Plants for Space Travel

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Plants Beyond Limits
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University of Central Florida
Human Life Support Requirements:

### Inputs

<table>
<thead>
<tr>
<th></th>
<th>Daily Rqmt.</th>
<th>(% total mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>0.83 kg</td>
<td>2.7%</td>
</tr>
<tr>
<td>Food</td>
<td>0.62 kg</td>
<td>2.0%</td>
</tr>
<tr>
<td>Water (drink and food prep.)</td>
<td>3.56 kg</td>
<td>11.4%</td>
</tr>
<tr>
<td>Water (hygiene, flush, laundry, dishes)</td>
<td>26.0 kg</td>
<td>83.9%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>31.0 kg</strong></td>
<td></td>
</tr>
</tbody>
</table>

### Outputs

<table>
<thead>
<tr>
<th></th>
<th>Daily</th>
<th>(% total mass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>1.00 kg</td>
<td>3.2%</td>
</tr>
<tr>
<td>Metabolic solids</td>
<td>0.11 kg</td>
<td>0.35%</td>
</tr>
<tr>
<td>Water (metabolic / urine)</td>
<td>29.95 kg</td>
<td>96.5%</td>
</tr>
<tr>
<td>Water (hygiene / flush)</td>
<td>12.3%</td>
<td></td>
</tr>
<tr>
<td>(laundry / dish)</td>
<td>24.7%</td>
<td></td>
</tr>
<tr>
<td>(latent)</td>
<td>55.7%</td>
<td></td>
</tr>
<tr>
<td>(latent)</td>
<td>3.6%</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>31.0 kg</strong></td>
<td></td>
</tr>
</tbody>
</table>

Source: NASA SPP 30262 Space Station ECLSS Architectural Control Document

Food assumed to be dry except for chemically-bound water.
International Space Station Life Support Systems

Source: Reuter and Reysa, 2001

Legend:
- Carbon Dioxide Removal
- Trace Contaminant Control
- Oxygen Generation
- Major Constituent Analyzer
- Sabatier
- Water Storage
- Water Processing (P=Potable; H=Hygiene)
- Urine Processing
- Personal Hygiene Facility
- Galley

O2 Compressor
Air Save Compressor
Pressure Control Assembly
Primary Temperature and Humidity Control
Vacuum System
Miscellaneous Equip: Fans, Valves, Filters, Smoke Detectors, Portable Fire Extinguishers
Plants for “Bioregenerative” Life Support

HUMANS

food
(CH₂O) + O₂ → CO₂ + H₂O

Clean Water → Waste Water

Metabolic Energy

PLANTS

(CH₂O) + O₂* + H₂O ← CO₂ + 2H₂O*

Clean Water ← Waste Water

Light

Inedible Biomass
Life Support Options for Different Missions

Role of Plants:
- Supplemental Food: 0.5 – 5 m² plant area
- "More" Food, Partial O₂, CO₂ removal: 5 – 25 m² plant area
- Most Food, All O₂, All CO₂ removal: 25 – 50 m² plant area
NASA’s Bioregenerative Life Support Testing

1980
- CELSS Program
  - Wheat (Utah State)
  - Algae

1990
- ALS / ELS Program
  - Gas Ex./Ethylene (Utah State)
  - Sweetpotato / Peanut (Tuskegee)
  - Potato (Wisconsin)
  - Soybean (NC State)
  - N-Nutrition (UC Davis)
  - Lettuce (Purdue)
  - STS-73 Potato Leaves

2000
- LSHS Program
  - ISS Mizuna Utah St./KSC
  - Hypobaria (TAMU)
  - ISS VEGGIE
  - Lettuce (KSC)
  - ISS Wheat Expmt

2010
- Advanced Plant Habitat ISS
  - ISS VEGGIE

Universities
- Purdue
- Rutgers
- Ames
- Kennedy
- Johnson
- Small Companies

NASA Centers
- Ames
- Kennedy
- Johnson

Habitat Demo Unit Plant Atrium (KSC)
Lunar Greenhouse (Arizona)

Large, Closed System
NFT
Lighting
Waste Recycling
Salad spp.
Habitat Testing

Solid Media
Pressure Human / Integration
BIOPLEX
BPS
VEGGIE
Aeroponics
Solar Conc.
HELIAC

SBIRs—Sensors, LEDs, Zeolite, BPS, VEGGIE, Aeroponics, Solar Conc., HELIAC
Crop Considerations for Space

- High yielding and nutritious (CHO, protein, fat)
  - Secondary Metabolites—e.g., antioxidants, lutein, zeaxanthin
- High harvest index (edible / total biomass)
- Dwarf or low growing types
- Environmental considerations
  - lighting, temperature, mineral nutrition, CO₂
- Horticultural considerations
  - planting, watering, harvesting, pollination, propagation
- Processing requirements
### Some Crops for Life Support

