Space Lab Technologies, LLC

Duckweed

A Tiny Aquatic Plant with Enormous Potential for Bioregenerative Life Support Systems

Christine M. Escobar and Adam C. Escobar
Space Lab Technologies, LLC, Pinecliffe, CO 80471

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Aquatic Plants for Bioregenerative Life Support

Challenges of Land Plants

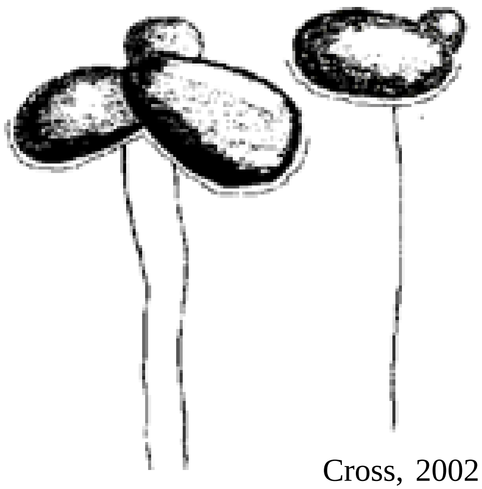
- Gravitropic complications in propagation
- Nutrient delivery in microgravity
- Large volumes of inedible biomass
- Root zone aeration

Benefits of Aquatic Plants

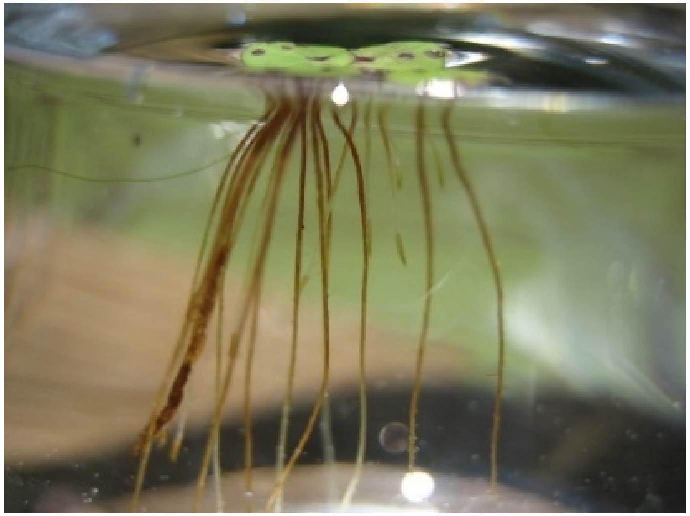
- Consumed around the world
- Often 100% edible and fast growing
- Thrive in nutrient rich water
- Growth less sensitive to gravity

What is Duckweed?

- Smallest flowering plants on Earth (*Journey et al., 1991*)
- Among fastest growing plants in the world (*Ziegler et al., 2015*)
- Subfamily Lemnoideae (in family Araceae): 5 genera, over 40 species
- Free floating or submerged, found in still/slow flowing fresh water
- Common in lakes, ponds, canals, rice fields, ditches, and even mud

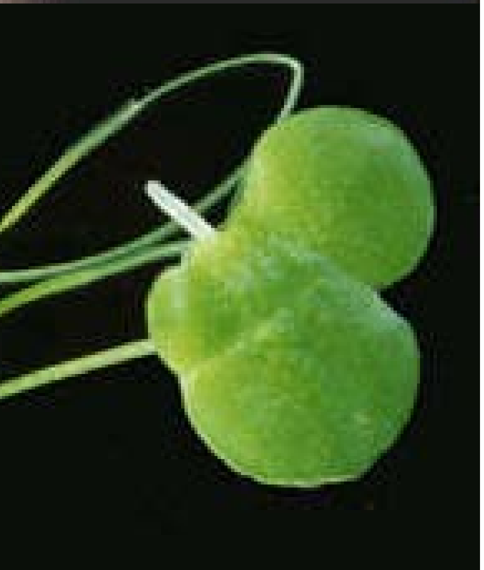


Cross, 2002

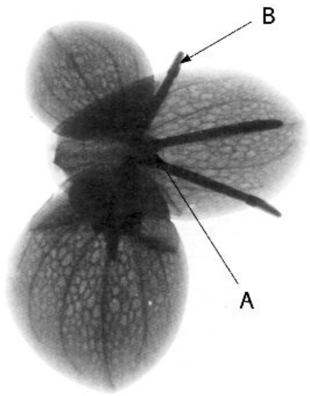


The content of this slide is subject to the propriety statement on the title slide.

