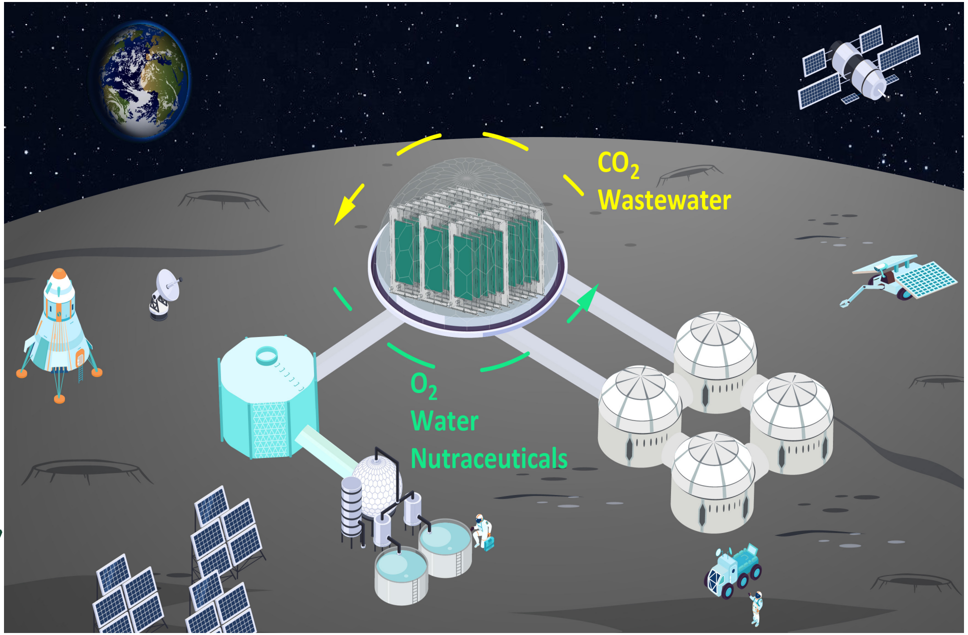
Membrane Bioreactors for Cyanobacterial Growth Using Lunar Regolith

"So how can grow anything on the moon with as little water usage, delivered payload, and energy cost as possible to recycle waste?"



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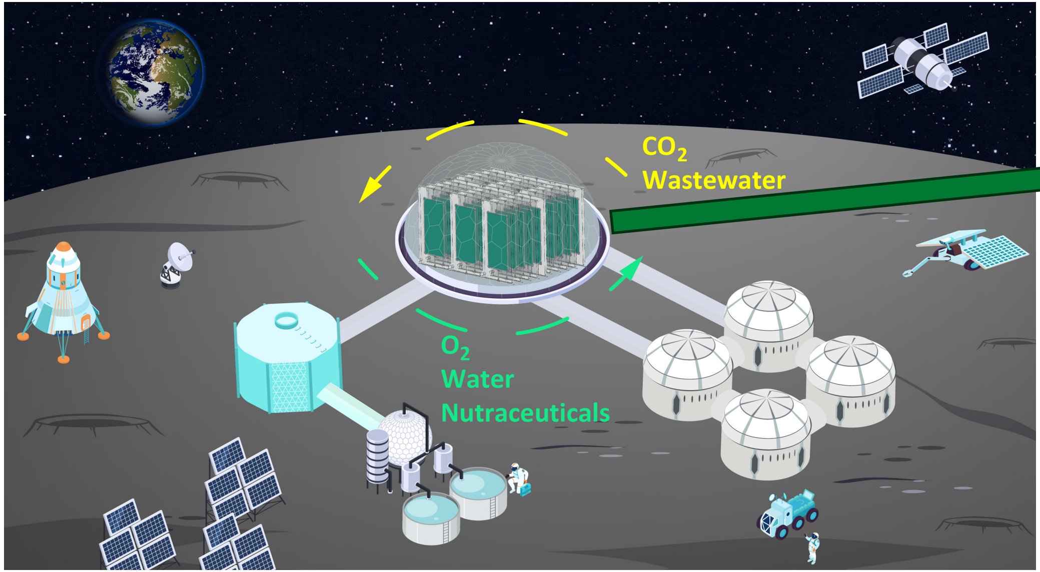
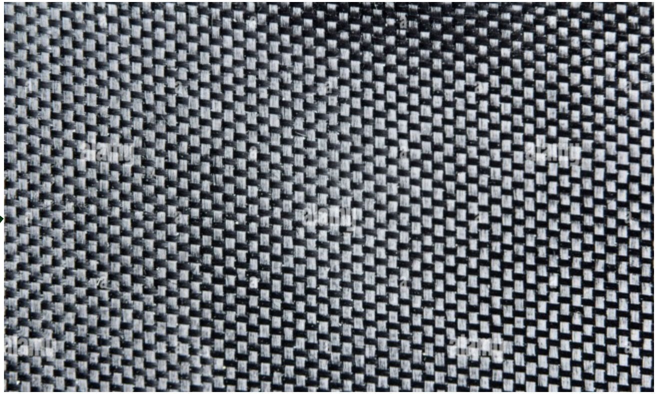
Spoiler Alert – It might be simply…

