



# **Designing biological autonomy in a space environment**

A literature review on the topic of Controlled Ecological Life Support Systems in Space Architecture

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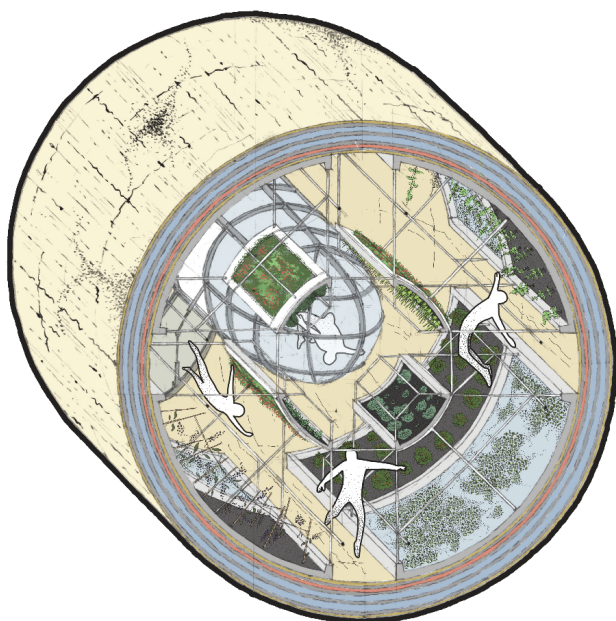
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# Abstract

The paper examines Controlled Ecological Life Support Systems (CELSS) as a core architectural and engineering challenge for long-duration spaceflight missions. It traces the historical evolution of plant growth chambers from early prototypes, i.e., on the Salyut and Mir space stations, to the integrated, crew-oriented systems of the International Space Station (ISS). Furthermore, a synthesis of key research findings on botanical candidates highlights their functional values, such as crop yield, photosynthetic gas exchange, and fertility.

It examines critical cultivation system components, including nutrient delivery, atmospheric control, lighting, and waste management, while emphasising the unique constraints of designing these systems under microgravity. A review of the literature reveals that current knowledge is largely reliant on small-scale and theoretical studies, leaving a significant gap in long-term, empirical data. The paper concludes that while foundational knowledge for a CELSS is strong, the successful development of autonomous habitats will require a shift from experimentation to large-scale integration and validation of a fully closed-loop system (CLS).



*Vision of a future CELSS module (by author)*

## Key words:

- atmospheric control, biological autonomy, bioregenerative life support, closed-loop systems, controlled ecological life support system, human-plant interaction, microgravity, nutrient delivery systems, photosynthesis, space architecture, space agriculture

## Abbreviations:

- ABRS = Advanced Biological Research System
  - APH = Advanced Plant Habitat
  - BLSS = Biological Life Support System
  - BPS = Biomass Production System
  - CCD = Charge-Coupled Device
  - CELSS = Controlled ecological life support system
  - CLS = Controlled life Support
  - DNA = Deoxyribonucleic acid
  - EMCS = European Modular Cultivation System
  - ESA = European Space Agency
  - HEPA filter = High-Efficiency Particulate Air filter
  - ISS = International Space Station
  - LED = Light Emitting Diode
  - MELiSSA = Micro-Ecological Life Support System Alternative
  - MTF = Mobile Test Facility
  - NASA = National Aeronautics and Space Administration
  - NDS = Nutrient Delivery System
  - NFT = Nutrient Film Technique
  - PEU = Plant Experiment Unit
  - PGBA = Plant Generic Bioprocessing Apparatus
  - PGC = Plant Growth Chamber
  - PGF = Plant Growth Facility
  - PGU = Plant Growth Unit
  - UV = Ultraviolet
  - VOC = Volatile Organic Compound
- 
- $\text{Ba(OH)}_2$  = Barium hydroxide
  - $\text{C}_2\text{H}_4$  = Ethylene
  - $\text{CO}_2$  = Carbon dioxide
  - $\text{H}_2\text{O}$  = Water
  - $\text{H}_2\text{O}_2$  = Hydrogen peroxide
  - $\text{KMnO}_4$  = Potassium permanganate
  - $\text{LiOH}$  = Lithium hydroxide
  - $\text{O}_2$  = Oxygen
  - ROS = Reactive oxygen species



# Table of contents

<b>I. Introduction</b> .....	<b>2</b>
<b>II. From prototype to orbit: a brief history summary</b> .....	<b>3</b>
<b>III. Botanical candidates</b> .....	<b>6</b>
III.I. Botanical legacy .....	6
III.I.I. Cultivated in orbit .....	6
III.I.II. Proposed crops for future habitats .....	7
III.II. Functional values .....	12
III.II.I. Harvest cycle .....	12
III.II.II. Crop yield .....	13
III.II.III. Photosynthetic gas exchange .....	15
III.II.IV. Seed viability and reproductive challenges .....	16
<b>IV. Designing cultivation systems beyond earth</b> .....	<b>16</b>
IV.I. Geometries .....	17
IV.II. Cultivation systems .....	18
IV.III. Nutrient delivery systems (NDSs) .....	21
IV.IV. Humidity control .....	23
IV.V. Atmospheric gas composition .....	23
IV.VI. Lighting requirements .....	25
IV.VII. Thermal regulations .....	27
IV.VIII. Waste management .....	27
IV.IX. Area required for a closed loop system (CLS) .....	29
IV.X. Microgravity constraints on design and plant physiology .....	31
<b>V. Human-plant interactions: health and psychology</b> .....	<b>33</b>
<b>VI. Conclusion</b> .....	<b>35</b>
<b>VII. Discussion of limitations</b> .....	<b>35</b>
References .....	36



# I. Introduction

A Closed Ecological Life Support System (CELSS), also referred to as a Bioregenerative Life Support System (BLSS) (De Pascale et al., 2021), is a balanced biotechnical ecological system (Skoog, 1984), that integrates biological processes with physicochemical functions such as gas separation and the condensation and collection of waste vapour (Schwartzkopf et al., 1992). It is widely regarded as the most promising strategy for sustaining human life during long-duration missions (Porterfield et al., 2003), where crops must reliably produce high-quality edible biomass rapidly and efficiently (Romano et al., 2021).

The primary functions encompassing a CELSS include oxygen production, carbon dioxide reduction, contaminant gas control, pressure and humidity regulation, thermal control, waste management, radiation protection, illumination, and food supply (Skoog, 1984; Schubert et al., 1984; Zabel et al., 2016). Beyond the technical roles, a CELSS must also contribute psychological benefits that support crew wellbeing (Zabel et al., 2016). To operate efficiently, the system must remain balanced, maintaining appropriate proportions of CO<sub>2</sub>, O<sub>2</sub>, biomass, water, food, and reserves (Skoog, 1984) (Figure 1 and Figure 2).

A CELSS can house a wide variety of potential crops (Salisbury et al., 1996). Selection criteria include gas exchange efficiency, genetic and physiological stability, resistance to stresses, nutritional value, and the capability to treat waste (Wilks, 1962). Successful cultivation of plants in space requires both a deep understanding of plant growth mechanisms (Hazard et al., 2010) and expertise in controlled environmental agriculture (Poulet et al., 2016). Plants thrive only within specific ranges of temperature and humidity, which are influenced by processes such as evaporation, condensation, freezing, melting, frost formation and sublimation (Rygalov et al., 2004).

The long-term effects of the space environment on plant growth are not yet well known and understood (Wolffl et al., 2014). Nevertheless, plants are expected to play an increasingly central role in CELSS, as the biological component is crucial to sustaining astronauts' lives and health (Hoehn et al., 1998). A key distinction between CELSS and conventional agronomy models is the confined environment in which plants must grow. In such a closed system, even small variations in environmental parameters can have significant effects on the whole system (Poulet et al., 2016). Modern life support systems must therefore meet a unique set of criteria, such as the capacity to support longer missions, larger crews, and reduce reliance on resupply from Earth (Schwartzkopf, 1992).

Research into space-based plant growth chambers began early, as plants were launched on unmanned missions as early as the 1960s, with dozens of experiments carried out on crewed missions, beginning with the launch of Oasis-1 in 1971 (Zabel et al., 2016).

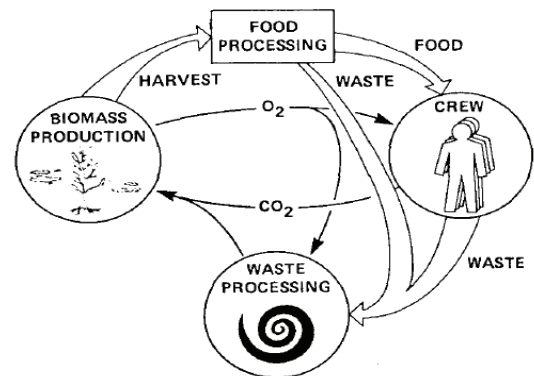


Figure 1 - Material cycle (MacElroy et al., 1984)

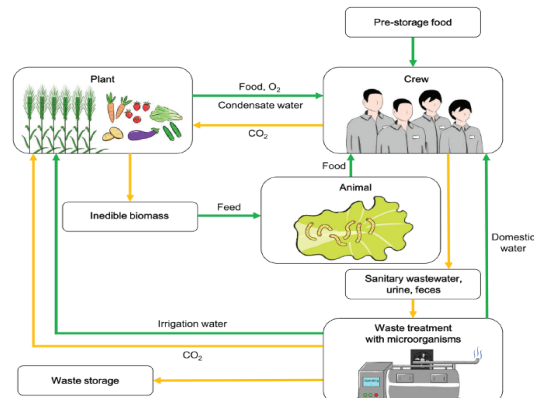


Figure 2 - Material cycle (Liu et al., 2021)



## II. From prototype to orbit: a brief history summary

Growing plants in space has been an ever-achieving goal of spaceflight hardware development since the 1960s, starting with Sputnik 4 (Porterfield et al., 2003). Missions throughout history have differed in the desired goal to accomplish. Early missions focused on simpler and more basic aspects, such as designing an appropriate nutrient delivery system. Whereas further missions have gone into more detail on specific, more complicated systems such as waste management and atmospheric control systems.

The complete history of fully documented plant growth chambers can be classified according to 4 general space missions: Salyut Space Stations, Mir, Space Shuttle, and International Space Station. (Zabel et al., 2016) (Figure 1). The Sputnik 4 plant growth experiment is a mention-worthy exception from the list (Porterfield et al., 2003). It served as the kick-starter to an ongoing exploration, documenting early limitations on plant growth in space (Porterfield et al., 2003).

A special acknowledgement has to be given to Zabel et al. (2016) and Porterfield et al. (2003) for presenting two information-rich and dense

documents about the history of plant growth chambers in a space environment. The presented chapter is, for the most part, a short summary, featuring key takeaways from the 2 aforementioned documents.

### I. Salyut Space Stations

The Oasis series featured 4 different plant cultivation systems (in chronological order): Oasis 1, Oasis 1M, Oasis 1AM, and Oasis 1A. (Zabel et al., 2016). Furthermore, a notable achievement of the series was developing basic knowledge about cultivation in space: a basic nutrient delivery system (Porterfield et al., 2003), illumination and ventilation requirements, and gas exchange (Halstead et al., 1984; Porterfield et al., 2003)

The Vazon series was flown on Soyuz 12 in 1973 (Zabel et al., 2016). The series is well known for its psychological improvement to crew mental health, by growing bulbous plants and tulip plants (Zabel et al., 2016)

Malachite is the first plant growth experiment specifically designed to inspect the psychological benefits of plant and human

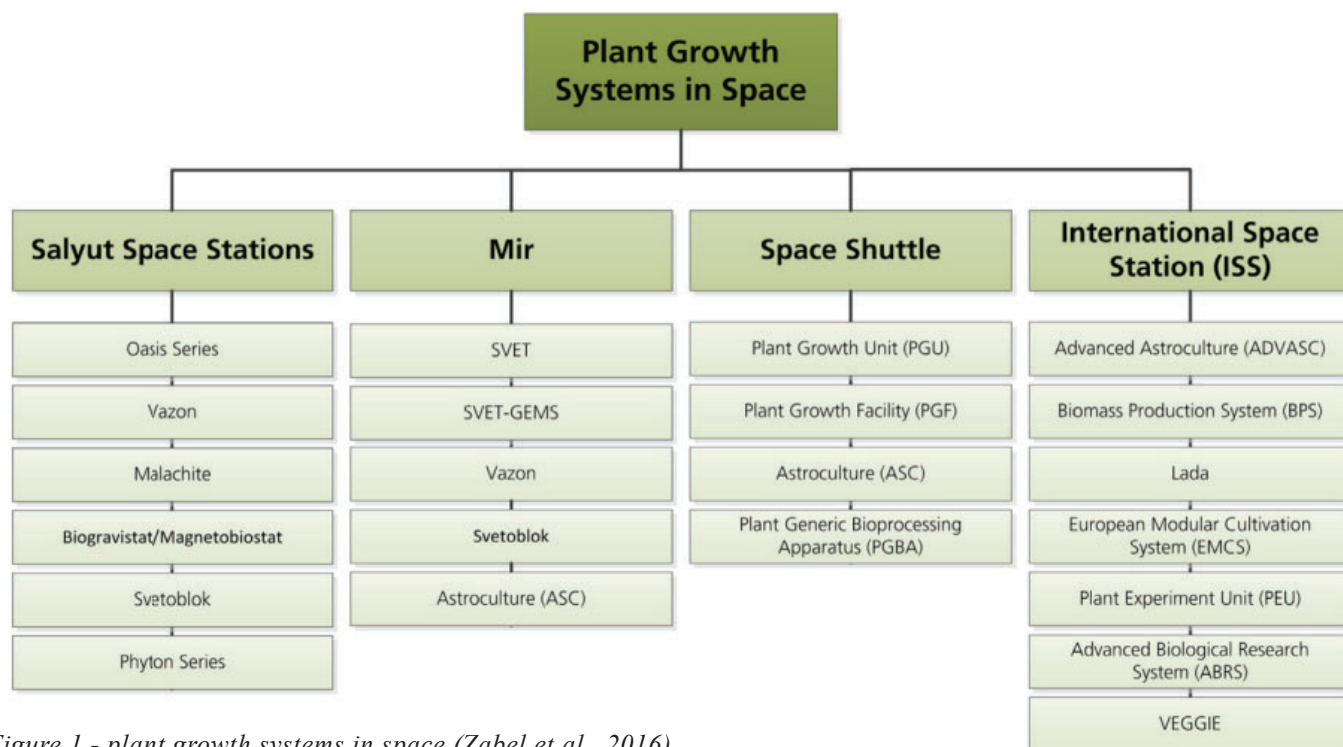


Figure 1 - plant growth systems in space (Zabel et al., 2016)



## II. From prototype to orbit: a brief history summary

interaction (Bingham et al., 2002).

**Biogravistat** features key technological advancements in nutrient delivery systems. Magnetobiostat is the upgraded version of Biogravistat. A key addition was the implementation of a magnetic field and the application of a centrifuge to simulate different levels of gravity (Zabel et al., 2016).

**Svetoblok** is known as the first plant cultivation chamber to be shown successful in growing plants in a 65-day sterile space environment (Zabel et al., 2016). Additionally, notable improvements include a new agar-based nutrient delivery system and a fluorescent light source. (Zabel et al., 2016)

The **Phyton series** features critical improvements in air contaminant management and the design of an automated seed sowing apparatus (Porterfield et al., 2003)

### II. Mir Space Station

The design of cultivation systems onboard the Mir Space Station were based on further enhanced models of the ones used on the Salyut stations.

The **SVET and SVET-GEMS** experiments feature extremely notable improvements in volatile organic compound mitigation, i.e., ethylene (Campbell et al., 2001), ventilation rate, and illumination. The acknowledgement of volatile organic compound presence offered an answer to why infertile seed production was present in past experiments. Moreover, SVET-GEMS is an improved version of SVET featuring an improved atmospheric control unit (environmental measurement unit), offering the possibility of air quality, soil condition, leaf temperature analysis and information on photosynthetic gas exchange rate (gas exchange monitoring system) (Zabel et al., 2016).

### III. Space Shuttle

The **Space Shuttle** experiments feature one of the most incremental improvements in space cultivation, which is the Plant Growth Unit (PGU) (Morrow et al., 2017; Porterfield et al., 2003; Zabel et al., 2016). The PGU consisted of 6 placement units. A placement unit could be used for a Plant Growth Chamber (PGC) or a hardware addition, i.e., an air exchange system (Porterfield et al., 2003). Furthermore, the PGU featured a timer for lighting systems, temperature sensors, electronically controlled fans, a heater, a data acquisition system, and internal batteries (Porterfield et al., 2003)

The **Plant Growth Facility (PGF)** represents an improved PGU, which could control nutrients, water, temperature, CO<sub>2</sub> and O<sub>2</sub> levels, humidity, lighting, and ethylene levels (Porterfield et al., 2003). The experiments ensured an improved understanding of the effects of microgravity on plant development (Musgrave et al., 1997)

**Astroculture** tested an improved nutrient delivery system (porous tubes) (Porterfield et al., 1984; Morrow et al., 1994), LED lighting, and a new volatile organic compound management system (Zabel et al., 2016). (Figure 2)

The last featured cultivation unit was the **Plant Generic Bioprocessing Apparatus (PGBA)**, which was developed for commercial



*Astroculture Unit (Zabel et al., 2016)*



## II. From prototype to orbit: a brief history summary

biotechnology research (Hoehn et al., 1998).

### IV. International Space Station (ISS)

The ISS features the most recent and technologically advanced plant growth systems. The first one, being **Advanced Astroculture**, was based on the original Astroculture unit, but twice the size (Porterfield et al., 2003). It featured technological increments in light, temperature and humidity control, a fluid nutrient delivery system, and the possibility of atmospheric control within the unit (Zhou et al., 2002).

The successor, being the **Biomass Production System (BPS)**, featured photosynthesis experiments under the acronym PESTO. The objective of the experiments was to ensure that the effects of a microgravity environment can be mitigated and ensure dependable plant growth by comparing the results with a control unit based on Earth (Evans et al., 2009; Morrow et al., 2000; Stutte et al., 2005).

The **LADA unit** was partially based on SVET-GEMS equipment (Zabel et al., 2016). The unit featured notable enhancements to plant illumination (by adding reflective film to the chamber walls) (Zabel et al., 2016) and root zone moisture control (Morrow et al., 2017). Furthermore, the psychological effects of plant presence onboard a space environment-based station were investigated (Bingham et al., 2002).

The **European Modular Cultivation System (EMCS)** featured a similar technology to that of the Magnetobiostat, which included a centrifugal system in order to apply different levels of gravity (0.001g - 2g) (Zabel et al., 2016).