Anatomy and Reproduction



- **Fronds:** oval shaped vegetative bodies (1-20 mm across), grow singly or in small groups
  - Take up gasses and nutrients
  - Permanently open stomata on top
  - Cutin (waxy, water repellant) on top
  - Air sacs provide buoyancy
  - Vascular system "practically absent"
  - Little structural tissue needed (floating)



- **Roots** give mechanical stability (grow in dilute water)
- **Reproduce** primarily asexually through budding (flowering rarely observed)
  - Up to 10 daughters in 10 days before dying
  - Doubles biomass in 1-3 days (ideal conditions)

Duckweed Environmental Requirements

[1]Leng, 1999 [2]Iqbal, 1999 [3]Hasan, 2009

- **Nutrient composition**:
  - Duckweed thrive on water rich in nutrients & dissolved organic compounds
  - Opportunistic growth spurts when flushes of nitrogen occur
  - Utilize a variety of N sources, including urea; prefer NH_4-N over NO_3-N
  - P & K needed in low amounts (concentrates in tissue during rapid growth)
  - Can metabolize sugars if nutrients not present, *without sunlight*
- **Temperature:** 6-33C (growth)[1]; 25-31C (optimal)[2]
- **Sunlight:** Increasing intensity increases growth; optimal range uncertain
- **Salinity:** Fresh to slightly brackish; saline water can be used
- **pH:** 3-10 (growth) & ~7 (optimal)[3]
- **Mat Density**: Full coverage that still accommodates rapid growth (400-800g/m^2)[3]
- **Water Velocity:** Maximum of 0.1[2]-0.3[3] m/sec
- **Water Depth:** Grows on water mm to meters deep – effects sunlight & water temp
- **Water O_2 Concentration:** Grows equally in aerobic & anaerobic water

Biomass Composition and Yield

[1]*Journey et al., 1991* [3]*Iqbal, 1999*
[2]*Ansal et al., 2010* [4]*Hasan, 2009*

- **100% Edible**
- **Water:** 92-94%[1]
- **Protein:** up to 45%[1] (comparable to soybean), high quality
  - Rich in lysine & arginine (usually low in plants), leucine, threonine, valine, isoleucine & phenylalanine; low in methionine & tyrosine
- **Fiber:** <5%[1]
- **Carbohydrates:** 30-35%[2]
- **Vitamins:** Good source of vitamin A and pigments (e.g. beta-carotene & xanthophyll)[2]
- **Calcium Oxalate:** Duckweed stores calcium as calcium oxalate crystals
- **Yield:** Reports vary widely (2-50 tons/hectare/yr[3]; 0.2- kg/m^2); dependent upon species, climate, location, nutrient supply, water depth, and crop management practices (like harvesting rates)

The Next Superfood?

Amino Acid Composition	Meets/ exceeds World Health Organization recommendations, comparable to legumes
Polyunsaturated Fats	48-71% of fatty acid content
Omega 6 to Omega 3 Ratio	0.1 to 0.75 (FAO recommends <5)
Phytosterol	5-fold higher than most other plant oils (lowers cholesterol absorption)
Antioxidants	High concentrations of lutein & zeaxanthin
Mineral Composition	Presence of trace elements depends on nutrient medium

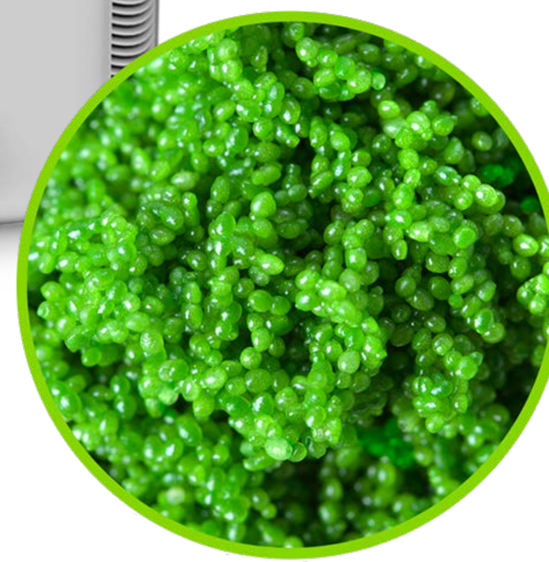
Appenroth, 2017

The Next Superfood?

