Food Production Module Systems for Extraterrestrial Planetary Surfaces

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In the previously proposed mission architecture scenarios for partial gravity conditions on the moon and Mars, food would have been brought from Earth, and a greenhouse produces fresh leafy green plants from a short list to supplement the crew's meals. However, recent studies propose a long list of plants that, in addition to providing psychological support for the crew, offers a variety of plants for fresh meals during long-duration missions. In this case, a greenhouse system allows the seed to grow into a product, and a food processing system that supports meal preparation from the products. In this paper, first, a greenhouse system, its subsystems, and components are explained. Then, a post-harvesting system and its elements are described. Considering a greenhouse to become a closed-loop system that provides a major food supply for the crew, all food production and processing systems within the structure are proposed. It is assumed that the effect of reduced gravity on water impact characteristics will not require significant system adjustments. The referred in this paper food production module architecture will consist of an inflatable module attached to a hard-shell structure. Therefore, all systems and components allocations are proposed for post-landing deployment operations.

Nomenclature

AMS	=	Atmospheric Management System
BLSS	=	Bioregenerative life support system
CELSS	=	Closed Environmental Life Support System
DLI	=	Daily Light Integral
EC	=	Electrical Conductivity
GFM	=	Greenhouse & Food Module
HM	=	Habitat Module
LSM	=	Logistic/Service Module
NFT	=	Nutrient Film Technique
PAR	=	Photosynthetic Active Radiation

I. Introduction

A greenhouse is an essential component of the moon and Mars's mission infrastructure, as plant-based closed-loop life support systems offer self-sufficiency. For LEO operations and short-term lunar surface missions, some studies show that open-loop systems resupply significantly reduced the total launch mass than recycling systems [1]. However, this paper discusses food production that aims to provide 100% support for the crew. Sustaining long-term missions on the moon will be restrictive and subject to launch vehicles' availability at launch window, landing systems readiness, and base locations. Therefore, resupply is prohibitive for long-duration surface missions as it increases the launch mass and, consequently, the launch costs.

The risk to the crews' lives is also increased by relying on frequent resupply from Earth. Greenhouses, on the other hand, can be used to produce edible biomass and as air and water regeneration processors as physical human factors, and a greenhouse module could also support the crew's psychological needs by providing a green region that resembles

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life on Earth. Human health has physical and psychological aspects that are influenced by passive and active factors. Dynamic elements such as diet and meal diversity interact directly with human physical and mental health and are considered active factors. Passive environmental aspects, such as aromas and color enrichment, are passive factors that affect cognitive conditioning [2].

II. Assumptions

A functional greenhouse has to integrate various systems that have to work together in a perfect way. To achieve that, we need to investigate and define what resources are required to support a greenhouse module. Our previous studies show that 494 m2 of plant cultivation area is needed to support a crew of four with 3000 Kcal per day [3]. It should be mentioned that this estimation is based on Non-Genetically Modified plant features and could be changed by engineering more dwarf plants. Since launching a hard-shell module with such a volume is impractical, it is assumed that a greenhouse module will have an attached inflatable section(s).

This study focused on operations of the Greenhouse and Food processing Module (GFM), which is one of the elements of the three-module system along with a Logistic/Service Module (LSM) and a Habitat Module (HM). Definition of interrelated and interdependent systems drive the selection of operational sequences and system allocations within the GFM. The LSM systems are derived from NASA's Big Idea Challenge 2019 competition [4]which assumes that the packaged inflatable greenhouse will be robotically transported from the landing zone to the habitation zone and connects to the habitat via the attachment interface. The airlock connection will have interfaces for water, power, command and data, and filtered air. Once connected to the habitat, the greenhouse will be inflated via remote commands. Additional resources for the GFM are provided from processing crew living by-products such as waste production and respiration. Therefore, the Closed Environmental Life Support System (CELSS) can be upgraded into a Bioregenerative Life Support System (BLSS). The GFM connects to the LSM and HM through the interface to access the resources.

