# NASA BLiSS and BioMFG: Using Microbes for Space Exploration

National Aeronautics and
Space Administration


**Luke Roberson, Ph.D**

Senior Principal Investigator
Exploration Research and Technology Directorate
NASA, Kennedy Space Center, FL

**Daniel H. Yeh, PhD, PE, BCEE**
Professor
Department of Civil & Environmental Engineering
University of South Florida, Tampa, FL


**Presented to the National Academies**

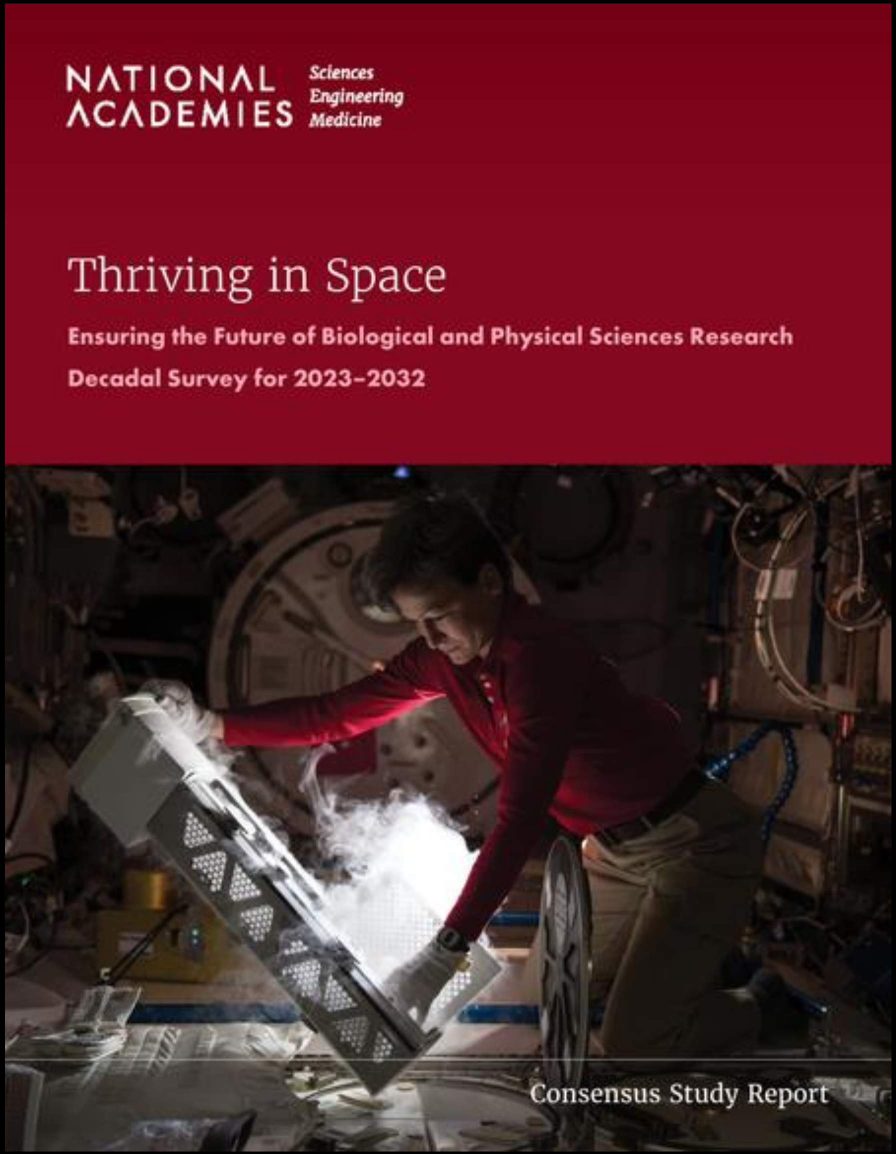
**August 6, 2024**

**Open Distribution**

# 2023 NASA DECADAL SURVEY

This report identifies key scientific questions, priorities, and ambitious research campaigns that will enable human space exploration and transform our understanding of how the universe works.

Report recommends NASA focus more on Bioregenerative Life Support Systems (BLiSS) and Manufacturing in space – specifically biomanufacturing (BioMFG).

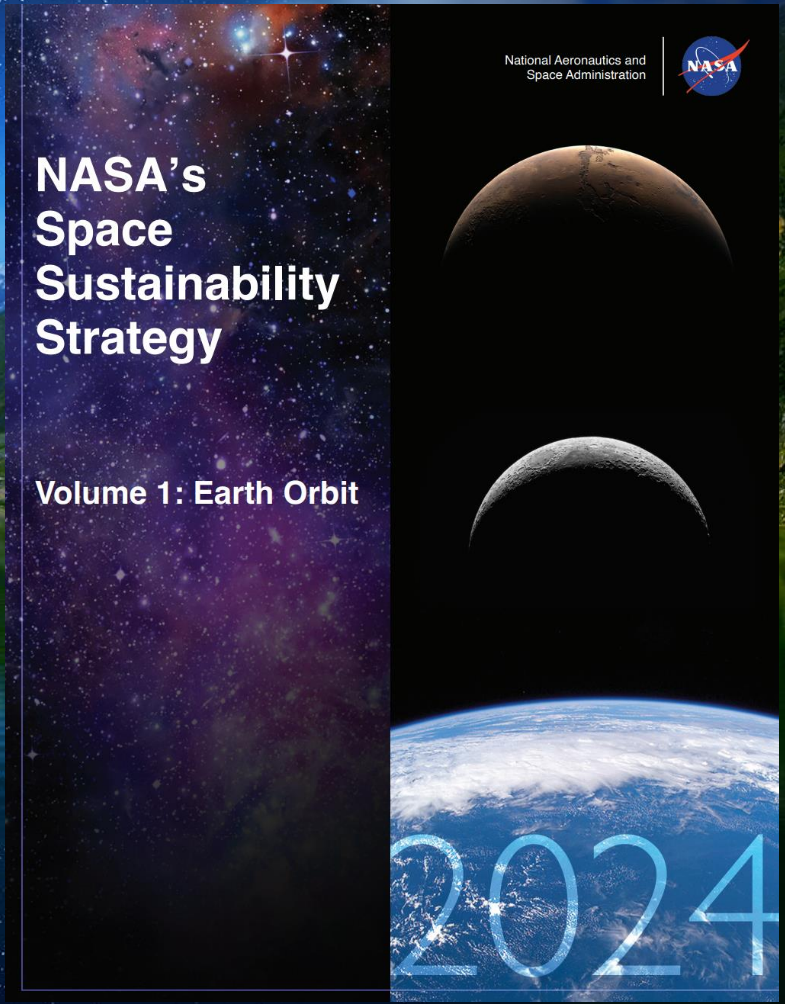



https://nap.nationalacademies.org/catalog/26750/thriving-in-space-ensuring-the-future-of-biological-and-physical

# 2023 NASA SPACE SUSTAINABILITY

National Aeronautics and Space Administration

EXPLORE MOON to MARS


National Aeronautics and Space Administration

NASA's Space Sustainability Strategy

Volume 1: Earth Orbit

2024

https://www.nasa.gov/wp-content/uploads/2024/04/nasa-space-sustainability-strategy-march-20-2024