The Japanese **Plant Experiment Unit (PEU)** introduced an LED lighting system, an automated watering system and a CCD camera (Zabel et al., 2016). The growth medium consisted of a rock wool growth medium, which was fed by

an integrated water line (Zabel et al., 2016).

The **Advanced Biological Research System (ABRS)** introduced an advanced lighting system with 303 LEDs, through which spectral peaks were controlled (Zabel et al., 2016).

The **VEGGIE unit** is one of NASA's most important biological life support systems (BLSS) advancements. It is the first cultivation system specifically designed for crew food production, primarily salad-type crops (Morrow et al., 2017) and human microbe interaction investigation (Massa et al., 2016) rather than experimentation (Zabel et al., 2016). The unit features a collapsible design, where components are easily replaceable (Massa et al., 2016). Moreover, the lighting system features customizable red, blue and green LEDs (Massa et al., 2016). A notable improvement is the nutrient delivery system, which was deeply studied (Massa et al., 2013), for which rooting pillows were selected (Zabel et al., 2016). The grown food still needs to be up to par with certain standards set by NASA's microbial standards for food (Zabel et al., 2016).

The latest addition is the **Advanced Plant Habitat (APH)** in 2017. The APH is a high-performance controlled environment chamber ensuring full atmospheric, nutrient delivery control (Massa et al., 2016). It includes sensors such as leaf temperature, root zone moisture, root zone temperature, and oxygen concentration sensors (Massa et al., 2016).



APH LED system



## II. From prototype to orbit: a brief history summary

### VI. Important ground-based research experiments

The **BIOS series** features 3 research initiatives (BIOS I, BIOS II, and BIOS III). The role of the research initiatives was to develop a bioregenerative life-support system for not only space stations but also surfaces such as the Moon and Mars (Salisbury et al., 1997). A notable experiment is the BIOS III. The facility consisted of three compartments: one for air revitalisation, one for crew habitation and meal preparation, and 2 for plant cultivation (Salisbury et al., 1997). Furthermore, BIOS III achieved sufficient air regeneration, but none of the 3 initiatives achieved ample food production, i.e.. Therefore, in BIOS III 25% of food (primarily protein-based) was supplied from outside (Salisbury et al., 1997). The experiments gave insight into a notable, long-term with controlled plant cultivation, which is exposure to potentially harmful microorganisms, requiring crew members to work in sterile

sterile equipment preventing cross-contamination (Salisbury et al., 1997).

The MELiSSA initiative (Microbial Ecological Life Support System Alternative), led by ESA (European Space Agency) is a microorganism-based ecosystem project to study artificial life-support systems (Poughon et al., 1997). It consists of 5 compartments: 3 with microorganisms degrading the organic crew wastes into usable elements to feed the 4th compartment, which is based on higher plants and algae, and in return provides necessary nutrients and air composition to the 5th compartment, which is the crew (Poulet et al., 2016). The project's main goal is to maintain compartmental balance while preventing contamination (Poulet et al., 2016). To ensure reliability, all biological behaviours must be predictable; thus, all of the crops need to achieve standards set by ESA (Poulet et al., 2016).

## III. Botanical candidates

### III.I. Botanical legacy

#### III.I.I. Cultivated in orbit

The aforementioned space missions performed growth experiments on various fruitage, covered in detail by Zabel et al. (2016).

The choice of crops started with lower-growing, resilient plants such as peas and onions. Further experiments started, including more palatable crops such as tomato plants, cucumbers,

and modified dwarf plants. The table below, illustrated by Zabel et al. (2016), covers the history of used crops according to the previously mentioned space missions (Table 1). Non-edible plants include plants grown to promote psychological well-being, such as tulips, bulbous plants and roses (Zabel et al., 2016).

	Barley	Cabbage	Carrots	Chinese Cabbage	Corn	Cress	Dwarf Cucumbers	Flax	Garlic	Leek	Lentil	Lettuce	Mizuna	Mustard	Onion	Parsley	Pea	Radish	Rice	Soybean	Spinach	Swiss chard	Tomato	Wheat	Non-edible plants	
Oasis		x		x				x	x															x	x	
Vazon																x									x	
Malichte																										x
Svetoblok																							x			x
Phyton			x				x		x														x	x		x
Biogravistat / Magnetobiostat	x						x					x				x							x	x		x
SVET																										
SVET-GEMS				x															x							
Skylab												x	x	x											x	
PGU																										
PGF													x													x
ASC																										x
PGBA																										x
BIS																										x
ADWASC													x											x		x
Lada																										x
EMES	x						x						x				x	x								x
PEU						x					x															x
ABRS																										x
VEGGIE												x														x

Table 1 - History of crops from past space missions (Zabel et al., 2016)



### III. Botanical candidates

#### III.I.II. Proposed crops for future habitats

With focus on cultivation being limited in space missions up until recently, lists of possible candidate crops are noted by several research papers and are thus highly extensive.

Candidate crops from ground-based research experiments, the BIOS series (notably BIOS III), are extensively covered by Salisbury in multiple experiments. (Table 2, Table 3)

**A. Grains** (protein 10 to 14%):

1. Wheat\*
2. Rice\*
3. Oats (difficult to hull)
4. Quinoa (S. Amer. grain)
5. Millets
6. Sorghum
7. Flax

**B. Starchy roots & tubers:**

1. Sweet potato\*
2. White potato
3. Table beet

**C. Green Vegetables** (vit., min.):

1. Broccoli\*
2. Kale\*
3. Swiss chard
4. Snow peas
5. Cabbage
6. Garden peas
7. Lettuce\*

**D. Yellow vegetables:**

1. Carrots\*
2. Butternut squash (seeds)
3. Pumpkin
4. Various squash cultivars.
5. Mushrooms (if possible)

**E. Seeds: oil & to eat:**

1. Rape seed (canola)\*
2. Sunflower
- (3. Peanut)
- (4. Soybean)

**F. Legumes:**

1. Soybean (also molasses)\*
2. Peanut\*
3. Pinto beans
4. Chickpea\*
5. Lentil\*
6. Cowpea

The fruits and condiments are needed for full nutrition but would add important variety. Unnumbered spices might be grown in odd corners for pleasure but mostly brought from earth in dried condition.

**G. Fruits:**

1. Strawberries
2. Tomatoes\*
3. Melons (e.g., cantaloupe)
4. Tomatillo

**H. Condiments:**

1. Onions\*
  2. Garlic
  3. Chilies (spicy pepper)\*
- Others listed: sage, fennel, oregano, ginger, horseradish, thyme, chives, parsley, radish.

The MELiSSA initiative is actively evaluating a list of candidate crops for future space missions, primarily for a lunar base (Pughlon et al., 1997), following specific parameters set by ESA to ensure closed-loop life support efficiency (Poulet et al., 2016). Specific conclusions include:

1. Achieving 20% of an individual's diet should achieve an adequate water recycling rate (Eckhart, 1994)
2. Achieving 50% of an individual's diet should achieve adequate atmosphere revitalisation, ensuring enough oxygen production through photosynthesis (Eckhart, 1994)
3. Each candidate crop has to achieve a strict recycle rate of 1.1-1.3 mol of O<sub>2</sub> per mol of CO<sub>2</sub> (Poulet et al., 2016).

Some of the candidate crops under investigation include tomatoes, rice, lettuce, potatoes, soybeans, spinach, onions, and wheat. The performance of these crops has been studied in detail using stoichiometric equations to model nutrient yield and water demands by Poughon et al. (1997) (Table 4).

\*All these were recommended by the vegetarians; those with an asterisk (\*) were also recommended by the nutritionists.

Table 2 - Suggestion for crops grown (Salisbury et al., 1996)

Crops	Expected			Actual		
	Diurnal needs of the crew (g)	Yield (g · m <sup>-2</sup> · d <sup>-1</sup> )	Area (m <sup>2</sup> )	Area (m <sup>2</sup> )	Harvest (g/d)	Harvest index (% <sup>a</sup> )
Wheat ( <i>Triticum aestivum</i> ), grain (dry mass)	520	13	40.0	39.6	496	34.7
Chufa ( <i>Cyperus esculentus</i> ), tubers (dry mass)	234	26	9.0	8.6	120	48.1
Pea ( <i>Pisum sativum</i> ), grain	52	13	4.0	4.0	26	25.4
Carrot ( <i>Daucus carota</i> ), edible roots (fresh mass)	220	160	1.4	1.2	236	54.9
Radish ( <i>Raphanus sativus</i> ), edible roots (fresh mass)	110	125	0.9	0.9	266	59.8
Beets ( <i>Beta vulgaris</i> ), edible roots and leaves (fresh mass)	130	170	0.9	0.9	132	67.5
Kohlrabi ( <i>Brassica oleracea gongylodes</i> ), stems and leaves (fresh mass)	180	170	1.1	1.0	164	37.1
Onion ( <i>Allium</i> sp.), leaves and bulbs (fresh mass)	120	170	0.7	0.6	110	90.1
Dill ( <i>Anethum graveolens</i> ), greens (fresh mass)	30	30	— <sup>b</sup>	— <sup>b</sup>	16	93.0
Tomatoes ( <i>Lycopersicon esculentum</i> ; fresh mass)	150	110	1.4	1.2	88	33.1
Cucumbers ( <i>Cucumis sativus</i> ; fresh mass)	100	250	0.4	0.4	276	54.6
Potatoes ( <i>Solanum tuberosum</i> ; fresh mass)	250	80	3.2	4.8	22	5.9

<sup>a</sup>Harvest index was calculated on a dry-mass basis.

<sup>b</sup>Area is not known because the crop was grown between other culture rows.

Table 3 - BIOS III crops during third experiment (Salisbury et al., 1997)



### III. Botanical candidates

	Mass % of fresh plant		Edible part [% wet mass]					Waste part [% wet mass]	
	Waste	Edible	Water	Proteins	Fat	Carbohyd.	Fibre	Water	Dry waste
Tomato	55	45	93.60	0.94	0.21	3.43	1.82	50	50
Rice	55	45	13.26	7.31	2.23	74.30	2.90	15	85
Lettuce	15	85	95.87	1.26	0.22	1.11	1.53	80	20
Potato	17	83	79.50	2.08	0.11	15.74	2.56	50	50
Soybean	50	50	10.42	41.33	22.18	7.47	18.60	50	50
Spinach	30	70	94.56	2.60	0.31	0.63	1.90	80	20
Onion	25	75	89.44	1.28	0.26	5.91	3.11	50	50
Wheat	60	40	13.44	11.95	2.04	62.09	10.49	12	88

	Digestible part						Fibre				CO <sub>2</sub>	H <sub>2</sub> O	NH <sub>3</sub>	HNO <sub>3</sub>	O <sub>2</sub>	H <sub>2</sub> SO <sub>4</sub>
	Coeff	C	H	O	N	S	Coeff	C	H	O						
Tomato	1	1	1.7928	0.8004	0.0546	0.0005	0.4040	1	1.6560	0.8280	-1.4040	-1.1799	-0.0232	-0.0313	1.4744	-0.0005
Rice	1	1	1.6650	0.7546	0.0257	0.0006	0.0335	1	1.6667	0.8333	-1.0335	-0.8360	-0.0109	-0.0147	1.0836	-0.0006
Lettuce	1	1	1.7107	0.4464	0.1348	0.0019	0.5016	1	1.6537	0.8268	-1.5016	-1.1435	-0.0019	-0.0774	1.7627	-0.0019
Potato	1	1	1.6492	0.7750	0.0335	0.0006	0.1413	1	1.6513	0.8257	-1.1413	-0.9097	-0.0142	-0.0192	1.1803	-0.0006
Soybean	1	1	1.6878	0.2952	0.1321	0.0035	0.2022	1	1.6000	0.8000	-1.2022	-0.8799	-0.0562	-0.0758	1.5344	-0.0035
Spinach	1	1	1.6406	0.2835	0.1870	0.0088	0.4215	1	1.6467	0.8233	-1.4215	-0.9855	-0.0796	-0.1074	1.7777	-0.0088
Onion	1	1	1.8113	0.7510	0.0742	0.0010	0.4183	1	1.6560	0.8280	-1.4183	-1.1823	-0.0316	-0.0426	1.5266	-0.0010
Wheat	1	1	1.6548	0.7215	0.0430	0.0012	0.1320	1	1.6667	0.8333	-1.1320	-0.8963	-0.0183	-0.0247	1.2039	-0.0012

	Waste						CO <sub>2</sub>	H <sub>2</sub> O	NH <sub>3</sub>	HNO <sub>3</sub>	O <sub>2</sub>	H <sub>2</sub> SO <sub>4</sub>
	Coeff	C	H	O	N	S						
Tomato	1	1	1.43	0.62	0.017	0.007	-1	-0.6923	-0.0072	-0.0098	1.0648	-0.0070
Rice	1	1	1.43	0.62	0.017	0.007	-1	-0.6923	-0.0072	-0.0098	1.0648	-0.0070
Lettuce	1	1	1.43	0.62	0.017	0.007	-1	-0.6923	-0.0072	-0.0098	1.0648	-0.0070
Potato	1	1	1.43	0.62	0.017	0.007	-1	-0.6923	-0.0072	-0.0098	1.0648	-0.0070
Soybean	1	1	1.43	0.62	0.017	0.007	-1	-0.6923	-0.0072	-0.0098	1.0648	-0.0070
Spinach	1	1	1.43	0.62	0.017	0.007	-1	-0.6923	-0.0072	-0.0098	1.0648	-0.0070
Onion	1	1	1.43	0.62	0.017	0.007	-1	-0.6923	-0.0072	-0.0098	1.0648	-0.0070
Wheat	1	1	1.43	0.62	0.017	0.007	-1	-0.6923	-0.0072	-0.0098	1.0648	-0.0070

Table 4 - detailed MELiSSA candidate crop analysis (Poughon et al., 1997)

Cloutier et al. (2001) have gone through a detailed crop analysis process in order to determine the required area in order to achieve crop standards based on the MELiSSA initiative objectives.

Furthermore, his proposed theoretical crops are covered in further detail in the following tables (5 and 6), shedding light on valuable information regarding them.

Crop	Density (plants m <sup>-2</sup> )	PPF (μmol m <sup>-2</sup> s <sup>-1</sup> ) PAR	Photo-period (hrs)	°C (day/night)	Edible Biomass (g plant <sup>-1</sup> , dwb)	Harvest Index (%)	Days to Harvest	Number of Staggered Plantings	Source
Broccoli	5.5	600	16	20/15	130.4	35	83	9	Reekie et al (1998)
Beet	39	700	14	18/18	25.5	98	84	9	Wurr et al (1998)
Bean	81	600	16	26/20	28.5	72	55	6	Jolliffe and Ehret (1985)
Cauliflower	5.5	600	16	20/15	114.1	20	83	9	Reekie et al (1998)
Carrot	307	640	16	17/11	8.7	63	86	9	Mortensen (1994)
Kale	5.5	600	16	20/15	28.7	80	43	5	Reekie et al (1998)
Lettuce	30.4	640	16	17/11	6.4	94	26	3	Wheeler et al (1994)
Onion	76.2	640	16	17/11	16.8	66	93	10	Mortensen (1994)
Potato	5.88	800	12	16/16	383.3	79	90	9	Wheeler et al (1991)
Rice	235	1000	12	31	10	47	110	11	Bugbee (website)
Sweet Potato	-	800	13	28/24	900	38	112	12	Goins et al (1999)
Soybean	24	600	9	26/20	76	45	90	9	Sionit et al (1987)
Spinach	39	600	16	24/18	12.8	74	33	4	Both et al (1995)
Wheat	1000	1300	24	23	2	37	82	9	Barta & Henderson (1998)
Cabbage	30.7	640	16	17/11	51.4	-	67	7	Mortensen (1994)

Table 5 - crop cultural requirements used for candidate crops (Cloutier et al., 2001)



### III. Botanical candidates

Crop	Crop Productivity (Kg edible dw m <sup>-2</sup> day <sup>-1</sup> )	Dry Weight Required in Menu Cycle (g)	Area (m <sup>2</sup> ) (Continuous Production)	Kg ESM/usable Kg dry weight	Kg ESM/ menu cycle	Kg ESM crew <sup>-1</sup> day <sup>-1</sup>	Inedible Biomass Produced in Menu Cycle (g. dwb)
Broccoli	0.00300	26.30	0.95	30.91	0.81	0.01	48.85
Beet	0.01180	175.31	1.59	9.12	1.60	0.03	3.58
Bean	0.04200	2704.40	7.02	2.39	6.46	0.11	1051.71
Cauliflower	0.00150	0.00	0.00	65.74	0.00	0.00	0.00
Carrot	0.03110	406.53	1.37	2.88	1.17	0.02	238.75
Cucumber	0.04094	19.99	See Text	19.06	0.38	0.01	See Text
Herbs	0.01500	0.95	0.01	19.06	0.02	0.00	0.24
Kale	0.02040	47.61	0.27	4.03	0.19	0.00	11.90
Lettuce	0.07480	19.54	0.03	1.31	0.03	0.00	1.25
Onion	0.01380	381.82	2.98	7.4	2.83	0.05	196.70
Green Onion	0.01500	2.85	0.02	7.4	0.02	0.00	0.18
Peppers	0.00601	543.96	See Text	19.06	10.37	0.17	See Text
Peanut	0.00450	9733.52	216.30	9.27	90.23	1.50	38934.10
Potato	0.02500	1215.82	4.86	3.47	4.22	0.07	323.19
Rice	0.01000	5123.78	51.24	8.04	41.20	0.69	5777.88
Sweet Potato	0.02050	3051.79	14.89	4.72	14.40	0.24	4979.24
Swiss Chard	0.00500	0.00	0.00	26.65	0.00	0.00	0.00
Soybean	0.02030	6987.97	34.42	3.87	27.04	0.45	8540.85
Spinach	0.01510	105.14	0.84	6.38	0.67	0.01	36.94
Tomato	0.00970	10483.88	See Text	8.4	88.06	1.47	See Text
Wheat	0.02440	25323.55	113.91	5.69	144.09	2.40	43118.48
Alfalfa	0.01500	30.68	0.22	19.06	0.58	0.01	52.23
Cabbage	0.00900	17.52	0.19	7.53	0.13	0.00	1.12
Chilli Peppers	0.01500	3.65	0.03	19.06	0.07	0.00	1.68
Mushrooms	0.01500	179.55	1.29	19.06	3.42	0.06	119.70
Snow Peas	0.01500	41.37	0.30	19.06	0.79	0.01	16.09
Squash	0.01500	27.79	0.21	19.06	0.53	0.01	18.53
<b>Crop Total</b>		<b>66655.25</b>	<b>452.94</b>	<b>-----</b>	<b>439.32</b>	<b>7.32</b>	<b>103473.18</b>
Water (L)		26.18					
Earth Ingredients (fresh)	<b>Closure = 94 %</b>	<b>4598.10</b>					

Table 6 - candidate crops production (Cloutier et al., 2001)

Zabel's study, done in 2016, also gives insight into a valuable crop table used but also proposed for space missions (Table 7), highlighting a study done by Wheeler (2004). Crops highlighted in green have been cultivated during past space missions.