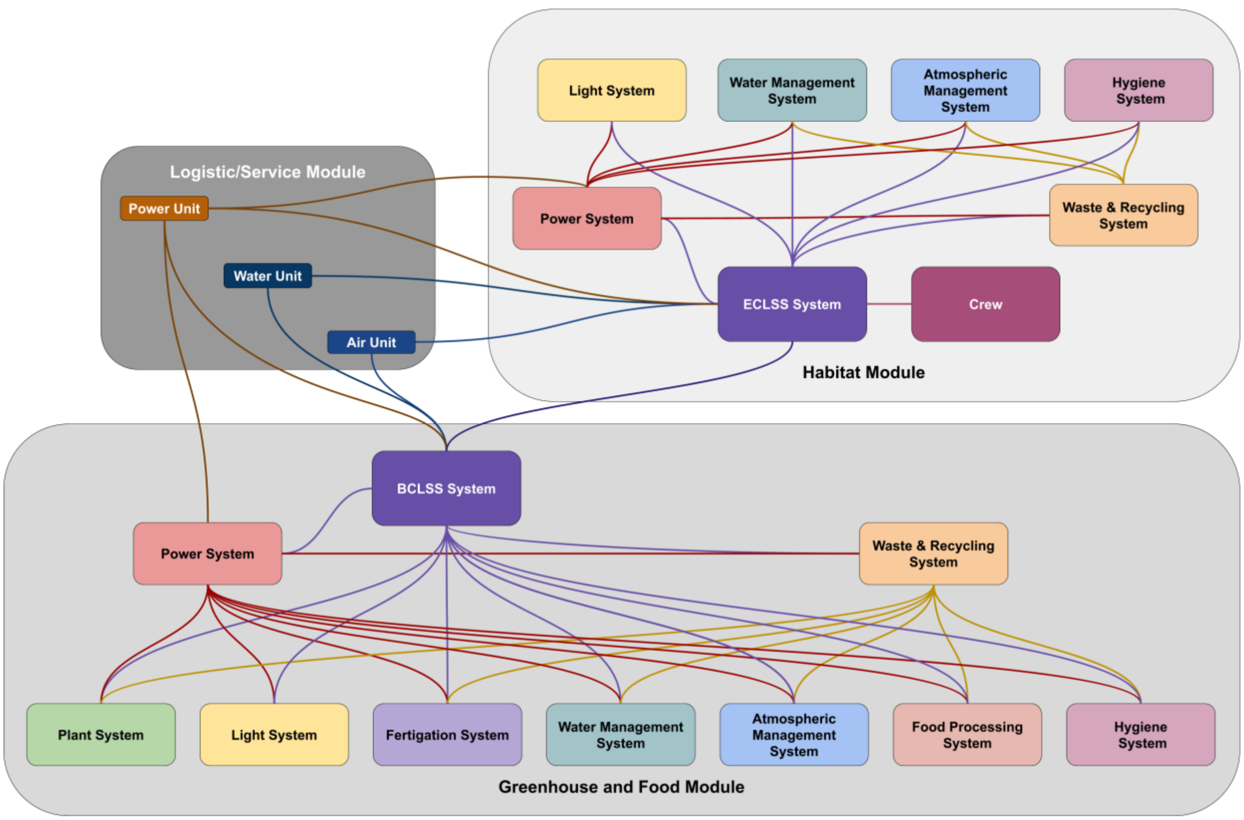

Figure 1 Systems Integration Diagram

III. Greenhouse Systems

A. Plant System

1. Plant lists

In NASA's report "Nutritional and Cultural Aspects of Plant Species Selection for a Controlled Ecological Life Support System" [5], three plant selection scenarios for a Mars mission are defined: Minimum, Modest and Generous.

The "minimum" version represents the essential dietary requirements with less than ten plants included. Nutritious plants with a higher harvest index (ratio of edible portion to total biomass) are on this list. The number of species has been dictated strictly by nutritional needs without regard to palatability and diversity.

The "modest" list has been derived from a vegetarian diet with 15 plants on the list. Simplicity is the primary driving factor, but the ability to create pleasing dishes was also considered.

Finally, the "generous" scenario pays attention to all the previous factors and better efficiency of nutrient recycling by the Controlled Ecological Life-Support Systems (CELSS) than the other two lists. This list has more than 35 plants making for the most dietary variety.

Table 1 of the Appendix compares the diversity of plant lists provided by different countries. It categorizes plants into eight types: Fruit, Grain, Herb and Spices, Leaf and Flower, Leguminous, Root and Tuber, Salad, and Sugar. The number of plants in each category reflects cultural preferences for flavor profiles in meals. Unexpectedly, the number of shared plants among the lists is not significant. For example, in the minimum list that provides for the crew's basic needs, only peas, potato, and wheat are shared, 3 out of 13. This ratio increases in the generous list to 17 out of 36, or just above 47%.