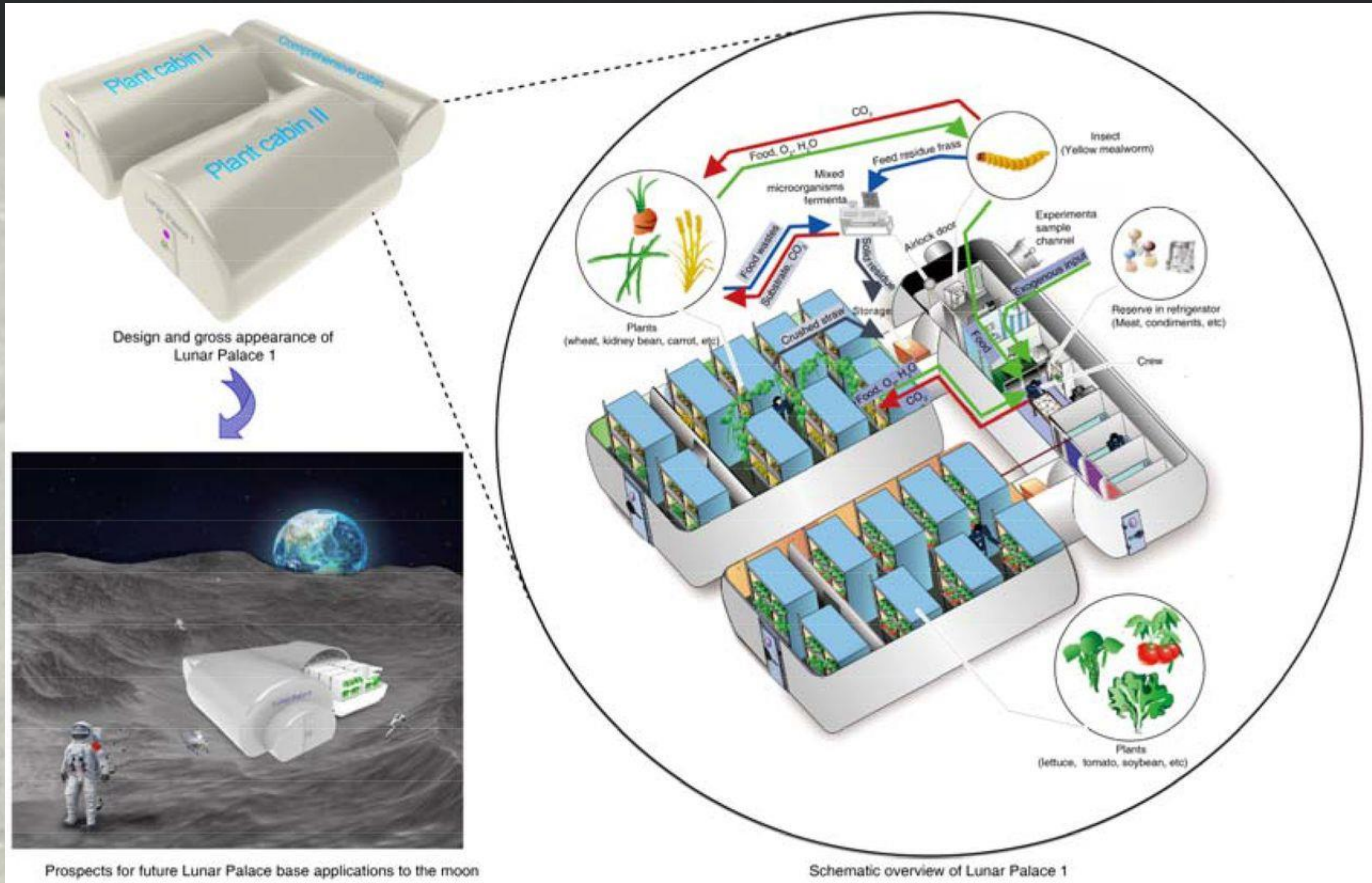
This report identifies key areas for making space sustainable including in-space biomanufacturing.

NSPIRES F.21 calls for ELSI for Lunar Architecture

DARPA is funding our group to determine ELSI Impacts of BioMFG in Space

# State-of-the-Art Foreign BLSS Technologies

## Lunar Palace – Managed by PRC



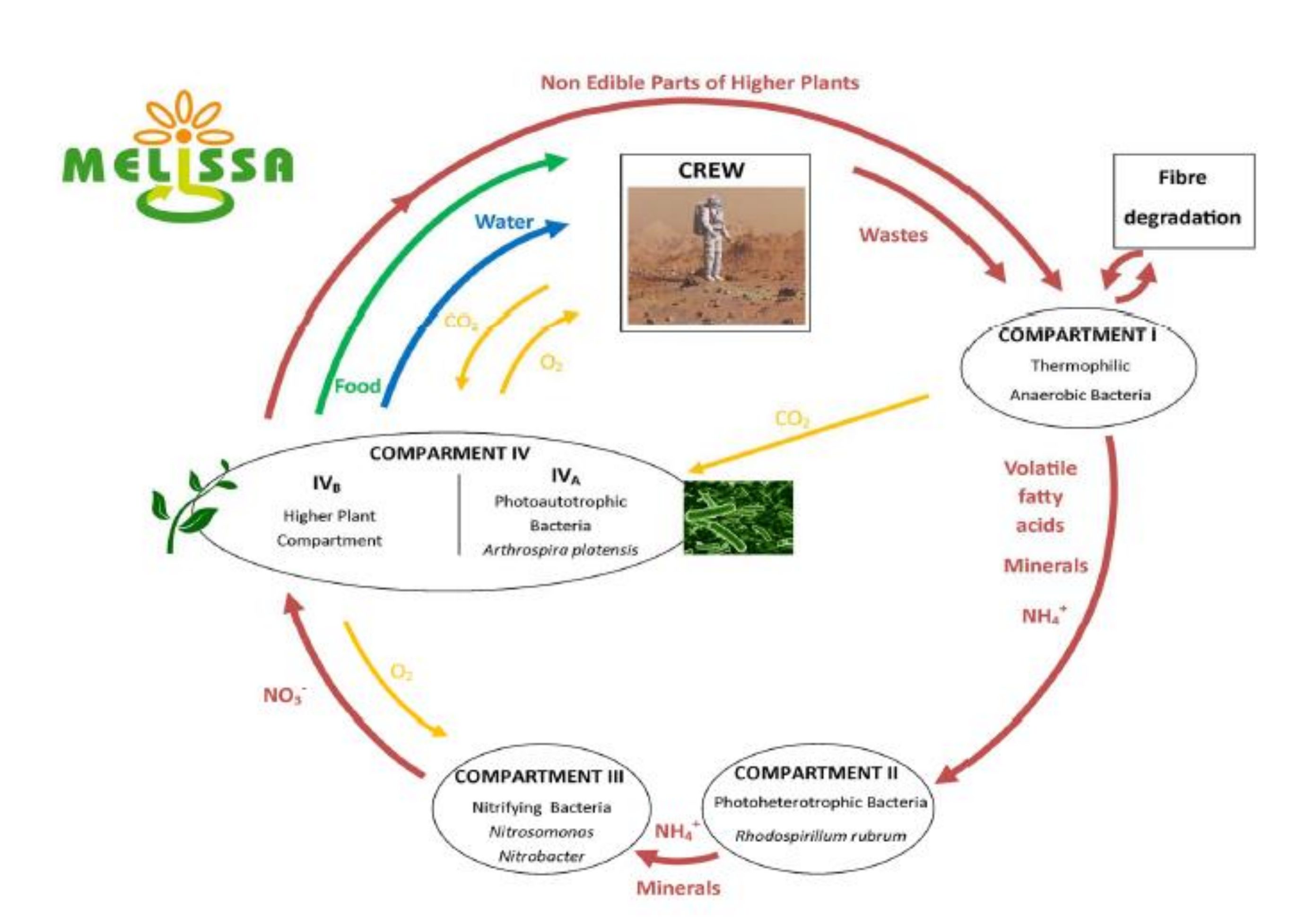

- Beihang University, China
- Crew Cabin + 2 Plant Cabins
- Lunar Palace 365
  - 370-day experiment with shifting crew members.
    - Successful regulation of gases, production efficiency of plants, purification of wastewater.

