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Designing Biological Autonomy for Orbital Habitats - Inflatable Controlled Ecological Life Support System (ICELSS)

Luka Pejic^{a*}, Sandra Häuplik-Meusburger^a

^a *Department of Building Construction and Design, TU Wien, Karlsplatz 13, 1040 Vienna, Austria*

* Corresponding Author

Abstract

A Controlled Ecological Life Support System couples biological and physicochemical processes to facilitate resource regeneration, thereby minimising dependence on Earth-based resupply during long-duration missions. Despite decades of flight heritage and ground analogue missions, operational deployment remains at a conceptual stage. Low Earth Orbit implementations are restricted to modest rigid chambers measuring in centimetres, whereas viable partially closed loops necessitate square metres of growing area per individual alongside balanced system flows. Taking resupply autonomy as a foundational criterion, this paper argues that bioregenerative architecture must optimise cultivation area arrangement, crop productivity, and crew habitat quality. Applying these principles, the geometry of an Inflatable Controlled Ecological Life Support System module is derived from the cultivation demand of the crop portfolio and constrained by the SpaceX Starship payload envelope. The module layout allocates around 19 m² of cultivation area per crew member across seven distinct groups sharing compatible environmental requirements. The inflatable module architecture proposes four functional variations, each applicable to an envisioned mission scenario, while contributing to psychological well-being by enabling human-plant interactions. In its deployed state, the module consists of four main sectors: (1.) cultivation, (2.) monitoring, (3.) processing, and (4.) waste management and a supplemental Environmental Control and Life Support System. Quantitatively, the resulting module approximately halves terrestrial resupply mass and covers over 40% of caloric demand, and closes the carbon loop through biomass recycling, while oxygen closure requires water electrolysis, with complete mass and power budgets following from the resulting geometry. Comparative benchmarking against literature indicates that substantial dietary and metabolic closure is predominantly driven by high-yielding species that simultaneously impose the steepest penalties on supporting infrastructure and design iteration.

Keywords: orbital greenhouse, inflatable module, crop-derived geometry, life support system, partial closure

Acronyms/Abbreviations

Controlled Ecological Life Support System (CELSS), oxygen (O₂), carbon dioxide (CO₂), International Space Station (ISS), volatile organic compounds (VOCs), Advanced Plant Habitat (APH), Bigelow Expandable Activity Module (BEAM), ultimate burst pressure (UBP), Environmental Control and Life Support System (ECLSS), crew member (CM), Life Support Baseline Values and Assumptions Document (BVAD), mature plant height (MPH), day/night temperature (D/N), photoperiod (PP), daily light integral (DLI), edible dry biomass (EDB), inedible fresh biomass (IFB), transpiration (TSP), growth period (GP), exclusion (E), launch mass offset (LMO), Common Berthing Mechanism (CBM), Inflatable Controlled Ecological Life Support System (ICELSS), nutrient delivery system (NDS), light-emitting diode (LED), photosynthetic photon flux (PPF), photosynthetic photon efficacy (PPE),

1. Introduction

A Controlled Ecological Life Support System (CELSS) is a balanced biotechnical ecological system [1] that combines biological processes with physicochemical ones [2]. It is widely regarded as the most promising strategy for sustaining human life during long-duration missions [3], where crops must reliably produce high-quality edible biomass rapidly and efficiently [4]. The primary functions encompass oxygen (O₂) production, carbon dioxide (CO₂) reduction, contaminant gas control, pressure and humidity regulation, thermal control, waste management, radiation protection, illumination and food supply [1, 5, 6]. Beyond the technical roles, a CELSS must also contribute psychological benefits that support crew wellbeing [5].

Crop choice in early space missions was determined by hardware rather than by nutritional adequacy: Oasis 1 on Salyut 1 offered roughly 0.001 m² of growth area and grew flax, onion and Chinese cabbage, and it was onion from Oasis 1M that in 1975 became the first space-grown

vegetable eaten by a crew [5]. Only with Veggie in 2014, at 0.11 m² [7], did a flight system exist whose stated purpose was the investigation of food production, and the crops consumed from it remained salad crops [5, 8].

1.1 Human-plant interactions

Enhancing crew psychological well-being has served as a deliberate design objective since the inception of orbital cultivation. Early interest in crew-plant dynamics emerged during the Salyut program, when cosmonaut Valery Ryumin noted that tending the onboard Vazon garden provided a countermeasure for his depression [5]. The Malachite payload on Salyut 6 was developed as the first flight system to specifically assess the psychological benefits of crew-plant interaction using orchids [3, 5].

Terrestrial closed-loop analogues integrated similar approaches; i.e. the BIOS-3 closure trials integrated a supplemental crop compartment explicitly for its behavioural health value alongside fresh nutrient delivery [9]. Modern spaceflight platforms have formalised this approach. The Veggie facility aboard the International Space Station (ISS) was conceived around a pick-and-eat supply of salad crops while serving as a microorganism research apparatus [7]. Reviewing such systems, Häuplik-Meusburger framed human-plant interaction not as an incidental byproduct of food production, but as a core architectural requirement for long-duration missions [10].

The psychological benefits stem less from passive visual presence and more from active tactile engagement, such as regular maintenance, harvesting, and the sensory contrast provided by living biomass [5, 10]. In parallel, freshly harvested crops provide plausible physiological countermeasures, supplying antioxidants and micronutrients that mitigate cellular oxidative damage induced by radiative effects [11]. However, maximising psychological and dietary returns introduces biocontainment challenges.

In BIOS-3, microbial loads fluctuated with crop life-cycle phases and rose to levels capable of halting the system, requiring slight positive chamber pressure to prevent inward air leakage, and on scheduling crew entry seasonally to limit pathogen invasion [9]. Because closed life-support systems lack planetary-scale atmospheric and hydrological buffers, perturbations propagate through the loop faster than on Earth [12]. Long-term testing in NASA's Biomass Production Chamber demonstrated that while closed cultivation permits regular human intervention, crew health risks are concentrated in discrete events (i.e. fungal spore release during the removal of degraded plant material) rather than steady-state conditions [13].

1.2 Microgravity limits on design and plant physiology

Microgravity constrains space cultivation systems by imposing surface-tension dominance and the absence of natural convection [14]. These produce three effects. Firstly, surface tension thickens the boundary layers around roots, restricting gas exchange and inducing root hypoxia [14]. Secondly, the absence of convection thickens the mass boundary layers at the leaf surface, suppressing photosynthetic capacity [14]. Thirdly, it slows transpiration while allowing volatile organic compounds (VOCs) to accumulate [14]. Consequently, poor growth in early missions was frequently misattributed to microgravity when it stemmed from confinement, specifically VOC accumulation and elevated CO₂ [14]. In reality, plants can grow normally in a well-ventilated area in a space environment [14]. Inadequate airflow induces gradients in thermal conditions, CO₂ levels, and humidity, driving non-uniform plant growth [15]. Flight validation in the Biomass Production System, a payload flown on the ISS Expedition 4 in 2002 carrying PESTO, confirmed that when the secondary effects of microgravity were mitigated, plants were comparable to ground control plants [5], while achieving identical photosynthetic and transpiration rates [5]. Responses to microgravity are species- and cultivar-dependent, which complicates the identification of general growth patterns [14].

Plants grow according to three tropisms: gravitropism (shoot -, root +), phototropism (shoot +), and hydrotropism (root +) [16]. Alterations in these tropisms explain present morphological changes, such as increased lateral root formation at the expense of a dominant primary root [14]. Notably, sprouting plant seedlings of *Arabidopsis thaliana* exhibited a positive phototropic response to red light that was absent in the 1-g control unit, indicating that the removal of gravitropic competition alters which light cues elicit directional growth [17]. In microgravity, the lighting layout replaces the gravity vector as the orientation-defining element of the habitat. Gravity supplies convection and drainage at no cost on Earth, and in orbit each must be reinstated with hardware measures, which consume volume, mass and power.