Continuing on the work of R. Wheeler, two of his studies cover crops in extensive detail, one from 2003 and one from 2012. Taking into consideration research relevance, the study done in 2012 has been taken as of bigger importance.

Wheeler (2012) compiled an extensive list of candidate crops considered suitable for space-based food production, drawing on decades of plant biology and controlled-environment agriculture research. The proposed crops include grains such as wheat and rice, protein-rich sources like soybean, pea, chickpea, dry bean and lentil, as well as starchy tubers such as potato, sweet potato, and taro. In addition, a variety of vegetables, leafy greens, and fruits are listed, including lettuce, chard, cabbage, kale, broccoli, carrot, cucumber, onion, dill, chilli pepper, and strawberry. Oilseed crops such as peanut and rapeseed (canola) also appear on the list. The mentioned crops have been gathered by Wheeler through literature resources. Nevertheless, Wheeler's earlier work (2003) offers further relevant information regarding plant cultivation specifics, i.e., nutrient solution temperature, air temperature, photosynthetic photon flux, and photoperiod. This information is presented in the following tables (8 and 9).

	Pilgrim and Johnson (1962)	Tibbits and Alford (1982) (Tibbits and Alford, 1982)	Hoff et al. (1982) (Hoff et al., 1982)	Waters et al. (2002) (Waters et al., 2002)	NASA (1998) (NASA 1998)	Salisbury and Clark (1996) (Salisbury and Clark, 1996)	Gitelson et al. (1989) (Gitelson et al., 1989)
Sweet potato	Wheat	Wheat	Wheat	Lettuce	Wheat	Wheat	
Tambala	Soybean	Soybean	Soybean	Spinach	Soybean	Salad Spices	
Chinese Cabbage	Lettuce	Potato	Lettuce	Radish	Lettuce	Potato	
Cabbage	Sweet potato	Carrot	Sweet potato	Cabbage	Sweet potato	Radish	
Cauliflower	Peanut	Peanut	Rice	Green onion	Kale	Beet	
Kale	Rice	Rice	Bean	Carrot	Broccoli	Nut Sedge	
Collards	Sugar beet	Tomato	Beet	Tomato	Carrot	Onion	
Turnip	Taro	Dry bean	Cabbage	Pepper	Canola	Cabbage	
Swiss Chard	Winged bean	Chard	Broccoli	Strawberry	Rice	Tomato	
Endive	Broccoli	Cabbage	Cauliflower	Different Herbs	Peanut	Pea	
Dandelion	Onion		Carrot		Chickpea	Dill	
Radish	Strawberry		Kale		Lentil	Cucumber	
New Zealand Spinach			Spinach		Tomato	Carrot	
Spinach			Potato		Onion		
			Onion		Chilli pepper		

Table 7 - candidate crop list (Zabel et al., 2016)



### III. Botanical candidates

Crop ( <i>Genus species</i> )	Nutrient Solution Temperature	Air Temperature (Light/Dark)	Photosynthetic Photon Flux (PPF)	Photoperiod (Light/Dark)
<b>Staple Crops</b>	(°C)	(°C)	( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	(h)
Wheat ( <i>Triticum aestivum</i> ) <sup>1</sup>	~18	20/16	750 – 800	20/4 or 24/0
Soybean ( <i>Glycine max</i> ) <sup>2</sup>	~24	26/22	500 – 800	12/12
Potato ( <i>Solanum tuberosum</i> ) <sup>3</sup>	~18	20/16	500 – 800	12/12
Sweetpotato ( <i>Ipomoea batatas</i> ) <sup>4</sup>	~24	26/22	500 – 800	12/12
Peanut ( <i>Arachis hypogaea</i> )	~24	26/22	500 – 750	12/12
Rice ( <i>Oryza sativa</i> ) <sup>5</sup>	~24	28/24	750 – 800	12/12
Bean ( <i>Phaseolus vulgaris</i> )	~26	28/24	350 - 400	18/6
<b>Supplemental Crops</b>				
Lettuce ( <i>Lactuca sativa</i> ) <sup>6</sup>	~ 23	23	300	16/8
Spinach ( <i>Spinacia oleracea</i> ) <sup>7</sup>	~ 23	23	300	16/8
Tomato ( <i>Lycopersicon esculentum</i> ) <sup>8</sup>	~ 24	24	500 – 750	12/12
Chard ( <i>Beta vulgaris</i> )	~ 23	23	300	16/8
Radish ( <i>Raphanus sativus</i> )	~ 23	23	300	16/8
Red Beet ( <i>Beta vulgaris</i> )	~ 23	23	300	16/8
Strawberry ( <i>Fragaria x ananassa</i> ) <sup>9</sup>	~ 18	20/16	400 – 600	12/12

Table 8 - candidate crops requirements (Wheeler, 2003)

Crop ( <i>Genus species</i> )	Best Performing Cultivar (from KSC tests)	Propagation and Germination	Plant Density (initial/final)	Seedling Establishment	Thinning Time
<b>Staple Crops</b>			(plants m <sup>-2</sup> )	(days)	(days)
Wheat ( <i>Triticum aestivum</i> )	Apogee	Seed <sup>1</sup>	~1200	4	NA
Soybean ( <i>Glycine max</i> )	Hoyt	Seed <sup>2</sup>	32/12-16	5	10
Potato ( <i>Solanum tuberosum</i> )	Norland	Plantlets <sup>3</sup>	12/6-8	NA	10
Sweetpotato ( <i>Ipomoea batatas</i> )	TU – 155	Cuttings <sup>4</sup>	12/6-8	NA	7
Peanut ( <i>Arachis hypogaea</i> )	Pronto	Seed <sup>2</sup>	12/6-8	4	14
Rice ( <i>Oryza sativa</i> )	Ai-Nan Tsao	Seed <sup>1</sup>	~ 800	4	NA
Bean ( <i>Phaseolus vulgaris</i> )	Etna	Seed <sup>2</sup>	32/12-16	4	10
<b>Supplemental Crops</b>					
Lettuce ( <i>Lactuca sativa</i> )	Waldmann's Green	Seed <sup>5</sup>	40/20-24	4	10
Spinach ( <i>Spinacia oleracea</i> )	Nordic IV	Seed <sup>6</sup>	40/20-24	10	14
Tomato ( <i>Lycopersicon esculentum</i> )	Reimann Philipp	Seed <sup>5</sup>	20/10	6	10
Chard ( <i>Beta vulgaris</i> )	Ruby Red	Seed <sup>5</sup>	40/20	4	10
Radish ( <i>Raphanus sativus</i> )	Giant White Globe	Seed <sup>5</sup>	50/40	4	7
Red Beet ( <i>Beta vulgaris</i> )	Ruby Queen	Seed <sup>6</sup>	40/20	7	14
Strawberry ( <i>Fragaria x ananassa</i> )	Oso Grande	Runners <sup>7</sup>	12-16	NA	14

Table 9 - candidate crops establishment considerations (Wheeler, 2003)



### III. Botanical candidates

A further notable study done by Nelson et al. (2009) explores a projected diet based on ten major crops, based for a Martian CELSS. The findings from the candidate crops are presented in the tables below (10 and 11).

Further recommended crops cited by read literature include:

- Kitaya et al. (2000) - barley (low light requirements)
- De Pascale et al. (2021) - microgreens, tubers, and fruit vegetables
- Meinen et al. (2018) - lettuce, cucumber, radish, tomato, spinach, red mustard, swiss chard, and herbs
- Polutchko et al. (2022) - orange peppers and corn
- Mitrea et al. (2018) - strawberries, grapes, wheat, broccoli, rice bran, brussels sprouts, cabbages, tomatoes, carrots, watermelon, gac, papayas, green tea extract, saffron
- Schwartzkopf (1992) - soybean, peanut, rice, wheat, potato, carrot, chard, cabbage, lettuce, tomato
- MacElroy et al. (1984) - algal culture
- Skoog et al. (1984) - higher plants, leek, dill, cabbage, endive, chicory, cress, parsley, spinach
- Olson et al. (1984) - lettuce, tomato, carrot, dry beans, peanuts, cabbage, potato, green beans, melons, peas, wheat, mustard greens, rice, pea pod, split pea, corn, kale, turnip greens, chickpea, oats, broccoli

Crop	% of diet	Kcal/ person/ day	Crop wt/calorie content (Kcal/g)	Gams of crop per day	Protein content grams	Protein from crop/day	Fat con- tent/ gram	Fat from crop/day
Rice	15%	450	3.5	128.57	0.13	16.71	0.01	1.29
Wheat	10%	300	3.3	90.91	0.13	11.82	0.02	1.82
Sweet potato	25%	750	1.06	707.55	0.01	7.08	0.0028	1.98
Peanut	5%	150	5.84	25.68	0.26	6.68	0.48	12.33
Soybean	5%	150	4.02	37.31	0.08	2.99	0.18	6.72
Pinto bean	10%	300	3.42	87.72	0.24	21.05	0.0086	0.75
Winter squash	7.50%	225	0.634	354.89	0.01	3.55	0.001	0.35
Beet root	7.50%	225	0.445	505.62	0.01	5.06	0.0002	0.1
Banana	10%	300	0.6	500.00	0.006	3.00	0.02	10
Papaya	5%	150	0.26	576.92	0.003	1.73	0.0007	0.4
<i>Total</i>		3,000		3,015.18		79.66		35.74

Table 10 - candidate crops establishment considerations (Wheeler, 2003)

Crop	Kcal required for 4 crew daily	Best yield Bio (kg m <sup>-2</sup> d <sup>-1</sup> )	Light level (mol <sup>-1</sup> m <sup>-2</sup> d <sup>-1</sup> )	Correction factor for 50 mol <sup>-1</sup> m <sup>-2</sup> d <sup>-1</sup>	Extrapolated Yield in 50 mol <sup>-1</sup> m <sup>-2</sup> d <sup>-1</sup> kg m <sup>-2</sup> d <sup>-1</sup>	Extrapolated yield in Kcal/m <sup>-2</sup> d <sup>-1</sup>	Area 4 required for feeding crew
Wheat	1,200	0.0024	16	3	0.0073	24.38	49.22
Rice	1,800	0.0057	25	2	0.0114	40.55	44.39
Sweet potato	3,000	0.0160	25	2	0.0320	33.89	88.51
Peanut	600	0.0014	25	2	0.0028	16.32	36.77
Soybean	600	0.0013	25	2	0.0026	10.64	56.41
Pinto Bean	1,200	0.0037	25	2	0.0074	25.36	47.32
Beet (root)	900	0.0232	25	2	0.0464	20.45	44.01
Winter squash	900	0.0425	25	2	0.0850	54.32	16.57
Banana	1,200	0.0498	25	1	0.0498	29.64	40.48
Papaya	600	0.1084	25	1	0.1084	28.68	20.92
	12,000						445

Table 11 - candidate crops establishment considerations (Wheeler, 2003)



### III. Botanical candidates

#### III.II. Functional values

This chapter offers insight into relevant information found and gathered from literature regarding expected plant cultivation values from space environment-simulated experiments, such

as expected harvest cycle and crop yield, photosynthetic gas exchange rate, and changes in seed fertility/reproduction rate of specific plant species grown in a microgravity environment.

#### III.II.I. Harvest cycle

Harvest cycles vary across species. We differentiate 2 main harvest methods: single harvest and spread harvest (Mienen et al., 2018). Through decades of space-based experiments, it is critical to mention that the cultivation environment plays an ever-growing role in non-Earth conditions. As noted by Zabel et al. (2016), early trials such as Oasis 1M revealed that only a limited number of plant subjects reached maturity. Through time, limiting factors became more apparent, such as air flow, air composition, and ethylene levels (Zabel et al., 2016). The mentioned and related factors will be discussed in further detail later on.

Because of the limited experimentation, few studies delve into specific harvest cycle data. An aforementioned notable study done by Wheeler et al. (2003) gives detailed insight into harvest

cycles for a selected range of crops (Table 12).

A study done by De Pascale et al. (2021) highlights that crops with short cultivation cycles tend to exhibit reduced plant size but provide several key advantages for space-based agriculture. These include better adaptability to controlled environments, higher overall productivity, and greater resistance to diseases when compared to crops with longer cultivation periods.

However, research on Lemnaeae (duckweed) by Coughlan et al. (2022) highlights a drawback with frequent cultivation cycles, such as fruits (Meinen et al., 2018). While rapid harvests can boost biomass, they result in lower nutritional value. Moreover, Meinen et al. (2018) note that the lack of seasons in a controlled environment could result in multiple harvest phases.

Crop ( <i>Genus species</i> )	Anthesis/ Flowering <sup>1</sup>	Duration of Grow-Out	Canopy Height at Maturity	Harvest Index
Staple Crops	(days)	(days)	(cm)	(%)
Wheat ( <i>Triticum aestivum</i> ) <sup>3</sup>	~35	85	~ 50	~ 30 – 45
Soybean ( <i>Glycine max</i> ) <sup>4</sup>	~28	90 – 97	~ 45 – 70	~ 40
Potato ( <i>Solanum tuberosum</i> ) <sup>5, 6</sup>	NA	84 – 105	~ 50 – 80 <sup>2</sup>	~ 60 - 80
Sweetpotato ( <i>Ipomoea batatas</i> ) <sup>6</sup>	NA	120	~ 50 – 80 <sup>2</sup>	~ 20 – 60
Peanut ( <i>Arachis hypogaea</i> )	~35	120	~ 60 – 80 <sup>2</sup>	~ 20 – 30
Rice ( <i>Oryza sativa</i> )	~45	105	~ 80	~ 30
Bean ( <i>Phaseolus vulgaris</i> ) <sup>6</sup>	~28	70	~ 50	~ 35 - 45
Supplemental Crops				
Lettuce ( <i>Lactuca sativa</i> )	NA	28	~ 20 – 30	~ 90
Spinach ( <i>Spinacia oleracea</i> )	NA	28	~ 20 – 30	~ 90
Tomato ( <i>Lycopersicon esculentum</i> ) <sup>7</sup>	~35	84	~ 35 - 45	~ 40 – 50
Chard ( <i>Beta vulgaris</i> )	NA	40 +	~ 40 – 50	~ 60 +
Radish ( <i>Raphanus sativus</i> )	NA	21 – 25	~ 20	~ 50
Red Beet ( <i>Beta vulgaris</i> )	NA	35 – 42	~ 40 – 50	~ 60 +
Strawberry ( <i>Fragaria x ananassa</i> )	~60	140	~ 20 – 30	~ 30 – 40

Table 12 - developmental characteristics of candidate crops (Wheeler et al., 2003)



### III. Botanical candidates

#### III.II.II. Crop yield

Only a limited number of research papers investigated possible crop yields in detail, and which plant species should be prioritised for a CELSS.

Among the most significant contributions is a comprehensive NASA study on life support baseline values conducted by Ewert et al. (2022). This work compares several calculated characteristics of candidate crops, one of them being crop yield expressed as total biomass (Table 13). In addition, the dataset also displays key information regarding photosynthetic rate. The full particular aspects of this study will be further presented in greater depth later on.

Building on this, the study by Polutchko et al. (2022) emphasises that future crops with a high edible yield fraction and volume/cultivation area efficiency should be prioritised for future space

endeavours. A notable example from the study is duckweed, a small aquatic plant. Duckweed offers an edible yield of 100% and a high efficiency per unit of volume and surface area compared to i.e., corn or peppers.

Further information regarding crop yield per plant species is presented in a conceptual project done by Hava et al. (2019), where the team took the aforementioned NASA study by Ewert et al. (2022) and added hypothetical, non-tested crops into comparison (Table 14). Using the measured values presented in Table 13 as a reference point, the team estimated the functional values of the additionally proposed crops. The presented information in Table 14, although detailed, should not be taken literally, but should be seen as an adequate and proficient attempt at mathematically filling an existing gap in astrobiology.