<table>
<thead>
<tr>
<th>Hoff, Howe, and Mitchell (NASA)</th>
<th>Salisbury and Clark (NASA)</th>
<th>Crops Used in BIOS-3 (Russia)</th>
<th>Tako et al CEEF (Japan)</th>
<th>Waters et al. (ESA / Canada)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>Wheat</td>
<td>Wheat</td>
<td>Rice</td>
<td>Lettuce</td>
</tr>
<tr>
<td>Potato</td>
<td>Rice</td>
<td>Potato</td>
<td>Soybean</td>
<td>Wheat</td>
</tr>
<tr>
<td>Soybean</td>
<td>Sweetpotato</td>
<td>Carrot</td>
<td>Peanut</td>
<td>Potato</td>
</tr>
<tr>
<td>Rice</td>
<td>Broccoli</td>
<td>Radish</td>
<td>Sweetpotato</td>
<td>Tomato</td>
</tr>
<tr>
<td>Peanut</td>
<td>Kale</td>
<td>Beet</td>
<td>Sugar Beet</td>
<td>Carrot</td>
</tr>
<tr>
<td>Dry Bean</td>
<td>Lettuce</td>
<td>Nut Sedge</td>
<td>Tomato</td>
<td>Tomato</td>
</tr>
<tr>
<td>Tomato</td>
<td>Carrot</td>
<td>Onion</td>
<td>Spinach</td>
<td>Spinach</td>
</tr>
<tr>
<td>Carrot</td>
<td>Canola</td>
<td>Cabbage</td>
<td>Shungiku</td>
<td>Cabbage</td>
</tr>
<tr>
<td>Chard</td>
<td>Soybean</td>
<td>Tomato</td>
<td>Chinese Cabbage</td>
<td>Pea</td>
</tr>
<tr>
<td>Cabbage</td>
<td>Peanut</td>
<td>Pea</td>
<td>Pea</td>
<td>Dill</td>
</tr>
<tr>
<td></td>
<td>Chickpea</td>
<td>Dill</td>
<td>Cucumber</td>
<td>Cucumber</td>
</tr>
<tr>
<td></td>
<td>Lentil</td>
<td>Salad spp.</td>
<td>Onion/Leek</td>
<td>Onion</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td></td>
<td>Komatsuna</td>
<td>Kale</td>
</tr>
<tr>
<td></td>
<td>Onion</td>
<td></td>
<td>Pepper</td>
<td>Onion</td>
</tr>
<tr>
<td></td>
<td>Chili Pepper</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Hoff, Howe, and Mitchell (1982); b Salisbury and Clark (1996); c Gitelson and Okladnikov (1994).

d Tako et al. (2010); e Waters et al. (2002)
Targeted Crop Selection and Breeding for Space at Utah State University

Selection of Existing Rice Genotypes

Targeted Wheat Breeding

‘Apogee’ Wheat  ‘Perigee’ Wheat
Genetic Engineering Tools

Early Flowering and Fruit Set

Overexpression of FT flowering gene in plums (ARS researchers) resulted in dwarf growth habit and early flowering

No Dormancy Requirements
Water and Nutrients for Growing Crops

Recirculating Hydroponics

Wheat / Utah State

Soybean KSC

Sweetpotato Tuskegee

Rice / Purdue

Conserve Water & Nutrients
Eliminate Water Stress
Optimize Mineral Nutrition
Facilitate Harvesting

Root Zone Crops in Nutrient Film Technique (NFT)

Evapotranspiration from Plant Stand (potato)

Fig. 7

High Yields from NASA Sponsored Studies

Wheat - 3-4 x World Record
Potato - 2 x World Record
Lettuce-Exceeded Commercial Yield Models

Utah State Univ.

Wisconsin Biotron

Canopy CO$_2$ Uptake / O$_2$ Production
(20 m$^2$ Soybean Stand)

CO₂ Exchange Rates of Soybean Stands

Wheeler et al., 2004. EcoEngineering.
Ethylene Gas in Closed Systems

Epinastic Wheat Leaves at ~120 ppb

Epinastic Potato Leaves at ~40 ppb

Wheeler et al., 2004 HortScience
NASA’s Biomass Production Chamber (BPC)

Early Vertical Agriculture!

