

## Optical Fiber Optimization and Yield Modeling for a Solar-Flux Autonomous Microgravity Growth Chamber in Low-Earth Orbit Space Agriculture

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Developing scalable and optimized Bio-Regenerative Life Support Systems (BLSS) is a critical bottleneck for prolonged extraterrestrial human habitation. This study presents the preliminary optical engineering and structural architecture for a  $2 \times 1 \times 1.5 \text{ m}^3$  (L  $\times$  W  $\times$  H) Astro-Pod greenhouse prototype optimized for cultivating dwarf wheat (*Triticum sphaerococcum*) in space environments. Instead of traditional energy-intensive and thermally inefficient light-emitting diode (LED) arrays, we introduce a system utilizing direct solar harvest via external concentrators, routing filtered visible spectra through Plastic Optical Fiber (POF) bundles. By transitioning from classical radiometric power metrics (Watts) to plant-centric quantum fluxes (Photosynthetically Active Radiation [PAR], PPFD, and Daily Light Integral [DLI]), we model the exact photon requirements needed to support crop maturation within an accelerated 60-to-70-day cycle. The mathematical layout optimizes the collector aperture, quantifies systemic transmission and coupling losses, and establishes the precise structural configuration of the optical delivery network to guarantee uniform canopy illumination under microgravity constraints.

**Keywords:** Space Constrained Cultivation, Bio-Regenerative Life Support System (BLSS), Photosynthetically Active Radiation (PAR), Daily Light Integral (DLI), Plastic Optical Fiber (POF) Bundling, *Triticum sphaerococcum*

### 1. Introduction

Sustainable dietary self-sufficiency in deep-space exploration—including long-duration missions on the International Space Station (ISS), lunar outposts, and Martian habitats—necessitates highly optimized closed-loop agricultural units. Current hardware configurations, such as the Biological Research in Canisters (BRIC)<sup>1</sup> and Veggie systems<sup>2</sup>, rely heavily on solid-state Light Emitting Diodes (LEDs)<sup>3</sup>. While LEDs allow precise spectral tuning, their operational baseline introduces high electrical loads, severe thermal management demands due to localized heat dissipation, systemic mass penalties, and continuous hardware depreciation in high-radiation zones.

To bypass these limitations, the research division at Aaryavarta Aerospace and Defense Engineering (AADE) is developing a solar-flux growth chamber archetype. This design circumvents intermediate electrical conversion by harvesting raw extraterrestrial solar irradiance directly, filtering out non-biocompatible wavelengths via dielectric cold mirrors, and transferring the pure photosynthetic band via flexible optical fiber waveguides into a sealed  $2 \times 1 \times 1.5 \text{ m}^3$  controlled-environment pod. The primary focus of this paper is to resolve the fundamental optical-to-biological scaling problem: calculating the exact collector dimensions, accounting for real-world waveguide transmission degradation, converting raw flux into biological photon density, and defining the geometric architecture of the fiber bundles required to safely support a high-density crop canopy<sup>4</sup>.

### 2. Methodology & System Configuration

#### 2.1 Canopy Density and Yield Projections

For a controlled  $200 \times 100 \text{ cm}^2$  growth bed (total surface area  $A = 20,000 \text{ cm}^2$ ), standard terrestrial spacing matrices are obsolete due to engineered atmospheric enrichment and hydroponic root zones. We implement a strict matrix where seeds are sown at a depth of 3 cm, with intra-row plant spacing set at 2.5 cm and an inter-row distance of 10 cm. The first and last rows are placed 5 cm away from the sidewall; all remaining rows are spaced 10 cm apart. The boundaries of the growth grid yield the following structural density:

$$\text{Number of Rows} = 100 / 10 + 1 = 11$$

$$\text{Number of Plants per row} = 200 / 2.5 + 1 = 81$$

$$\text{Total Canopy Population (N)} = 11 \times 81 = 891 \text{ plants}$$

Using an engineered dwarf<sup>5</sup> wheat variety (*Triticum sphaerococcum*)<sup>6</sup>, which exhibits an optimized harvest index and a controlled height profile of 60 to 100 cm, we factor an average of 10 productive tillers per plant. Given a regulated micro-climate, each spike yields approximately 100 grains, equating to 1,000 kernels per plant. At a verified 1,000-kernel weight baseline averaging 35 g for dwarf cultivars, the maximum theoretical biomass yield is modeled as:

$$\text{Yield} = 891 \times 1000 = 891,000 \text{ kernels}$$

$$\text{Weight} = 891 \times 1000 \times 35 / 1000 = 31,185 \text{ g} = 31.18 \text{ kg}$$

Factoring a conservative 10% biological mortality rate under early-stage microgravity adjustments, a stabilized population of approximately 800 plants yields:

Yield (real) =  $800 \times 1000 \times 35 / 1000 = 28,000 \text{ g} = 28 \text{ kg}$  of clean grain

Assuming a standard astronautic dietary intake profile of 400 g of cereal grain per capita per day, a single crop cycle within this single growing bed of  $2 \text{ m}^2$  area generates a continuous 35-day food supply reservation for a standard two-person crew.