2. Inflatable geometry from biological demand

2.1 Cultivation demand as a sizing driver

Plant cultivation hardware has flown continuously since the 1960s, across the Salyut Stations, Mir, the Space Shuttle and the ISS [5]. Almost without exception, these were small scientific chambers rather than active components of the life support loop, sized to fit standardised experiment carriers rather than to meet a dietary demand [5]. Zabel et al. anticipated that near-term

chambers would not substantially exceed this scale, since installation opportunities remain bounded by ISS resources [5]. Literature estimates for the growing area necessary to sustain one person vary widely, ranging from 1.35-65.29 m² based on assumed diet [18], 13 m² for a wheat monoculture covering calories and gas exchange [19], a modelled value of 23.6 m² [20], up to 28-40 m² dependent on harvest index [21], and 100-120 m² for full dietary coverage [22]. However, translating area into actual volumetric demand requires accounting for realistic canopy heights, operational and maintenance clearances, and multi-level configurations. Spaceflight cultivation systems reflect spatial constraints: the Advanced Plant Habitat (APH) provides a 0.19 m² growing area with a maximum shoot height of 45 cm [7], the Veggie facility offers 0.11 m² with adjustable heights between 5 and 45 cm [7], and the Space Plant Box encompasses 0.03 m³ of volume at a 30 cm height [15]. By contrast, the ground-based BIOS-3 facility measured 14 m×9 m×2.5 m (315 m³) [9]. The discrepancy highlights a scale contrast: historic spaceflight payloads were measured in centimetres, whereas functional closed-loop terrestrial analogues require metres; i.e. a 25 m² cultivation area with 0.5 m of canopy implies roughly 12 m³ of volume, against a fraction of a cubic metre for APH. Consequently, space-based crop production remains fundamentally volume-limited [5]. That constraints turns attention toward inflatable architecture, which offers a viable pathway toward terrestrial-analogue cultivation scales.

2.2 Expandable geometry and mass scaling

Airflow uniformity is more readily achieved across planar stands than around curved ones. Coupled with crew accessibility and maintenance constraints, these factors favour cross-sectional horizontal decks over continuous cylindrical growth surfaces. While cylindrical geometries maximise cultivation area within slender modules, they significantly complicate hardware integration by requiring individually qualified structural interfaces in contact with the softgoods shell as illustrated in Morgan et al. [23]. Architecturally, a continuous horizontal floor gives a cultivation footprint of $\pi \times r^2$ per level.

In launch vehicle architecture, length is rarely the primary constraint; rather, module diameter is strictly bounded by the launch fairing envelope for traditional rigid structures. Expandable module technology overcomes this by treating radius as an expandable variable. For example, Sierra Space's proposed LIFE 285 habitat is stated to expand from a fairing envelope of approximately 5 m to a deployed diameter of roughly 8.2 m [23], achieving a calculated post-deployment expansion ratio of 1.64.

Inflatable module diameter therefore acts as an

enabling variable, satisfying target surface area requirements within an envelope of reduced length and structural mass relative to rigid counterparts. The utility of this expansion depends upon the scale of cultivation demand. When the required cultivation area exceeds payload fairing boundaries, post-inflation radius delivers floor area that could otherwise not be launched, at the cost of outfitting the cultivation system after deployment. In contrast, when the demand fits within the fairing, such as partial-closure regimes, the area is fixed at stowage, and expansion instead supplies the operational volume surrounding it.

NASA investigated the viability of expandable habitat technology through the TransHab concept, sized for an internal volume of approximately 329.4 m³ and an estimated volume-mass penalty of 32.4 kg/m³ (when considering its full stated mass of 10,663 kg) [18]. No inflatable module of that scale has yet flown, but the technology was demonstrated in orbit with the Bigelow Expandable Activity Module (BEAM), installed on the ISS in 2016 [18]. At a volume of 16 m³, BEAM exhibits a higher volume-mass penalty of 85 kg/m³ [18]. Because fixed dead-weight structures such as bulkheads, internal tankage, and primary load-bearing structures, penalise smaller designs disproportionately [18] and shielding mass scales with surface area, a wider pressure vessel encloses a larger volume with a lower volume-mass penalty rather than a slender geometry. The volumetric advantage of expandable structures is thus a property of absolute scale rather than of expandability itself.

2.3 Technology readiness and the sizing gap

Since 2018, the development of Sierra Space's inflatable modules has been coordinated with NASA's JSC-67721 guidelines [23]. Because softgoods possess limited spaceflight heritage relative to conventional systems, NASA mandates a factor of safety of 4.0, nearly triple that of aluminium, governing both maximum expected operating pressure and longevity [23]. For LIFE 285, this yields a minimum ultimate burst pressure (UBP) of 60.8 psi [23]. After UBP testing, Sierra's LIFE 285 module burst at 77 psi [23], about 27% above the requirement. Consequently, the present ceiling on inflatable module scale is not set by material limits, but by the certification factors applied to them.

2.4 Aims of the paper

The proposition that life support should precede structure in habitat design is not new: Cohen et al. argue that Environmental Control and Life Support Systems (ECLSS) requirements are routinely subordinated to a predetermined structural envelope [24]; Schwartzkopf

sized cultivation envelopes on that basis, presenting metal, hybrid and inflatable growth units of 100, 224, and 528 m² growing area for a lunar surface application [2]; Hava et al. quantify packing factors for a Mars surface greenhouse whose envelope is inherited from the Ice Home [25]; and Zeidler et al. defined crop production requirements, generated five candidate external geometries with associated internal configurations, and ranked them using the Analytical Hierarchy Process, with cultivation area following from the channel stacking achievable within the selected petal envelope [26].

To the authors' knowledge, what has not been attempted is the derivation for orbital inflatable geometry from crop parameters and nutritional requirement. This paper therefore takes cultivation demand as the sizing input and derives envelope geometry from it under launch envelope constraints. The resulting portfolio requires under 20 m² per crew member (CM) at partial closure while offsetting approximately half the dry food allocation.

3. Crop selection method

3.1 Selection criteria

The selection process evaluated all candidate crops proposed by Ewert et al. in the Life Support Baseline Values and Assumptions Document (BVAD) [18], with mushrooms excluded from consideration. As heterotrophs, they do not share the parameter set on which the table is built on and cannot be evaluated against the same criteria. The following three criteria were applied:

Firstly, the 19.503 m²/CM "Diet Using Salad-and-Carbohydrate Crops" from the BVAD was taken as the dietary breadth reference. Consequently, plant species falling outside this nutritional regime were excluded from selection. This criterion constitutes the most restrictive of the three, prioritising crops with published consumption data for a partial-closure diet. Thus, under this regime, species are eliminated on dietary grounds rather than on

performance metrics. Secondly, crop grouping. The criterion produces the number of independently controlled environments required within the module, derived from candidate species sharing compatible photoperiods and diurnal temperature regimes. Crops lacking environmental compatibility with viable clusters were excluded, unless their contribution to the diet's launch mass offset was sufficient to justify a dedicated environment. This trade is assessed against the crop's edible dry yield per unit growing area and its share of the reference diet's total offset. The assessment is stated for each affected species rather than applied as a fixed threshold. Thirdly, a data-quality check applied to the candidate set. Growth parameters were primarily derived from a single source to maintain methodological and environmental consistency across all baseline measurements. Reported values originating from a different cultivation regime for given species are identified and reported.

Additionally, traits such as mature plant height, net photosynthetic rate, photosynthetic photon flux, inedible fresh biomass, and transpiration rate were treated as system design parameters which determine closure performance, rather than exclusion criteria.

3.2 Crop chart

The section outlines the author-compiled crop matrix (Table 1) alongside its governing inclusion and exclusion criteria. Plants were sorted according to the crop categories set by Hoff et al. [20], with baseline characteristics established using data from the BVAD [18], supplemented by Cloutier et al. [27] for photoperiod and temperature absences from the main dataset.

The chart compares 22 candidate crops across ten parameters: mature plant height (MPH), CO₂ absorption rate (CO₂), day/night temperature (D/N), photoperiod (PP), daily light integral (DLI), edible dry biomass (EDB), inedible fresh biomass (IFB), transpiration (TSP), and growth period (GP), followed by exclusion (E).