Lentein™ Complete from Parabel, made from "Water Lentils", i.e. Duckweed

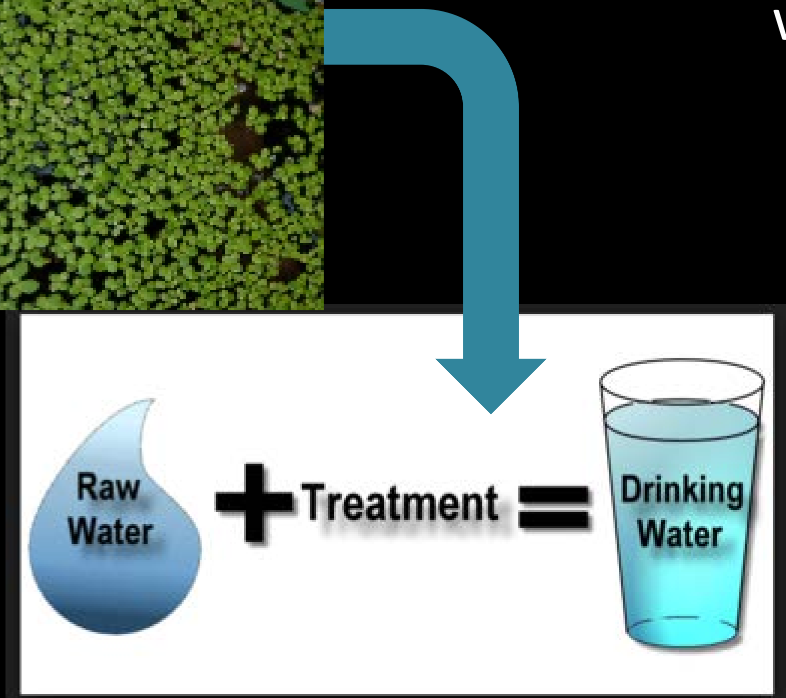
Image Source: www.lentein.com

Wolffia arrhiza "Khai Nam"



http://www.greenonyx.biz/

Water Treatment with Duckweed?



Lemna populated lagoons treat sewage in as many as 100 facilities around the world, with effluent often exceeding US water quality standards.

Leng, 1999

(Iqbal, 1999)

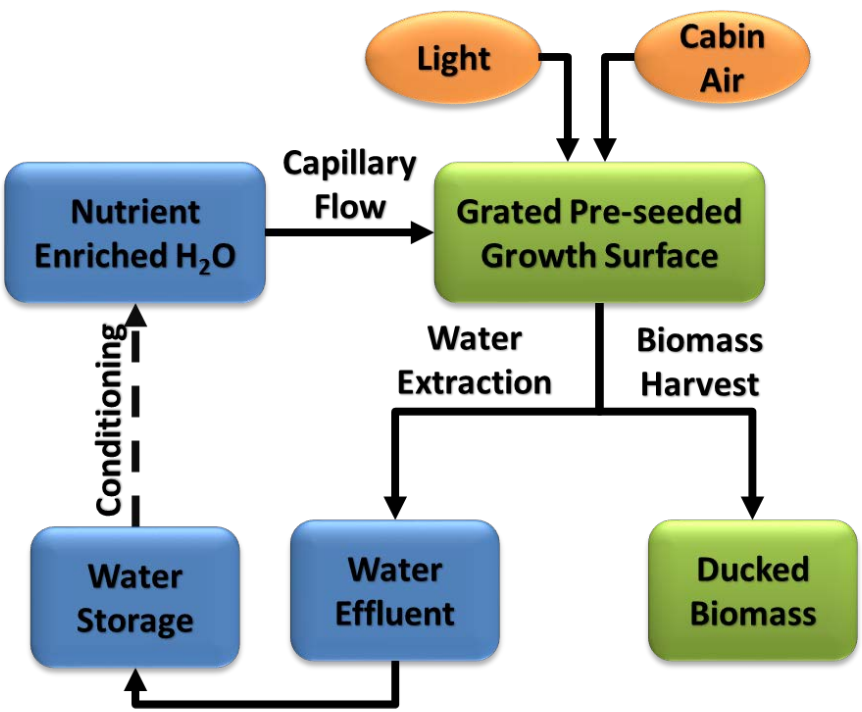
Potential Utilization in a Space Habitat