<i>Crop yield</i>	Total Biomass (Edible + Inedible), Dry Basis [g <sub>dw</sub> /m <sup>2</sup> -d]		Carbon Content [%]	Metabolic Reactants and Products			References
	Nominal	High		Oxygen (O <sub>2</sub> ) Production [g/m <sup>2</sup> -d]	Carbon Dioxide (CO <sub>2</sub> ) Uptake [g/m <sup>2</sup> -d]	<i>Photosynthetic rate</i> Average Water (H <sub>2</sub> O) Uptake / Transpiration [kg/m <sup>2</sup> -d]	
Cabbage	6.74	10.0	40	7.19	9.88	1.77	Information from Drysdale 2001 except as noted. ( <sup>1</sup> ) Wheeler, et al. (1995) ( <sup>2</sup> ) Calculated ( <sup>3</sup> ) Orcun and Wheeler (2003)
Carrot	14.97	16.7	41	16.36	22.50	1.77	
Chard	10.77		40	11.49	15.79	1.77	
Celery	11.47		40	12.24	16.83	1.24	
Dry Bean	25.00		40	30.67	42.17	2.53	
Green Onion	10.00		40	10.67	14.67	1.74	
Lettuce	7.30	7.9	40 <sup>(1)</sup>	7.78	10.70	2.10	
Onion	11.25		40	12.00	16.50	1.74	
Pea	26.83		40 <sup>(3)</sup>	32.92	45.26	2.46	
Peanut	22.50	36.0	60 <sup>(2)</sup>	35.84	49.28	2.77	
Pepper	23.17		40	24.71	33.98	2.77	
Radish	11.00		40 <sup>(2)</sup>	11.86	16.31	1.77	
Red Beet	10.00		41	7.11	9.77	1.77	
Rice	30.23	39.0	42	36.55	50.26	3.43	
Snap Bean	29.70		40	36.43	50.09	2.46	
Soybean	11.34	20.0	46 <sup>(1)</sup>	13.91	19.13	4.70	
Spinach	7.30		40	7.78	10.70	1.77	
Strawberry	22.25		43 <sup>(2)</sup>	25.32	34.82	2.22	
Sweet Potato	37.50	51.3	41 <sup>(2)</sup>	41.12	56.54	2.88	
Tomato	23.17	37.8	43 <sup>(2)</sup>	26.36	36.24	2.77	
Wheat	50.00	150.0	42 <sup>(1)</sup>	56.00	77.00	11.79	
White Potato	30.08	50.0	41 <sup>(1)</sup>	32.23	45.23	4.00	

Table 13 - biomass production, carbon content, and metabolic rates (Ewert et al., 2022)



### III. Botanical candidates

*Crop yield*

*Photosynthetic rate*

Crop	Diet Target	Total Area	Edible Mass	Key Nutrients	Key Functions			O2 Output		CO2 Uptake	Avg. H2O Uptake
	CM-d	m2	kg/yr		Diet	Psych	Med	kg/yr	kg/yr	kg/yr	
<b>Zone 1 - Keyhole Wicking Beds</b>											
Lettuce	4	0.64**	30.66 <sup>††</sup>	Vit (C), Min (Mn, K, Cu, Fe), fiber	x			1.816 <sup>‡‡</sup>	2.498 <sup>1‡</sup>	490.187 <sup>1‡</sup>	
Spinach	2	1.096**	29.2 <sup>††</sup>	Vit (A, B, E, K), Min (Mn, Mg, Fe, Cu), folate	x			3.113 <sup>‡‡</sup>	4.282 <sup>1‡</sup>	708.291 <sup>1‡</sup>	
Kale	4	1.965 <sup>§§</sup>	30.66 <sup>***</sup>	Vit (A, B, K), folate, protein, fiber, α-linolenic acid, lutein, zeaxanthin	x			29.412 <sup>†††</sup>	37.303 <sup>†††</sup>	1506.467 <sup>†††</sup>	
Ground cherry	3	0.496**	0.477 <sup>***</sup>	Vit (A, C), Min (Fe, Ca, P), niacin, thiamin, riboflavin	x	x		7.417 <sup>†††</sup>	9.407 <sup>†††</sup>	501.126 <sup>§§§</sup>	
Sorrel	2	1.381 <sup>§§</sup>	15.33 <sup>***</sup>	Vit (C), Min (P, Fe), fiber, oxalic acid, flavonoids	x	x	x	20.668 <sup>†††</sup>	26.213 <sup>†††</sup>	1058.599 <sup>‡‡</sup>	
Green onion	3	0.165	4.928 <sup>††</sup>	Vit (B, C), quercetin, fiber	x			0.643 <sup>‡‡</sup>	5.870 <sup>1‡</sup>	104.792 <sup>1‡</sup>	
Bok choy	4	0.834	21.921 <sup>****</sup>	Vit (A, V)	x			12.481 <sup>†††</sup>	15.829 <sup>†††</sup>	639.261 <sup>‡‡</sup>	
Carrot	3	1.464	39.986 <sup>††</sup>	Vit (K), fiber, lutein, α- and β-carotene, lycopene	x	x		8.742 <sup>‡‡</sup>	12.023 <sup>‡‡</sup>	945.817 <sup>1‡</sup>	
Radish	3	0.294	9.837 <sup>††</sup>	Vit (A, B, K), Min (P), folate, α-linolenic acid, lutein, zeaxanthin, fiber, protein	x			1.273 <sup>‡‡</sup>	1.750 <sup>1‡</sup>	189.939 <sup>1‡</sup>	
Potato	2	3.229**	124.1 <sup>††</sup>		x			37.984 <sup>‡‡</sup>	53.305 <sup>‡‡</sup>	4714.150 <sup>‡‡</sup>	
<b>Zone 2 - Ebb and Flow Beds</b>											
Strawberry	4	2.48	130.448 <sup>††††</sup>	Vit (C), Min (P), folic acid, fiber	x	x		101.680 <sup>†††</sup>	128.960 <sup>†††</sup>	3665.754 <sup>§§§</sup>	
Tomato	3	3.626**	229.95 <sup>††</sup>	Vit (A, C), lycopene, lutein, α- and β-carotene	x	x		34.884 <sup>1‡</sup>	47.959 <sup>1‡</sup>	3665.754 <sup>‡‡</sup>	
Pepper	4	1.665 <sup>††††</sup>	90.52 <sup>††</sup>	Vit (A, C, E, K), fiber	x			14.690 <sup>1‡</sup>	20.652 <sup>1‡</sup>	1683.499 <sup>1‡</sup>	
Ginger	4	0.52	6.921 <sup>***</sup>	gingerol		x	x	77.818 <sup>†††</sup>	27.040 <sup>†††</sup>	759.200 <sup>§§§§</sup>	
Turmeric	4	0.52	4.55 <sup>***</sup>	curcumin		x	x	77.818 <sup>†††</sup>	27.040 <sup>†††</sup>	759.200 <sup>§§§§</sup>	
Aloe	2	0.26	0.139 <sup>***</sup>	Vit (C), anthraquinones		x		3.891 <sup>†††</sup>	4.935 <sup>†††</sup>	474.500 <sup>†††</sup>	
Marigolds	4	0.52	0.064 <sup>***</sup>	calendulin, linolenic acid, carotenoids	x	x		7.782 <sup>†††</sup>	9.870 <sup>†††</sup>	398.580 <sup>†††</sup>	
Banana	4	2 <sup>*****</sup>	48.48 <sup>***</sup>	Min (P), carbohydrates, fiber	x			299.30 <sup>†††</sup>	104.0 <sup>†††</sup>	7300.0 <sup>†††††</sup>	
Oca	4	3.229 <sup>†††††</sup>	43.913 <sup>***</sup>	antioxidants, starch, fiber	x			48.320 <sup>†††</sup>	61.284 <sup>†††</sup>	4714.150 <sup>§§§§</sup>	
Cilantro	4	0.52	5.2 <sup>***</sup>	lutein, zeaxanthin, β-carotene	x	x	x	7.782 <sup>†††</sup>	9.870 <sup>†††</sup>	398.580 <sup>†††</sup>	
Chamomile	2	0.74 <sup>§§</sup>	0.37 <sup>***</sup>	terpenoids, flavonoids	x	x		11.074 <sup>†††</sup>	14.045 <sup>†††</sup>	567.210 <sup>†††</sup>	
Basil	4	0.52	12.199 <sup>***</sup>	Vit (A, K), Min (Mn, Mg)	x	x		7.782 <sup>†††</sup>	9.870 <sup>†††</sup>	398.580 <sup>†††</sup>	
Mint	3	0.39 <sup>§§</sup>	1.685 <sup>***</sup>	Vit (C), rosmarinic acid	x	x	x	5.836 <sup>†††</sup>	7.402 <sup>†††</sup>	298.935 <sup>†††</sup>	
<b>Zone 2 - Wicking Bed</b>											
Nasturtium	4	0.52	1.596 <sup>***</sup>	Vit (C), Min (Fe)		x		7.782 <sup>†††</sup>	9.870 <sup>†††</sup>	949.000 <sup>†††</sup>	
Mashua	2	1.614 <sup>††††</sup>	21.956 <sup>***</sup>	antioxidants, starch, fiber	x			24.160 <sup>†††</sup>	30.642 <sup>†††</sup>	2357.075 <sup>§§§§</sup>	
Sweet potato	2	6.961 <sup>**</sup>	131.4 <sup>††</sup>	Vit (A, C), Min (Ca, K)	x			104.470 <sup>‡‡</sup>	143.646 <sup>‡‡</sup>	3811.326 <sup>‡‡</sup>	
<b>Zone 2 - Biowick</b>											
Dwarf lemon	1	1 <sup>*****</sup>	45 <sup>***</sup>	Vit (C), Min (K)	x	x		14.965 <sup>†††</sup>	52.0 <sup>†††</sup>	3650.0 <sup>†††††</sup>	
Barbados cherry	3	3 <sup>*****</sup>	39.6 <sup>***</sup>	Vit (A, C), niacin	x	x		44.895 <sup>†††</sup>	56.940 <sup>†††</sup>	10950.0 <sup>†††††</sup>	
Kumquat	1	2 <sup>*****</sup>	119 <sup>***</sup>	Vit (C), fiber	x	x		14.965 <sup>†††</sup>	18.980 <sup>†††</sup>	3650.0 <sup>†††††</sup>	
Dwarf plum	3	3 <sup>*****</sup>	110.1 <sup>***</sup>	Vit (C), zeaxanthin	x			44.895 <sup>†††</sup>	56.940 <sup>†††</sup>	10950.0 <sup>†††††</sup>	
Passionfruit	3	2.5 <sup>*****</sup>	64 <sup>***</sup>	Vit (A, C), fiber, β-carotene	x	x	x	44.895 <sup>†††</sup>	56.940 <sup>†††</sup>	10950.0 <sup>†††††</sup>	
Kiwi	3	2.5 <sup>*****</sup>	68.1 <sup>***</sup>	Vit (C, K), Min (Ca), fiber	x			44.895 <sup>†††</sup>	56.940 <sup>†††</sup>	10950.0 <sup>†††††</sup>	
Crop Totals & Avg.	3.1	51.65	1715.39	Avg. Edible Biomass Density (kg/m <sup>2</sup> /d)	33.21			1168.127	1124.3	94160.0	
<b>Aquatic Crops: Photobioreactor and IMTA Crops</b>											
Spirulina (Dry mass)	4	400L	3.65	Vit (B), Min (Ca, K, Mg, Fe), niacin, essential amino acids	x			21.90	53.290	N/A	
Duckweed	N/A	N/A	3.37	protein, antioxidants	x			N/A	N/A	N/A	
Watercress	N/A	N/A	2.56	Vit (C, K), carotenoids	x	x		N/A	N/A	N/A	
Sacred lotus	N/A	N/A	8.27	TBD	x	x		N/A	N/A	N/A	
Aquatic Crop Totals & Avg.	4.0	400L	17.86					21.90	46.720	N/A	
<b>IMTA Seafood Species</b>											
Tilapia	N/A	N/A	36.31	Protein	x	x		N/A	N/A	N/A	
Jade perch	N/A	N/A	54.46	Protein, omega-3 fatty acids	x	x	x	N/A	N/A	N/A	
Barramundi	N/A	N/A	54.46	Protein, omega-3 fatty acids	x	x	x	N/A	N/A	N/A	
Prawn	N/A	N/A	10.14	Protein	x	x		N/A	N/A	N/A	
Crayfish	N/A	N/A	24.31	Protein	x	x		N/A	N/A	N/A	
Mussel	N/A	N/A	17.64	Protein	x	x		N/A	N/A	N/A	
Seafood Total			197.32								
<b>Total SIRONA Edible Biomass (kg/yr)</b>			<b>1930.56</b>	<b>Avg. Total SIRONA Edible Biomass = (kg)/CM-d</b>	<b>1.32</b>			<b>1190.027</b>	<b>1171.0</b>	<b>94160.0</b>	

Table 14 - biomass production, carbon content, and metabolic rates (Hava et al., 2019)



### III. Botanical candidates

#### III.II.III. Photosynthetic gas exchange

The process of photosynthetic gas exchange is one of the most crucial yet under-researched topics in space biology, with many current models still relying on limited theoretical estimates, rather than experimental data. Understanding the rate of photosynthesis directly links to edible biomass production, making it a cornerstone of any CELSS.

A notable early experiment conducted by Wilks (1962) contributes to this field by presenting 2 figures, which illustrate the photosynthetic rates for the family Lemnaceae (duckweed) (figures 2 and 3) over specific time intervals.

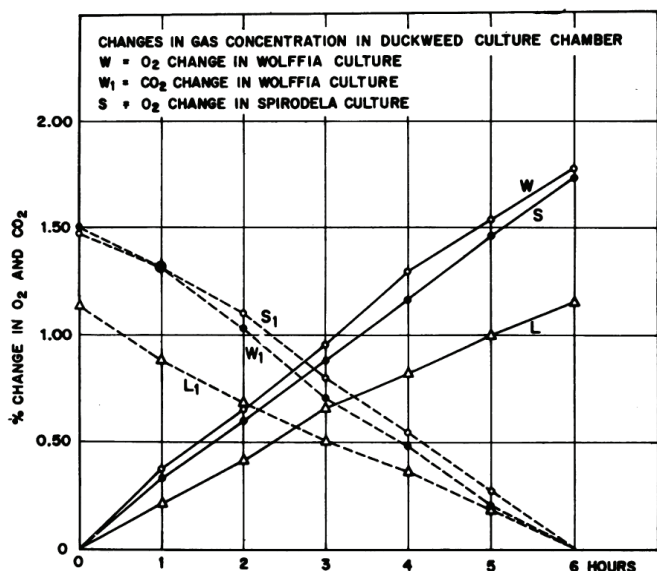


Figure 2 - changes in CO<sub>2</sub> and O<sub>2</sub> concentration in a growth chamber (Wilks, 1962)

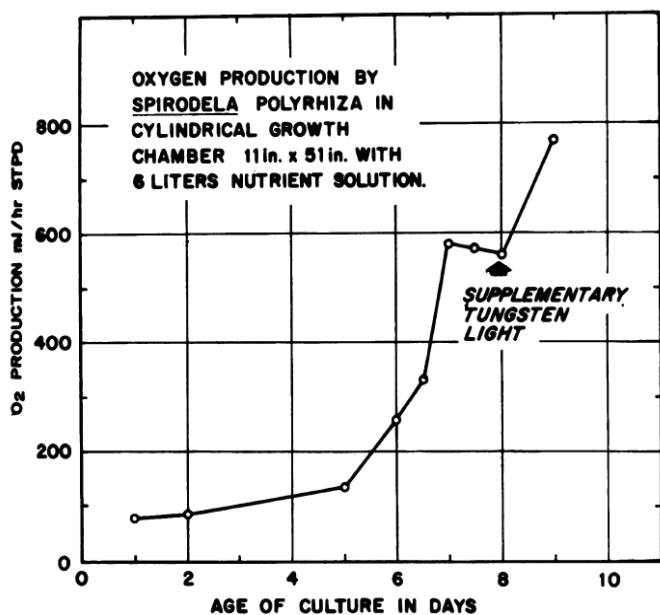


Figure 3 - rates of O<sub>2</sub> accumulation (Wilks, 1962)

Tables 13 and 14, besides crop yield, additionally give valuable insight into calculating the theoretical photosynthetic rate of crops in a controlled ecological environment.

A further study on photosynthetic gas exchange rates was conducted by Wheeler et al. (2003), providing valuable insights into how different crop species perform under controlled environmental conditions.

Multiple specimens of several key candidate crops - including wheat, soybean, lettuce, potato, and tomato - were cultivated and monitored. Each plant was grown in multiple methods: using a certain amount of the growth chamber, in combination with other species, and harvested before maturity, which explains the different results gathered for photosynthetic gas exchange rates.

The results of the study are summarised in Table 15 below, demonstrating different gas exchange rates. The findings highlight the sensitivity of crops to their surrounding environment and underline the importance of precise management of cultivation parameters in a CELSS.

Crop/Date	Days of Operation	Total Biomass	Edible Biomass	CO <sub>2</sub> <sup>1</sup> Fixed	O <sub>2</sub> <sup>1</sup> Produced	Water Collected
	(d)	(kg)	(kg)	(kg)	(kg)	(kg)
Wheat 881 <sup>2</sup>	77	23.06	9.24	35.5	25.8	3615
Wheat 882 <sup>3</sup>	64	26.14	early harvest	40.3	29.3	5700 <sup>4</sup>
Wheat 891	86	37.76	11.01	58.2	42.3	6903
Wheat 892	85	44.24	13.12	68.1	50.7	7809
Wheat 931	85	64.11	18.25	98.7	71.8	7500 <sup>4</sup>
Wheat 941 <sup>5,6</sup>	84	66.68	19.07	102.7	74.7	7600
Soybean 891	90	26.62	8.58	45.0	32.7	7758
Soybean 901	97	18.94	6.34	32.0	23.3	8211
Soybean 902	97	20.80	7.79	32.5	25.6	8450
Soybean 951 <sup>6,7</sup>	90	13.51	5.18	22.8	16.6	2594
Lettuce 901	28	---	sequential	harvest	study	---
Lettuce 902	28	2.84	2.60	4.2	3.1	976
Lettuce 911	28	3.54	3.24	5.2	3.8	998
Lettuce 921	28	3.57	3.36	5.2	3.8	1000 <sup>4</sup>
Lettuce 931 <sup>6</sup>	30	3.99	3.71	5.9	4.3	1074
Potato 911	105	45.58	14.89	68.4	49.7	8778
Potato 912	90	50.67	22.03	76.2	55.4	9361
Potato 921	105	55.42	37.64	83.1	60.5	7954
Potato 931	105	55.88	34.12	83.8	61.0	8546
Potato 941 <sup>6</sup>	418	272	167	409	296	28446
Tomato 951 <sup>6,7</sup>	84	11.03	5.15	16.6	12.1	3426
Tomato 961	87 <sup>8</sup>	33.87	17.06	50.9	37.0	12,700
<b>Total</b>	<b>1991</b>	<b>880</b>	<b>409</b>	<b>1344</b>	<b>980</b>	<b>149390</b>

<sup>1</sup> Estimated from total biomass and the percentage of carbon in tissue.  
<sup>2</sup> Only the upper half of the chamber used.  
<sup>3</sup> 3/4 of available growing area used; plant harvest prior to maturity.  
<sup>4</sup> Some missing data; totals estimated by interpolation of water use trend.  
<sup>5</sup> Data collected from level four only; water estimated until final data compiled.  
<sup>6</sup> Studies where half the plants were grown on recycled nutrients from an aerobic bioreactor.  
<sup>7</sup> Simultaneous test with tomato (10 m<sup>2</sup>) in half of the chamber and soybean (10 m<sup>2</sup>) in the other half.  
<sup>8</sup> Upper chamber harvested at 84 days; lower chamber harvested at 91 days.

Table 15 - life support outputs (Wheeler, et al., 2003)



## III. Crops

### III.II.IV. Seed viability and reproductive challenges

The creation of fertile seeds posed a significant problem in early space endeavours (Zabel et al., 2016).

The Salyut Space Station mission Malachite is one of the first space missions to study the fertility of plants in a microgravity environment. According to Harvey et al. (2011), the planted seeds grew and flowered, but in the end wilted, without producing any seeds. A similar situation appeared in Svetoblok, where seeds were produced, but none were viable (Zabel et al., 2016).

The first space mission to bring back created seeds from space was Phytion 2, from the Phytion series. 200 seeds were produced in a microgravity environment, and brought back to Earth (Zabel et al., 2016). According to further research, half of the seeds were immature, and around half of them (42%) produced normal plants (Harland, 2004; Salisbury, 1999)

Another notable space mission is the SVET GEMS, where 280 wheat heads were produced, but none of them contained any seeds, leading to the conclusion that pollen was either not formed or not released (Zabel et al., 2016).

The first recorded space mission to ensure normal seed productivity was the PGU and PGF units (Zabel et al., 2016). Further investigation showed that CO<sub>2</sub> enrichment and adequate ventilation were required to ensure acceptable seed production in a microgravity environment (Zabel et al., 2016).

Poulet et al. (2016) delve deeply into plant responses to a microgravity environment. This idea came to fruition after seed compositions and developmental stages from Earth and space were compared, and certain differences were noted (Musgrave et al., 2005; Brown et al., 1994).