Fu, Y.; Yi, Z.; Du, Y.; Liu, H.; Xie, B.; Liu, H. Establishment of a Closed Artificial Ecosystem to Ensure Human Long-Term Survival on the Moon. *bioRxiv (Cold Spring Harbor Laboratory)* 2021. https://doi.org/10.1101/2021.01.12.426282.

# State-of-the-Art Foreign BLSS Technologies

## MELiSSA – Managed by ESA

- Goal: Habitats functioning autonomously in deep space that incorporate microbes to recycle human waste as a means of providing food, water and air to the crew.
- Loop to the right depicts MELiSSA's process
  - Five compartments connected through tubing.
  - Consists of consumable plants, and microbiota.




Walker, J.; Granjou, C. MELiSSA the Minimal Biosphere: Human Life, Waste and Refuge in Deep Space. *Futures* 2017, *92*, 59–69. https://doi.org/10.1016/j.futures.2016.12.001.

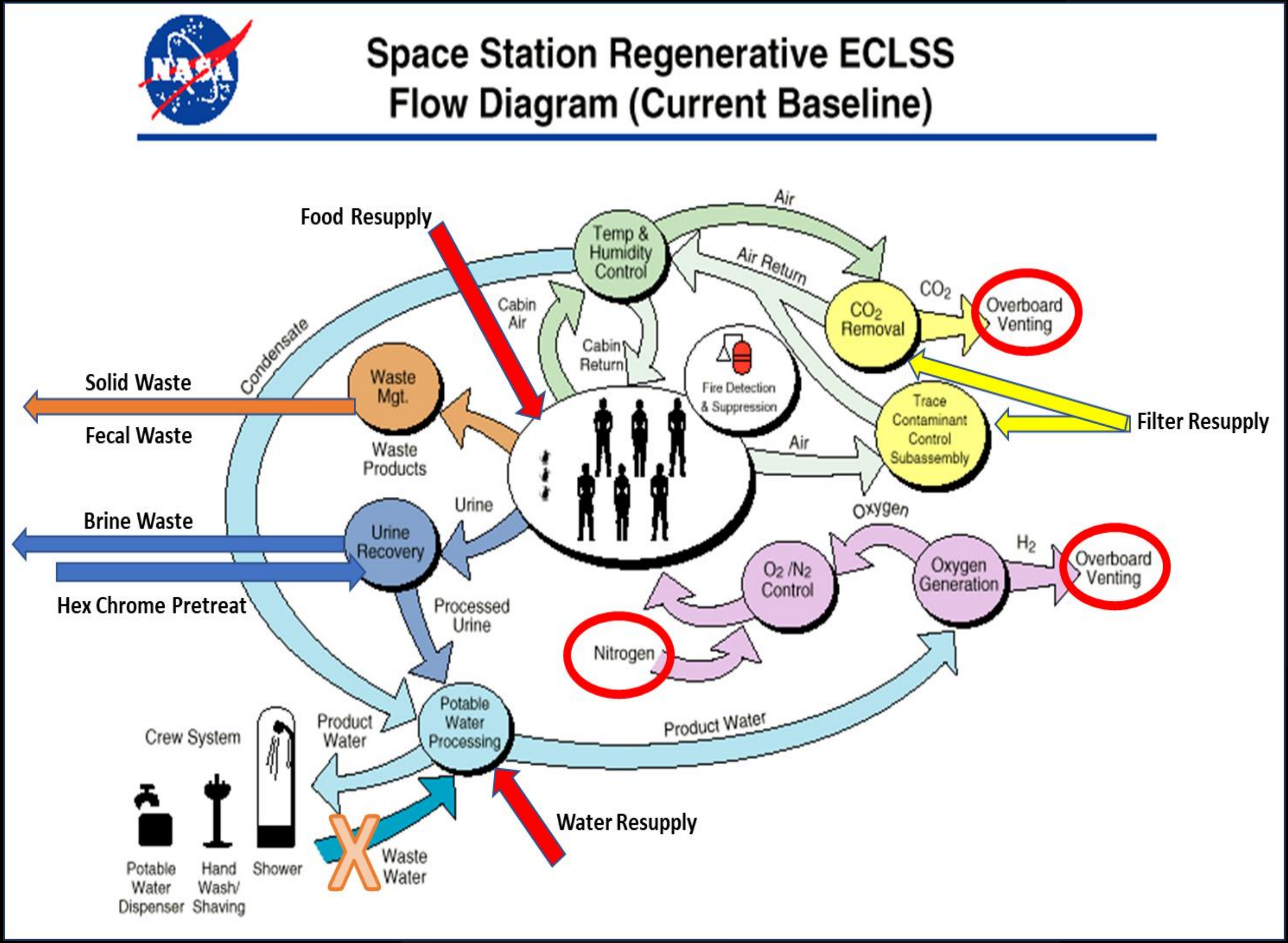
# Current Physical/Chemical Architecture for ISS

NASA's current "ECLSS Flow" doesn't include half of the operations and inputs/outputs of the real system!

