Plants for Space Travel

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Kennedy Space Center, Florida, USA

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</td>
<td>3.56 kg</td>
<td>11.4%</td>
</tr>
<tr>
<td></td>
<td>(drink and food prep.)</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>26.0 kg</td>
<td>83.9%</td>
</tr>
<tr>
<td></td>
<td>(hygiene, flush laundry, dishes)</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>31.0 kg</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</td>
<td>29.95 kg</td>
<td>96.5%</td>
</tr>
<tr>
<td></td>
<td>(metabolic / urine)</td>
<td>12.3%</td>
</tr>
<tr>
<td></td>
<td>(hygiene / flush)</td>
<td>24.7%</td>
</tr>
<tr>
<td></td>
<td>(laundry / dish)</td>
<td>55.7%</td>
</tr>
<tr>
<td></td>
<td>(latent)</td>
<td>3.6%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>31.0 kg</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
Plants for “Bioregenerative” Life Support

**HUMANS**

(food) \( (CH_2O) + O_2 \rightarrow CO_2 + H_2O \)

Clean Water  →  Waste Water

**Metabolic Energy**

**PLANTS**

\( (CH_2O) + O_2* + H_2O \leftarrow CO_2 + 2H_2O* \)

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
Bioregenerative Life Support Testing Around the World

1960
- US Military
- USSR Military

1980
- Russia - Inst. for Biomedical Problems – IMPB (Moscow)
- Russia - Inst. of Biophysics – IBP (Krasnoyarsk, Siberia)
- US NASA
- NASA (CELSS)  NASA (ALS)  NASA (LSHS)  AES/HDU
- Japan Aerosp. Lab.; Inst. Env. Sci. (IES); JAXA Chofu
- France Cadarache
- European Space Agency MELISSA

2000
- University Studies (US, Europe, Japan, Canada)
- Canada Univ. Guelph / CSA
- China Natl. Space Ag.
NASA’s Bioregenerative Life Support Testing

1980

- CELSS Program
  - Wheat (Utah State)
  - Gas Ex./Ethylene (Utah State)
  - MIR Wheat (Utah St.)
  - Sweetpotato / Peanut (Tuskegee)
  - Potato (Wisconsin)
  - Soybean (NC State)
  - N-Nutrition (UC Davis)
  - Lettuce (Purdue)

1990

- ALS / ELS Program
  - STS-73 Potato Leaves
  - Rutgers NSCORT

2000

- LSHS Program
  - ISS Mizuna Utah St./KSC
  - Hypobaria (TAMU)
  - Lunar Greenhouse (Arizona)
  - ISS VEGGIE Lettuce (KSC)

2010

- Advanced Plant Habitat ISS

Universities

- Ames
  - Algae
  - Closed Systems
  - Salad Machine

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

- Johnson
  - Solid Media
  - Pressure Human / Integration
  - BIO-Plex
  - ISS Wheat Expmt

NASA Centers

- Small Companies
  - 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>Sweetpotato</td>
</tr>
<tr>
<td>Peanut</td>
<td>Kale</td>
<td>Beet</td>
<td>Sugar Beet</td>
<td>Rice</td>
</tr>
<tr>
<td>Dry Bean</td>
<td>Lettuce</td>
<td>Nut Sedge</td>
<td>Carrot</td>
<td>Tomato</td>
</tr>
<tr>
<td>Tomato</td>
<td>Carrot</td>
<td>Onion</td>
<td>Tomato</td>
<td>Spinach</td>
</tr>
<tr>
<td>Carrot</td>
<td>Canola</td>
<td>Cabbage</td>
<td>Tomato</td>
<td>Shungiku</td>
</tr>
<tr>
<td>Chard</td>
<td>Soybean</td>
<td>Tomato</td>
<td>Chinese Cabbage</td>
<td>Chinese Cabbage</td>
</tr>
<tr>
<td>Cabbage</td>
<td>Peanut</td>
<td>Pea</td>
<td>Pea</td>
<td>Pea</td>
</tr>
<tr>
<td></td>
<td>Chickpea</td>
<td>Dill</td>
<td>Dill</td>
<td>Onion/Leek</td>
</tr>
<tr>
<td></td>
<td>Lentil</td>
<td>Cucumber</td>
<td>Cucumber</td>
<td>Komatsuna</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td>Salad spp.</td>
<td>Salad spp.</td>
<td>Pepper</td>
</tr>
<tr>
<td></td>
<td>Onion</td>
<td></td>
<td></td>
<td></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

USU APGEE WHEAT

USU PERIGEE WHEAT

SUPER DWARF RICE

MICRO TINA TOMATO

TRITON PEPPER

HOYT SOYBEAN

FARTILNE WHEAT
Genetic Engineering Tools

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

Early Flowering and Fruit Set

No Dormancy Requirements
Water and Nutrients for Growing Crops
Recirculating Hydroponics

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

Root Zone Crops in Nutrient Film Technique (NFT)

Evapotranspiration from Plant Stand (potato)

Days After Planting

Water Use (L m\(^{-2}\) d\(^{-1}\))

First Study
655 µmol m\(^{-2}\) s\(^{-1}\) PAR

Second Study
865 µmol m\(^{-2}\) s\(^{-1}\) PAR

High Yields from NASA Sponsored Studies

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

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 m$^2$ growing area; 113 m$^3$ vol.; 96 400-W HPS Lamps; 400 m$^3$ 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*)
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

Solar Collectors for Crop Production

Buried Plant Growth Chambers

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

Triple Point of Water
0.01°C and 0.6 kPa

Plants Held Here for 30 min

Human Habitats and Crops for Supplemental Food

Habitat Demonstration Unit (HDU) Test 2011

Plant Atrium or Growing Shelf

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

Dreschel and Sager. 1989. HortScience

Porous Ceramic to Sub-irrigate Growing Media
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

Massa et al. 2013, Grav. and Space Res.
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.