As we proposed in our previous study [6], the industrial mass production of food, for example, might show impressive numbers in theory but ignores other essential human needs like biophilia. Typically, an industrial strategy uses a small plant list to achieve its caloric goals. One might think that increasing the number of the same plants might help the situation. However, changing the plant list alone does not address human needs unless accompanied by the module's responsive design, especially considering cultural and social differences.

2. Cultivation Method

Minimizing launch and landing mass, maintenance operations and requirements, level of automation as well as technology maturity defined the final selection of a cultivation method to be used in the GFM [7]. From all of the traditional hydroponic systems seen in Figure 2, the Nutrient Film Technique (NFT) and aeroponics systems, which use nutrient solutions in a bath and aerosols, respectively, were investigated in the past decades and have proven successful to sustain crop production for relatively long periods [8]9, [9] [10].

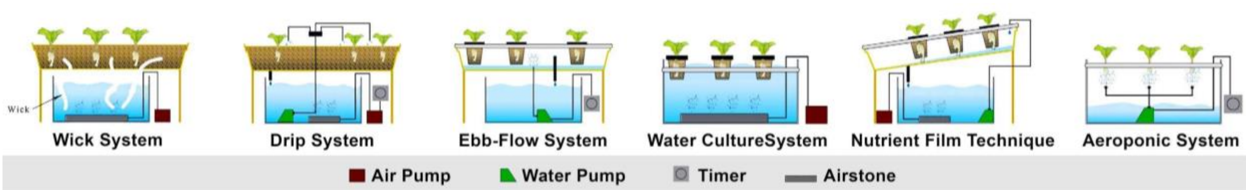

Figure 2 Cultivation Methods [11]

Additional design consideration is the potential for upgrading and replacing the systems as needed and according to plants' needs. Rotation of plants or replacement with different plants may be required as the mission progresses and expands.

3. Crop Cycle

Plants have different needs in each phase of their life cycle, requiring flexibility in plant pots and adaptability to environmental conditions. Their water and nutrient intake change dramatically through stages, while the light intake and space needed for roots and leaves increase through the process of maturation[12]. This growth affects the greenhouse's system design in component scale—the location and size of the pots in the greenhouse change through each phase.

One complete life cycle of plants is shown in Figure 3. It starts from the juvenile phase, and after the adolescent phase, it reaches the final mature stage. Some plants bypass the formation of seeds to generate new plants by vegetative propagation. For example, potatoes can be divided into pieces, and each piece can germinate a new plant (fruiting to germination). A mature strawberry plant needs to reach its runners to the ground to start germinating (maturing to germination).

Each stage of the crop cycle is associated with a certain level of need in resources. That affects module operations and, therefore, design requirements. Four primary resources that need special design consideration are water, fertilizer, light conditions, and adequate space/volume.