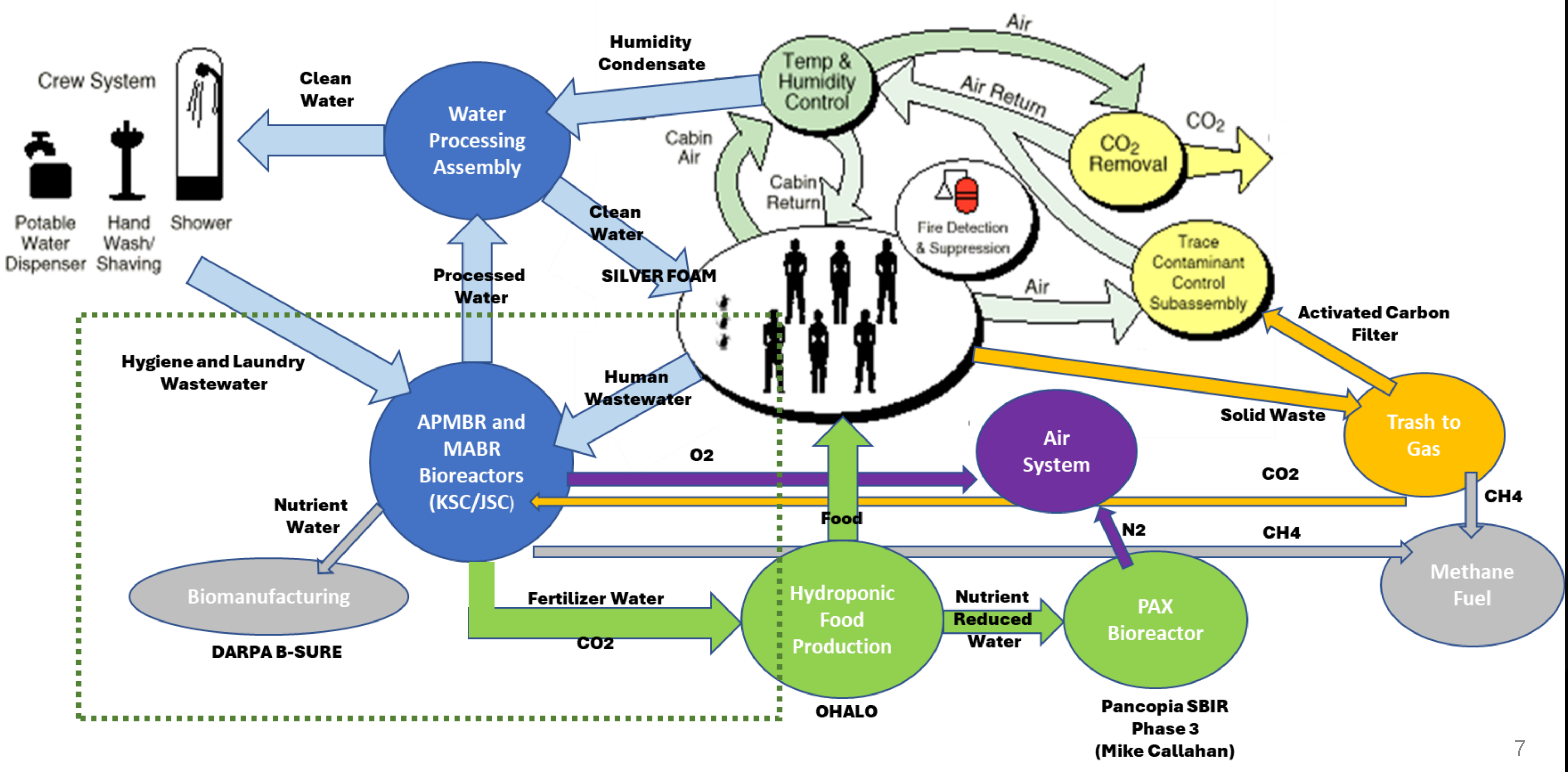
There are NO human inputs into the system that are regenerative aside from O2. Meaning the system ISN'T regenerative.

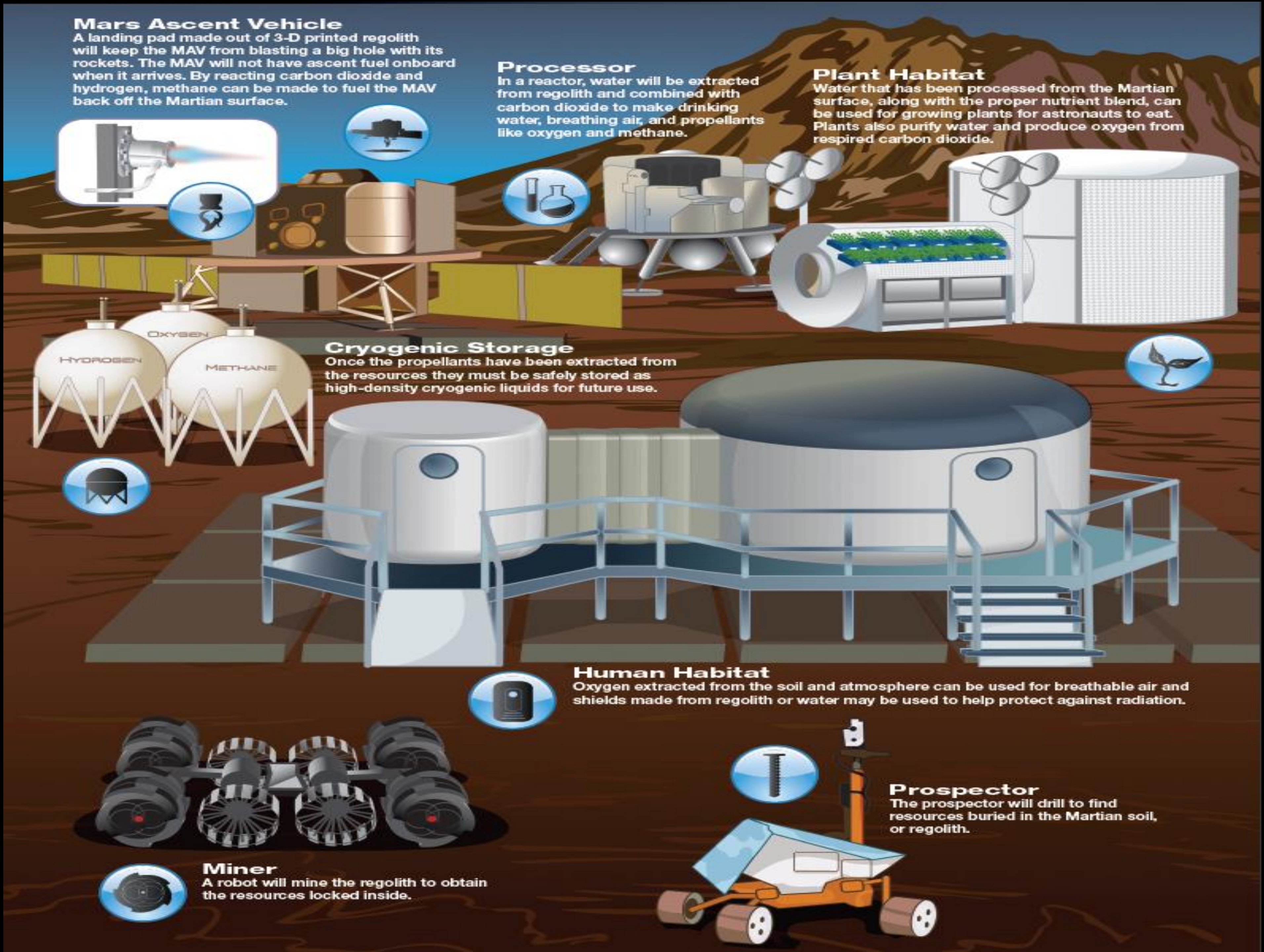
ALL food, water, air (nitrogen) MUST be brought or resupplied.