- Preferential **uptake of ammonia** as a nitrogen source (making it attractive for waste processing)
- **Rapid, uniform growth** through unlimited vegetative budding
- **Robust**: Grows under a wide range of conditions and can "survive and recover from extremes of temperature, nutrient loadings, nutrient balance, and pH." (*Journey et al., 1991*)
- **Volume Efficient**: Can grow on thin films of water, allowing more growth area in less volume
- **Indefinite maintenance of stock cultures** in light, or in darkness with sugar supplement, allowing survival and rapid restart of the crop in the event of prolonged darkness from power or lighting failure
- Inactive, **permanently open stomata**, allowing for irregular photoperiods and continuous CO_2 uptake
- **100% harvest index** of **highly nutritious** material (10-45% protein)

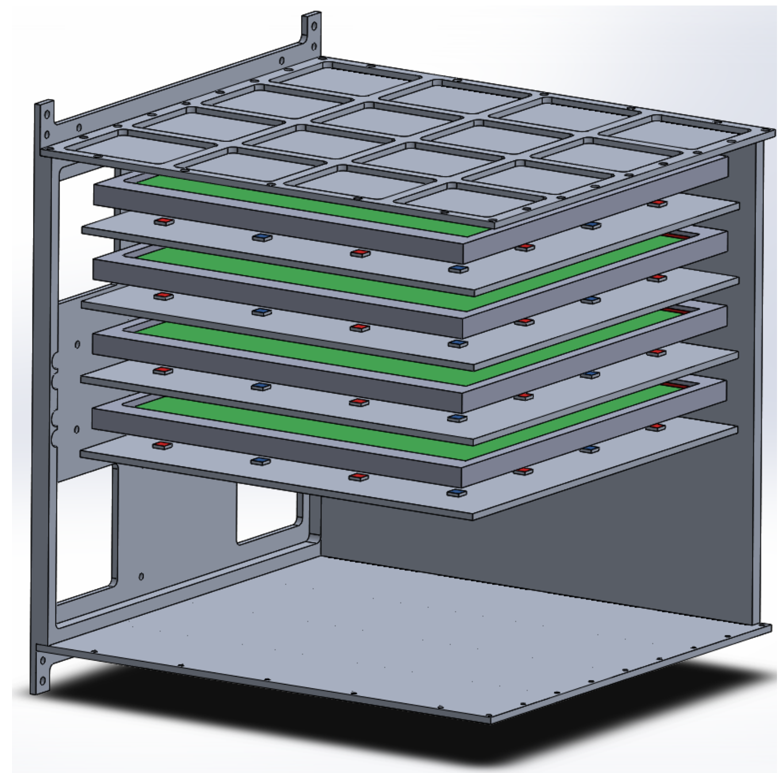
μG-Lilypond NASA STTR Phase 1

Space Lab Technologies, University of Colorado Boulder
NASA, Kennedy Space Center (Technical Monitor)

Phase 1: Conceptual design & feasibility (passive water delivery, continuous harvest)
Features: Low maintenance, passive water delivery, volume efficient, seed to seed



Other system operations include means for **pre-seeding** and for **cleaning biofouling**



Conceptual Prototype for ISS EXPRESS Rack

Operational & Design Challenges

CHALLENGE	GOAL	POTENTIAL SOLUTION
Nutritional Quality	• Maximize protein • Reduce oxalic acid	• Control nutrient supply • Control light spectrum • Post-processing
Food Preparation	• Max. nutritional value • Palatability	• Heating, pulping, drying
Daily Harvest Requirements	• Reduce crew time needed for operation	• Autonomous harvesting mechanisms
Thermal Control	• Maintain stable temp	• Heat dissipation
Crop Loss	• Rapid restart of crops if system fails/is unused	• Dormant stock cultures
Water Delivery	• Maintain stable thin film	• Passive capillary flow
Biofilm, Deposits	• Maintain water flow	• Cleaning mechanisms

Future Research Questions

General:

- Optimal conditions for biomass yield & nutritional quality, by species
- Submerged versus ‘floating’ growth
- Effects of water depth (or surface area to volume) on growth
- Necessity of oxygen in water (aeration needs?)
- Preferred CO_2 source (air/water)
- Relationships w/ root-zone microbes (nitrifying, etc.)?

