Controlled Environment Horticulture for Space and Earth

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Why horticulture for space?
**Human Life Support Requirements:**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily Rqmt. (% total mass)</td>
<td>Daily (% total mass)</td>
</tr>
<tr>
<td>Oxygen 0.83 kg 2.7%</td>
<td>Carbon 1.00 kg 3.2%</td>
</tr>
<tr>
<td>Food 0.62 kg 2.0%</td>
<td>dioxide</td>
</tr>
<tr>
<td>Water 3.56 kg 11.4% (drink and</td>
<td>Metabolic 0.11 kg 0.35% solids</td>
</tr>
<tr>
<td>food prep.)</td>
<td>Water 29.95 kg 96.5% (metabolic/urine)</td>
</tr>
<tr>
<td>Water 26.0 kg 83.9% (hygiene,</td>
<td>(hygiene/flush 24.7%)</td>
</tr>
<tr>
<td>flush, laundry, dishes)</td>
<td>(laundry/dish 55.7%)</td>
</tr>
<tr>
<td>Total 31.0 kg</td>
<td>(launey/sink 3.6%)</td>
</tr>
</tbody>
</table>

*Source: NASA SPP 30262 Space Station ECLSS Architectural Control Document
Food assumed to be dry except for chemically-bound water.*

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**Plants and “Bioregenerative” Life Support**

**HUMANS**

- Metabolic Energy
- (CH₂O) + O₂ → CO₂ + H₂O → Waste Water
- Clean Water → Waste Water

**PLANTS**

- Light
- (CH₂O) + O₂ + H₂O → CO₂ + 2H₂O
- Clean Water ← Waste Water
- Clean Water ← Waste Water
Space habitats for humans will require protected, controlled environments. The same will be true for plants.

→ To grow crops in space would also require a controlled environment approach.

**Controlled Environment Considerations for Space**

- Temperature
- Humidity
- Air Circulation
- Lighting
  - Electric Sources
  - Solar
- Carbon Dioxide

- Atmospheric Closure
  - Super-elevated CO₂, pO₂, Volatile Organic Compounds (VOCs)
- Gravity
  - μ-g Orbiting or Transit, 1/3 g (Mars), 1/6 g (Moon)
- Radiation
  - Shielding for solar events, cosmic rays
If plants and are used for life support, they must be measured against competing options, such as stowage / resupply or physico-chemical technologies.

**Key Factors for Choosing Life Support Technologies**

- Mass
- Power Requirements
- Volume
- Stowage and Deployment
- Ease of Integration
- Reliability / Risk of Failure
Some Drivers for Space Horticulture and Life Support:

- Maximize yields to reduce system mass and volume
- Select nutritious and easily managed crops
- Consider dwarf and high harvest index crops
- Energy efficient lighting
- Develop reliable support hardware to reduce failures

Bioregenerative Life Support Testing around the World

1960 | 1980 | 2000
--- | --- | ---
US Air Force | US Air Force | Inst. for Biomedical Problems (Moscow)
USSR Air Force | Inst. of Biophysics (Krasnoyarsk, Siberia) | NASA
NASA | NASA (CELSS) | NASA (ALS)
Natl. Aerospace Lab (Japan) | Inst. Env. Sci. (IES) | MELISSA / ESA
Cadarache, France | University Studies (US, Europe, Japan, Canada) | Univ. of Guelph / CSA

Chinese Space Agency
Potential Crops for Life Support

- Wheat
- Soybean
- Potato
- Lettuce
- Sweetpotato
- Peanut
- Rice
- Sugar Beet
- Pea
- Taro
- Winged Bean
- Broccoli
- Onion
- Strawberry

- Wheat
- Potato
- Soybean
- Rice
- Peanut
- Dry Bean
- Tomato
- Carrot
- Chard
- Cabbage

- Wheat
- Rice
- Sweetpotato
- Broccoli
- Kale
- Lettuce
- Carrot
- Rape Seed (Canola)
- Soybean
- Peanut
- Chickpea
- Lentil
- Tomato
- Onion
- Chili Pepper

- Wheat
- Potato
- Carrot
- Radish
- Beet
- Nut Sedge
- Onion
- Cabbage
- Tomato
- Pea
- Dill
- Cucumber
- Salad spp.