It has been noted by Poulet et al. (2016) that changes in secondary metabolism cause stress-induced morphogenic responses, which are triggered by the new environment, “helping” the plant to survive and adapt. Furthermore, the responses can be attributed to the absence of gravity or the presence of UV. Stress-induced morphogenic responses are visible not only in different seed development and establishment, but also in flavour, aroma, and nutritional content compared to normal seeds (Musgrave et al., 1997).

## IV. Designing cultivation systems beyond earth

The following chapter represents the most extensively developed and comprehensively researched section of this review. It addresses the fundamental aspects of the process of plant cultivation in a microgravity environment and provides both theoretical considerations and evidence-based findings.

The chapter begins with an overview of the biological and technical requirements for plant cultivation in space. From this foundation, the chapter progressively explored specific aspects in further depth. As the chapter develops, the analysis moves beyond technical feasibility to highlight

broader implications, such as physiological effects on plants and psychological effects on human well-being.

Emphasis is placed on cultivation systems that have been implemented during previous missions, which serve as proven benchmarks for understanding the possibilities and limitations for growing plants in a space environment, but also for identifying existing gaps in knowledge.

The chapter forms the core of the paper, providing broad, yet insightful information for cultivation in a controlled ecological life support system based in an extraterrestrial environment.



## IV. Designing cultivation systems beyond earth

### IV.I. Geometries

Throughout history, the geometries of cultivation systems have generally followed a consistent pattern, most commonly taking the form of box structures with a rectangular base. This design offers simplicity, familiarity, and ease of integration into existing systems.

A notable exception from this rule is the Biogravistat system (Figure 4), which adopted the shape of a 1-foot-wide abstract depiction of a star, in order to enable cultivation under different levels of centrifugal force (Zabel et al., 2016). Further systems have adopted the aforementioned geometry. A detailed table has been provided by Zabel et al. (2016), showcasing the growth area (highlighted in red) of every aforementioned system from the “Evolution of plant growth chambers in space” chapter (Table 16).

Moreover, cultivation systems have been designed around the principle of integration into existing space. I.e., the Space Shuttle featured a 51cm x 36cm x 27cm design, which could fit into a middeck locker, similar to i.e.. Astroculture, PGBA, BPS (Zabel et al., 2016) and PGU (Porterfield et al., 2003).

As time went on, the cultivation geometries increased in size, as visible in Table 16 below. A notable mention is one of the latest cultivation systems, VEGGIE, which features a deployable design, allowing it to be stowed to 10% of its nominal deployed volume. Furthermore, in its collapsed configuration, 6 VEGGIE units can be stored in a single middeck locker. The growth units also provide a variable height of 5cm to 45cm (Zabel et al., 2016).



Figure 4 - Biogravistat system  
<https://asajournal.lt/articles/the-curious-case-of-lithuanian-astrobotany/>

	Spacecraft	First Launch	Platform (e.g. MDL)	Growth Area (m <sup>2</sup> )	Notable Information
Oasis 1	Salyut 1	1971	Wall mounted	0.001	first plant growth system in a crewed spacecraft
Oasis 1M	Salyut 4	1974	Wall mounted	0.010	produced first space grown crops (onions) eaten by humans
Oasis 1AM	Salyut 6	1977	Wall mounted	0.010	
Oasis 1A	Salyut 7	1982	Wall mounted	0.010	
Vazon	Salyut 6/ 7; Mir	1973	Wall mounted	n.a.	first ornamental plants
Malachite	Salyut 6	1973	Wall mounted	n.a.	first psychological investigations of human-plant interactions
Biogravistat/ Magnetobiostat	Soyuz 22; Salyut 6/7	1976	Wall mounted	n.a.	centrifuge to simulate different gravity levels; application of magnetic fields to plants
Svetoblok	Salyut 7; Mir	1982	Wall mounted	n.a.	first flowering of plants in space
Phyton	Salyut 7	1982	Wall mounted	n.a.	first successful seed-to-seed experiment
SVET	Mir	1990	Wall mounted	0.100	
SVET-GEMS	Mir	1995	Wall mounted	0.100	
PGU	STS	1982	MDL	0.050	
PGF	STS	1997	MDL	0.055	
ASC	STS	1992	MDL	0.021	
PGBA	STS	1996	2x MDL	0.075	
ADVASC	ISS	2001	2x MDL	0.052	
BPS	ISS	2002	EXPRESS	0.104	
Lada	ISS	2002	n.a.	0.050	first hazard analysis and critical control point (HACCP) plan for vegetable production units in space
EMCS	ISS	2006	4x MDL	0.077	
PEU	ISS	2009	n.a.	0.027	
ABRS	ISS	2009	MDL	0.053	Green Fluorescent Protein Imaging System
VEGGIE	ISS	2014	MDL	0.170	first plant growth system purposed for investigating food production in space

Table 16 - summary of plant growth chamber data (Zabel et al., 2016)



## IV. Designing cultivation systems beyond earth

A similarly proportioned growth chamber, but without variable height, is the APH measuring at 45,4cm x 40,8cm x 5,1cm, providing precise environmental control possibilities (Massa et al., 2016). Another example of environmental control possibility is the PGBA, which was developed for commercial space biotechnology research, featuring a growth volume of 0,075m<sup>3</sup> (Hoehn et al., 1998). The restricted growth areas on space missions are a result of spaceflight constraints, where mass, volume, and power limitations play a key role (Hoehn et al., 1998).

On the other hand, earth-based experiments allow bigger growth chambers, but less reliable results related to microgravity environment plant growth. The BIOS III experiment featured three food growth chambers, measuring at 14m x 9m x 2,5m each, adding up to 378m<sup>2</sup> of surface area in each chamber (Salisbury et al., 1997). An additionally notable Earth-based experiment is the SPB (Space Plant Box) (Kitaya et al., 2000). The paper served essentially as the conceptual and developmental blueprint for the SPB that later matured into an actual small ISS plant growth experiment inside the Japanese Kibo module.

### IV.II. Cultivation systems

This chapter provides a broad review of selected space missions and approaches to key subsystems for plant cultivation: atmospheric gas composition control, lighting requirements, thermal regulation, nutrient delivery, humidity control, and waste management. Each of the mentioned aspects will be analysed in further detail in the following chapters, but here they are introduced through a historical survey.

The history of these systems reflects a steady advancement in technology, attributed to not only technological advancements but also to lessons learned through trial and error. One of the earliest examples, Malachite, incorporated a

The growth chamber was shaped like a bag with 0,03m<sup>3</sup> of growth volume (Figure 5).

Further notable Earth-based research, done in the Neumayer III Antarctic research station, is the Mobile Test Facility (MTF) (Meinen et al., 2018). The facility featured 40 racks of cultivation spaces of 40cm x 60cm.



Figure 5 - Space Plant Box  
[https://global.jaxa.jp/press/2021/10/20211022-1\\_e.html](https://global.jaxa.jp/press/2021/10/20211022-1_e.html)

simple ion exchange resin, a basic water supply, and an illumination system (Porterfield et al., 2003).

A few space missions later, the Phyton chamber marked a step forward with the inclusion of a powerful lamp, a nutrient medium, and a ventilation system fitted with bacterial filters, which proved to be critical to enhance seed fertility and plant maturation (Zabel et al., 2016; Poulet et al., 2016). Phyton also introduced an automated seed-sowing apparatus (Porterfield et al., 2003).

Subsequent systems steadily expanded in complexity. SVET integrated light, ventilation, air supply, water, and power supply systems, along



## IV. Designing cultivation systems beyond earth

with a removable root module for plant cultivation (Zabel et al., 2016). Its successor, GEMS, featured an additional environmental monitoring system, replacing earlier sensors with new ones capable of monitoring air, soil conditions, leaf temperature, irradiance and oxygen (Zabel et al., 2016).

The Astroculture system consisted of tightly integrated controls, including temperature, humidity, LED lighting, fluid delivery control, and an ethylene scrubber unit to counteract plant growth inhibitors (Zabel et al., 2016). Its refinement, the Advanced Astroculture, expanded the original model with a fully enclosed plant growth chamber, upgraded light, temperature, and humidity control units, a fluid nutrient delivery system, and the possibility of atmospheric regulation (Zhou et al., 2002).

Other missions built on these principles with more specialised innovations. The PGBA featured a containment structure with a thermal and electrical control subsystem (Zabel et al., 2016). The LADA system distributed its functions across 4 interconnected modules: a control and display module, two growth modules, and a water tank. Furthermore, its root module, 9cm deep, was designed to house the substrate for the roots (Zabel et al., 2016)

The EMCS added the novel ability to apply different artificial gravity levels via 2 independent rotors, while also providing basic life support functions, and an internal video system for experiment observation (Zabel et al., 2016). Similarly, the PEU consisted of a CCD camera for monitoring but also a LED lighting system with red and blue LEDs and an automated watering system (Zabel et al., 2016). The ABRS further refined environmental control by enabling precise regulation of temperature, relative humidity, and CO<sub>2</sub> levels (Zabel et al., 2016).

One of the most recent developments,

VEGGIE, represents a simplified yet scalable approach. Each unit consists of three major subsystems: the lighting subsystem, the bellows enclosure, and the root mat, demonstrating operational simplicity for use onboard the ISS (Zabel et al., 2016).

R.M. Wheeler stands out as one of the most influential researchers in the field of CELSS. His extensive Earth-based experiments and theoretical studies provide an important framework on which current and future CELSS concepts are built.

In his 2012 work, Wheeler outlined a range of possible plant growth chamber concepts that illustrate the possible versatility of CELSS approaches. Among these were designs for an algal production system (Krauss et al., 1962) (Figure 6) and a surface deployable greenhouse (Rygalov et al., 2004) (Figure 7). Taken together, Wheeler's work and research introduce conceptual diversity.

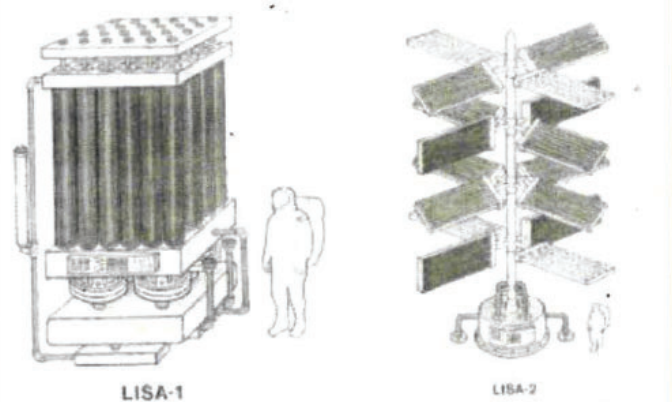


Fig. 6 - algal production system concept (Wheeler, 2012)



Figure 7 - deployable greenhouse concept (Wheeler, 2012)



## IV. Designing cultivation systems beyond earth

Another noteworthy conceptual cultivation system is the green wall garden prototype (Figure 8) developed by Sierra Nevada Corporation (SNC), explored by Morrow et al. (2017). The system, standing approximately 9 feet (2,75m) tall and consists of multiple modules measuring 4 feet (1,22m) x 2 feet (0,61m) x 2 feet (0,61m). The prototype is fitted with white, red, and blue LEDs to optimise photosynthesis, illustrating a vertical, wall-mounted approach to plant cultivation.

In parallel, a significant body of research has been conducted on the cultivation systems of Lemnaceae (duckweed), a group of small aquatic plants with considerable potential for CELSS application (Escobar et al., 2017). Duckweed is a fast-growing, high-nutrient-content plant, typically cultivated in shallow trays containing a few mm of water (Coughlan et al., 2022).

Coughlan et al. (2022) highlight 2 principal cultivation methods: stationary (batch) and flow-through (or continuous). Flowthrough (Figure 9) operates on the basis of nutrient solution circulation, whereas stationary cultivation provides no flow of nutrients. Both systems can be configured as flat or stacked systems. Importantly, duckweed cultivation aligns with the broader recommendation that most CELSS should employ hydroponics, given the extensive history of hydroponic experiments in space research. This

body of prior work provides a degree of reliability and maturity for hydroponics as the baseline cultivation method for space-based plant cultivation (Nelson et al., 2009).

Further cultivation strategies include spread harvesting (Meinen et al., 2018), most commonly applied to salad-type crops. The harvest method consists of cutting outer or larger leaves, leaving a central portion of the plant intact.

In addition, planting density plays a significant role in determining yield. Studies have demonstrated that plants grow thicker and smaller when placed densely (Meinen et al., 2018; Zhang et al., 2020), but result in higher photosynthetic value (Meinen et al., 2018).

Another important design factor of plant growth chambers in CELSS is their encapsulated structure. Such systems typically require a different atmospheric composition compared to humans (Hoehn et al., 1998), with controlled CO<sub>2</sub> and humidity levels optimised for photosynthesis and growth.

Finally, crop morphology influences the design of structural supports within cultivation systems. Tall-growing crops (i.e., wheat, tomatoes) require mechanical support structures, whereas low-growing (i.e, salad-type crops) can be cultivated without additional support systems (Wheeler et al., 2003).



Figure 8 - deployable greenhouse concept (Wheeler, 2012)

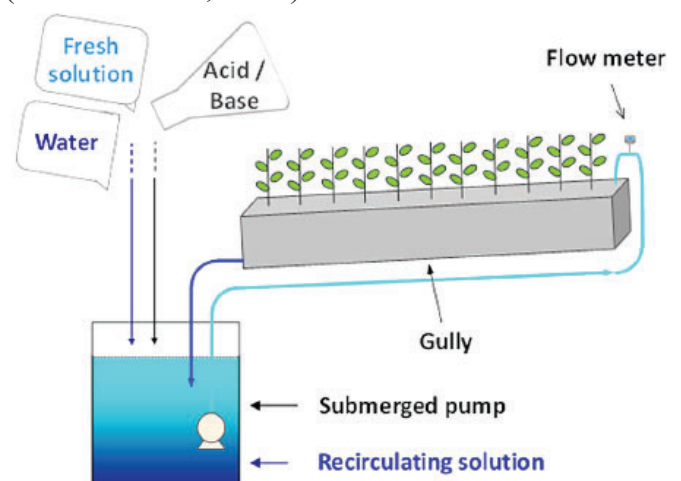


Figure 9 - flowthrough cultivation (De Pascale et al., 2021)



## IV. Designing cultivation systems beyond earth

### IV.III. Nutrient delivery systems (NDSs)

A water and nutrient delivery system (NDS) forms the operational backbone of any CELSS, ensuring the provision of enough water, nutrients, and aeration to the roots, while supporting growth from seed to harvest (Morrow et al., 2017; MacElroy et al., 1984; Poulet et al., 2016).

OASIS 1M, one of the earliest space missions to date, employed vessels filled with a fibrous ion exchange medium pre-charged with nutrients, while its water reservoir contained a mixture of water and silver ions (Porterfield et al., 2003). Building on this foundation, Malachite similarly relied on ion exchange resins, whereas Svetoblok introduced a 1,5% agar-based nutrient delivery system in combination with the Oasis water supply approach (Porterfield et al., 2003). Continuing the use of agar-based media, the PGC utilised a layered structure of urethane foam and Miracloth positioned over an agar slab (Porterfield et al., 2003).

Significant innovation in NDSs' design can be attributed to the Phyton series. In particular, Phyton-2 introduced an interchangeable plant pod system with ion-exchange nutrient media, as well as an automated watering system capable of delivering precisely defined quantities of water (Zabel et al., 2016). Similarly, the PEU featured a lower chamber containing a rockwool growth medium, which was supplied via an integrated water line (Zabel et al., 2016).

The VEGGIE units, by contrast, are infamous for their operational simplicity. They employed a passive nutrient delivery system approach using a root mat (Zabel et al., 2016). The root mat required a minimal amount of crew intervention to add water and nutrient solution (Morrow et al., 2005). Following a period of trial and error, specially developed rooting pillows were selected as the preferred growth medium,

after extensive testing of alternative substrates (Massa et al., 2013; Stutte et al., 2011)..

To consolidate decades of progress, Zabel et al. (2016) compiled a comparative table summarising the variety of NDS technologies used in past space missions, providing a valuable overview of the evolution (Table 17).

Nutrient delivery subsystem	
Oasis 1	Two compartment system (water and ion exchange resin)
Oasis 1M	Fibrous ion exchange medium
Oasis 1AM	Cloth ion exchange medium
Oasis 1A	Included root zone aeration system
Vazon	Cloth sack filled with ion exchange resin
Malachite	Ion exchange resin, water supply
Biogravistat/ Magnetobiostat	n.a.
Svetoblok	Agar based, later also used other media
Phyton	1.5% agar nutrient medium
SVET	Polyvinyl formal foam surrounded perforated tubing wrapped in a wick within zeolite based substrate enriched with nutrients
SVET-GEMS	Similar to SVET but with additional sensors
PGU	Passive system capable of containing varied substrates/materials
PGF	Passive system capable of containing varied substrates/materials
ASC	Porous tubes in matrix
PGBA	Agar, soil or growth substrate in gas permeable polypropylene bags with option to connect bags to water supply
ADVASC	Porous tubes in matrix
BPS	Porous tubes in matrix
Lada	Perforated tubing wrapped in a wick within a matrix
EMCS	Water reservoir providing water to experiment unique nutrient delivery equipment
PEU	Rock wool fed by integrated water line
ABRS	Experiment specific
VEGGIE	Passive NDS, rooting pillows, manual water and nutrient supply

Table 17 - history of NDSs (Zabel et al., 2016)

The most recent system, the APH, represents the state-of-the-art, integrating a porous-tube water delivery system embedded within a solid substrate containing controlled-release fertiliser, allowing efficient root growth (Massa et al., 2016).

Porous tubes (and plates) have been repeatedly highlighted as a particularly promising candidate for future NDSs (Zabel et al., 2016; Kitaya et al., 2000; De Pascale et al., 2021; Monje et al., 2003; Poulet et al., 2016; Hoehn et al., 1998). Their advantage lies in the way they counteract water distribution issues in microgravity (Poulet et al., 2016). The paper from Poulet et al. (2016) gives an adequate explanation: due to cohesive forces, water in microgravity tends to accumulate



## IV. Designing cultivation systems beyond earth

around water supply tubes rather than dispersing evenly, which prevents uniform root hydration (Dreschel et al., 1989; Casado, 2006).

Earlier NDSs, such as the Oasis series, struggled with precisely this problem - poor water distribution and lack of aeration in the roots (Porterfield et al., 2003). By contrast, later systems such as Astroculture or SVET introduced porous tubes to deliver water and nutrients to the plants by capillary action (Porterfield et al., 1984; Morrow et al., 1994), improving hydration and oxygenation at the root zone. Capillary-based systems offer a highly reliable NDS for long-duration missions. They counteract the challenge of controlling fluid flows in microgravity (Morrow et al., 2017), due to their gravity independence (Kitaya et al., 2000; De Pascale et al., 2021), while also simultaneously preventing oxygen deprivation (Hava et al., 2019). Building on this principle, De Pascale et al. (2021), explored membrane hydration systems, which, like porous tubes, operate on capillary action.