External View - Back

20 m² growing area; 113 m³ vol.; 96 400-W HPS Lamps; 400 m³ min⁻¹ air circulation; two 52-kW chillers
NASA’s Biomass Production Chamber (BPC) …an early example of a Vertical Agriculture Systems
Wheat
(Triticum aestivum)

planting

harvest
Soybean

*(Glycine max)*
Lettuce

(*Lactuca sativa*)
Potato
(*Solanum tuberosum*)
Automation Technologies for CEA

ALSARM Robot in NASA Biomass Production Chamber
### Electric Lamp Options for Lighting

<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>Intermd.</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>30-35%</td>
<td>25,000</td>
<td>Intermd.</td>
</tr>
<tr>
<td>Low Pressure Sodium</td>
<td>35%</td>
<td>25,000</td>
<td>Narrow</td>
</tr>
<tr>
<td>Microwave / RF Sulfur</td>
<td>35-40%+</td>
<td>?</td>
<td>Broad</td>
</tr>
<tr>
<td>LEDs (red and blue)****</td>
<td>&gt;40%</td>
<td>50,000</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.

**** State-of-Art Blue and Red LEDs most efficient.
LED Studies

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

North American Patent for Using LEDs to Grow Plants Developed with NASA Funding at University of Wisconsin – WCSAR

Solar Collector / Fiber Optics For Plant Lighting

Up to 400 W light delivered to chamber (40-50% of incident light)
Takashi Nakamura, Physical Sciences Inc.

2 m² of collectors on solar tracking drive (NASA KSC)

Nakamura et al. 2010. Habitation
The Importance of Light for Crop Yield

Includes:
- Wheat (4)
- Soybean (4)
- Potato (4)
- Lettuce (3)
- Tomato (2)

Photosynthetically Active Radiation (mol m$^{-2}$ d$^{-1}$)

Crop Yield (g m$^{-2}$ d$^{-1}$)

Total Biomass

Edible Biomass

Buried Plant Growth Chambers

Solar Collectors for Crop Production

Sadler and Giacomelli, 2002
Life Sup. Biosphere Sci.
Photosynthetic Radiation at Mars Surface over 2 Martian Years (J. Clawson, 2006)

Figure 11 The daily integrated total, direct, and diffuse PPF versus latitude and Martian Sol for two Mars years. The labeled sols correspond to the start of each season on Mars. For example, sol 150 corresponds to the Northern Autumnal equinox.
University of Arizona Lunar / Mars Greenhouse
Deployable Mars Greenhouse - Low Pressure Systems
Hypobaric Testing with Plants

Testing at:
NASA KSC
Univ. of Guelph
Texas A&M
Univ. of Florida
Lettuce, radish, and wheat plants exposed to rapid pressure drop (27 days old)
Phase Change of Water

Pressure (kPa)

Temperature (°C)

Vapour

Liquid

Plants Held Here for 30 min

Triple Point of Water 0.01°C and 0.6 kPa

Human Habitats and Crops for Supplemental Food

Plant Atrium or Growing Shelf

Habitat Demonstration Unit (HDU) Test 2011

NASA's HDU at Desert Test Site

HDU Test 2012
Current Plant Testing on the International Space Station—VEGGIE Plant Chamber

Passive Capillary Watering
Watering Systems for Weightlessness -- Special Challenges

Porous Ceramic Tubes to Contain the Water

Porous Ceramic to Sub-irrigate Growing Media

Dreschel and Sager. 1989. HortScience
Some other Benefits of Plants in Space

- Fresh Foods
- Colors
- Texture
- Flavor
- Nutrients

- Bright Light
- Aromas
- Gardening Activity

Plant Chamber at US South Pole Station

Plants and Human Well-Being—Biophilia Concept? (E.O. Wilson)
Sequential Development for Space Agriculture

- VEGGIE 0.15 m²
- "Salad Machine" Growth Unit (2.0 m²)
- MPLM or Cygnus-like Module (10 m²)
- Surface System Food Production Module (20 m²)
NASA “Salad” Crops for Near Term Missions

- “Pick-and-Eat” Fresh Food for ISS
  - Lettuce
  - Chinese Cabbage
  - Mizuna
  - Dwarf Tomato
  - Dwarf Pepper
Technologies from “Space” Agriculture

LEDs for growing plants--patented through NASA funded center at Univ. of Wisconsin, ca. 1990

Potatoes in NFT at NASA KSC 1992, ↑ and at commercial “seed potato” facility (Sklarczyk Farms, MI) 2016 ↓
Agriculture in Space

As we explore sustainable living for space, we will learn more about sustainable living on Earth.
Some Lessons Learned from NASA CEA Research

• 20-25 m² of crops could provide all the O₂ for one person, and 40-50 m² all of the food (dietary calories)
• Better adapted crops are needed—short growth, high harvest index, improved nutrition—Use genetic engineering?
• Lighting is key to sustaining high yields
• CEA systems require large quantities of water (e.g., 50 L m⁻²) and this water must be recycled.
• Up to 90 kg of fertilizer would needed per person per year, emphasizing the need for recycling nutrients.
• Plants can provide psychological benefits to humans—this needs further study.
• The use of agriculture for space life support will likely evolve sequential, as mission infrastructures expand.