Table 1. Compiled crop chart

Species	MPH [m]	CO ₂ [g/m ² d] ^A	D/N [C°]	PP [h/d]	DLI [mol/(m ² d)]	EDB [g/m ² d]	IFB [g/m ² d] ^B	TSP [kg/m ² d]	GP [d]	E
Leguminous Crops										
Dry Bean	0.50	42.17	28 / 24	18	24	10.00	150.00	2.53	85	
Pea	0.50	45.26	n.a	n.a.	24	10.73	161.00	2.46	75	
Peanut	0.65	49.28	26 / 22	12	27	5.63	168.75	2.77	104	X
Snap Bean	0.50	50.09	28 / 24	18	24	11.88	178.20	2.46	85	

Species	MPH [m]	CO ₂ [g/m ² d] ^A	D/N [C°]	PP [h/d]	DLI [mol/(m ² d)]	EDB [g/m ² d]	IFB [g/m ² d] ^B	TSP [kg/m ² d]	GP [d]	E
Soybean	0.55	19.13	26 / 22	12	28	4.54	68.04	4.70	97	X
Root and tuber crops										
Carrot	0.25	22.50	17 / 11 ^C	16 ^C	28	8.98	59.87	1.77	75	
Radish	0.20	16.31	23 / 23	16	26	5.50	55.00	1.77	25	X
Red Beet	0.45	9.77	23 / 23	16	17	6.50	35.00	1.77	40	X
Sweet Potato	0.65	56.54	26 / 22	12	28	24.70	225.00	2.88	85	
White Potato	0.65	45.23	20 / 16	12	28	21.06	90.25	4.00	132	
Leaf and flower crops										
Cabbage	0.35	9.88	17 / 11 ^C	16 ^C	28	6.06	6.74	1.77	85	
Chard	0.45	15.79	23 / 23	16	17	7.00	37.69	1.77	45	X
Spinach	0.25	10.70	23 / 23	16	17	6.57	7.30	1.77	30	
Salad crops										
Celery	0.25	16.83	n.a.	n.a.	17	10.33	11.47	1.24	75	
Green onion	0.25	14.67	25 / 25	n.a.	26	9.00	10.00	1.74	50	X
Lettuce	0.25	10.70	23 / 23	16	17	6.57	7.30	2.10	28	
Onion	0.25	16.50	17 / 11 ^C	16 ^C	17	9.00	22.50	1.74	50	X
Pepper	0.40	33.98	n.a.	n.a.	27	10.43	127.43	2.77	85	
Tomato	0.40	36.24	24 / 24	12	27	10.43	127.43	2.77	85	
Grain crops										
Rice	0.80	50.26	28 / 24	12	33	9.07	211.58	3.43	85	X
Wheat	0.50	77.00	20 / 20	24 ^C	115	20.00	300.00	11.79	75-90	
Fruit crops										
Strawberry	0.25	34.82	20 / 16	12	22	7.79	144.46	2.22	100	X

^A With a photosynthetic quotient of unity, O₂ yield from CO₂ is 0.727

^B Inedible biomass water content taken as 90% for all crops, per Ewert et al. [18]

^C Values from Cloutier et al. [27]

3.3 Selection outcome

In accordance with the 19.503 m²/CM nutritional baseline, candidate crops including peanut, soybean, radish, red beet, chard, onion, rice, and strawberry were excluded from the proposed cultivation profile due to their omission from the BVAD's Table 4-92 [18].

Clustering candidates by D/N temperature regimes and PP identified four distinct outliers: green onion, wheat, sweet potato, and white potato. Green onion required a uniform 25°C/25°C D/N regime; given its modest EDB offset value of 3.74 g/CM-d, dedicating an isolated

environment to this species could not be justified, and it was excluded. In contrast, wheat, sweet potato, and white potato represent the three highest-yielding crops in the baseline portfolio, with EDB offset rates of 193.603, 52.196, and 33.991 g/CM-d, for their allocated area. Sweet potato and white potato ended up singled-out due to the dietary criterion removing plausible groupmates, while wheat does not share a similar D/N regime or PP with other plants. Despite the architectural overhead of single-chamber isolation, their superior daily offset rate provides a rationale for solitary cultivation. Moreover, three species

were provisionally assigned to clusters despite their lack of stated D/N temperature and PP: pea (group 1 due to similar PPF), celery (group 3 based on similar MPH and PPF), and pepper (group 5 predicated on similar PPF, IFB, TSP, and GP). While Ewert et al. state a D/N regime of >25°C without defining a PP value for cabbage [18], the present dataset adopts the 17°C/11°C D/N regime and a 16-hour PP established by Cloutier et al. [27].

Consequently, remaining candidate crops were clustered based on matching D/N temperature and PP, totalling in 19.087 m²/CM compared to Ewert et al.'s 19.503 m²/CM [18], with the sole difference being exclusion of green onion. Cultivation area footprints follow the surface area allocation model defined in the salad-and-carbohydrate diet, resulting in substantially varying area allocation ranging from 9.68 m² for wheat to 0.033 m² for cabbage.

A nominal crew diet, expressed in a dry mass equivalent, (BVAD Table 4-51), establishes a range of 0.617 (lower bound), 0.80 (nominal), and 0.96 (upper bound) kg/d-CM [18]. The resupply assumption for BVAD's 19.503 m²/CM diet relies on the lower baseline of 0.617 kg/d-CM [18]. Thus, this analysis adopts the identical baseline to maintain methodological comparability across results. The daily launch mass offset LMO_{daily} [kg/d-CM], representing reduced Earth-resupply, can be calculated by multiplying the plant-specific daily EDB yield [kg/m²d] with its provisioned area A_{CM} [m²/CM]:

$$LMO_{daily} = EDB \times A \quad (1)$$

Applying this formulation yields a daily resupply offset of 0.325 kg/d-CM (52.60% of the 0.617 kg/d-CM dry food allocation) for the baseline salad-and-carbohydrate diet, compared to 0.321 kg/d-CM (51.99% of the 0.617 kg/d-CM dry food allocation) for the proposed cultivation diet. Although absolute mass offset remains comparable, the configurations vary marginally in launch offset area efficiency. The baseline diet arrives at a value of 0.0166 kg/m²d, and the proposed diet at 0.0168 kg/m²d, differing by about 1%. Moreover, wheat dominates both the areal footprint and the LMO metrics of the chosen system. It accounts for more than half of the total cultivation surface at 9.679 m² (50.71% of the proposed profile) and contributes 193.603 g/CM-d of EDB (60.35% of the aggregate LMO). Excluding wheat reduces the daily offset to 0.127 kg/d-CM, equivalent to 20.63% of the dry food allocation, across 9.408 m²/CM. The wheat performance

metrics reported in the BVAD are derived from a near-continuous lighting regime of 20-24h at daily light integral (DLI) of 115 mol/m²d [18], consistent with the DLI of 112.3 mol/m²d and implemented 24h PP documented by Cloutier et al. [27].

Since the two portfolios differ marginally, the composition of the residual food mass (resupply value 48.01% in the proposed assortment vs 47.40% in the baseline) is taken as unchanged, following BVAD's resupply model, comprising primarily meat and oil at approximately 40% moisture content [18].

The surviving portfolio consists of thirteen crops grouped around their PP and D/N temperature (Table 2).

Table 2. Final crop portfolio.

Group	Species	D/N [C°]	PP [h/d]	Area [m ²]
I	Dry bean	28 / 24	18	1.170
	Pea	28 / 24 ^A	18 ^A	0.311
	Snap bean	28 / 24	18	0.067
II	Sweet potato	26 / 22	12	3.480
III	Spinach	23 / 23	16	0.548
	Celery	23 / 23 ^A	16 ^A	0.073
	Lettuce	23 / 23	16	0.160
IV	White potato	20 / 16	12	1.614
V	Pepper	24 / 24 ^A	12	0.208
	Tomato	24 / 24	12	1.209
VI	Carrot	17 / 11 ^C	16 ^C	0.535
	Cabbage	17 / 11 ^C	16 ^C	0.033
VII	Wheat	20 / 20	24	9.679

^A Assumed values

^C Values from Cloutier et al. [27]

4. From crop demand to envelope

The following section details the proposed module, its subsystems, and functional configurations (Fig. 1), derived from the results developed in the previous section.