In contrast, several authors have emphasised aeroponics as a promising NDS candidate (MacElroy et al., 1984; Morrow et al., 2017). Compared to porous tubes or membrane hydration approaches, aeroponics eliminates the need for a rooting matrix, reduces system mass, improves logistical efficiency, and offers advantages in robustness, maintenance, and repair (Morrow et al., 2017).

Another candidate is the Nutrient Film Technique (NFT) recommended by some authors (Polutchko et al., 2022; Wheeler et al., 2003). NFT exploits the cohesive properties of water, allowing small films of water to adhere to shallow growth trays and support plant growth, i.e., Lemnaceae (duckweed) (Polutchko et al., 2022). However, NFT requires a continuous flow of water to remain effective (MacElroy et al., 1984).

Morrow et al. (2017) emphasise the use of

premixed nutrient solution or slow-release pills incorporated into the rooting material, while sponges or gels are noted as adequate short-term NDS options (Morrow et al., 2017).

The required nutrient composition varies across studies: Wilks (1962) reports using Hoagland's solution with iron sequesterant, a standardised hydroponic mix, providing essential elements for plant nutrition in a large variety of plant species, whereas Wheeler et al. (2003) specify a tailored salt-based solution required for NFT cultivation (Table 18).

Coughlan et al. (2022) highlight that growth media should be purpose-specific, i.e., synthetic substrates for biomass growth or waste streams for phytoremediation of water.

Earlier to this study, MacElroy et al. (1984) explored a microbial and chemosynthetic food source for growing plants, while Hava et al. (2019) emphasised nutrient recycling technologies such as growstone with housed bacteria that process waste into plant-available nutrients.

Nutrient uptake is not constant, as it depends on the species, growth phase, and environment (Poulet et al., 2016). A baseline water rate value required to sustain CO<sub>2</sub> uptake and growth is estimated at 1-10L/m<sup>2</sup>d, which in turn influences chamber humidity (Rygalov et al., 2004)

Macro-nutrients						
Salt	N	P	K (mmol L <sup>-1</sup> )	Ca	Mg	S
KNO <sub>3</sub>	2.5		2.5			
Ca(NO <sub>3</sub> ) <sub>2</sub>	5.0			2.5		
MgSO <sub>4</sub>					1.0	1.0
KH <sub>2</sub> PO <sub>4</sub>		0.5	0.5			
Startup Concentration	7.5	0.5	3.0	2.5	1.0	1.0
Refill Concentration	70	10	56	12	10	10
Micro-nutrients						
	Fe	Mn	Zn mmol L <sup>-1</sup>	Cu	B	Mo
Fe-HEDTA	50					
MicroNutrients		7.4	0.96	0.52	9.5	0.01
Startup Concentration	50	7.4	0.96	0.52	9.5	0.01
Refill Concentration	134.0	96.0	12.5	6.8	123.5	0.13

Table 18 - Nutrient solution for NFT (Wheeler et al., 2003)



## IV. Designing cultivation systems beyond earth

### IV.IV. Humidity control

The backbone of photosynthesis is the water cycle, where humidity control plays a crucial role (Hoehn et al., 1998). Within a plant growth chamber, water enters the air due to evaporation primarily through the stomata, but also through evaporation in the root zone, growth substrate, and plant tissue (Hoehn et al., 1998).

Uncontrolled water loss can compromise the overall efficiency of a CELSS, making planned compensations mandatory. Such measures include proper root zone closure (Hoehn et al., 1998) and the systematic recycling of condensate back into the NDS (Massa et al., 2016).

Hoehn et al. (1998) provide a detailed framework for how a humidity control system should be approached. The system should be based on dew point control, where surface tension and centrifugal forces are harnessed to separate condensed water from the airstream, ensuring its recovery and reintegration back to the NDS. A

practical example of this is seen in the PGBA, which implemented a gravity-independent humidity control system known as porous-plate technology. In this system, porous, sintered, stainless-steel plates, primed with water, are mounted over a water-filled cavity. By cooling the plates below the dew point and applying constant suction pressure, condensation is achieved directly on the plate surface. The condensed water was then collected and recycled, with daily recovery rates ranging between 100-200g. General humidity was controlled through adjustments to plate temperature and suction levels.

Beyond simple air humidity, control and monitoring of moisture distribution within the growth medium itself is equally important for optimising plant growth in microgravity (Monje et al., 2003). Massa et al. (2016) emphasised that maintaining chamber humidity between 50% and 86% should be prioritised.

### IV.V. Atmospheric gas composition

Spaceflight plant growth systems depend on highly complex and controlled environmental control systems, where regulation must extend beyond pressure and temperature to include the composition of atmospheric gases such as oxygen ( $O_2$ ), carbon dioxide ( $CO_2$ ), and trace gases (Hoehn et al., 1998). Maintaining the correct balance of the aforementioned gases is essential for both plant physiology and overall system stability. Gas composition is dependent on multiple interacting factors, including light intensity, day-night cycles, net  $O_2$  production through photosynthesis, and net  $CO_2$  uptake (Hoehn et al., 1998).

Zabel et al. (2016) note that SVET was the first documented space mission to incorporate a ventilation system. Positioned near the lamps, it provided both thermal regulation and an air flow up to 0,3m/s, while its main function was ensuring

adequate  $O_2$  supply to the plant roots. Its successor, SVET-GEMS, introduced a more advanced atmospheric control system by dividing the airflow into two separate streams. This upgrade also enabled analysis of the  $CO_2$  and  $H_2O$  levels of both incoming and outgoing air, as well as measurements of absolute and differential pressure (Zabel et al., 2016; Porterfield et al., 2003).

Atmospheric regulation continued to advance with later space missions. On the Space Shuttle mission, enhancements to gas composition systems allowed for direct control of  $CO_2$  levels (Zabel et al., 2016). A comprehensive overview of these systems, along with their capabilities, is provided by Zabel et al. (2016) in a detailed comparative table of atmosphere management technologies used in plant growth chambers (Table 19).



## IV. Designing cultivation systems beyond earth

	Temperature and humidity control	CO <sub>2</sub> control	Trace gas control	Additional information
Oasis 1	no	no	no	Closed vegetation boxes.
Oasis 1M	no	no	no	Closed vegetation boxes.
Oasis 1AM	no	no	no	Closed vegetation boxes.
Oasis 1A	n.a.	n.a.	n.a.	Ventilation fan to remove excessive heat generated by lamps. Plants grew in cabin atmosphere.
Vazon	n.a.	n.a.	n.a.	Plants grew in cabin atmosphere.
Malachite	no	no	no	Closed vegetation box.
Biograssiat	no	no	no	Closed vegetation box.
Magnetobiostat	no	no	no	Closed vegetation box. Sterile environment.
Svetoblok	no	no	no	Ventilation including bacterial filters.
Phyton	partly	no	no	Ventilation fan to remove excessive heat generated by lamps. Oxygen supply to the root module. Environmental condition sensor package including temperature, humidity, substrate moisture.
SVET	partly	no	no	Two separate air streams (one for plants one for cooling lamps). Large environmental sensor package, including: photosynthesis and transpiration measurements, CO <sub>2</sub> and O <sub>2</sub> sensors, temperature, humidity, substrate moisture.
SVET-GEMS	only temperature	no	no	Could be equipped with an air exchange system, when sacrificing 1/5 of the cultivation area.
PGU	only temperature	no	no	Ethylene filter.
PGF	yes	yes	yes	Ethylene scrubber unit to fully oxidize ethylene to CO <sub>2</sub> and water.
ASC	yes <sup>a</sup>	yes <sup>b</sup>	yes <sup>c</sup>	Ventilation with cabin air. Adsorption beds to keep CO <sub>2</sub> level within requirements. Same ethylene scrubber technology as ASC.
PGBA	yes	yes	yes	Same equipment as in ASC.
ADVASC	yes	yes	yes	Injection of pure CO <sub>2</sub> . Ethylene scrubber and particulate filter. Photosynthesis and transpiration measurements.
BFS	yes	yes	yes	Gas supply unit, pressure control unit, ethylene removal unit.
Lada	yes	no	no	VOC removal with potassium permanganate (KMnO <sub>4</sub> ).
EMCS	yes	yes	yes	Cabin air to control temperature and CO <sub>2</sub> level.
PEU	yes	yes	no	
ABRS	yes	yes	yes	
VEGIE	only temperature	no	no	

<sup>a</sup> First integrated for ASC-3 mission.

<sup>b</sup> First integrated for ASC-6 mission.

Table 19 - atmospheric control systems (Zabel et al., 2016)

The APH incorporates a sophisticated atmospheric control unit capable of regulating CO<sub>2</sub> concentrations between 500-5000 μmol/mol and maintaining the air flow in the range of 0,3-1,5m/s. The system can also disable CO<sub>2</sub> regulation to conduct CO<sub>2</sub> drawdowns for photosynthesis studies (Massa et al., 2016).

From a broader life-support perspective, maintaining the balance between CO<sub>2</sub> uptake and O<sub>2</sub> production is critical. The average human respiratory quotient lies in the range of 0,8 and 0,9 (Poughon, 1997), which led ESA's MELiSSA project to establish an objective of recycling 1,1-1,3 mol of O<sub>2</sub> per mol of CO<sub>2</sub> consumed, a balance which is achieved by all candidate crops (i.e., wheat, rice, soybean, potato, and lettuce) (Poulet et al., 2016).

However, gas regulation presents challenges on both sides of the cycle. A high concentration of O<sub>2</sub> can inhibit photosynthesis and limit plant growth, necessitating oxygen removal systems such as semi-permeable membrane systems (i.e., pressure swing adsorption units) or oxygen absorbers (Hoehn et al., 1998). Conversely, CO<sub>2</sub> has to be supplied to the plant chamber atmosphere either from pressurised pure CO<sub>2</sub> systems or drawn from the cabin atmosphere (Hoehn et al., 1998).

On the other hand, accurate monitoring of CO<sub>2</sub> levels is essential. Hoehn et al. (1998),

Kitaya et al. (2000), Samsonov et al. (1993) recommend the use of small infrared gas sensors with high accuracy to track CO<sub>2</sub> concentrations, while increased CO<sub>2</sub> concentrations can be controlled using chemical scrubbers, such as lithium hydroxide (LiOH) or barium hydroxide (Ba(OH)<sub>2</sub>), or in some cases, venting excess CO<sub>2</sub> directly into space (Samsonov et al., 1993).

Maintaining an appropriate gaseous environment is critical for plant development, but optimal values remain a subject of debate. For example, Salisbury et al. (1997) reported optimum growth rates in the BIOS III experiment when CO<sub>2</sub> exceeded 0,3% of the atmospheric composition of the growth chamber (Table 20), whereas Meinen et al. (2018) identified that 750ppm (0,075%) of CO<sub>2</sub> was the most beneficial concentration.

Keeping CO<sub>2</sub> levels within a safe range could be of importance, as elevated levels can trigger plants to produce excessive levels of ROS (Reactive Oxygen Species) (Polutchko et al., 2022), however, this phenomenon appears to be context-dependent, as some sources suggest that its environment environment-dependent.

Gas composition is also closely linked to pressure regulation. Rygalov et al. (2004) note that a baseline value below 1atm (101 325Pa) would deem feasible, but reducing pressure below 25kPa compromises plant physiology, as it renders growth incompatible with normal development (Rygalov et al., 2004).

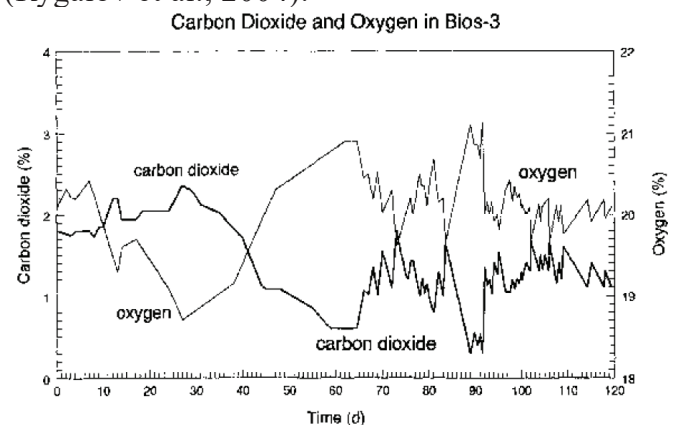


Table 20 - BIOS III CO<sub>2</sub> levels (Zabel et al., 2016)



## IV. Designing cultivation systems beyond earth

### IV.VI. Lighting requirements

Lighting remains one of the major challenges because of its high power demand (Morrow et al., 2017). Beyond simply providing illumination for photosynthesis, lighting systems must account for additional factors such as photoperiod, intensity and spectral composition, all of which seem to play an ever-growing role in supporting plant growth (Hoehn et al., 1998).

Early space missions experimented with a variety of illumination strategies for plant cultivation. In Oasis 1AM, the lighting system was modular, allowing easier maintenance (Zabel et al., 2016). By contrast, Vazon, had no dedicated lighting system at all, as the illumination was simply provided by the spacecraft's own lighting system (Zabel et al., 2016). A breakthrough came with Phyton-II, where it was observed for the first time that plants grew better when exposed to natural sunlight near a porthole (Zabel et al., 2016). The SVET system presents a major advancement by introducing 12 small fluorescent lamps (Zabel et al., 2016). From that point until Astroculture, most systems relied on fluorescent lighting. The shift began with Astroculture, and later, i.e.. ABRS and VEGGIE, which all employed LED (Light Emitting Diode) lighting (Zabel et al., 2016; Stutte et al., 2011; Poulet et al., 2016). ABRS, in particular, implemented a system of 303 LEDs, primarily red and blue, but also including white and green (Zabel et al., 2016).

According to Massa et al. (2006) and Morrow et al. (2017), LEDs represent the future of space-based plant lighting. Their advantages include small size, low weight, long operational lifetimes, and a cool-emitting surface (Bourget, 2008). As solid-state light sources, they also reduce power consumption and energy costs per unit of growing area compared to fluorescent lighting (Poulet et al., 2014a).

Spectral composition strongly influences plant growth and development, with each major wavelength playing distinct physiological roles:

- **Red light plays** a key role in photosynthesis by supporting the development of the photosynthetic apparatus (De Pascale et al., 2021). Together with blue light, it presents one of the most efficiently absorbed wavelengths by plants (McCree, 1971). When combined with blue wavelengths, red light forms the backbone of photosynthesis (De Pascale et al., 2021; Zabel et al., 2016), often reducing need for high-intensity lighting (Poulet et al., 2016).
- **Green light** has unique properties that complement red and blue wavelengths. Because of its deeper penetration into leaf mesophyll and canopy layers, it reaches the deepest chloroplasts located in less irradiated leaves (De Pascale et al., 2021). This enables a more efficient rate of acclimation to light conditions in parts of the plant canopy that would otherwise remain under-illuminated (De Pascale et al., 2021).
- **Blue light** influences a wide range of physiological processes beyond photosynthesis. It regulates stomatal opening, promotes chlorophyll biosynthesis, and affects plant morphology, including plant height (De Pascale et al., 2021). Although blue light is less efficient for photosynthetic conversion, it is critical for photomorphogenesis, supporting stem elongation and leaf expansion (Hoenecke et al., 1992; Dougher et al., 2001).
- **Far-red light** acts primarily as a developmental signal. It stimulates flowering in long-day plants and, when combined with red light, regulates processes such as stem elongation, branching, leaf expansion, and reproduction (De Pascale et al., 2021).



## IV. Designing cultivation systems beyond earth

Most of the early plant growth chambers (excluding Oasis systems and the PGU) were capable of providing more than  $200\mu\text{mol}/\text{m}^2\text{s}$ , which is generally sufficient for the cultivation of most crops in space (Zabel et al., 2016). For instance, the SVET-GEMS's system reached intensities up to  $500\mu\text{mol}/\text{m}^2\text{s}$ , which enabled extensive experiments on wheat (Zabel et al., 2016).

Hava et al. (2019) noted that intensities of around  $350\mu\text{mol}/\text{m}^2\text{s}$  served as adequate to sustain consistent carbon fixation. Building on this, Meinen et al. (2018) tested 4 different light intensity levels - 200, 300, 450, and  $600\mu\text{mol}/\text{m}^2\text{s}$  - combined with  $35\mu\text{mol}/\text{m}^2\text{s}$  of far-red radiation. Their results indicated that high light intensities ( $>600\mu\text{mol}/\text{m}^2\text{s}$ ) reduce crop quality (Table 21), although Hoehn et al. (1998) reported that higher light levels can enhance net  $\text{O}_2$  production.

Other studies point to the benefits of short-term bursts of high-intensity light. For example, Hava et al. (2019) suggest that short pulses ranging from 800 to  $1000\mu\text{mol}/\text{m}^2\text{s}$  for 5 minutes, repeated 5 to 6 times daily, increased the photoprotective carotenoid content of leafy crops without reducing biomass production. However, Zabel et al. (2016) cautioned that prolonged exposure to higher light intensities has been shown to damage or even kill

plants (Zabel et al., 2016). Conversely, insufficient light,  $20\text{-}80\mu\text{mol}/\text{m}^2\text{s}$ , results in a net  $\text{O}_2$  consumption and net  $\text{CO}_2$  release, making it unsuitable for sustaining plant growth.

Meinen et al. (2018) also investigated the effects of simulating natural light cycles by gradually adjusting illumination levels and providing plants with periods of little to no illumination (Table 22). This approach mimics natural transitions, reducing plant stress. Similarly, a report by Wilks (1962) emphasises the importance of simulating full day-night cycles, reporting significant benefits for growth and biomass production when photoperiods were maintained (Table 23).

Drysdale (1994) and Poulet et al. (2016) highlight that significant efficiency gains could be achieved by utilising natural sunlight directly for plant photosynthesis during the day, thereby reducing the overall energy consumption of artificial lighting systems. One proposed method is the integration of sunlight collection systems in addition to LEDs, where parabolic mirrors collect sunlight and transmit it through optical fibres to a greenhouse module (Nakamura et al., 2009; Nakamura et al., 2013).

Time	Light strategy	R:FR ratio
04:00-04:15	Simulation of sunrise, $90\mu\text{mol m}^{-2}\text{s}^{-1}$	0.77
04:15-05:00	50% desired light intensity	
05:00-20:00	100% desired light intensity	4-12*
20:00-20:45	50% desired light intensity	
20:45-21:00	Simulation of sunset, $90\mu\text{mol m}^{-2}\text{s}^{-1}$	0.77
21:00-04:00	Night	

\* depending on maximum light intensity.