Waste is use as a VERY generic catch-all to include metal, plastic, fecal, menstrual/blood, hazmat. Where does that really go? Overboard ISS isn't possible on the Moon or Mars…



# Proposed BLiSS Architecture for Partial Gravity Habitats




Mars Ascent Vehicle
A landing pad made out of 3-D printed regolith will keep the MAV from blasting a big hole with its rockets. The MAV will not have ascent fuel onboard when it arrives. By reacting carbon dioxide and hydrogen, methane can be made to fuel the MAV back off the Martian surface.
Processor
In a reactor, water will be extracted from regolith and combined with carbon dioxide to make drinking water, breathing air, and propellants like oxygen and methane.
Plant Habitat
Water that has been processed from the Martian surface, along with the proper nutrient blend, can be used for growing plants for astronauts to eat. Plants also purify water and produce oxygen from respired carbon dioxide.
Oxygen
Hydrogen
Methane
Cryogenic Storage
Once the propellants have been extracted from the resources they must be safely stored as high-density cryogenic liquids for future use.
Human Habitat
Oxygen extracted from the soil and atmosphere can be used for breathable air and shields made from regolith or water may be used to help protect against radiation.
Prospector
The prospector will drill to find resources buried in the Martian soil, or regolith.
Miner
A robot will mine the regolith to obtain the resources locked inside.

# Stages for Habitat Evolution

Assumptions:

1. Partial Gravity Habitat will build up over years
2. Durations of dormancy will occur requiring system stability
3. Crew of 4 humans
4. Vehicles and Habitats will have different systems for different cycles
5. Resupply must be minimized and eventually eliminated for Mars
    1. Food must be grown rather than brought
    2. Waste must be recycled rather than collected/stored

Outcomes:

1. Initial stages will focus on survivability; later stages on sustainability
2. Trade study findings show after 120-day BLiSS outperforms current physical/chemical systems

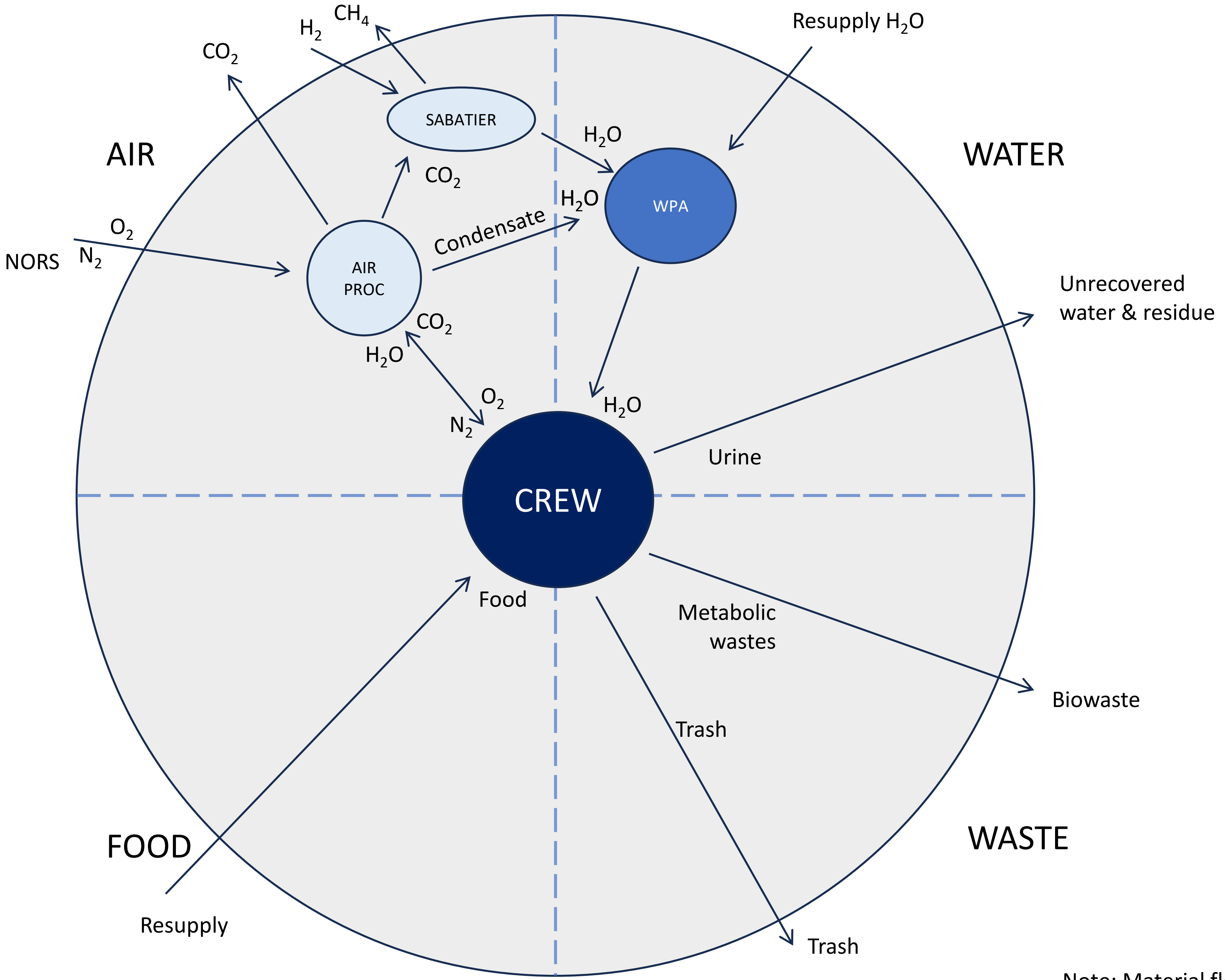
Proposed Stages:

1. Survival Stage – Air and Water focus
2. Intermediate Stage – Air, Water, and Metabolic waste
3. Sustainable Stage – Air, Water, Waste, Food
4. Mature Stage – Economy drives Food and Biomanufacturing in Space