4.1. Sizing

The resulting groups are configured as annular platforms concentric to a central core comparable in scale to the TransHab baseline (ϕ3.35 m) [28]. By departing from the curved geometry of the outer hull, a concentric ring layout provides planar growing surfaces, uniform chamber dimensions, and repeatable hardware interfaces.

Based on these dimensions, the core has an area of 8.813 m² (A_{Core}). To maximise stowage density of the packed inflatable, the outer radius of the crop portfolio (r_{Portfolio}) is determined using:

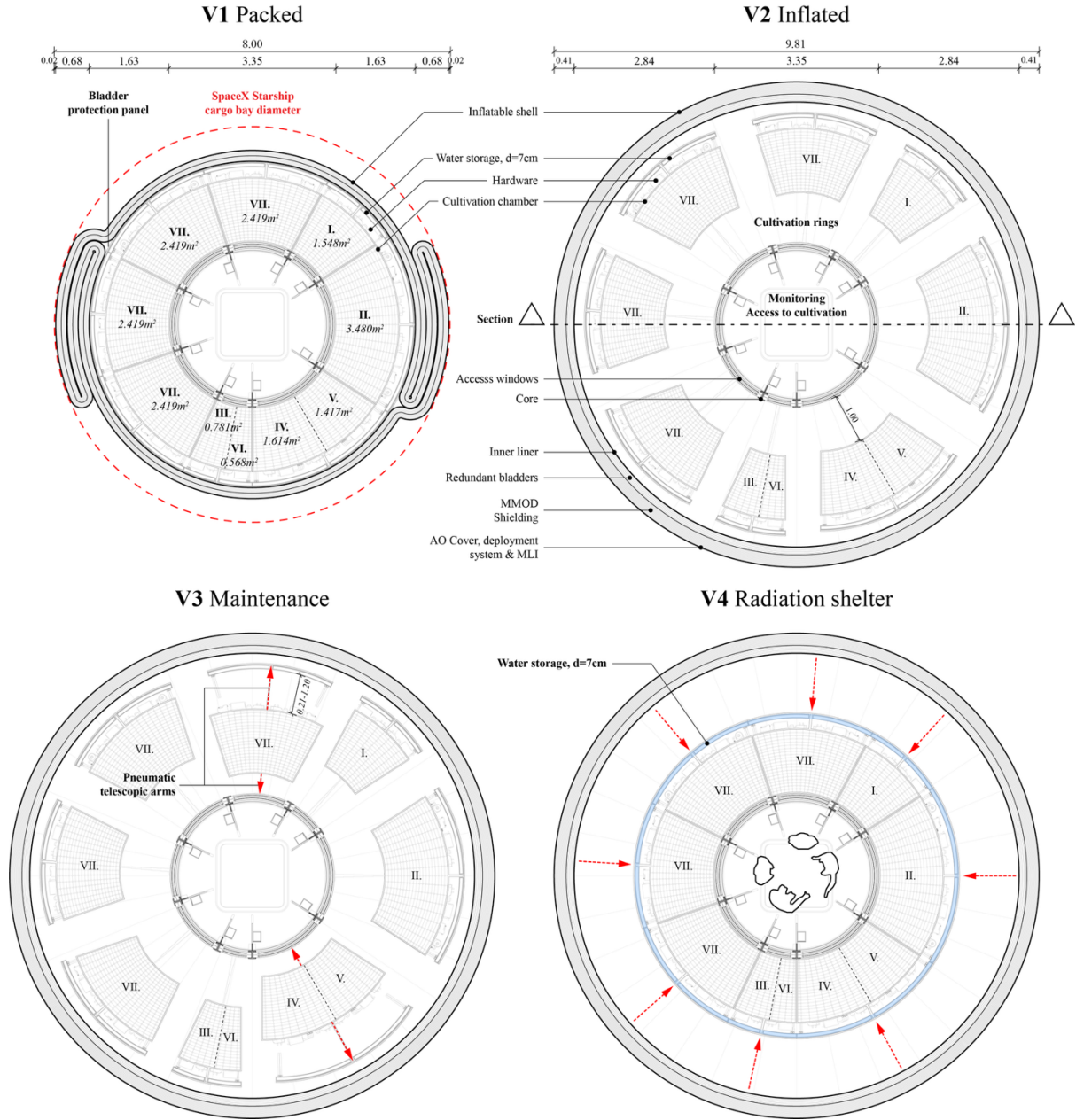


Fig. 1. Functional configurations of the ICeLSS module: (V1) stowed configuration within the launch vehicle envelope; (V2) fully inflated configuration for routine operations, featuring radially deployed cultivation chambers; (V3) maintenance configuration for chamber and hardware maintenance; and (V4) radiation-shelter configuration, with cultivation units retracted into the core to utilise surrounding water reservoirs for supplemental radiation protection.

$$r_{Portfolio} = \sqrt{\frac{A_{Core} + A_{Portfolio}}{\pi}} \quad (2)$$

The total crop portfolio area ($A_{Portfolio}$) of 19.087 m², yields an outer radius of 2.98 m from the core centre. To determine the proportional area allocated to each functional group (α_{Group}), the following formula is applied:

$$\alpha_{Group} = \frac{A_{Group} \times 360}{\pi \times (r_{Portfolio}^2 - r_{Core}^2)} \quad (3)$$

The parameter A_{Group} represents the specific area demand of each group (Table 2). The corresponding angular sectors of each group are illustrated in Table 3.

Table 3. Angles at $r_{Portfolio}=2.98$ m, $A_{Portfolio}=19.087$ m².

Group	Angle (α_{Group})
I	~29.199°
II	~65.640°
III	~14.731°
IV	~30.443°
V	~26.728°
VI	~10.714°
VII	~182.566°

The respective groups are sequenced along the circular array based on their PP requirements. Groups with the shortest PP demands are positioned centrally (i.e. II, IV, and V at a PP of 12), with subsequent adjacent groups exhibiting progressively longer PPs. This continuous gradient further minimises lighting variations caused by stray light spillover between adjacent chambers.

At the resulting scale of partial-closure crop area, a rigid envelope satisfies the dimensional constraints required to fit within the SpaceX Starship payload fairing [29]. However, an inflatable architecture offers several distinct advantages. Following hull expansion, the proposed design integrates pneumatic telescopic arms that deploy the chambers radially outward, increasing spacing to minimise stray light interference, expanding accessibility for operational maintenance, and enabling secondary functional roles beyond crop cultivation.

Following the expansion argument, the data for Group VII in Table 3 indicates an angle requirement exceeding half of the available annular footprint. Expanding a single sector beyond a semi-circle while maintaining inner and outer radii introduces geometric constraints. Consequently, the footprint allocated to Group VII was partitioned into four equivalent subunits (~2.417 m² each), yielding chamber area more comparable with the remaining ones (Table 2). Furthermore, groups III/VI and IV/V were appropriately assigned to a shared pneumatic arm, while their atmospheres stay separate, in order to ensure similar geometry of chambers and clearance between them, after expansion.

In its stowed configuration, the module spans $\phi 7.31$ m $\times$ 12.60 m across extremities, accounting for softgood folds and the Common Berthing Mechanism (CBM), fitting into the SpaceX Starship payload volume of $\phi 8.00$

m $\times$ 17.24 m [29]. The calculated diameter provides an operational margin of 0.69 m, in the stated payload envelope. Consequently, accounting for plant chamber hull thickness (~1cm), an additional 32 cm were integrated on the exterior ring: bladder protection panels (2 cm), water tanks (~8 cm with casings), and subsystem mounting (21 cm); spacing between compartments (~1cm); resulting in a stowed diameter of $\phi 7.97$ m (V1, Fig. 1).

4.2 Inflatable Controlled Ecological Life Support System

The proposed Inflatable Controlled Ecological Life Support System (ICELSS) module deploys to an operational diameter of $\phi 9.81$ m (V2, Fig. 1), yielding a stowed-to-inflated expansion ratio of approximately 1.23. This is lower than the expansion ratios reported for TransHab (~1.9; [28]) and Sierra Space's LIFE 285 module (~1.64; [23]). The lower volumetric expansion ratio of ICELSS is attributable to stowing the softgoods envelope around a pre-integrated cultivation assembly, rather than packing it against the $\phi 3.35$ m core for subsequent post-deployment outfitting. Consequently, bladder protection panels are proposed (Section 4.1), to mitigate mechanical wear and puncture risk to the internal bladder layers from hardware contact during stowage and ascent.