Table 22 - daylight simulation (Meinen et al., 2018)

Light ( $\mu\text{mol m}^{-2}\text{s}^{-1}$ ) Crop	Harvest	Proportional shoot biomass relative to the biomass at $200\mu\text{mol m}^{-2}\text{s}^{-1}$			
		200	300	450	600
Lettuce 'Expertise'	single	1	1.28	1.61	1.26
	spread	1	1.16	1.15	1.21
Lettuce 'Outredgeous'	single	1	1.10	1.16	1.25
	spread	1	1.11	1.28	1.35
Lettuce 'Othilie'	single	1	0.86	0.87	0.98
	spread	1	1.04	1.16	1.21
Red mustard 'Frizzy lizzy'	single	1	0.70	1.32	1.18
	spread	1	1.49	1.10	1.89
Rocket 'Rucola cultivated'	single	1	0.94	0.93	0.72
	spread	1	1.15	0.83	0.91
Swiss chard 'Ruby red'	single	1	1.09	1.11	1.15
	spread	1	1.09	0.86	0.99
Spinach 'Golden eye'	single	1	1.20	1.09	0.98
	spread	1	0.93	1.23	1.11

Table 21 - effects of light intensity (Meinen et al., 2018)

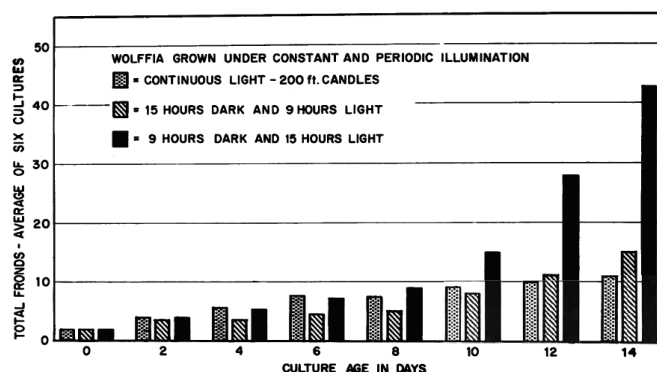


Table 21 - effects of simulating (Wilks, 1962)



## IV. Designing cultivation systems beyond earth

### IV.VII. Thermal regulation

A fully electronically equipped CELSS would produce considerable amounts of heat (Drysdales, 1994). In space, however, thermal regulation presents a unique challenge because natural convective cooling is impossible in microgravity. (Morrow et al., 2017).

To address this, Hoehn et al. (1998) proposed designing temperature and cooling systems that can operate in the absence of natural convection. Forced convection, achieved by moving air or using fluid-to-fluid heat exchangers, can maintain lamps at an acceptable temperature (Morrow et al., 2017). Kitaya et al. (2000) further explored two potential solutions: 1. a simple heat sink and a fan, and 2. a thermoelectric Peltier cooler. The latter has the added advantages of being directly linked to humidity regulation, as it can condense water vapour for reusing liquid water. Importantly, every thermal management strategy should balance efficiency with minimal electric power consumption (Kitaya et al., 2000).

Historically, thermal regulation hasn't been a major limitation in space cultivation,

since excess heat could easily be vented (Zabel et al., 2016). For example, the Space Shuttle featured an environmental control system using fans and a heater (Zabel et al., 2016), while the PGU employed temperature sensors, electronically controlled fans, and a heater (Porterfield et al., 2003). The APH represents a more advanced system. capable of sensing leaf and root-zone temperature, while maintaining the temperature in the growth chamber between 18°C and 30°C.

Optimal cultivation temperature depends on the crop species. Meinen et al. (2018) suggest that a general temperature range of 21°C-25°C would suit most plants, with 20°C being the most energy-efficient. Some crops, such as Lemnaceae (duckweed) prefer higher ranges (25°C-31°C (Escobar et al., 2017)) but show unfavourable growth below 15°C (Romano et al., 2021). Some other species, such as potatoes and wheat, thrive in cooler conditions (Wheeler et al., 2003).

Finally, an avenue worth exploring would be the use of thermal differentials for power scavenging, turning excess heat into usable energy.

### IV.VIII. Waste management

Contaminants, VOCs (Volatile Organic Compounds), such as trace gases (i.e., ethylene), and accumulation of inedible biomass can significantly impair plant growth and development, making their management a critical concern (Morrow et al., 2017).

In early space missions, ethylene levels posed as particularly problematic. Elevated ethylene levels interfered with plant fertility, leading to aborted seed production (Zabel et al., 2016). Ethylene (C<sub>2</sub>H<sub>4</sub>) regulates numerous aspects of plant physiology, including seed germination, tissue differentiation, growth regulation, and root branching and elongation (Schaller, 2012; Reid, 1987; Gamalero et al., 2015). Often considered as

an “ageing” hormone (Schaller, 2012), ethylene remains the primary substance of concern, as unstable concentrations can negatively influence overall cultivation outcomes (Morrow et al., 2017). This recognition prompted the introduction of ethylene control in missions such as SVET-GEMS, where ethylene filters and trace contaminant control became a necessity for future space missions such as the Space Shuttle (Zabel et al., 2016), PGF (Porterfield et al., 2003) and APH (Massa et al., 2016). In contrast, LADA and VEGGIE relied on cabin air, limiting the ability to measure ethylene levels and gas exchange accurately.

Ethylene removal has primarily relied on



## IV. Designing cultivation systems beyond earth

ethylene scrubbers, with absorbents such as  $\text{KMnO}_4$  or  $\text{LiOH}$ , or through photocatalytic systems (Morrow et al., 2017; Massa et al., 2016; Hoehn et al., 1998). AstroCulture was the first system to include active trace gas control via an ethylene scrubber (Zabel et al., 2016). Absorbent-based systems, while effective, are logistically intensive, require more power, and may introduce toxic compounds (such as  $\text{LiOH}$ ) (Morrow et al., 2017). Photocatalytic systems, on the other hand, require protection from crew members against UV light used to activate the catalyst (Morrow et al., 2017). Both methods produce vapour and  $\text{CO}_2$  as byproducts (Morrow et al., 2017). To ensure safe operation, some studies suggest maintaining ethylene levels below 25ppb (Massa et al., 2016), while others propose a limit of 50ppb (Poulet et al., 2016). Monje et al. (2003) and Hoehn et al. (1998) state that even such low concentrations may significantly impact crop yields. Wheeler et al. (1996), therefore, advocated for the cultivation of dwarf plants as a countermeasure, as a system reliant on many small plants would be less vulnerable to VOC-related plant failures.

On average, crops exhibit a harvest index of around 50%, meaning half of the biomass is inedible and must be (Poulet et al., 2016) (Figure 10). Wheeler (2003) proposed exploring woody ultra-dwarf fruit trees (<1m height), which

could not only provide food but also usable wood. Some of the possibilities of inedible biomass management include: 1. oxidation to resupply  $\text{CO}_2$ , 2. use of inedible biomass for creating soil or fertiliser, 3. oxygen yield ( $\text{CH}_2\text{O}$  into  $\text{CO}_2$  and  $\text{H}_2\text{O}$  and then electrolysis of  $\text{H}_2\text{O}$ ), and 4. usable products (i.e., paper, wood) (Wheeler, 2003).

Several other methods of handling wastewater and waste material have been investigated. Aerobic digestion employs aerobic bacteria to break down waste, while direct wet oxidation exposes organic matter to high temperatures and oxygen at high pressure, rapidly oxidising it into  $\text{CO}_2$  (MacElroy et al., 1987). Attention must also be given to nutrient and pollutant management from wastewater (Escobar et al., 2017; Coughlan et al., 2022). Duckweed has proven particularly promising in this regard, as several investigations observed faecal coliform reductions of 50% to 90% wastewater (Escobar et al., 2017). Escobar et al. (2017) noted that only around 2-3 $\text{m}^2$  of duckweed is required to treat wastewater for one individual. The ISS uses a physicochemical LSS (Life Support System) (Poulet et al., 2016). Through electrolysis and the Sabatier process,  $\text{H}_2\text{O}$  and  $\text{O}_2$  can be produced in small but considerable amounts (Bagdigian et al., 2005; Burkey et al., 2010). Urine is recycled into potable water with the Urine Processor Assembly,

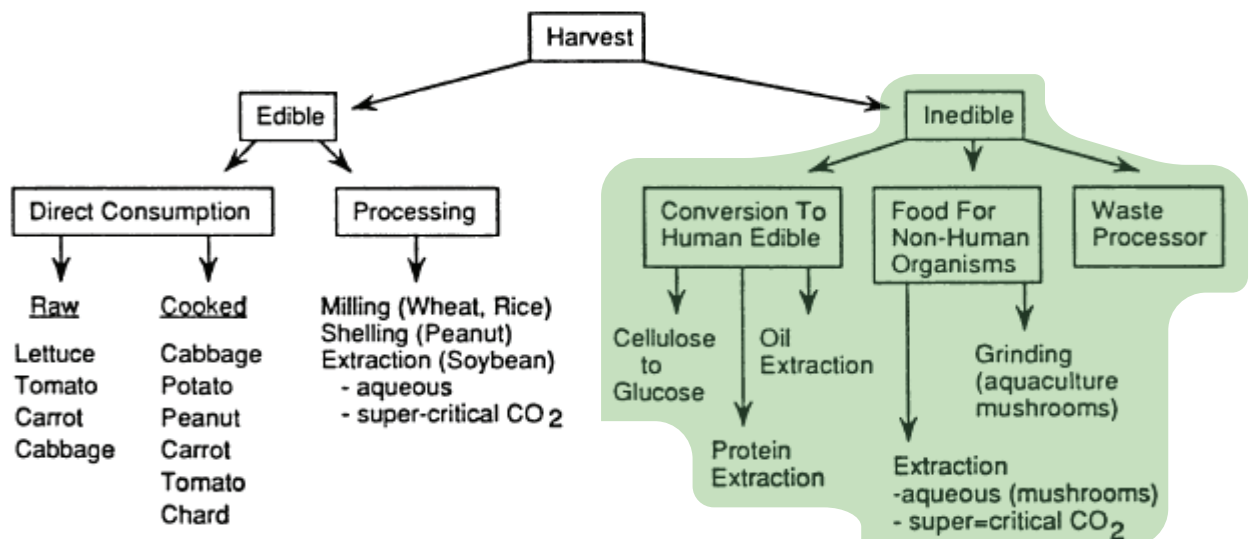


Figure 10 - food processing flow chart (Schwartzkopf, 1992)



## IV. Designing cultivation systems beyond earth

and water vapour from the cabin air is recovered and converted into potable water (Carter, 2010).

Air quality management complements the aforementioned strategies. For instance, the ABRS incorporated an air filter system to reduce VOC concentrations (Zabel et al., 2016). A typical example of an air filter system would be a high-efficiency particulate air (HEPA) filter (Wheeler et al., 2003).

Further important considerations are sterilisation procedures and the selection of construction materials. Plant chambers must be regularly cleaned and disinfected, as microbial control is essential to prevent cross-contamination between the external environment and the

### IV.IX. Area required for a Closed Loop System (CLS)

Considering the aforementioned points from the previous sections, we arrive at perhaps the most critical long-term design objective of a CELSS, which is achieving autonomy.

Estimates in literature vary substantially, with little to no agreement on the similar plant-growing area required per person. MacElroy et al. (1984) suggested that an intensive, controlled agricultural system in space would likely require 25m<sup>2</sup> per person (Table 22). About a decade later, Salisbury et al. (1997) reported that a cultivation area of 63m<sup>2</sup> for a 4-person crew could supply sufficient calories and maintain gas exchange, though external supplementation was still made to

cabin atmosphere (Liu et al., 2021; Coughlan et al., 2022).

The choice of material also influences how the growth chamber reacts with its environment, i.e., in relation to lighting. Trace gas off-gassing can occur under exposure to the low levels of UV wavelengths from artificial lighting (Hoehn et al., 1998). This effect can be minimised by using metallic materials instead of plastics, which often contain organic solvents and plasticisers prone to off-gassing (Hoehn et al., 1998). However, Salisbury et al. (1997), reported that in the BIOS-III cultivation facilities, the use of metallic construction led to the accumulation of heavy metals in plants by the end of the experiment.

provide meat.

Wheeler (2003) conducted detailed calculations of plant-growing areas needed to meet daily dietary requirements (2500kcal/person), presenting 3 scenarios dependent on the harvest index of the cultivated plants: 1. 40m<sup>2</sup> at a 50% harvest index, with waste biomass oxidised to retrieve CO<sub>2</sub> and H<sub>2</sub>O (Figure 11); 2. 36m<sup>2</sup> at a 50% harvest index, with some food generated from waste biomass (Figure 12); and 3. 28m<sup>2</sup> at a 70% harvest index, with waste biomass oxidised to resupply CO<sub>2</sub> and H<sub>2</sub>O (Figure 13).

Another study by Wheeler (2003) suggested that as little as 20m<sup>2</sup> per person could suffice. Nelson et al. (2009) demonstrated that 13m<sup>2</sup> of highly productive dwarf wheat could meet both the entire caloric requirements and gas exchange needs for one individual. More recently, Liu et al. (2021) estimated that 43m<sup>2</sup> could provide approximately 90% of an individual's nutritional demand.

Studies have also investigated alternative crops. Wilks (1962) proposed that an area of 25m<sup>2</sup> of duckweed would be sufficient to support one

	On Earth:	Bioregenerative System in Space:
Agricultural area for 4 people	5,200 m <sup>2</sup>	98 m <sup>2</sup>
Atmosphere reservoir for 4 people	6.5 x 10 <sup>6</sup> m <sup>3</sup>	100 m <sup>3</sup> (agric. area) 200 m <sup>3</sup> (crew area) 300 m <sup>3</sup> (total vol.)
Approximate gas exchange rate for CO <sub>2</sub> (or O <sub>2</sub> ) by agriculture only /5/	0.4 m <sup>3</sup> /day	0.4 m <sup>3</sup> /day
Volume CO <sub>2</sub> in atmosphere	1950 m <sup>3</sup>	0.09 m <sup>3</sup>
"Buffer ratio" (e.g. volume of atmosphere/volume CO <sub>2</sub> absorbed)	1.6 x 10 <sup>7</sup> (21,000)	750 (1)

Table 22 - calculated estimate (MacElroy et al., 1962)



## IV. Designing cultivation systems beyond earth

person in terms of gas exchange, whereas Escobar et al. (2017), suggests that only 10m<sup>2</sup> of duckweed could meet the same requirements for a crew of four.

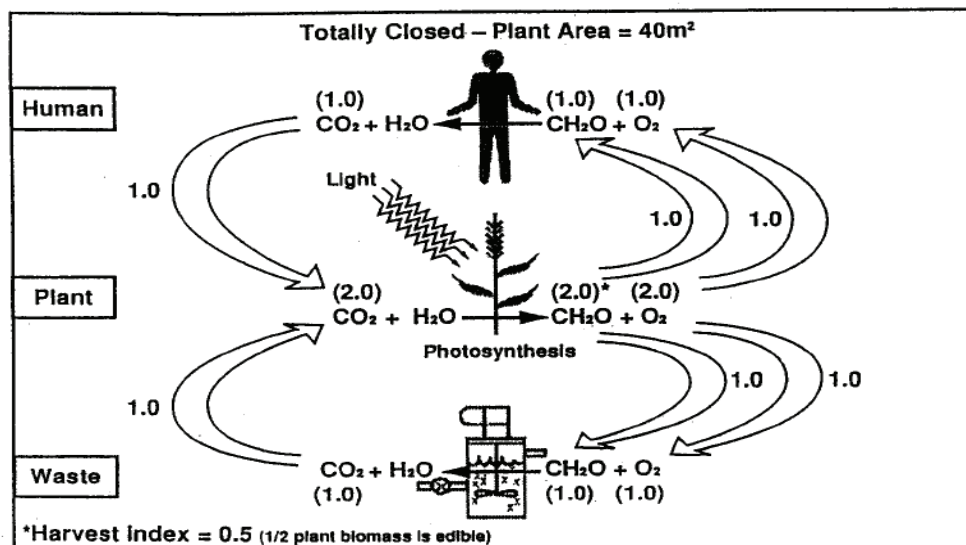


Figure 11 - 50% harvest index,  $\text{CO}_2$  and  $\text{H}_2\text{O}$  from oxidation (Wheeler, 2003)

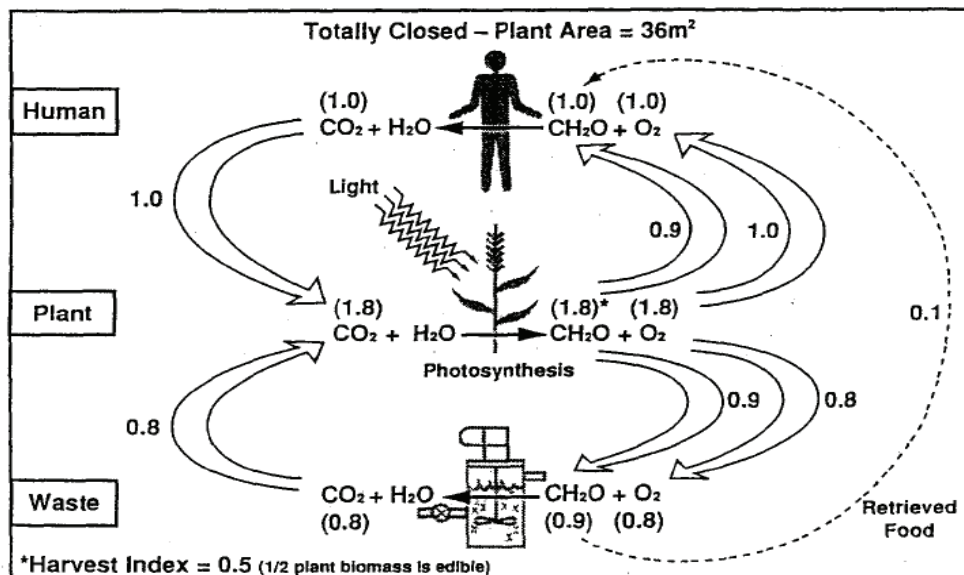


Figure 12 - 70% harvest index, food from biomass (Wheeler, 2003)

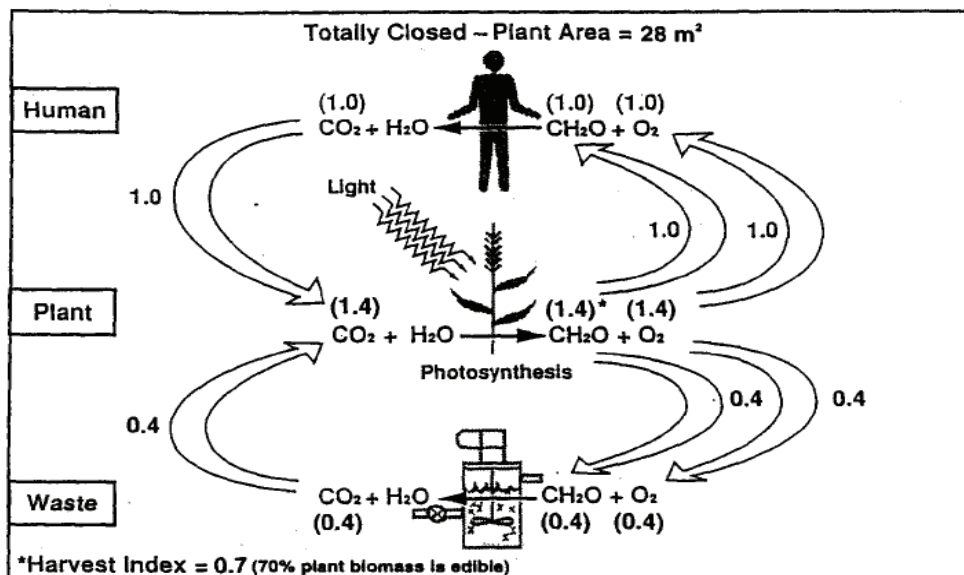


Figure 13 - 70% harvest index,  $\text{CO}_2$  and  $\text{H}_2\text{O}$  from oxidation (Wheeler, 2003)



## IV. Designing cultivation systems beyond earth

### IV.X. Microgravity constraints on design and plant physiology

The microgravity environment represents a major constraint in designing cultivation systems in space, as it alters physical, chemical, and biological processes. The Biogravistat experiment investigated the effects of microgravity on higher plant shoots (Harvey et al., 2011). On Svetoblok, tomato plants exhibited very slow growth, reaching only about 7.5cm after three weeks of growth (Zimmerman, 2003). In contrast, the Phyton-III mission reported that *Arabidopsis thaliana* flowered in space only four days later than control plants grown on Earth (Zabel et al., 2016). Similarly, the SVET mission reported stunted growth and uneven substrate moisture in cultivated radish and Chinese cabbage, attributed to the absence of gravity (Zabel et al., 2016).