# Life Support System (LSS) for Surface Habitats – Architecture based on Current Physicochemical Capabilities

**Short Duration**

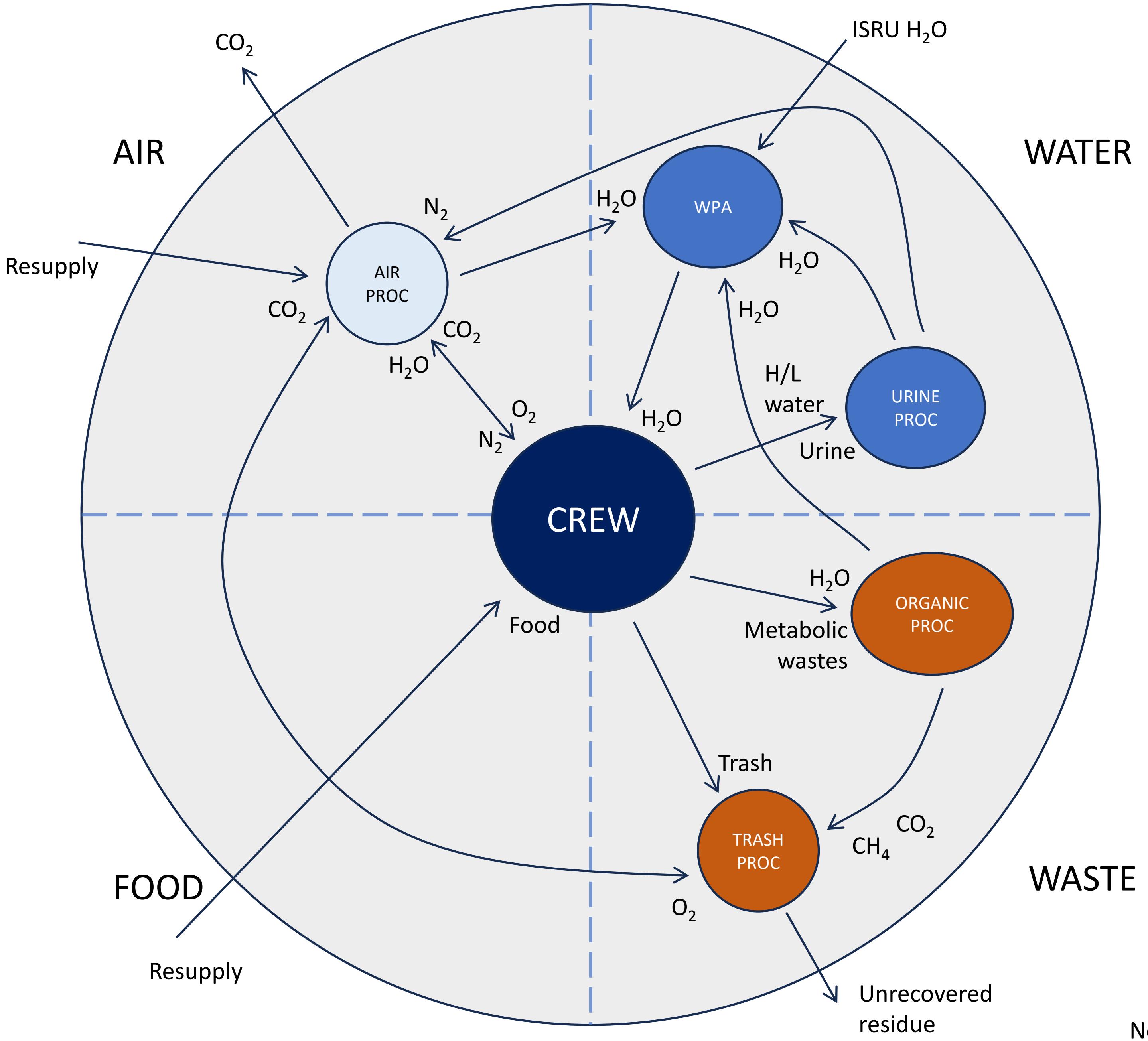
**1. Survival Stage (non-bioregenerative)**




Note: Material flow indicated by direction of adjacent arrowhead

# Bioregenerative Life Support System (BLSS) for Surface Habitats – KSC/USF Proposed Integrated Architecture

**Intermediate Duration**



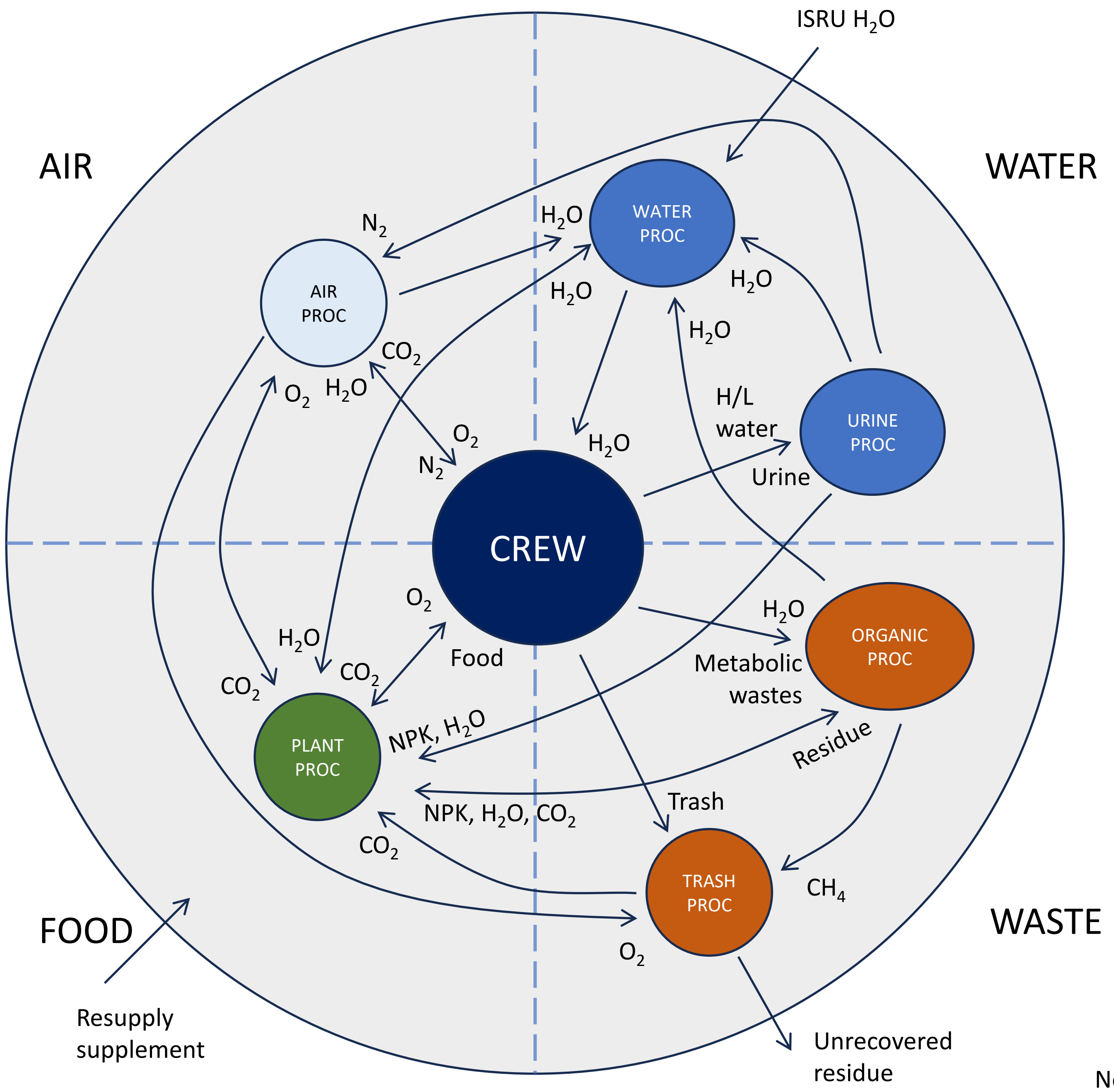

## 2. Intermediate Stage (bioregenerative to Reduce Resupply)

| Unit | Function | Hardware |
|---|---|---|
| **Air Processor** | • Provide clean air for crew<br>• Recover condensate<br>• Provide CO2 for plants | • Air revitalization system, CDRA, trace contaminant system |
| **Water Processor** | • Provide clean water for crew<br>• Provide clean water for plants | • Water processor assembly |
| **Urine Processor** | • Mitigate urine & hygiene/laundry water<br>• Recover resources (water/fertilizer/N2) | • SAMBR |
| **Organic Processor** | • Mitigate metabolic waste slurries (feces, food waste, vomit, etc),<br>• Recover resources (water, fertilizer, CH4/CO2) | • APMBR |
| **Trash Processor** | • Mitigate trash and reduce volume of residue<br>• Recover CO2 | • OSCAR |
| | | |
| | | |