---

*Tibbits and Afford (1982);*  
**Hoff, Howe, and Mitchell (1982);*  
*Salisbury and Clark (1996);*  
*Gelisso and Oktadnikov (1994) — diet also included supplemental animal protein and sugar.*
Some Observations from NASA-Sponsored Controlled Environment Horticulture

Use of Recirculating Hydroponics

Conserves Water & Nutrients
Optimizes Growth
Reduces System Mass
Including Root Zone Crops in Nutrient Film Technique

Peanut

Potato


High Light and CO₂ Enrichment to Increase Yield

Wheat - 3.4 x World Record
Potato - 2 x World Record
Lettuce-Exceeded Commercial Yield Models

Reduces mass and Volume requirements

NASA Kennedy Space Center
Wisconsin Biotron
Utah State Univ.
Understanding Atmospherically Closed Systems

NASA's Biomass Production Chamber (BPC)

20 m² growing area; 113 m³ vol.; 96 400-W HPS Lamps; 400 m³ min⁻¹ air circulation; two 52-kW chillers
Canopy CO$_2$ Uptake / O$_2$ Production
(20 m$^2$ Soybean Stand)

CO$_2$ Exchange Rates of Soybean Stands
**CO₂ Exchange Rate vs. CO₂ Concentration**

The graph depicts the relationship between CO₂ exchange rate (μmol m⁻² s⁻¹) and CO₂ concentration (μmol mol⁻¹). The optimal concentration is indicated by the downward arrow. The data suggest a linear relationship with an equation given as:

\[ y = 0.15x - 14.6 \]

with a correlation coefficient \( R^2 = 0.99 \).

**Some Volatile Organic Compounds in Closed Systems**

<table>
<thead>
<tr>
<th>Humans</th>
<th>Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetaldehyde</td>
<td>benzaldehyde</td>
</tr>
<tr>
<td>acetone</td>
<td>2-butanone</td>
</tr>
<tr>
<td>ammonia</td>
<td>carbon disulfide</td>
</tr>
<tr>
<td>n-butyl alcohol</td>
<td>ethylene</td>
</tr>
<tr>
<td>carbon monoxide</td>
<td>2-ethyl-1-hexanol</td>
</tr>
<tr>
<td>caprylic acid</td>
<td>heptanal</td>
</tr>
<tr>
<td>ethanol</td>
<td>hexanal</td>
</tr>
<tr>
<td>ethyl mercaptan</td>
<td>2-hexen-1-ol acetate</td>
</tr>
<tr>
<td>hydrogen</td>
<td>isoprene</td>
</tr>
<tr>
<td>hydrogen sulfide</td>
<td>limonene</td>
</tr>
<tr>
<td>indole</td>
<td>2-methylfuran</td>
</tr>
<tr>
<td>methanol</td>
<td>nonanal</td>
</tr>
<tr>
<td>methane</td>
<td>osmone</td>
</tr>
<tr>
<td>methyl mercaptan</td>
<td>α-pinene</td>
</tr>
<tr>
<td>propyl mercaptan</td>
<td>β-pinene</td>
</tr>
<tr>
<td>pyruvic acid</td>
<td>α-terpinene</td>
</tr>
<tr>
<td>skatole</td>
<td>tetrahydrofuran</td>
</tr>
<tr>
<td>valeraldehyde</td>
<td>tetramethylurea</td>
</tr>
<tr>
<td>valeric acid</td>
<td>thiobismethane</td>
</tr>
</tbody>
</table>
Physiological Disorders in Controlled Environments