In its fully deployed configuration, the ICELSS module is partitioned into four functional zones (following page Fig. 2): (i.) cultivation rings, (ii.) monitoring and access to cultivation, (iii.) transfer and processing stowage, and (iv.) water processing, waste management, and supplemental ECLSS infrastructure to support the proposed partial loop closure.

4.3 Cultivation rings

The structural and functional layering of inflatable modules is well established in the baseline literature by De La Fuente et al. [28]. Building upon this framework, two supplementary functional layers on the outer ring of the chambers are introduced due to the architecture. As outlined in Section 4.2, the bladder protection panels provide mechanical shielding, while water reservoirs serve a dual operational role: fluid storage/filtration for cultivation chambers and supplemental radiation protection during extreme radiation events. The shielding method mirrors TransHab architecture, which incorporated a ~5 cm water layer in the core to serve as a designated storm shelter [28]. During emergency radiation events, the pneumatic actuators retract the cultivation chambers into their stowed positions, creating a storm shelter (V4, Fig. 1). It should be noted that while the water tanks feature an areal density to ~7 g/cm², they provide partial dose reduction, as the module ends lack equivalent shielding coverage.

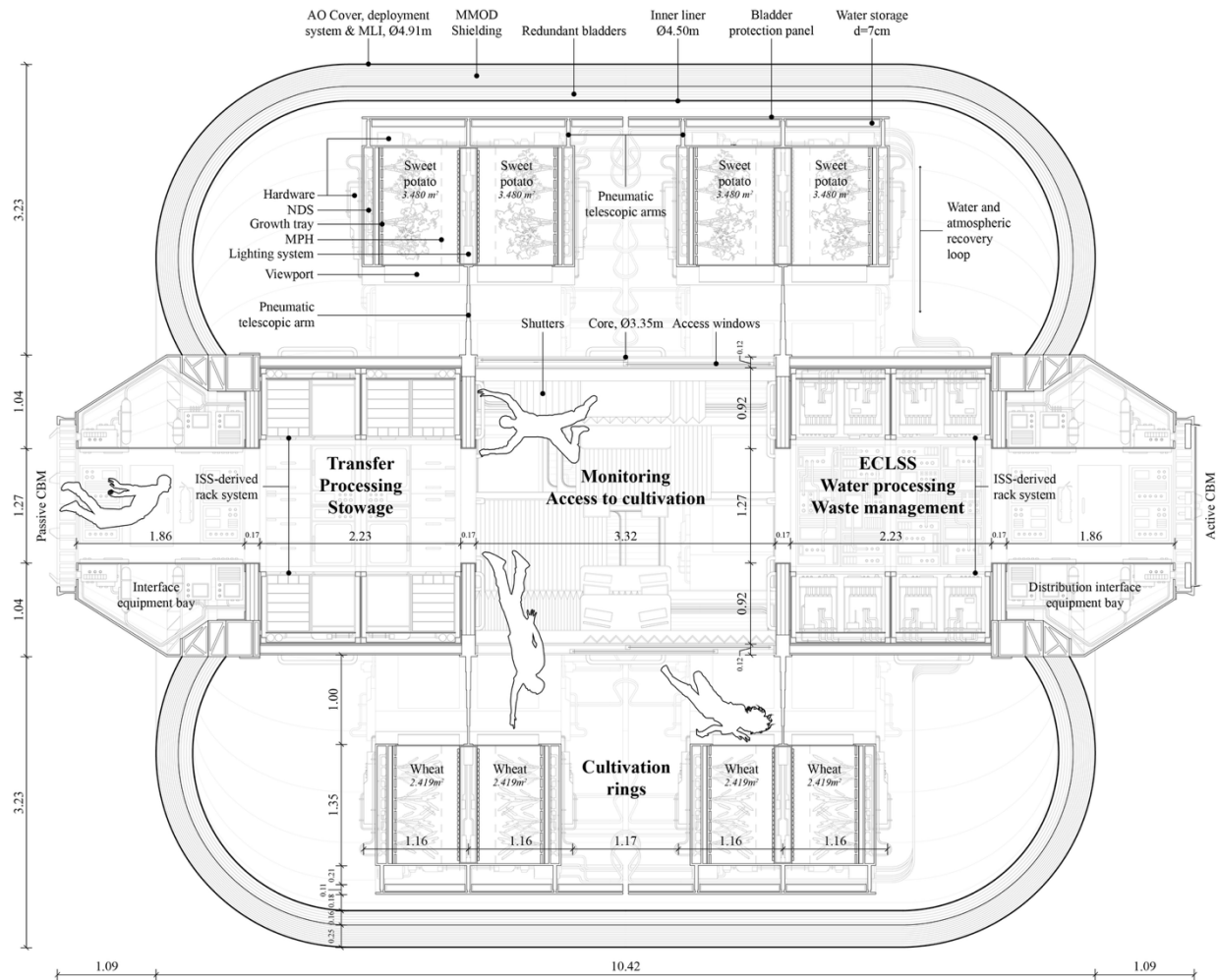


Fig. 2. Longitudinal section of the deployed ICeLSS module, illustrating the translation of crop-cultivation demands into architectural organisation. The four core functional sectors comprise the central cultivation rings; central monitoring and crew-access area; transfer, processing, and stowage; and water management and supplemental ECLSS infrastructure. The architectural arrangement combines biological and technical system requirements with crew accessibility, and multisensory engagement with the plant-growth environment.

As defined in Table 3, the growth chambers are configured as annular sectors, with each deck allocated to one CM. To minimise lighting power demands and overall hardware mass, ICeLSS utilises a two-ring architecture, with each ring containing two mirrored decks and providing partial nutritional coverage for two CM ($19.087 \text{ m}^2 \times 2 \text{ CM}$).

Thus, plant development is directed toward a centralised lighting array positioned between adjacent decks. The absence of gravitropic cueing means canopy orientation is reinforced by phototropism but ultimately set by the root module orientation. Moreover, each ring sector is actuated by a dual pneumatic telescopic assembly: the primary actuator governs chamber retraction toward the central core across an operational stroke of 0.00-1.00 m, while the secondary arm extends the bladder protection panel to provide hardware

maintenance access, operating across a stroke of 0.21-1.20 m (excluding water reservoir and bladder protection panel thickness) (V3, Fig. 1).

The overall chamber height is determined by several vertical allocations: (i.) the lighting system (0.10 m, or 0.20 m when accounting for opposing chambers), sized conservatively to accommodate dual-sided emitter boards and diffusers; (ii.) a lighting standoff distance (0.20 m); (iii.) the MPH value of 0.25-0.65 m based on species-specific values from the BVAD [18]; (iv.) the root module and nutrient delivery system (NDS) (0.20 m), which exceeds flown heritage benchmarks, i.e. the 5 cm root tray in the APH [7], to support full-cycle crops rather than salad greens and model plants; and (v.) an operational hardware margin of 0.18 m. Additionally, a clearance of at least 1.00 m is maintained between the two rings to facilitate routine maintenance operations and

hardware reach envelopes.

Subsystem hardware is integrated along the outer and upper perimeters of the cultivation chambers. Because opposing decks feature mirrored group arrangements, the decks share lighting infrastructure and atmospheric conditioning loops. Thus, overall subsystem mass and component redundancy are reduced relative to a separate four decks or fully separated chamber configuration. The chambers are sealed volumes with independent atmospheres, resulting in the surrounding volume being set at the environmental parameters of the three crew-usage heavy ones.