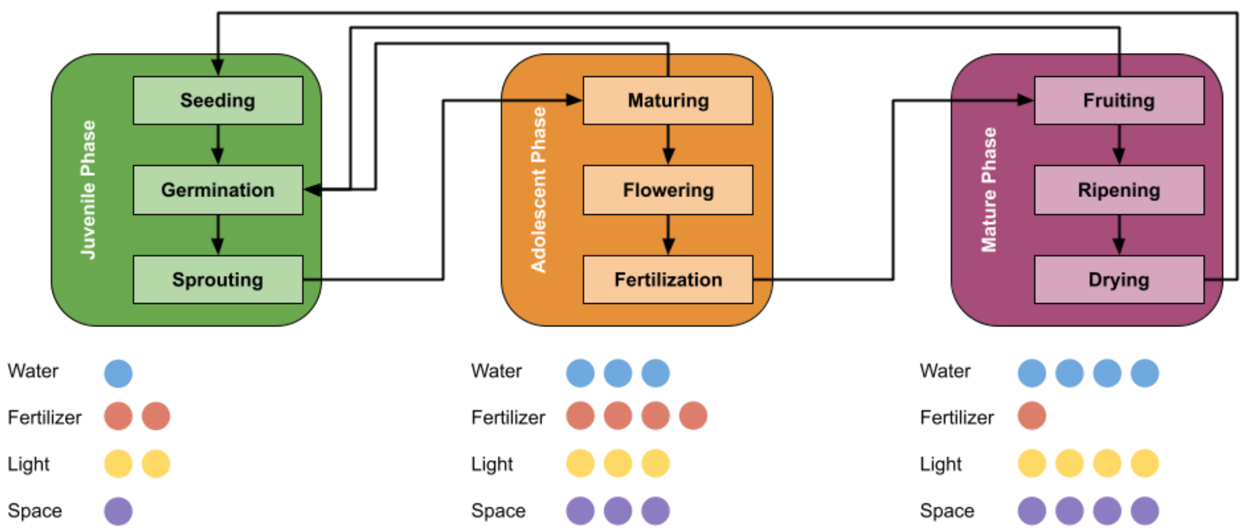

Figure 3 Crop Cycle and Crop Needs

B. Water System

The water system is the heart of the greenhouse requires special consideration. First, to prevent contamination of the whole system in the event of a hazard, the water for the greenhouse needs to be tested for any abnormality, which requires a reservoir tank. Afterward, the water continues to the water tank and pumps into different outputs with adequate pressure (Figure 4). Plants need cycles of water flow at controlled rates. In early phases, they need lower rates, and the larger the plant becomes, the higher the rate should be to prevent water and nutrient deficiencies [12]. Although more experimental data is needed to fully understand how fluid dynamics will be affected by partial gravity conditions, the current research considers the relatively low effect of gravity on water impact characteristics. However, additional means (e.g., pumps and piping design and arrangements) for consistent water distribution may be required. Water system regular maintenance operations will be needed ideally with a high level of automation, e.g., for filter replacements [13].

Water also goes to the hygiene system for the crew's usage in the post-harvesting process, the lab, and the bathroom. The water is also distributed into the air-cooling system to mist and fog the environment. The air revitalization system treats the water using electrolysis to produce O_2 for plants and crew use. It also produces O_3 to sanitize the air and water systems. Simultaneously, a fertigation system controls the water's nutrients and provides chemicals for attaining the desired concentrations. Returning pipes will pour used water into the water recycling system. The final destination of the water before completing the entire cycle is the water recycling system.

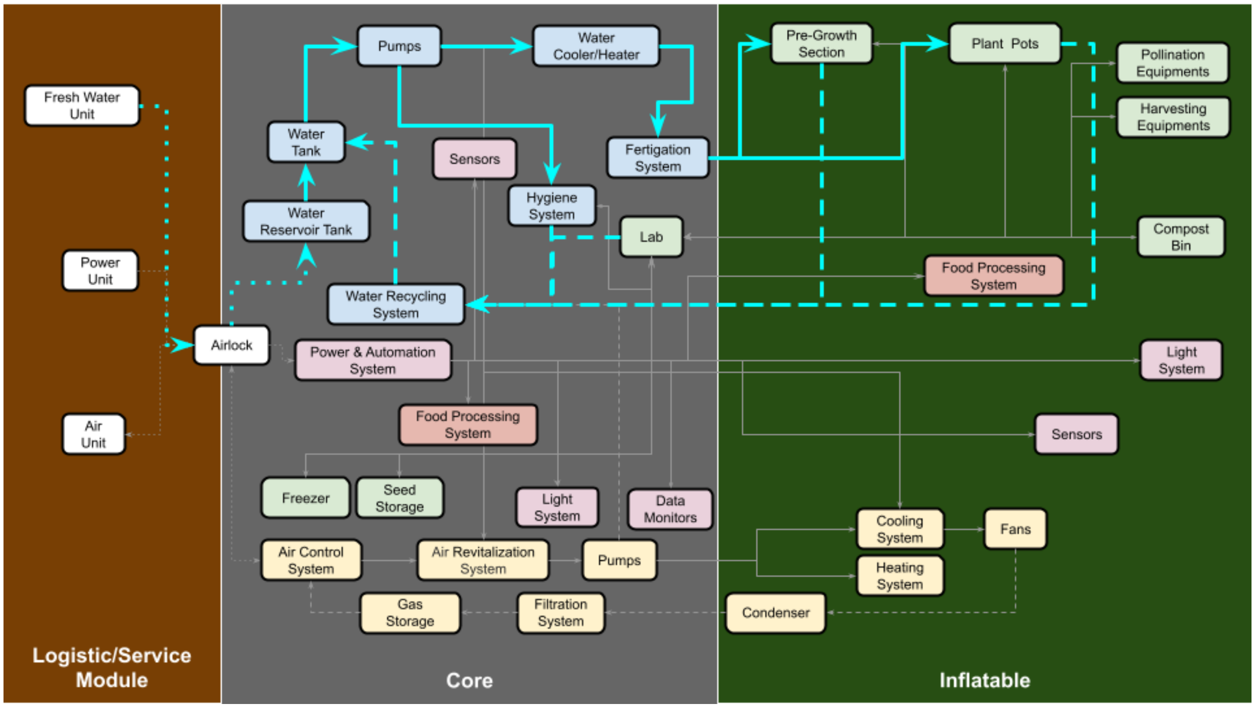

Figure 4 Greenhouse Systems Water Circulation Diagram (the continuous lines are clean water, dashed are gray and black water, and the dotted lines are water supply from LSM module)