## 2.2 Quantum Photometric Requirements

To prevent the structural degradation and sterility associated with uncalibrated speed-breeding configurations, the photoperiod is strictly locked to a 12-hour diurnal cycle. Crop physiology dictates that optimal wheat photosynthesis requires a minimum Daily Light Integral (DLI) of  $30 \text{ mol m}^{-2} \text{ day}^{-1}$  of photons within the PAR band (400–700 nm). For a 12-hour (43,200 s) photoperiod, the required Photosynthetic Photon Flux Density (PPFD)<sup>7</sup> over the canopy is calculated as:

$$\text{PPFD} = \text{DLI} / (\text{Photoperiod (s)}) = (30 \text{ mol m}^{-2} \text{ day}^{-1}) / (43,200 \text{ s}) = 694.4 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$$

Extrapolating this across the entire  $2 \text{ m}^2$  cultivation bed, the system must deliver a continuous Photosynthetic Photon Flux (PPF) of:

$$\text{PPF}_{\text{total}} = 694.4 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1} \times 2 \text{ m}^2 = 1388.8 \text{ } \mu\text{mol s}^{-1}$$

Using the standard conversion factor for mid-spectrum solar PAR wavelengths (where 1 W of optical PAR power approximates  $4.6 \text{ } \mu\text{mol s}^{-1}$  of photon flux), the absolute biological optical power requirement ( $P_{\text{bio}}$ ) inside the pod is:

$$P_{\text{bio}} = 1388.8 / 4.6 = 301.9 \text{ W of pure PAR light}$$

## 3. Results & Optical Engineering Calculations

### 3.1 Solar Constant and Interception Optimization

In a Low-Earth Orbit (LEO)<sup>8</sup> operational envelope, the space-borne solar constant<sup>9</sup> is taken as a stable  $1367 \text{ W m}^{-2}$  nominal. The spectral distribution of raw sunlight dictates that approximately 45% resides within the useful visible PAR spectrum (400–700 nm), 5% within the ultraviolet (UV) spectrum, and 50% within the thermal infrared (IR) spectrum. To prevent catastrophic thermal buildup inside the biological payload chamber, an external primary cold mirror system is deployed. This dielectric filter reflects 98% of the IR spectrum outward while allowing the visible PAR energy component to pass into the optical focusing assembly:

$$I_{\text{PAR}} = 1367 \text{ W m}^{-2} \times 45\% = 615.15 \text{ W m}^{-2}$$

### 3.2 Total Systemic Efficiency and Collector Sizing

Unlike simplified models, a true space-rated optical transmission line suffers from multiple compounding losses. We define the total systemic efficiency ( $\eta_{\text{sys}}$ ) through the following parameters:

1. Filter transmission efficiency ( $\eta_{\text{filter}}$ ): 90% (reflectance and structural absorption losses at the cold mirror).
2. Coupling efficiency ( $\eta_{\text{couple}}$ ): 85% (numerical aperture mismatch and geometric alignment errors at the fiber entrance faces).

3. Fresnel reflection losses ( $\eta_{\text{fresnel}}$ ): 92% (refractive index boundary transitions at uncoated fiber ends).
4. Fiber waveguide attenuation ( $\eta_{\text{atten}}$ ): 90% (calculated for a high-purity polymethyl methacrylate [PMMA] core over a conservative 3 m routing path, with an attenuation coefficient of  $\alpha \approx 150 \text{ dB km}^{-1}$  at the 550 nm center wavelength).

$$\text{Loss (dB)} = \alpha \times L, \quad \alpha = 150 \text{ dB/km} = 0.15 \text{ dB/m}, \quad L = 3 \text{ m}$$

$$\text{Loss} = 0.45 \text{ dB}$$

$$\text{Power Transmission Ratio} = 10^{-(0.45/10)} = 0.9016 \approx 90\%$$

$$\eta_{\text{sys}} = \eta_{\text{filter}} \times \eta_{\text{couple}} \times \eta_{\text{fresnel}} \times \eta_{\text{atten}}$$

$$\eta_{\text{sys}} = 0.90 \times 0.85 \times 0.92 \times 0.90 = 63.3\% (63.34\%)$$