4.3.1 Subsystem hardware (Fig. 3)

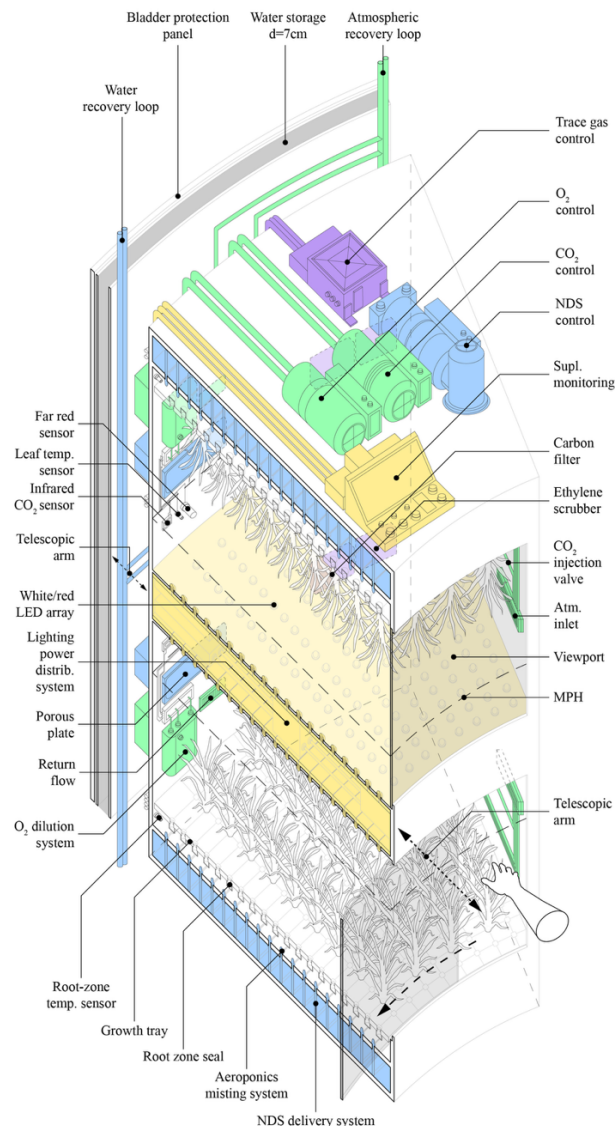


Fig. 3. Axonometric cross section through one ring, showing derived subsystem architecture of two opposing wheat chambers. Blue = nutrient delivery/humidity, green = atmosphere, yellow = lighting, purple = sorbent hardware.

The NDS relies on aeroponic cultivation recognised for its CELSS viability [8, 12]. Relative to porous-tube systems such as the APH [7], aeroponics omit solid substrate requirements, decreasing payload mass [10], and improving resupply logistics, reliability, serviceability, and maintenance [8]. However, microgravity-rated aeroponics currently lack an established Technology Readiness Level [8]. Implementing aeroponics therefore represents a deliberate trade-off, prioritising long-term scalability over flight heritage.

Since nutrient uptake rates and optimal temperatures vary by species, developmental stage, and environmental conditions [14], delivery protocols are tailored using BVAD data [18]. These tailored regimes account for species-specific nutrient solution temperatures (ranging from 18°C to 26°C) and water uptake rates (spanning 1.24 to 11.79 kg/m²d). Furthermore, the preferred water consumption rate governs chamber humidity [30], thus, precise moisture regulations plays a role in optimising plant growth [14]. Uncontrolled water loss can threaten the operational efficiency of a CELSS. Key measures involve effective sealing of the root zone [31] and continuous recovery of transpired condensate back into the NDS [7], keeping relative humidity within Massa et al.'s recommended 50% to 86% band, dependent on the species [7].

CO₂ concentrations within the cultivation chambers are regulated to a nominal setpoint of 750 ppm [32], drawing on ambient cabin air alongside supplemental ECLSS CO₂, with embedded infrared gas sensors to enable real-time monitoring [22, 31, 33]. Given the 19.087 m²/CM allocation and BVAD uptake rates, projected CO₂ absorption reaches 1.15 kg/d-CM, surpassing the daily baseline metabolic output of an individual (1.01 kg/d-CM) [18]. Consequently, the deficit of 0.14 kg/d-CM is bridged via the supplemental ECLSS (Section 5.1). The resulting O₂ surplus requires an air dilution system, as elevated levels can inhibit photosynthesis and biomass accumulation [31].

Light-emitting diode (LED) arrays serve as the primary illumination hardware, due to their compactness, low mass, longevity, and reduced radiant heat load on the canopy [14]. White/red LED fixtures follow Kusuma et al., as incorporating the green spectrum aids crew visual comfort and diagnostic inspection for pathology and nutrient disorders [34]. Spectral ratios are tuned per species: blue light inhibits stem elongation and leaf expansion [14]; red-blue combinations drive plant height and stomatal opening while lowering power demand [14, 35]; and green wavebands penetrate deeper into the canopy to reach under-illuminated layers [35]. Supplemental far-red wavelengths, calibrated against red light, act as a developmental signal [35]. Consequently, the ratio between the two is actively managed as the MPH control parameter.

Thermal control draws directly from the APH, incorporating leaf- and root-zone temperature sensing [7], while maintaining chamber temperatures within an operational range of 11°C and 28°C, each group's D/N allocation (Table 1).

Elevated ethylene levels impair plant fertility and seed viability [5]. Consequently, the chambers include dedicated scrubbing units using chemical sorbents such as potassium permanganate [7, 8, 31], holding ethylene levels below the 50 ppb threshold required for normal physiological development [14]. Activated-carbon filters are integrated into the chamber to manage trace gases and contaminant concentrations [31], positioned away from the air intake lines to prevent unwanted fluctuations in CO₂ readings [31].

To limit polymer off-gassing, the growth chambers use metals for bulk structure [31]. However, components of metallic construction, such as solder, untreated steel, a porous water filter and catalyst beds, carry the trade-off of potential heavy metal accumulation in plant tissue, an issue observed during BIOS-3, where concentrations of aluminium, nickel, chromium, and lead in biomass and nutrient solution increased by a factor of 10 to 20 relative to baseline levels, whereas titanium, zinc, and tin increased by a factor of 2 to 4 [9]. Furthermore, the BIOS-3 experiments note that even in the second experiment none of the elements reached harmful levels [9]. BIOS-3 resolved this the third experiment by changing solders and metal nets, modifying the catalytic converter, and avoiding new steel [9]. Accordingly, ICELSS eliminates solder from wetted paths, incorporates stainless steel for nutrient-loop contact surfaces, and anodised aluminium elsewhere.

4.4 Monitoring and access

The cultivation chambers are sealed volumes, meaning constant crew intervention would compromise the containment of the environments. Access is therefore provided through pressure-sealed sliding windows, integrated between the primary load-bearing members of the central core (Fig. 2). The windows open vertically in both directions to provide access across both annular decks for two distinct purposes; visual and sensory engagement; and scheduled physical entry for crop harvesting at defined stages of the growth cycle. Integrated within the compartment are adjustable shutters designed to prevent stray light ingress from the central cabin from disrupting PP regimes in the cultivation rings. Shutter retraction within a specific sector is restricted to that group's dark period, allowing a schedule to be coordinated based on the groups' PP. When retracted, the shutters yield unobstructed visual access to both rings necessary for additional monitoring and maintenance assist.

Environmental monitoring is carried out internally via dedicated units situated between the sliding windows.

The units integrate leaf- and root-zone temperature and humidity instrumentation, infrared imaging adapted from the APH design [7], and gas-exchange tracking and early pathology detection without unsealing the chambers. Relying on automated instrumentation rather than manual inspection ensures that limiting crew access does not compromise observational oversight.

Beyond the requirement for isolated atmospheric conditioning during cultivation phases for the chamber, the design demands the operational protocols proposed in Section 1.1. Regular crew access during the growth cycle is therefore minimised to mitigate health risks, such as human microbial introduction and fungal spore transfer, restricting direct involvement primarily to the harvesting of mature biomass. In addition, routine inter-cycle disinfection protocols are foreseen. Growth chambers undergo systematic cleaning and disinfection to maintain microbial control, mitigating cross-contamination risks between the plant environment and the internal cabin atmosphere [36], [37]. Nevertheless, deliberate interaction remains supported, as regular engagement offers psychological benefits, sensory variety, and habitability improvements [10], [38]. To accommodate this, three operational interaction tiers are defined: (i.) routine visual and short-term sensory exposure, (ii.) direct physical handling and crop harvesting, and (iii.) servicing of degraded or damaged hardware.