C. Fertigation System

As soon as the fertilizer dissolves in the water, it separates into positive and negative ions and produces heat. The more fertilizer added to water, the lower the pH becomes and the higher the electrical conductivity is. Some essential micronutrients (like iron, copper, zinc, manganese), and macronutrients (like phosphorus), become unavailable at the higher pH, and plants may start developing deficiency symptoms [14]. Since many micronutrients cannot be redistributed within plants, symptoms can appear if pH is not within the optimal range.

D. Atmospheric Management System

The Atmospheric Management System (AMS) supplies oxygen, removes carbon dioxide from the atmosphere, and prevents the accumulation of gases like ammonia and acetone, which humans and plants emit in small quantities. Vaporous chemicals from lab experiments are a potential hazard if they mix with other air supply elements. Air revitalization includes oxygen generation and recovery, removal of carbon dioxide, and control of trace contaminants and particulates (like dust and aerosols). Also, the AMS regulates pressure, temperature, and humidity through ventilation and airflow. Pumps push the air into the cooling and heating system, and horizontal and vertical fans circulate the air inside the module.

E. Waste and Recycling System

A greenhouse system needs to manage three types of waste [15]: Blackwater, Greywater, and Greenwaste. Blackwater denotes wastewater from toilets, which contains pathogens from feces and urine, and requires further processing. Greywater results from washing food, clothing, dishes, as well as from showering or bathing. As greywater contains fewer pathogens than blackwater, it is safer to recycle for non-potable uses like toilet flushing. Greenwaste contains raw organic materials such as crop residues and food garbage mixed with water. A mass of rotted organic matter made from greenwaste is called compost.

The waste and recycling system handles these different types of waste. It consists of crop transpiration water being condensed from the GFM interior atmosphere providing crew service water and further processed into potable water. The crew then utilizes this water for hygiene, washing, after processing for potable water, and ultimately yielding a crew wastewater stream. While maintaining the compost's proper moisture content, this wastewater is fed into the composter, and the resulting water vapor generated in its interior atmosphere being extracted and condensed, yielding crop hydroponic makeup water[16]. The composter condensate water is returned to the GFM, and the cycle is begun again. To supply a simulated crew wastewater stream to the composter, minus the urine/feces, wastewater components, soaps, liquid galley waste, etc., will be added with recycled GFM condensate water. Initially, bottled carbon dioxide (CO2) is utilized by being injected into the GFM system to support crop production, with the composter later replacing the bottled gas for the source of CO_2 [16].

F. Light System

Phototropism (the directional bending of plant organs in response to light conditions) and gravitropism (the directional bending of plant organs in response to gravity conditions) appear to serve important adaptive roles by providing plant organs the ability to seek out and grow towards the light to promote photosynthetic efficiency. As long as a seedling is growing in the darkness, gravitropism is the dominating response guiding growth orientation. After a seedling reaches the surface and is exposed to light, numerous photomorphogenic changes occur. After the primary shoot and root are properly orientated and secondary organs such as lateral branches start to grow, light and gravity continue to control the directional growth of different parts of a plant. For a plant to achieve maximum interception of light and gas exchange for photosynthesis, the lateral organs grow out from the main vertical stem at various angles. The angle of growth of the different organs is controlled, at least in part, by the Gravitational Set-point Angle (GSA) resulting from gravitropism and subject to light modulation, probably by the action of phytochrome [17].

A Greenhouse requires electrical light sources to produce light with appropriate wavelengths, termed Photosynthetic Active Radiation (PAR). It is the light of wavelengths 400-700 nm that is the portion of the light spectrum utilized by plants for photosynthesis. The color of the light affects plant growth in different ways. Blue light is necessary for vegetative growth in the juvenile phase, while red light is needed to promote flowering in adolescents and fruit production in the maturing phase [18].

PAR is quantified by the Daily Light Integral (DLI), which describes the number of photosynthetically active photons delivered to a specific area over 24 hours. This variable is valid to describe the light environment of plants. Plants need a different PAR range in each phase of their lifecycle. In high-PAR high-light, they grow less of their biomass in leaves and stems and more in roots [19].

The LED lamps provide the desired spectrum for the plants and have the option of color selection for different modes of the greenhouse. For example, in the plant lighting time, it should be purple, and in the use of the crew, it should turn into white.