a swatch of woven membrane impregnated with regolith





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Background

What are the underlying assumptions and needs that drove this work?

- **A long-term lunar colony will require self-sustaining systems**
  - Supply chain from earth will be expensive
    - Payload cost$
    - No Amazon prime to the moon
    - Priority will be for extraction and product
  - Recycling of waste will be critical
    - Carbon dioxide
    - Wastewater
- **Cyanobacteria offer a biological option**
- **But how do you reduce water needs, minimize payload costs and energy requirements, and make it robust?**

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Background

Why Cyanobacteria?

- **O.G. phototroph**
  - Converts CO_2 and H_2O into O_2 and biomass using photons
  - More tolerant of extremes than green alga
  - Demonstrated to uptake nutrients from multiple sources
    - Fix atmospheric N_2
    - Wastewater – urea and ammonia
- **Demonstrated extraction of nutrients from regolith**
- **Certain strains grow as biofilm "mats"**
- **Some strains are food sources on Earth**

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Background

Membrane bioreactor fundamentals

- **Vertical fibrous substrate**
  - Cyanobacteria will grow on the substrate
  - Growth media (water) flows “down” from distribution
- **Substrate is tensioned (capillary distribution)**
  - Gravity pulls flow “down”
  - Capillarity distributes media across the surface
- **Film flow creates an aquatic environment**
  - Cyanobacteria are in fluidic contact, getting water/media
  - Nutrients are more effectively distributed
- **High surface area per unit “footprint”**
- **Adjustable to optimize light exposure**

Cyanobacteria growing on a vertical membrane substrate

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Background

Back to the regolith factor

- **Regolith can be a limited nutrient source**
- **The challenge: how to transfer those nutrients**
- **Cyanobacteria in direct contact promotes leaching**
- **However, leaching also occurs in water**
- **Our system allows for both processes**
- **Pulverized regolith leached in slipstream**
  - Filtered before remixing
  - If regolith particle evades filtration, capture occurs by the membrane/mat
  - Captured particles will enhance substrate capillarity

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Membrane Bioreactor Design

Advantages and Disadvantages

- **Lightweight substrate tensioned from a header**
- **High surface area per unit "footprint"**
- **90%+ less water than tubular bioreactors**
  - Film flow vs pipe flow
  - Distribution header of membrane is relatively small
- **90%+ less payload and volume**
- **"Simple" harvesting of the cyanobacteria**
  - Low impact rapping (impulse)
  - Cells tends to stay together, facilitating dewatering
- **Adjustable "tilt" to optimize light exposure**
- **Film flow optimizes liquid-gas mass transfer**

Cyanobacteria growing in a membrane reactor (schematic)

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Membrane Bioreactor Design

Advantages and Disadvantages

- **Thin film disadvantages**
  - Sensitive to pressure and flashing
  - Low volume of water = less thermal mass
- **Biological systems are notoriously unstable**
- **Will not recycle 100% of wastes**
  - Need additional waste stream processing
  - Distribution header of membrane is relatively small
- **Need a plan for biomass use**
  - Do not want it to accumulate unused
  - Plan for use as a nutrient source (what are viable options?)