4.5 Transfer, processing, stowage

As highlighted by Hoff et al., raw crop biomass generally requires post-harvest processing to yield safe, palatable and nutritionally viable food products, necessitating the development of low-complexity processing workflows [20]. Food preparation workflows prioritise high palatability and operational simplicity, as dietary quality drives crew psychological well-being and overall mission success during extended spaceflight [39]. Consequently, the designated sector incorporates an ISS-derived modular rack system hosting seven sealed processing units equipped for dehydration, milling, pulverisation, phase extraction, and simple cooking methods [20]. Additionally, nine integrated stowage units accommodate harvested biomass, cold storage reserves, seed inventories, reserve hardware, and maintenance tools.

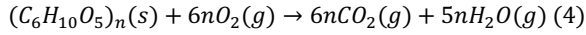
This sector also serves for separating inedible biomass, which is subsequently directed to the waste processing system described in the following section.

5. System budgets and closure performance

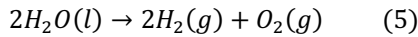
The section initially addresses distinct domains concerning ICELSS, with closure performance and comparative literature evaluations discussed in Section 5.5.

5.1 ECLSS, water processing, waste management

To meet the CO₂ demands of the four-crew ICELSS cultivation chambers, oxidising inedible biomass, as proposed by Wheeler [21], is the mechanism that closes the deficit, with capacity exceeding demand. The requisite is supported by the documented CO₂ absorption rate of 1.15 kg/d-CM relative to the standard human metabolic output, covered in Section 4.3.1. Because carbon constitutes 27% of the mass of CO₂, a total of 0.31 kg of carbon is fixed per day. Based on an average carbon content of 40.6% derived from available BVAD data for the portfolio [18], this corresponds to 0.765 kg/d-CM of dry biomass. Deducting the total EDB of 0.321 kg/d-CM leaves 0.444 kg/d-CM of inedible biomass. The subsequent combustion equation outlines the oxidation process for cellulose ((C₆H₁₀O₅)_n), which serves as an approximation for inedible biomass due to its ~44.4% carbon fraction; where *n* denotes the degree of polymerisation, which varies based on the specific cellulose chain length:



To bridge the deficit of 0.14 kg/d-CM, supplemental CO₂ is introduced into the growth chambers through the water and atmospheric recovery loop (Fig. 1). Given the molar masses of 162.14 g/mol for a single cellulose molecule and 264.05 g/mol for six molecules of CO₂, the resulting mass ratio is equal to 0.614. Applying this ratio to the target CO₂ demand results in ~0.09kg/d-CM of cellulose to be oxidised in order to supply the necessary supplemental CO₂. The yield of 0.444 kg/d-CM of inedible biomass covers the stated carbon deficit, eliminating the need for imported CO₂. In addition, while Section 4.3.1 notes an oxygen surplus, which is accurate within the plant chambers alone (26 mol/d-CM of O₂), accounting for crew consumption (25.5 mol/d-CM) and the combustion process (3.2 mol/d-CM) yields a net O₂ deficit of -2.7 mol/d-CM. Consequently, balancing the system for carbon cannot simultaneously balance for O₂, necessitating physicochemical supplementation. To offset the remaining demand, the system incorporates water electrolysis, producing H₂ and O₂ [14], via the entropy-increasing reaction:



Based on the TSP values in Table 1 and the surface area allocation in Table 2, the cumulative transpiration load reaches approximately 140 kg/d-CM, equivalent to roughly 560 kg/d across the entire crew. Consequently, systematic condensate recovery and recycling into the NDS proves critical [7]. While urine is recycled into additional potable water in a urine processing assembly and water vapour from the crew cabin recovered into potable water [14].

5.2 ICELSS structural mass

Module mass estimations were derived from BVAD's Table 3-9 [18]. To scale component mass estimates proportionally, both the inner surface area and internal volume of ICELSS were determined. Specifically, following data reported by Ewert et al., the TransHab softgoods shell provides an internal surface of 250.9 m² and a total internal volume (including the core) of 329.4 m³ [18].

The following formula was used to estimate the raw module mass of ICELSS:

$$m_{ICELSS} = m_{inflatable} + m_{core} + m_f + m_s \quad (6)$$

Based on volumetric modelling and manual calculations, the ICELSS module yields an internal surface area of 339.2 m² and an internal volume of 491.3 m³. The total structural mass for the proposal was estimated using dimensional scaling ratios and baseline mass parameters derived from TransHab literature [18, 28].

The TransHab core mass, which includes end cones, has a reported mass of 1,405 kg [18]. Scaling this value linearly with the overall length of ICELSS produces an upper-bound core mass (*m_{core}*) of ~2,527 kg. To determine the mass of the 0.406 m thick shell [28], an areal material density was established using the TransHab shell mass of approximately 4,708 kg [18]. Although De La Fuente et al., cite a slightly lower mass of 4,536 kg, representing a discrepancy of ~4%, the former figure was selected to maintain methodological consistency by drawing baseline parameters from a single reference source. Dividing the mass by the TransHab inner surface area yields an average areal density of 18.76 kg/m², which scales to an inflatable shell mass (*m_{inflatable}*) of ~6,364 kg when applied to ICELSS geometry. Fixed subsystem mass (*m_f*) incorporates the "Avionics and Power Management and Distribution" allocation of 1,398 kg from Table 3-9 [18]; it is assumed that these baseline systems do not scale significantly with module size. Secondary systems (*m_s*) were scaled based on their assumed relationship with area and volume: "Other (windows, deployment and attachment system)" was scaled by the surface area ratio of 1.352 to reach ~276 kg, whereas "Initial Inflation System" was scaled by the volumetric ratio of 1.492 to yield ~749 kg. Summing up the resulting values yields a total estimated ICELSS module mass of ~11,316 kg, which corresponds to a volume-mass penalty of ~23 kg/m³.

"Water Containment" and "Radiation Protection Media" were excluded from both mass figures, due to the differences in the architectural placement and geometric scaling. In TransHab, these systems are positioned at the core radius, whereas in ICELSS, they are integrated at a larger radial boundary. Consequently, these elements were not considered under the operational assumption

that the required water mass will be provisioned on-orbit. Cultivation chamber and subsystems masses were likewise excluded. Table 3-9 is a primary-structure table and does not state specific mass allocations to internal subsystems [18]. The comparison is therefore structure against structure on both sides, with subsystem mass considered as additive to the figures given.

5.3 ICELSS thermal budget

To estimate the module's electrical power budget and heat rejection requirement, the species-specific *DLI* [$\text{mol/m}^2\text{d}$] provided in Table 1 must be converted into photosynthetic photon flux (*PPF*) [$\mu\text{mol/m}^2\text{s}$] using the following formula:

$$PPF = \frac{DLI \times 10^6}{PP \times 3600} \quad (7)$$

Following the conversion, the power budget (P_{ICELSS}) in Watts [Js] is estimated by summing up the individual power demands across each species, multiplying their *PPF* demand with area allocation (A_x), divided by fixture photosynthetic photon efficacy (*PPE*) and multiplied with the number of designated CM. A uniform *PPE* value of $2.78 \mu\text{mol/J}$ for white/red LED fixtures was adopted from Kusuma et al. [34]. The following expression was implemented:

$$P_{ICELSS} = 4 \times \sum \frac{PPF_x \times A_x}{PPE} \quad (8)$$

The power demand of each species for one CM, in accordance with the formula, are illustrated in Table 4.

Group	Species	P [W]
I	Dry bean	~155.875
	Pea	~41.434
	Snap bean	~8.926
II	Sweet potato	~811.351
III	Spinach	~58.178
	Celery	~7.750
	Lettuce	~16.986
IV	White potato	~376.299
V	Pepper	~46.763
	Tomato	~271.808
VI	Carrot	~93.550
	Cabbage	~5.770
VII	Wheat	~4636.147

Based on the result, the lighting power demand equates to ~6.529 kW per CM, yielding a total of ~26.115 kW for the full four-person crew.