G. Power and BLSS Systems

Almost all greenhouse systems, subsystems, and parts use the power that needs to be controlled and monitored with sensors. The power unit is assumed to use nuclear energy and is the primary source of electricity. Reducing the greenhouse chores that need to be done manually will free up the crew to focus on other essential areas. Also, the accuracy of greenhouse systems helps the data-driven decisions to be more precise. Automation will increase quality and yield. For example, the biofeedback system allows light levels to control based on the plants' physiological performance.

IV. Food Production System

A. Harvesting Process

Harvesting is the process of collecting a ripe crop from the greenhouse and is the most labor-intensive activity. It requires the most complicated machinery and robots to mimic gentle gripping and pulling/removing by hand. The completion of harvesting indicates the end of the growing season or the growing cycle for a particular crop [20]. There are two types of harvesting. One Long Harvest for fruiting crops such as tomatoes, cucumbers, peppers, and eggplant that are raised for a long season of up to a year, and the same plants are harvested many times for an overall high yield. Plus, Multiple Quick Harvests for lettuce, greens, herbs, and microgreens are significantly quicker-cycle crops. It provides a high overall yield by being planted and harvested many times throughout a season.

B. Post-Harvesting Process

Post-harvesting is the stage immediately following the harvest. It starts by separating the edible quality food from the Greenwaste, including the crop's medium and remainder. Figure 5 shows that the food processing system begins from the edible produce and goes through various processing to turn into a dish [21]. Simultaneously, the waste & recycling system composts and extracts nutrients from green waste and returns it into the cycle.

C. Food Processing System

1. Primary Process

There are various definitions of post-harvesting processes [21][22][23][24][25], but in this paper, primary food processing is the process that transforms agricultural products, such as raw wheat and kernels, into safe food ingredients. This process does not change the product's physical form, and they are still not consumable. This method covers drying, threshing, winnowing, milling grain, shelling nuts. Contamination and spoilage problems in primary food processing can lead to significant health threats. Therefore, drying has a vital role since it reduces food's moisture content to where molds and other microbes fail to grow. It is essential to protect the dried product from both water and water vapor in high humidity. Refrigeration also extends the storage life of perishable foods. Products from primary processes make up the major part of our diet as they are either consumed raw or used as ingredients in secondary and tertiary processes. Failures in primary processing might cause widespread health problems.

This process happens outside of the main greenhouse area with types of machinery or countertops in today's greenhouses. Since the maximum greenwaste produce in this stage, it has to be located close to the recycling & waste management system.

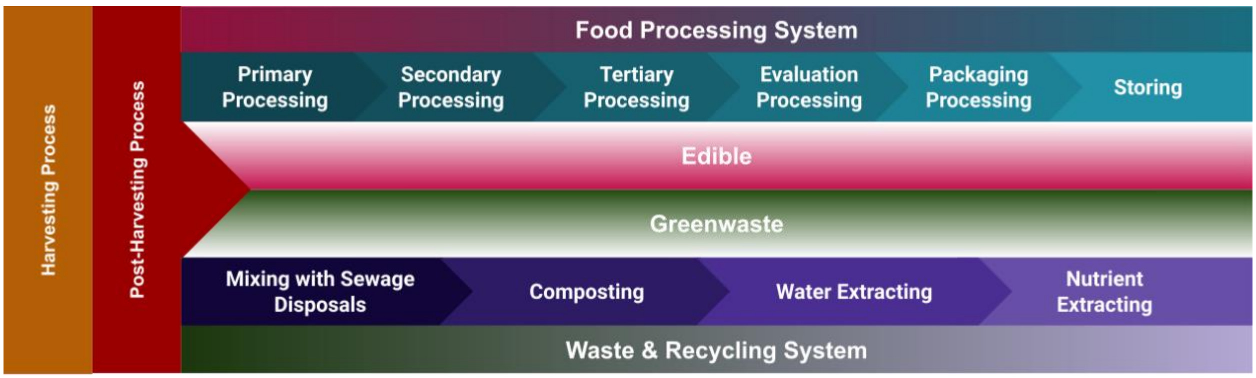

Figure 5 Post-Harvesting Process Diagram

2. Secondary Processing

Secondary food processing is a method to turn primary products into food by changing their physical form, like the everyday process of creating food from ready-to-use ingredients. Cutting, Mixing, cooking, frying, molding, baking, and fermenting are traditional forms of secondary food processing. On Earth, this step happens in the industrial or home kitchens. For GFM, we propose a hygiene kitchen lab. It would have a working area (countertops or an area with large equipment such as a fridge and oven) and multiple fridges and freezers for storage. This is the stage that requires attention to food characteristics. For instance, the flavor is a combination of aroma and taste. The ability to smell food aromas is impaired in partial gravity conditions due to the lack of normal air convection. Therefore, other food characteristics should be emphasized. Flavor enhancers like condiments can improve the taste, and colors, shapes, consistency, and textures of the food can alter without affecting storage requirements [26].