Effects of Microgravity:

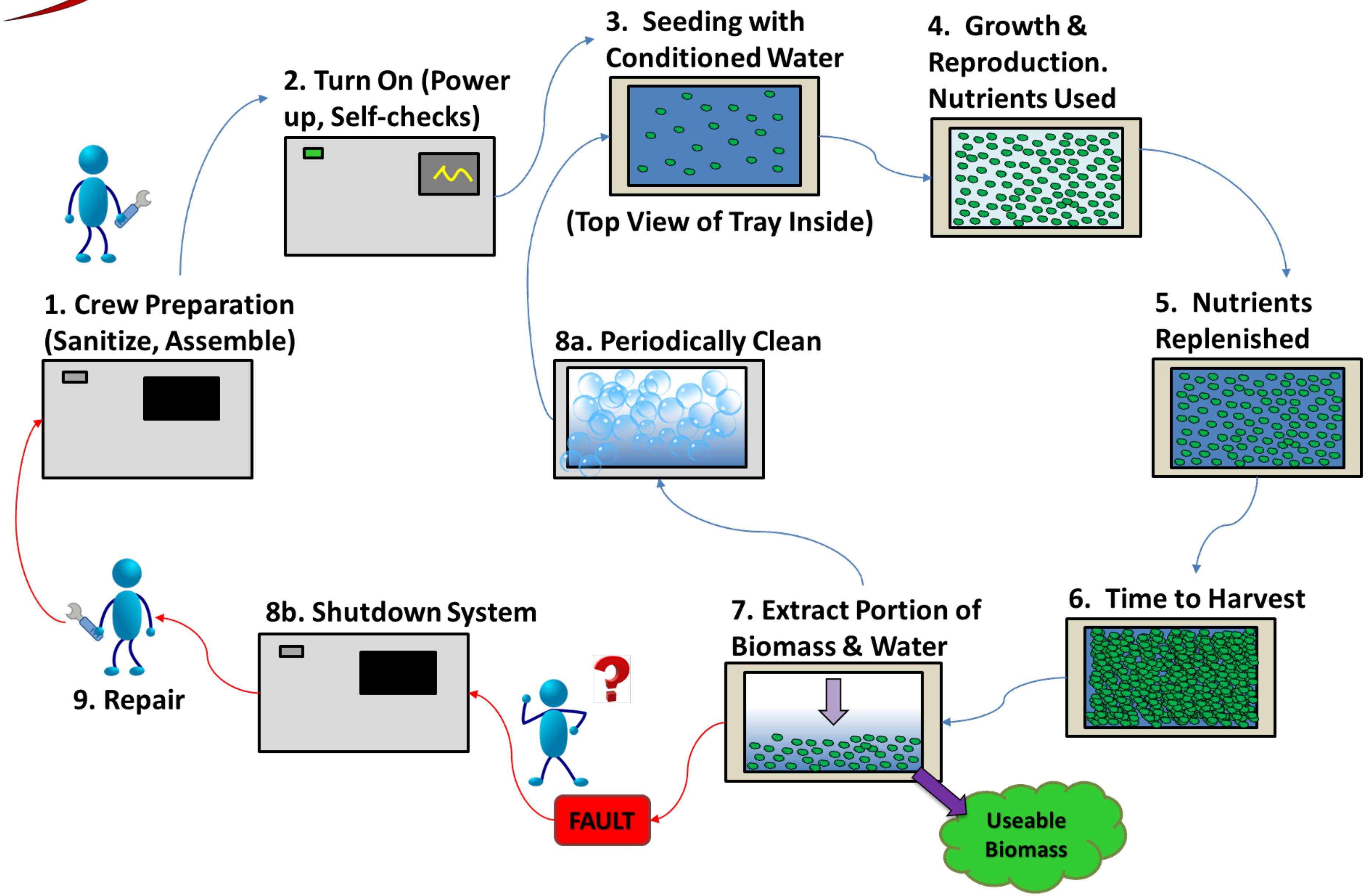
- Nutrient uptake (diffusion limited) and homogeneity
- Mechanical behavior of fronds at air/liquid interface

Much research exists.

Comparison of published empirical trials is difficult.

QUESTIONS?

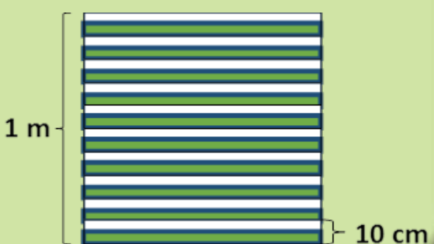
µG-LilyPond Concept of Operations – Food Production Mode



Potential Utilization in a Space Habitat

In an environmentally controlled system, yield and biomass composition can be optimized in a small volume

Thin (10 cm) stacked 1m^2 trays = 10 m^2 growing area in **1 m^3 volume**



Could produce up to 0.15-0.25 kg DM/day in 1 m^3 volume[1] ➔

17-28 g protein/crew member/day!

(assuming 4-person crew)

[1]Gale et al, 1989