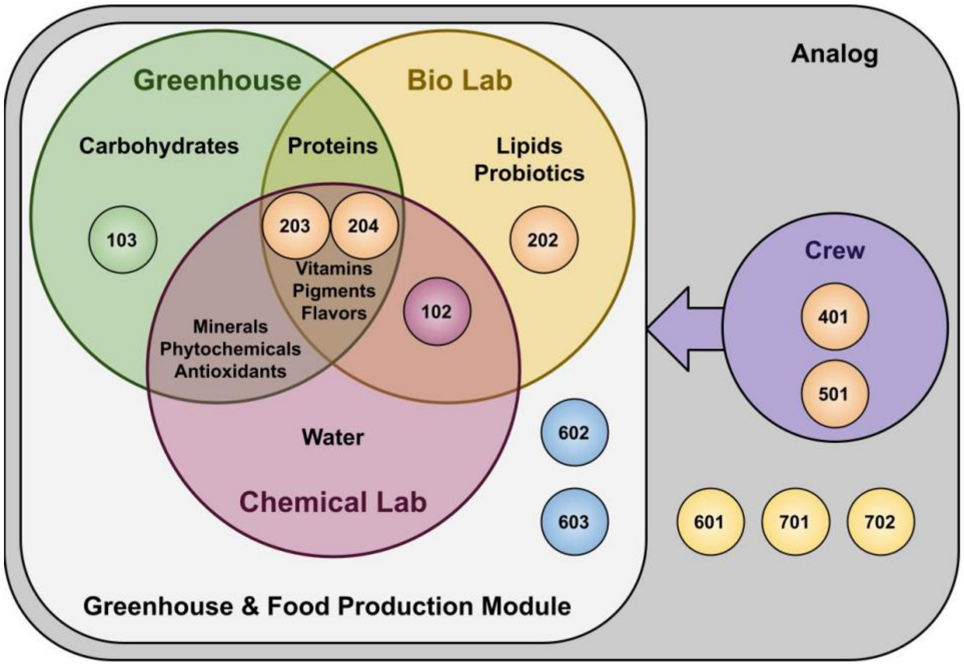



**Figure 5 Proposed Food Production/Preparation Module**

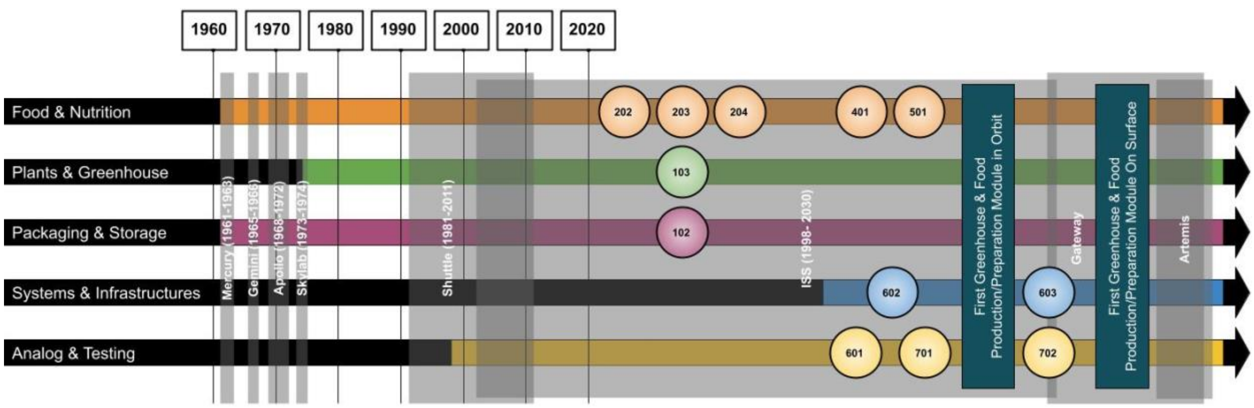



**Figure 6 Timeline and Milestones of Greenhouse and Food production/Preparation Module**

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## Appendix A

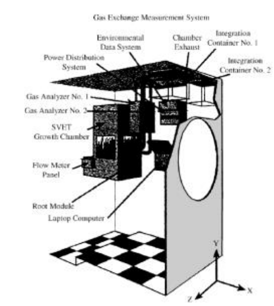
**Oasis Series**[5]

**Malachite**[5]


**Svetoblok**[11]

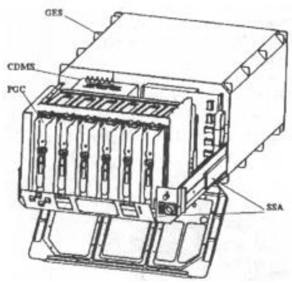
**SVET**[11]

**Astroculture (ASC)**[43]




**SVET-GEMS**[44]

**Plant Generic Bioprocessing Apparatus (PGBA)**[11]



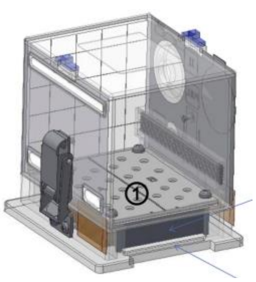

**Plant Growth Facility (PGF)**[11]

**Advanced Astroculture (ADVASC)**[45]

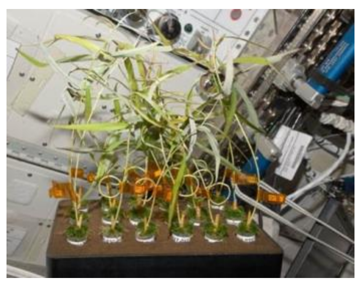
**Biomass production system (BPS)**[46]

**Lada**[47]

**European modular cultivation system (EMCS)**[48]



**Plant experiment unit (PEU)**[49]



**Advanced biological research system (ABRS)** [50]

**VEGGIE**[51]

**Advanced Plant Habitat (APH)**[52]

**Habitation and Logistics Outpost (HALO)**[53]