Leaf Tipburn

Lettuce cv. Flandria
Long Photoperiod Intolerance

Potato cv. Denali

Note: Upright, chlorotic leaves

Oedema or Intumescence

Potato cv. Denali
Blossom End Rot

Pepper cv. Fruit Basket

Early Stage

Also common in tomato

Late Stage

Super-Elevated CO₂ Injury

Soybean-5000 ppm CO₂

Radish-10,000 ppm CO₂
Leaf Epinasty from Ethylene

Potato cv. Denali

Wheat cv. Yecora Rojo

The Importance of Lighting
### Electric Light Options

<table>
<thead>
<tr>
<th>Lamp Type</th>
<th>Conversion* Efficiency</th>
<th>Lamp Life* (hrs)</th>
<th>Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent/Tungsten**</td>
<td>5-10%</td>
<td>2000</td>
<td>Interm.</td>
</tr>
<tr>
<td>Xenon</td>
<td>5-10%</td>
<td>2000</td>
<td>Broad</td>
</tr>
<tr>
<td>Fluorescent***</td>
<td>20%</td>
<td>5,000-20,000</td>
<td>Broad</td>
</tr>
<tr>
<td>Metal Halide</td>
<td>25%</td>
<td>20,000</td>
<td>Broad</td>
</tr>
<tr>
<td>High Pressure Sodium</td>
<td>30%</td>
<td>25,000</td>
<td>Interm.</td>
</tr>
<tr>
<td>Low Pressure Sodium</td>
<td>35%</td>
<td>25,000</td>
<td>Narrow</td>
</tr>
<tr>
<td>Microwave Sulfur</td>
<td>35-40%+</td>
<td>?</td>
<td>Broad</td>
</tr>
<tr>
<td>LEDs (red and blue)****</td>
<td>40% +</td>
<td>100,000 ?</td>
<td>Narrow</td>
</tr>
</tbody>
</table>

* Approximate values.
** Tungsten halogen lamps have broader spectrum.
*** For VHO lamps; lower power lamps with electronic ballasts last up to ~20,000 hrs.
**** Green LEDs -10-15% efficient; state-of-art white LEDs ~ 20-25% efficient.

### LEDs for Growing Plants

- **Red...photosynthesis**
- **Blue...photomorphogenesis**
- **Green...human vision**

John Sager, KSC, Testing Prototype
Flight Plant Chambers with LEDs
Atmospheric Pressures Considerations

Advantages of low pressure:
- Reduced structural mass
- Reduced gas leakage (and resupply)
- More possibilities for transparent materials

Low Pressure, Deployable Greenhouse Concepts
- Inflatable, low mass, easy stowage
- Low pressure to reduce leakage
- Might be covered at night
Physiologia Plantarum
An International Journal for Plant Biology

Hypobaric Chambers
Texas A&M University

How Can Controlled Environment Horticulture for Space Relate to Earth?
Help Improve:
Hydroponic Techniques
Monitoring and Control Technologies
Automation
Electric Lighting Efficiency
Explore New Crops, Develop New Cvs.

Automation Technologies for CEA

ALSARM Robot in NASA Biomass Production Chamber
"Plant Factory" Applications

Leafy vegetables and herbs in multi-layered production system

Photo Courtesy of C. Kubota, Univ. Arizona
Vertical Agriculture for Urban Settings

Graphics from Website for D. Despomier, Columbia Univ.

Solar Collector / Fiber Optic Delivery
(Kennedy Space Center, FL)

Up to 400 W light delivered to chamber (40-50% of incident light)

2 m$^2$ of collectors on solar tracking drive (SLSL Bldg, KSC)
Vertical Farming Happening Right Now

Texas Plant-Expressed Vaccine Consortium
Photos Courtesy of Illumitex
Austin, TX

Concluding Thoughts on Benefits from Space Horticulture

• Improved productivity of crops in CEA
• Introduction of new crops and cultivars
• Improved energy efficiency
• Approaches for sustainable living, e.g., water and nutrient conservation
• Help develop urban and vertical ag concepts
Kennedy Space Center Advanced Life Support Team

Light, Productivity, and Crop Area Requirements

Area Required (m²/person) vs. Light (mol m² day⁻¹)

- Area
- Productivity

- Bright Sunny Day on Earth
- Bright Sunny Day on Mars