To model the module's residual power load, SIRONA's "Subsystem Power and Mass Summary" from Hava et al. was established as an empirical baseline

to derive a proportional scaling factor for the remaining subsystems [25]. The reference table reported a lighting load of 20,075W, combining LED fixtures and Himawari solar concentrators [25]. From the baseline table the following subsystems and their total power values were considered: power conditioning (2000 W), air pumps (300 W), water pumps/heaters (880 W), data and control (2255 W), grow system fan (820 W), air temperature (720 W), humidity control (1080 W), robotics (220 W), controls (2.4 W) and miscellaneous plumbing (60 W) [25]. Summing these subsystems yields a value of 8,337.4 W. When combined with SIRONA's stated lighting demand (20,075W) [25], the cumulative power footprint reaches 28.41 kW, taken as the reference total against which ICELSS is compared.

Dividing the secondary subsystems value with the lighting value, yields a ratio of ~0.42. On the other hand, applying the same calculation method to data from Zeidler et al., by dividing the wattage of non-lighting systems by illumination power consumption, yields a ratio of approximate ~0.25 [26]. The dissimilarity between the two stems from the presence of additional subsystem hardware wattage specified in SIRONA; and due to Zeidler et al. providing 64% of lighting demand from light collection [26]. Consequently, the former coefficient has been adopted as an empirical worst-case power scaling factor to account for the remaining subsystems within ICELSS, resulting in an estimated total module power demand of ~37 kW. Consistent with the assumption established by Zeidler et al. [26], onboard power generation falls outside the scope of ICELSS; as a berthed element of larger orbital station, its electrical power is supplied through the passive CBM, and distributed via the interface equipment bay (Fig. 2).

To determine the required radiator surface area, the Stefan-Boltzmann law was applied:

$$Q = e \times \sigma \times A \times T^4 \quad (9)$$

Q denotes the calculated thermal load (P), e is the emissivity of the radiator assumed at 0.9, σ is the Stefan-Boltzmann constant, and T the absolute temperature assumed at 300 K. The implemented values follow in similarity to Zeidler et al. [26], yielding a required radiator surface area (A) of ~89.5 m^2 for ICELSS.

5.4 Caloric yield per CM

SIRONA's proposal supplies 77.81% of the total dietary mass (in fresh mass), corresponding to 18.59% of the total metabolic (caloric) energy intake for a four-person crew during envisioned mission duration [25]. To enable a direct comparative evaluation, it is necessary to convert the EDB values of chosen species listed in Table 1 into daily metabolic energy per crew member (ME) [kcal/CM-d], according to the following expression:

$$ME = \frac{K}{100 - N} \times EDB \times A \quad (10)$$

In this formulation, K represents the energy density [kcal/100 g] and N represents the water content [g/100 g] of the processed food item, with the values retrieved from the USDA FoodData Central database [40]. The variable A represents area in m², as specified in Table 2. The resulting metabolic energy yields across all chosen crops are summarised in Table 5.

Table 5. Metabolic energy per species according to area.

Group	Species	ME [kcal/CM-d]
I	Dry bean	~46.0
	Pea	~13.3
	Snap bean	~3.1
II	Sweet potato	~201.2 ^A
III	Spinach	~13.3
	Celery	~2.7
	Lettuce	~3.9
IV	White potato	~131.3
V	Pepper	~8.3
	Tomato	~52.3
VI	Carrot	~18.7
	Cabbage	~0.8
VII	Wheat	~790.9

^A Sweet potato dry-basis reported as 24.70 g/m²d in [18]; does not reconcile with the fresh-basis value and water content given in the same table. The fresh-basis derivation (15.00 g/m²d) is applied for consistency with the growing-area allocation of Table 4-92.

ICELSS yields an estimated dietary contribution of ~1,285.8 kcal/CM-d. Benchmarked against SIRONA's reference target of 3,033 kcal/CM-d [25], ICELSS fulfils ~42.4% of the total caloric target, compared to SIRONA's aforementioned 18.59%.

5.5 Closure performance

The baseline salad-and-carbohydrate diet provides an offset of 0.325 kg/d-CM (52.60% of the 0.617 kg/d-CM dry food allocation) [18], whereas ICELSS offsets 0.321 kg/d-CM (51.99%). Section 5.1's inedible biomass yield of 0.444 kg/d-CM is sufficient to close the carbon loop, whereas achieving O₂ closure requires supplementary electrolysis.

Against Zeidler et al.'s six-crew module, ICELSS trades gas-exchange rate for area efficiency. Their CO₂ absorption (~1.81 kg/d-CM) and O₂ generation (~1.36 kg/d-CM) both exceed metabolic need by a wider margin than ICELSS [26]. On the other hand, per unit area ICELSS is roughly four times more efficient (0.060 vs. 0.016 kg/m²d-CM). The difference traces to scope and source data: Zeidler et al. target full dietary closure using MELISSA and 2004 BVAD figures [26], while ICELSS targets partial closure using the 2022 BVAD.

Structurally, ICELSS's ~11,316 kg mass translates to a volume-mass penalty of ~23 kg/m³, against TransHab's 24.95 kg/m³ (8,217 kg) [18]. ICELSS achieves an estimated 7.7% improvement that buys 49% more pressurised volume for only 38% more structural mass.

That volumetric gain is accompanied by a higher power cost. ICELSS draws roughly 30% more power than SIRONA, mainly because SIRONA offsets its lighting load with solar concentrators [25], being a strategy that is inefficient for LEO, where eclipse cycles make direct optical delivery impractical. Thus the 30% gap is ICELSS paying the full price for illumination that SIRONA gets partly free. Though, per-species, ICELSS is more streamlined: its wheat lighting power demand of ~480 W/m² is more efficient than Zeidler et al.'s stated ~650 W/m² [26]; a reduction driven by the implementation of modern LEDs in comparison to their 30%-efficient fixtures.

On caloric yield, ICELSS reaches roughly 2.3 times the ME closure of SIRONA. SIRONA targets fresh dietary mass, while ICELSS optimises for calories. The same gap shows up against Zeidler et al.: normalising their 4,115 kg EDB yield [26] over mission duration and crew size results in 1.046 kg/d-CM across 110 m²/CM, or 0.0095 kg/m²d in areal efficiency, in comparison to 0.017 kg/m²d achieved by ICELSS. Unlike the approach used in SIRONA, both architectures prioritise carbohydrate-dense crops. The performance gap stems from stated discrepancies in the baseline reference data used to model crop yields.

Wheat is the reason for both the gain and the cost. It drives roughly 70% of total lighting demand (Table 4). Excluding wheat drops closure from 51.99% to 20.63% and power demand from ~37 kW to ~10.8 kW, translating to 0.049 kg/d per kW of lighting power with wheat, compared to 0.067 kg/d per kW without it. Similarly, transpiration load falls by 81% and radiator area by 71%. Wheat is therefore indispensable to meaningful caloric closure, despite imposing disproportionate resource penalties in power demand, transpiration, and heat.

6. Conclusions

In accordance with Section 2.4, the defined objectives have been addressed within the payload fairing and expansion-ratio constraints characteristics of orbital architectures. The portfolio's demand of 19.087 m²/CM established the baseline ø7.31m envelope through Equations 2 and 3, with structural stack-up and expansion resulting in the fully deployed diameter, with the stated equations being applicable to alternative crop selections. Overall, ICELSS offsets roughly half the dry food resupply allocation and achieves carbon loop closure utilising inedible biomass with O₂ requiring electrolysis, while yielding a volume-mass penalty comparable to TransHab alongside a 49% increase in pressurised

volume. The derivation is envelope independent, and inflatable architecture is selected due to enabling cultivation, maintenance and radiation-shelter configurations. Consequently, this work proposes that module envelope is configured around functional demand. This aligns structural form-finding with Louis Kahn's distinction between Form (the essential nature of an object) and Design (its realisation). Here, the Form embodies the portfolio's physiological demand, while the annular arrangement represents one Design that satisfies it. Ultimately, the portfolio's reliance on wheat to balance metabolic offset against high power demand illustrates a paradox in partial life-support closure: the crops that render closure worth attempting are also the ones that make it expensive. By extension, ICELSS suggests that biological autonomy cannot be measured by mass-balance efficiency alone. An effective bioregenerative architecture must simultaneously fulfil crew metabolic demands and provide a liveable, engaging human environment. Designing for biological autonomy therefore means choreographing the reciprocity between plants, technology, and people.

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