Cyanobacteria growing on a membrane (before harvesting)

Results with *Synechococcus*

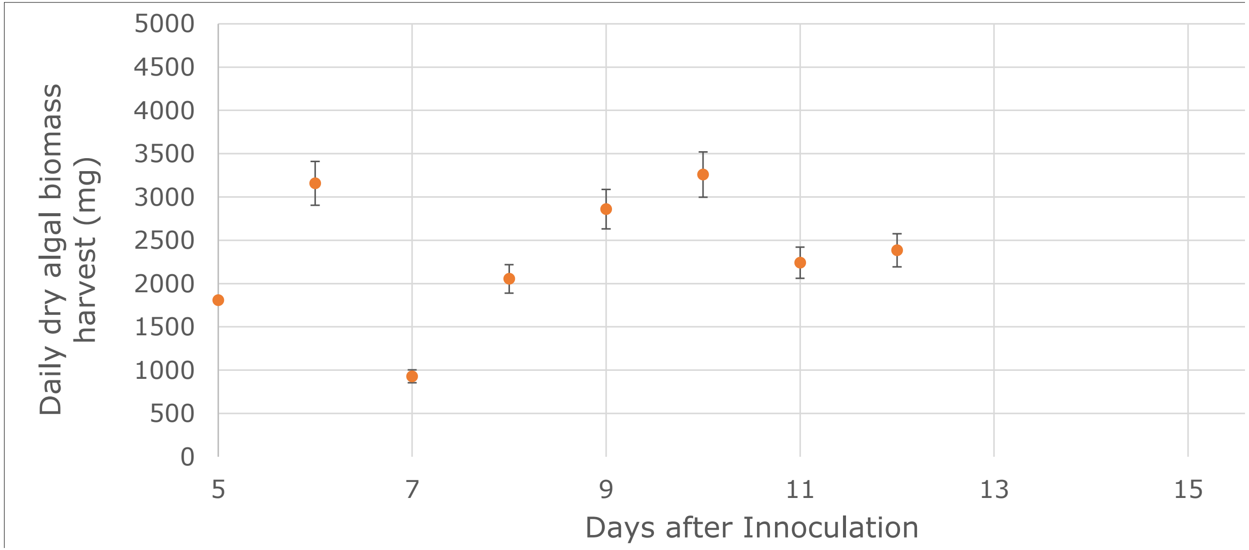
Why I am optimistic about this system

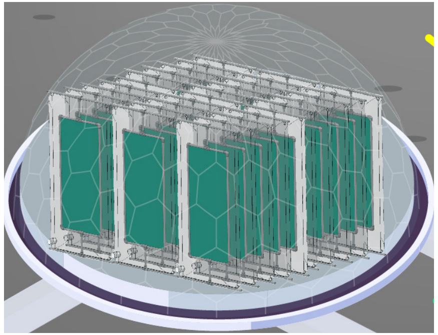
- **Initial setup**
  - *Initially* cultured in BG-11 (not axenic!)
  - Grown on 1mx2m vertical substrate of polypropylene
  - Underwent one harvest on BG-11
- **Switched media reservoir to "lunar" media**
  - *Diluted* human wastewater (1:30)
  - Leached simulant (using packed bed with filter)
  - Hydrothermal carbonization (HTC) process water (1:90)
- **Operated for ten more days**
  - Replaced 10% of media daily
  - Daily harvesting for dried biomass measurements
  - Measurement of levels of N, P, and COD/BOD levels

Cyanobacteria growing on a membrane (after harvesting)