Note: Material flow indicated by direction of adjacent arrowhead

# Bioregenerative Life Support System (BLSS) for Surface Habitats – KSC/USF Proposed Integrated Architecture

**Long Duration**

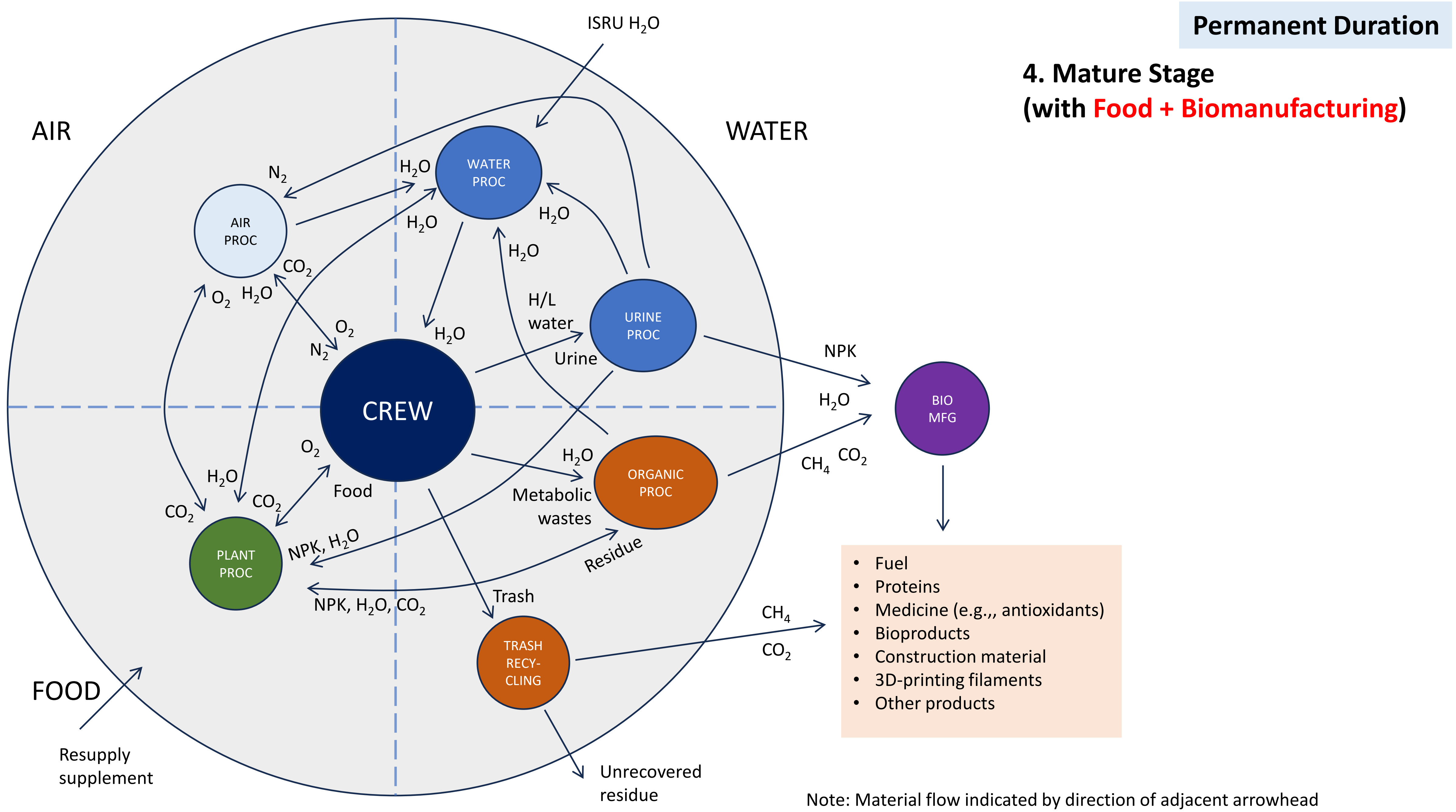


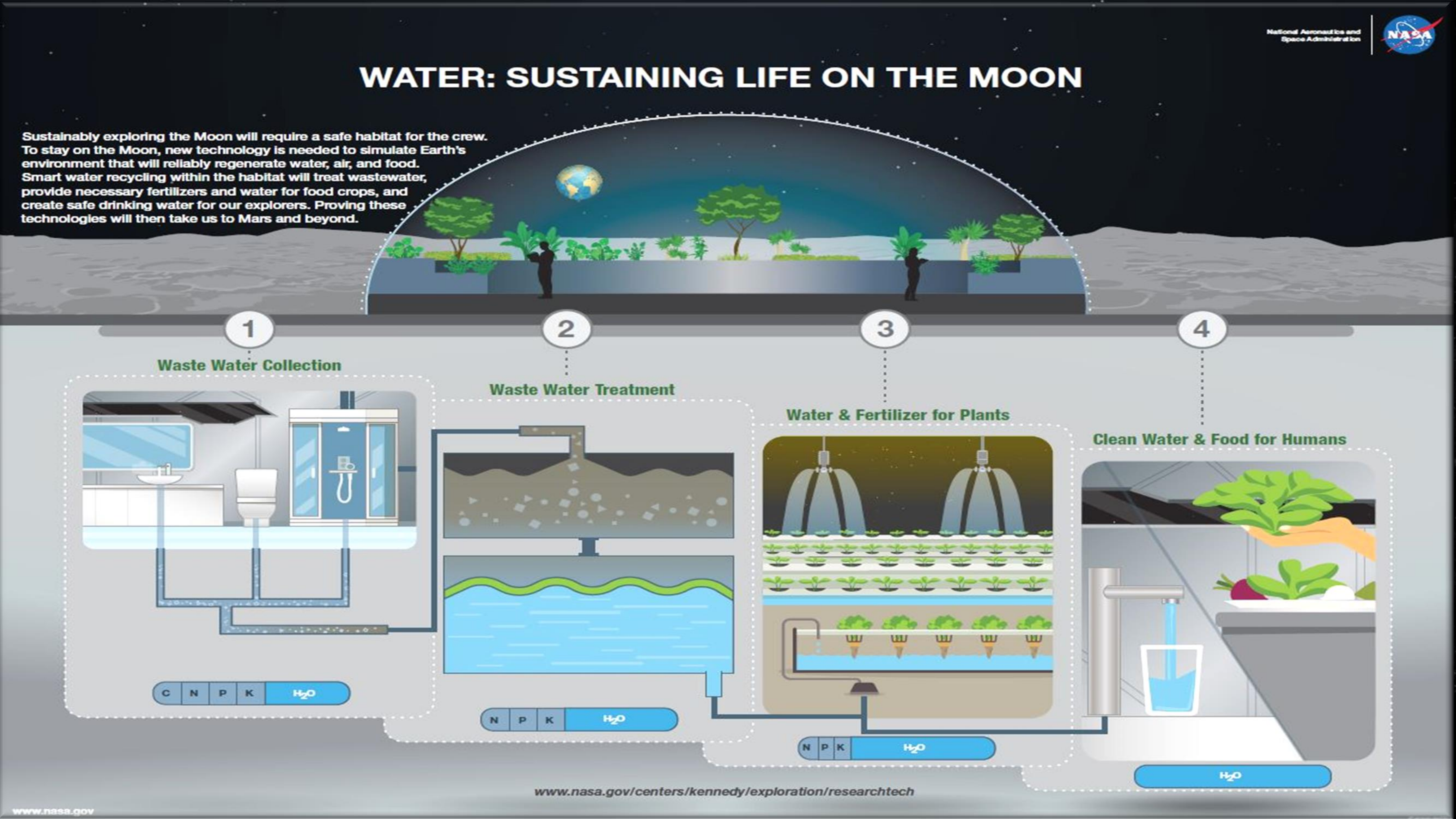

## 3. Sustainable Stage (with Food Production)

| Unit | Function | Hardware |
|---|---|---|
| **Air Processor** | • Provide clean air for crew<br>• Recover condensate<br>• Provide CO2 for plants | • Air revitalization system, CDRA, trace contaminant system |
| **Water Processor** | • Provide clean water for crew<br>• Provide clean water for plants | • Water processor assembly |
| **Urine Processor** | • Mitigate urine & hygiene/laundry water<br>• Recover resources (water/fertilizer/N2) | • SAMBR |
| **Organic Processor** | • Mitigate metabolic waste slurries (feces, food waste, vomit, etc),<br>• Recover resources (water, fertilizer, CH4/CO2) | • APMBR |
| **Trash Processor** | • Mitigate trash and reduce volume of residue<br>• Recover CO2 | • OSCAR |
| **Plant Processor** | • Produce food for crew<br>• Revitalize air (O2)<br>• Further purify water | • Plant production systems |
| | | |

Note: Material flow indicated by direction of adjacent arrowhead

# Bioregenerative Life Support System (BLSS) for Surface Habitats – KSC/USF Proposed Integrated Architecture



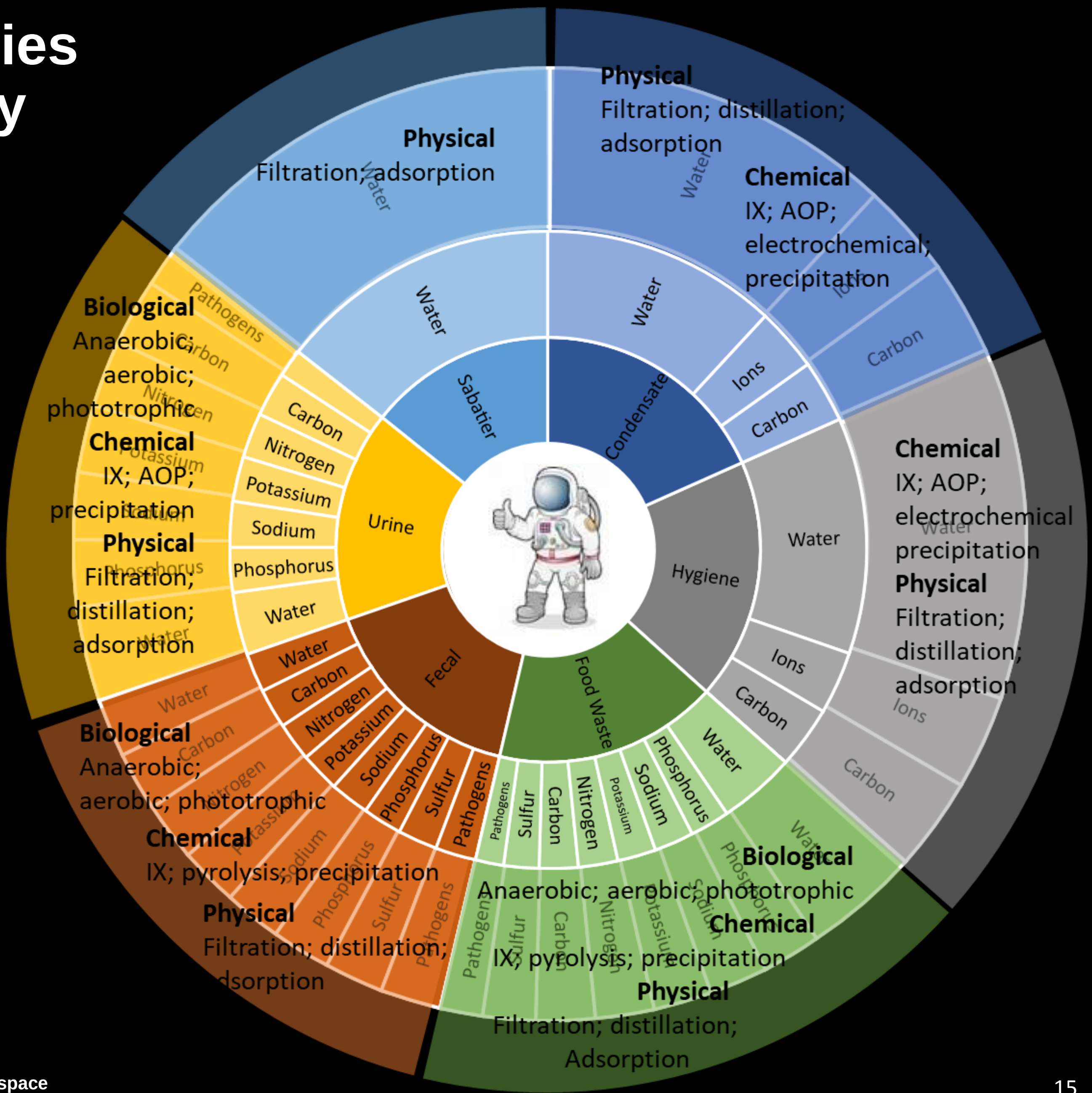


National Aeronautics and Space Administration
NASA
WATER: SUSTAINING LIFE ON THE MOON
Sustainably exploring the Moon will require a safe habitat for the crew. To stay on the Moon, new technology is needed to simulate Earth's environment that will reliably regenerate water, air, and food. Smart water recycling within the habitat will treat wastewater, provide necessary fertilizers and water for food crops, and create safe drinking water for our explorers. Proving these technologies will then take us to Mars and beyond.