The PGU and PGF can be considered key projects, where secondary effects of microgravity were further highlighted, demonstrating that they can significantly influence normal plant development (Musgrave et al., 1997). In Astroculture, roses were cultivated to study the effects of microgravity on essential oil production (Musgrave et al., 1997), while Advanced Astroculture aimed to autonomously provide a stable environment for plant cultivation under microgravity (Zabel et al., 2016). The BPS serves of particular importance because it demonstrated that plants, when the secondary effects of microgravity are mitigated, can grow comparably to ground control crops (Zabel et al., 2016), featuring identical rates of photosynthesis and transpiration (Evans et al., 2009; Morrow et al., 2000; Stutte et al., 2005).

Restricted air movement in spaceflight chambers can induce spatial variations in air temperature, CO<sub>2</sub> concentration, and humidity, which contribute to non-uniform growth (Kitaya et al., 2000). Early space missions often

mistakenly attribute poor growth to microgravity rather than confinement, such as VOC accumulation and elevated CO<sub>2</sub> (Paul et al., 2013). In reality, plants can grow normally in a well-ventilated area in a space environment (Monje et al., 2005; Ferl et al., 2002), although some reports, such as Levinskikh et al. (2000) suggest exceptions.

Fundamental plant growth experiments have sought to elucidate growth and development, from germination through reproduction mechanisms, including tropisms and circumnutation, molecular biology (Paul et al., 2013), such as chromosome aberration and cell cycle changes (Kitaya et al., 2000). Plants grow according to three tropisms: gravitropism (shoot = negative, root = positive), phototropism (shoot = positive), and hydrotropism (root = positive) (Levine, 2010). Alterations in these tropisms under microgravity explain many observed morphological changes (Poulet et al., 2016), such as increased lateral root formation at the expense of a dominant primary root (Ferl et al., 2002). Notably, *Arabidopsis thaliana* seedlings displayed a stronger phototropic response to blue light in microgravity than in Earth gravity (Millar et al., 2010). Furthermore, Paul et al. (2012) report that plants tend to keep their characteristic skewing and waving patterns in microgravity.

Elevated radiation levels also affect plant growth and development, though the precise mechanisms are not fully understood (Poulet et al., 2016). Plants are known for tolerating radiation doses far exceeding those of mammals (De Pascale et al., 2021; Arena et al., 2014). An interesting hypothesis proposed by De Micco et al. (2011) and Wolff et al. (2014) suggests that small radiation doses might even lead to positive outcomes, such as increased growth and a greater rate of photosynthesis. Conversely, ionising radiation can increase embryo lethality, affect



## IV. Designing cultivation systems beyond earth

reproductive success, alter yield, reduce tolerance to water stress, and potentially influence photosynthesis and nutritional quality, with outcomes highly dependent on species (De Pascale et al., 2021) (Figure 14).

At the organ level, microgravity produces two major physical effects: the dominance of surface tension forces and the absence of convection (Poulet et al., 2016). Water forms thicker boundary levels around roots, which can become oxygen-deficient due to respiration, leading to root hypoxia (Porterfield et al., 1997; Monje et al., 2003). Hypoxia can also be similarly caused by the lack of convection, as thicker boundary layers formed around leaves limit gas diffusion, reducing photosynthesis and inducing localised depletion of essential gases (Poulet et al., 2016). Lack of convection also slows down water vapour transfer, and allows the accumulation of gases and VOCs, disrupting various metabolic pathways (Levinskikh et al., 2000).

In addition to the direct effects of microgravity, plants are also subject to secondary physical effects of the spaceflight environment, including altered convection, fluid and gas behaviour, and atmospheric conditions within the spacecraft (Stutte et al., 2011). It is important to distinguish between secondary effects of microgravity on plant physiology and effects of microgravity on secondary metabolism, as these two terms may be confused. Changes in secondary metabolism are associated with stress responses, defence mechanisms, and hormonal regulation (Poulet et al., 2016). Mazars et al. (2014) and Zhang et al. (2015) reported that certain plants in microgravity exhibit increased levels of proteins related to stress, defence, alongside decreased expression of proteins related to auxin metabolism and trafficking, which may also alter the taste of the plant. Hypoxic stress induced by the microgravity

environment, and the associated metabolic limitations (i.e., induction of fermentative metabolism), arise from disrupted gravity-dependent buoyancy-driven thermal convection (Porterfield et al., 2003). Herranz (2014) proposed that plants perceive microgravity as a novel stress environment and that certain genomes lack sufficient genetic mechanisms to respond, resulting in widespread up- and down-regulations of genes.

Plant responses to microgravity are species- and cultivar-dependent, complicating attempts to identify general patterns of plant growth and development (Paul et al., 2013). For example, Lemnaceae (duckweed) demonstrated enhanced growth under simulated microgravity (Yuan et al., 2017), whereas i.e., other species from past missions did not. De Pascale et al. (2021) suggested the implementation of a uniaxial clinostat in Earth-based experiments to simulate some aspects of microgravity.

Relying exclusively on plants for a CELSS environment would not be practical, as, for example, a plant-based water recovery system may fail within 3 years (Drysdale, 1994). Ultimately, the architecture of a CELSS is critical for success, as design choices in cultivation layout, ventilation, nutrient delivery, and radiation protection determine both plant growth and system longevity.

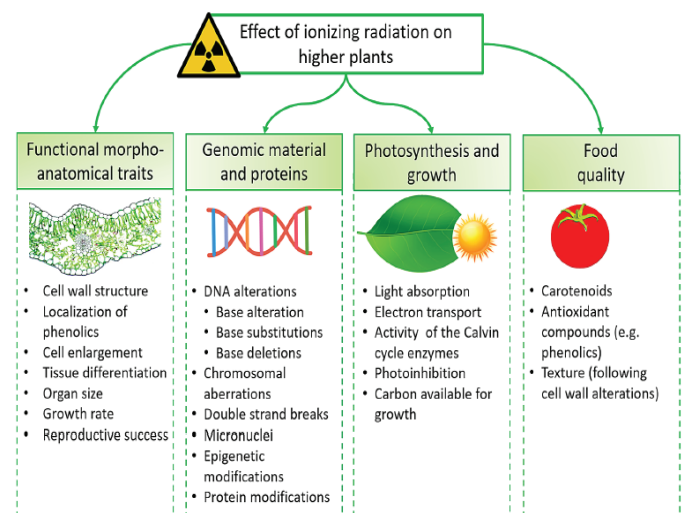


Figure 14 - radiation effects (DePascale et al., 2021)



## V. Human-plant interactions: health and psychology

Plants provide psychological benefits on Earth and in space, as they are expected to positively impact crew mental health (Zabel et al., 2016; Massa et al., 2016).

As noted in the chapter „From prototype to orbit: a brief history summary“, the interest in psychological effects of plants in space emerged with the Vazon missions, during which tulip plants and a kalanchoe tree were flown up to the station to enhance crew mood (Zabel et al., 2016). Cosmonaut Ryumin, who operated the plant growth chamber, reported that tending the station’s garden helped him to cope with his depression (Zabel et al., 2016). The Malachite mission was the first experiment specifically designed to investigate the psychological benefits of crew interaction with plants, specifically orchids (Zabel et al., 2016; Porterfield et al., 2003). Lada became the first in-orbit greenhouse module to study the psychological effects of crew-plant interactions (Bingham et al., 2002). Similar to the Vazon missions, the BIOS-II closure experiment reported that living inside a closed ecological system was not only viable, but also enjoyable (Nelson et al., 2009).

Beyond psychological benefits, plants also offer physiological benefits, particularly through the provision of dietary antioxidants, vitamins, and other compounds that may mitigate radiation effects (Mitrea et al., 2018; Polutchko et al., 2022). Cosmic radiation produces multiple physiological impacts, including DNA damage, disrupted signal transduction, redox activation, mutations, genome instability, gene expression changes, cell cycle perturbations, apoptosis, fibrosis, cataracts, and increased cancer risk (Mitrea et al., 2018) (Figure 15). Ionising radiation generates ROS (Reactive Oxygen Species), via water radiolysis, superoxides and  $H_2O_2$  that cause DNA damage, protein oxidation, and lipid peroxidation

(Mitrea et al., 2018). Oxidative stress accounts for approximately two-thirds of DNA damage, with the brain being particularly susceptible due to its lower antioxidant capacity (Mitrea et al., 2018).

Certain vitamins and nutrients play key roles in mitigating radiation effects:

- Vitamin A (Ushakov et al., 2011)
- Vitamin C - interacts with hydroxyl resulted during oxidative stress and forms less toxic free radicals (Mitrea et al., 2018; Ushakov et al., 2011)
- Vitamin E - doses lower than 200UI/day considered beneficial and protect the cell membrane against lipid peroxidation (Mitrea et al., 2018; Ushakov et al., 2011; Hava et al., 2019)
- Selenium (Mitrea et al., 2011; Hava et al., 2019)
- Folic acid (Mitrea et al., 2011)
- Lipoic acid (Mitrea et al., 2011)
- Omega-3 fatty acids (Mitrea et al., 2011)
- Sulphoraphane (Mitrea et al., 2011)
- Lycopene (Mitrea et al., 2011)
- Ferulic acid (Mitrea et al., 2011)
- Polyphenols (Ushakov et al., 2011)
- Anthocyanins (Ushakov et al., 2011)
- Flavonoids (Ushakov et al., 2011)
- Isthocyanates (Ushakov et al., 2011)
- Beta carotene (Hava et al., 2019)
- Antioxidants (ie. zeaxanthin, lutein (Polutchko et al., 2022; Hava et al., 2019), and quercetine (Ushakov et al., 2011))

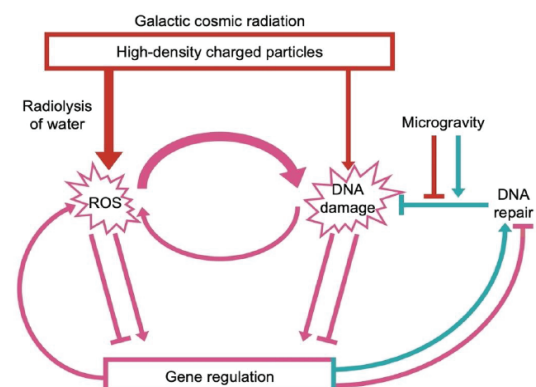


Figure 15 - Effect of radiations (Polutchko et al., 2022)



## V. Human-plant interactions: health and psychology

Polutchko et al. (2022) emphasises that identifying space crops rich in essential dietary nutrients with radiation-mitigating properties is crucial for protecting humans from radiation damage and chronic inflammation in space environments.

Some specific crops recommended for radiation mitigation include:

- **Strawberries** (Mitrea et al., 2011)
- **Grapes** (Mitrea et al., 2011)
- **Wheat** (Mitrea et al., 2011)
- **Brocoli** (Mitrea et al., 2011)
- **Rice bran** (Mitrea et al., 2011)
- **Brussels sprouts** (Mitrea et al., 2011)
- **Cabbage** (Mitrea et al., 2011)
- **Tomatoes** (Mitrea et al., 2011)
- **Carrots** (Mitrea et al., 2011)
- **Watermelon** (Mitrea et al., 2011)
- **Gac** (Mitrea et al., 2011)
- **Papaya** (Mitrea et al., 2011)
- **Duckweed** (Polutchko et al., 2022; Escobar et al., 2017)
- **Lettuce** (Ushakov et al., 2011) - grown under a specific regime

In particular, duckweed accumulates high levels of antioxidants, such as lutein and zeaxanthin, which counter chronic inflammation and support mental health (Polutchko et al., 2022) (Figure 16). Lutein is constitutively present in leafy crops, whereas zeaxanthin is formed only under high light intensity and diminishes quickly under lower light levels (Polutchko et al., 2022). The plant species features multiple additional benefits for space cultivation, including rapid growth, high photosynthetic efficiency, high harvest index, exceptional nutritional quality, and a very high protein content across the entire plant, producing up to 20 times greater edible protein production rate per plant cultivation area than soybean, higher than any other know terrestrial

plant as they accumulate storage protein throughout the whole plant (Polutchko et al., 2022). Consuming naturally grown foods is preferable to synthetic foods, which can produce undesirable effects, such as nausea and diarrhoea (Schwartzkopf, 1992).

Additional protection can be achieved through approved radioprotective drugs, such as cysteamine dichlorohydrate, amifostine, indraline, and mexamine (Ushakov et al., 2011), as well as phytochemicals (Hava et al., 2019).

Individual factors, including age, genetics, and pre-existing health conditions, influence susceptibility to radiation and response to dietary countermeasures (Skrizweski et al., 2024). Nevertheless, diets rich in ROS-balancing antioxidants represent a robust strategy to support astronaut health (Polutchko et al., 2022), but dietary preferences must also be taken into consideration (De Pascale et al., 2021), as menus must be nutritionally adequate and palatable to maintain morale and health (Hava et al., 2019).

Finally, maintaining a hygienic cultivation system is critical, as exposure to harmful microorganisms must be minimised (Salisbury et al., 1997), as even small imbalances in the system can have serious consequences (MacElroy et al., 1984). Measures include proper ventilation, use of masks, mats at entrances, and cleaning of plant trays and plumbing systems (Wheeler et al., 2003).

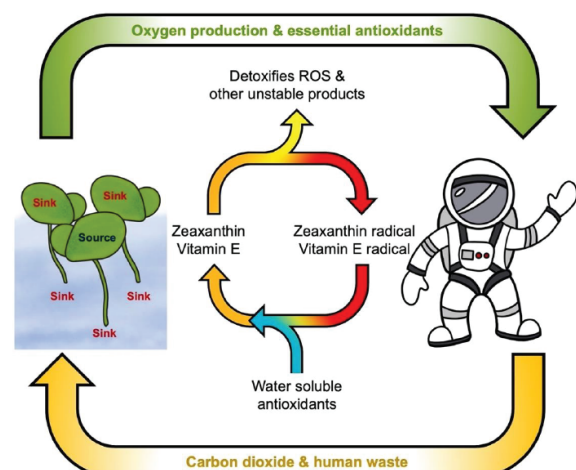


Figure 16 - duckweed antioxidants (Polutchko et al., 2022)



## VI. Conclusion

This paper has traced the progressive evolution of plant growth chamber technology in microgravity, from the modest origins of early missions to the more integrated systems of recent years. The earliest missions focused on addressing fundamental challenges, such as the construction of a basic nutrient delivery system, developing an adequate light source, and understanding gas exchange in the absence of gravity. These initial steps, although small in scale, provided the fundamental biological and engineering building blocks upon which all subsequent thoughts have been built.

Over time, significant improvements have been achieved across all major subsystems, such as nutrient delivery systems, atmospheric regulation, and waste management, with each mission adding incremental improvements. The VEGGIE and APH units represent pivotal milestones, marking a shift from experimentation to practical, crew-oriented food production. These units signal the slow, but crucial, transition toward supporting long-duration

missions and increasing crew reliance on such a system. Alongside these advancements, the field has begun to address finer details such as crop selection, day-night cycles, minimum harvest index, inedible biomass utilisation, and even nutrition-based radiation protection.

Yet, despite these achievements, the realisation of an independent, closed-loop life support system remains visionary, with full-scale concepts being limited by high cost, limited testing opportunities, and unpredictable performance. The ultimate test of CELSS technology will be its reliability as a core subsystem within multiple integrated components, capable of sustaining human life beyond Earth. Bridging the gap between theoretical models and empirical data from long-duration, large-scale systems is therefore essential. The future of complex, self-sustaining extraterrestrial habitats depends on the ability to develop biological life support systems that are not only technically robust and reliable but also capable of achieving true biological autonomy.

## VI. Discussion of limitations

The review of available literature reveals a common limitation across much of the research on bioregenerative life support, which is the predominance of conceptual and small-scale studies with highly variable results. While these works are foundational and invaluable, the majority are not based on large-scale, long-duration missions conducted in microgravity environments.

As a result, a substantial gap exists between the theoretical understanding of CELSS and the practical, real-world data required for reliable application. For instance, much of the data presented in the chapter “Crop yield” and “Photosynthetic gas exchange” relies on assumptions, short-duration experiments, or ground-based calculations, making it difficult to

assess the efficiency and stability of a CELSS in an environment different from Earth over an extended mission.

This review, therefore, not only represents a synthesis of a segment of the existing knowledge but also highlights the need for a paradigm shift from small-scale and theoretical proposals to large-scale, long-term testing and empirical data collection. Bridging this gap will prove to be essential if CELSS and similar systems are to transition from experimental studies to mission-critical infrastructure for future human spaceflight and colonisation.



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