Results

Biomass growth using simulated wastewater, solid waste and regolith





Cyanobacteria growing on a membranes (schematic)

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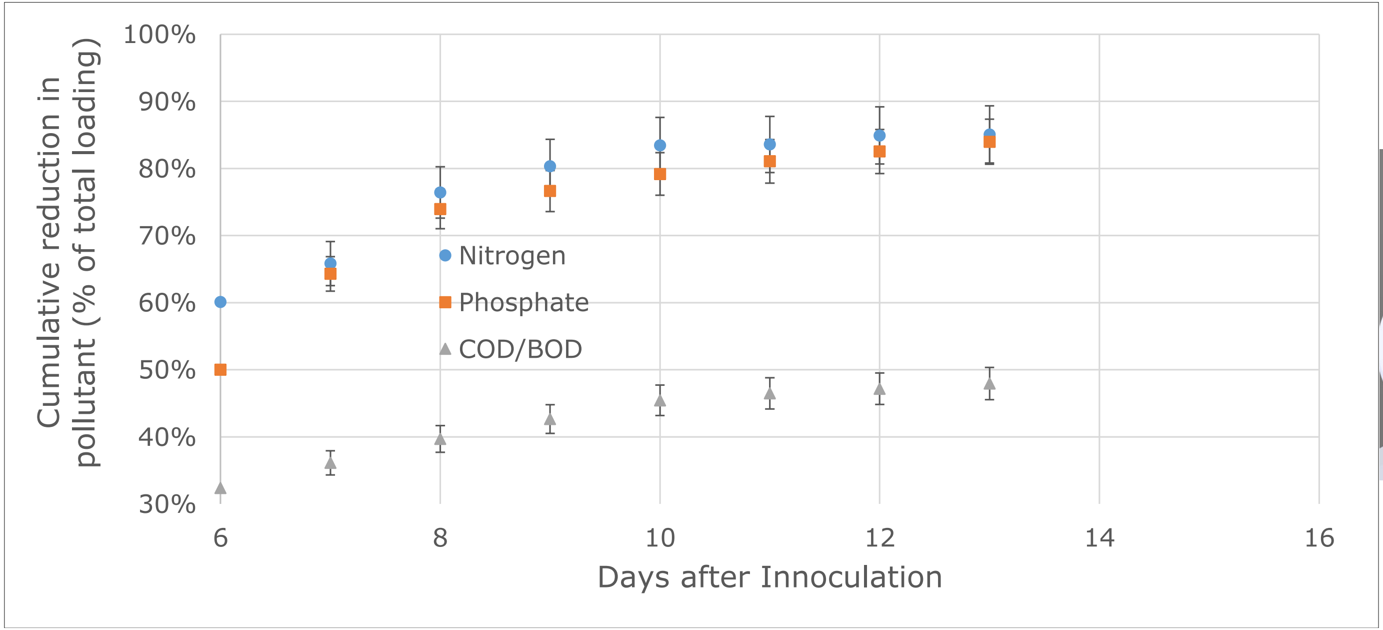
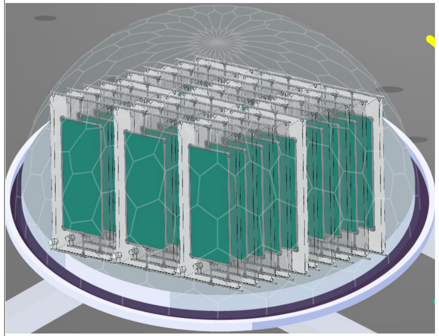
Results

N/P/BOD removal from simulated wastewater, solid waste and regolith





Cyanobacteria growing on a membranes (schematic)

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Conclusions

What are the next steps?

- **Preliminary results are encouraging**
  - Recycling of waste will be critical for long-term colonization
  - Design offers real advantages compared to other bioreactor systems
  - But many questions remain unanswered
- **Are we willing to “try” unpredictable biological systems?**
- **Need to identify key factors and risks**
- **Continue testing to quantify issues and remove risks**

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