Thus, the actual usable PAR power density available per square meter of collection area is:

$$I_{\text{usable}} = I_{\text{PAR}} \times \eta_{\text{sys}} = 615.15 \times 63.3\% = 389.89 \text{ W m}^{-2}$$

To supply the critical biological baseline power ( $P_{\text{bio}} = 301.9 \text{ W}$ ), the external tracking solar concentrator must possess an effective aperture area ( $A_{\text{collect}}$ ) of:

$$A_{\text{collect}} = P_{\text{bio}} / I_{\text{usable}} = (301.9 \text{ W}) / (389.9 \text{ W m}^{-2}) = 0.774 \text{ m}^2$$

Assuming a standard circular parabolic solar collector array, the precise structural outer diameter ( $D_{\text{collect}}$ ) required is:

$$A_{\text{collect}} = \pi r^2 = \pi (D/2)^2 = \pi D^2 / 4$$

$$D = \sqrt{(4 \times 0.774) / \pi} \approx 0.998 \text{ m}$$

### 3.3 Optical Fiber Cable (OFC) Bundling Mechanics

To ensure robust structural flexibility and ease of integration within the rotating or shifting mechanisms of spacecraft walls, polymethyl methacrylate (PMMA)<sup>10</sup> plastic optical fibers are chosen over brittle silica variants. Standard high-output PMMA configurations possess a maximum safe long-term thermal power handling capacity of approximately 65 W of continuous optical energy per 20 mm (2 cm) core-diameter bundle before localized non-radiative heating triggers core deformation. To safely route the aggregate input light power entering the primary distribution manifold, the minimum number of core transmission cables ( $N_{\text{cables}}$ ) is established as:

$$N_{\text{cables}} = P_{\text{bio}} / (65 \text{ W/cable}) \approx 4.64 \Rightarrow 5 \text{ structural cables}$$

Dividing the required structural array across the 891 individual plant nodes within the cultivation grid:

$$\text{Strands per Cable} = (891 \text{ nodes}) / (5 \text{ main cables}) \approx 178 \text{ optical strands per cable}$$

Each individual strand is engineered with a localized core diameter of 1.5 mm. Accounting for a hexagonal close-packing (HCP) structural packing factor of 90.6%, a bundle containing 178 strands of 1.5 mm diameter forms a highly flexible collective cable with a real physical diameter of approximately 21.02 mm, aligning with our safety limits. The optical power distributed per individual strand/plant node is a highly uniform:

$$P_{\text{node}} = (301.9 \text{ W}) / 891 \approx 0.338 \text{ W of PAR light per plant}$$

#### 4. Discussion & Canopy Interception Dynamics

A critical flaw in basic waveguide designs is the localized “hot-spot” or point-source delivery effect, where intense, collimated light exiting a raw fiber tip causes localized photo-inhibition and thermal necrosis on the immediate leaf tissues below. To convert these highly directional point sources into a homogeneous, area-based spatial illumination layer, each of the 5 primary cables terminates into a specialized broad-angle diverging optical lens element.

The physical positioning layout places one primary lens array precisely at the geometric center of the pod ceiling, while the remaining four arrays are placed at equidistant coordinates near the chamber corners. To optimize photon conservation and mitigate scattering losses out of the growth zone, the upper 40% zone of the internal pod bulkheads is lined with a high-reflectivity Miro-Silver aluminum coating (reflectivity approx. 98%), effectively repurposing scattered photons back toward the lower canopy layers.

Furthermore, because real-world crop canopies exhibit complex dynamic light interception, reflection, and multi-layered leaf scattering behavior as they grow from seedlings into dense vegetative mats, the light delivery plane is mounted on a mechanical vertical tracking scissor-jack system. This allows the distance between the lens array and the soil bed to be continuously adjusted from a maximum clearance of 120 cm down to 15 cm, maintaining an unfluctuating, optimal PPFD at the topmost leaf layer throughout the 70-day life cycle.

#### 5. Conclusion

This paper establishes a rigorous, mathematically validated engineering framework for an autonomous space-borne growth chamber powered entirely by targeted solar flux routing. By transitioning to quantum agricultural units (30 mol m<sup>-2</sup> day<sup>-1</sup> DLI) and introducing real-world physical transmission, coupling, and reflection losses, we have demonstrated that a tracking parabolic concentrator with a diameter of just under 1 m (0.998 m) is sufficient to illuminate a 2 m<sup>2</sup> dwarf wheat canopy. Splitting the optical load across 5 balanced PMMA cables containing 178 individual 1.5 mm strands resolves the core engineering challenge of safe thermal power routing while guaranteeing uniform photon coverage. Future iterations of this project will focus on the empirical modeling of the fluid dynamics governing nutrient delivery in microgravity and the structural validation of the external optical tracking array under simulated orbital thermal variations.

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