3. Tertiary Process

Tertiary food processing is the production of Ready-To-Eat or Heat-And-Serve pouched, boxed, canned, or frozen meals. In this process, food may be served after reconstituting or reheating. This section uses the same facilities as the secondary process, and it can happen at the same place or in the habitat's kitchen.

4. Evaluation Process

The handling, storage, and preservation of food often involve changes in nutritive value, most of which are undesirable. The freezing process (pre-freezing treatments, freezing, frozen storage, and thawing), if properly conducted, it is generally regarded as the best method of long-term food preservation when judged based on retention of sensory attributes and nutrients. However, the freezing process is not perfect, as is apparent from the fact that substantial amounts of the more labile nutrients can be lost. Vitamin losses during freezing preservation vary greatly depending on the food, the package, and processing and storage conditions. Losses of nutrients can result from physical separation (e.g., peeling and trimming during the pre-freezing period, exudate loss during thawing), leaching (especially during blanching), or chemical degradation. These losses' seriousness depends on the nutrient (whether it is abundant or meager in the average diet) and on the particular food item (whether it generally supplies a major or a minor amount of the nutrient in question) [27].

5. Packaging Process

Storage is the holding of foods until consumption. Staple foods such as cereal grains may be stored for several years. Semi-perishable foods such as fresh fruits, most tubers, and oil can be stored successfully for periods of one or two weeks to many months if handled correctly. There is a need to provide more storage facilities, particularly for durables such as cereals and oilseeds.

D. Waste & Recycling System

Greenwaste and Graywater produce since the cultivation begins, and it increases dramatically after harvesting. In the food system's primary and secondary processes, the greenwaste is at the peak, but even at the end of the evaluation process, there might be greenwaste caused by mispackaging or storage failure. Therefore, at any stage, sinks and countertops are connected to the waste & recycling system.

Later, Blackwater is added to the system to assist composting by supporting bacteria and pathogens (even though it has particles and contaminants, they are not considered dangerous).

Despite composting bin needs for moisture, the excessive water needs to be extracted, disinfected, and back to the water system. On the other hand, the time-consuming composting process would return the nutrient to the CELSS after a careful procedure.

V. Conclusion

The greenhouse system's requirements and arrangements are dependent on the presence of gravity to function. They will require adjustments when partial gravity on fluid dynamics in the systems and plants will be fully understood. This research aimed to identify systems, elements, and processes necessary for sustainable food and nutrition support for the crew for long-term surface missions. Therefore, a greenhouse design must be a multifunctional pressurized structure requiring sufficient volume and real estate for fine selection and amount of produce, support and processing systems, functional zoning, and circulation. A greenhouse as a food supplier of the crew is not feasible unless it provides all these functions in Figure 6 in full. In addition, a greenhouse with food production capacity will require large volume and real estate accommodations, special atmospheric conditions (e.g. similar to greenhouses on Earth), maintenance procedures that comply with closed environment safety requirements, and contingency plans for systems malfunctioning.

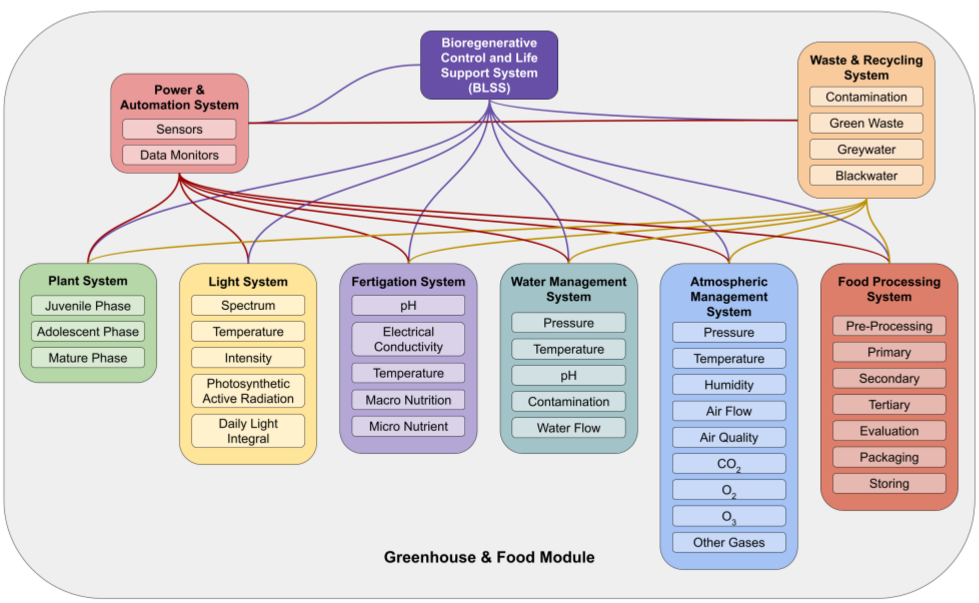

Figure 6 Greenhouse & Food Module Design Factors

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Appendix

Table 1 Various Plant Lists[6]

Russian Academy of Sciences [28]	**NASA** [5]	**ESA/Canada** [29]	**University of Utah** [30]	**NASA** [31]	**Institute for Environmental Sciences in Japan** [32]	**ESA/Canada** [29]	**NASA** [5]	**University of Utah** [30]
Beets	Beans	Beans	Broccoli	Beets	Beans	Alfalfa	Banana	Beans
Carrots	Broccoli	Beets	Canola	Broccoli	Cabbages	Beans	Barley	Beets
Cucumber	Corn	Broccoli	Carrots	Corn	Carrots	Beets	Beans	Broccoli
Dill	Kale	Cabbages	Chilies	Cucumber	Cucumber	Broccoli	Beets	Cabbages
Earth Almond	Mustard Greens	Carrots	Kale	Kale	Komatsuna	Cabbages	Broccoli	Canola
Kohlrabi	Oats	Cauliflower	Lentil	Lettuce	Lettuce	Carrots	Cabbages	Carrots
Onions	Peanuts	Kale	Lettuce	Mustard Greens	Mitsuba	Cauliflower	Cantaloupe	Chard
Peas	Peas	Lettuce	Onions	Oats	Onions	Chard	Carrots	Chilies
Potato	Potato	Onions	Peas	Onions	Peanuts	Chilies	Cauliflower	Chives
Radishes	Rice	Potato	Peanuts	Peanuts	Peas	Cucumber	Celery	Fennel
Tomato	Soybeans	Rice	Rice	Peas	Peppers	Herbs	Chard	Flax
Wheat	Turnip	Soybeans	Soybeans	Potato	Radishes	Kale	Chives	Garlic
	Wheat	Spinach	Sweet Potato	Rice	Rice	Lettuce	Corn	Ginger
		Sweet Potato	Tomato	Soybeans	Shiso	Mushrooms	Garlic	Kale
		Wheat	Wheat	Spinach	Shungiku	Onions	Grape	Lentil
				Strawberries	Soybeans	Peanuts	Kale	Lettuce
				Sugar Beets	Spinach	Peas	Lettuce	Melons
				Sweet Potato	Sugar Beets	Peppers	Mint	Millets
				Tomato	Tomato	Potato	Oats	Mushrooms
				Wheat	Turnip	Rice	Onions	Oats
						Soybeans	Parsley	Onions
						Spinach	Peanuts	Oregano
						Squash	Peas	Parsley
						Sweet Potato	Peppers	Peanuts
						Tomato	Potato	Peas
						Wheat	Rice	Potato
							Rye	Pumpkin
							Soybeans	Quinoa
							Spinach	Radishes
							Strawberries	Rice
							Sugar Cane	Sage
							Sweet Potato	Sorghum
							Taro	Soybeans
							Tea	Squash
							Tomato	Strawberries
							Wheat	Sunflower
								Sweet Potato
								Thyme
								Tomatillo
								Tomato
								Wheat

Fruit	0	0	0	0	1	0	0	4	3
Grain	1	4	2	3	4	1	2	6	6
Herb & Spices	1	0	0	1	0	4	4	6	9
Leaf & Flower	0	3	5	2	4	3	7	6	6
Leguminous	1	4	2	4	3	4	4	4	6
Root & Tuber	6	2	4	2	3	3	4	5	5
Salad	3	0	2	3	4	4	5	4	5
Sugar	0	0	0	0	1	1	0	1	1
Total	**12**	**13**	**15**	**15**	**20**	**20**	**26**	**36**	**41**