1
Waste Water Collection
C N P K $H_2O$
2
Waste Water Treatment
N P K $H_2O$
3
Water & Fertilizer for Plants
N P K $H_2O$
4
Clean Water & Food for Humans
$H_2O$
www.nasa.gov/centers/kennedy/exploration/researchtech
www.nasa.gov

# Primary Wastewater Streams: Constituents and potential technologies for treatment and resource recovery

| | | Constituents by type | | | | | | | | | | Constituents by size | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Process Stream** | **Description** | **C** | **N** | **P** | **K** | **S** | **Na** | **Ca** | **Mg** | **Other ions** | **Pathogens** | **Particulate** | **Colloidal** | **Dissolved** |
| **Food Waste** | High content of complex particulate OM, fibers, COD | 4 | 3 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 4 | 4 | 3 |
| **Fecal** | High content of complex particulate OM, fibers, COD, pathogens | 4 | 3 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 4 | 4 | 4 | 3 |
| **Urine** | Mod COD, organic N, urea, ammonium, phosphate, other salts | 3 | 4 | 4 | 4 | 2 | 3 | 2 | 2 | 3 | 2 | 0 | 2 | 4 |
| **Hygiene** | Low COD, constituents from skin and body secretions, environmental contaminants | 2 | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 3 |
| **Humidity** | Mostly pure condensate, with contaminants from air and surfaces | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 2 |
| **Sabatier** | Pure, potentially aggressive, can use for dilution, regeneration, backwash | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |

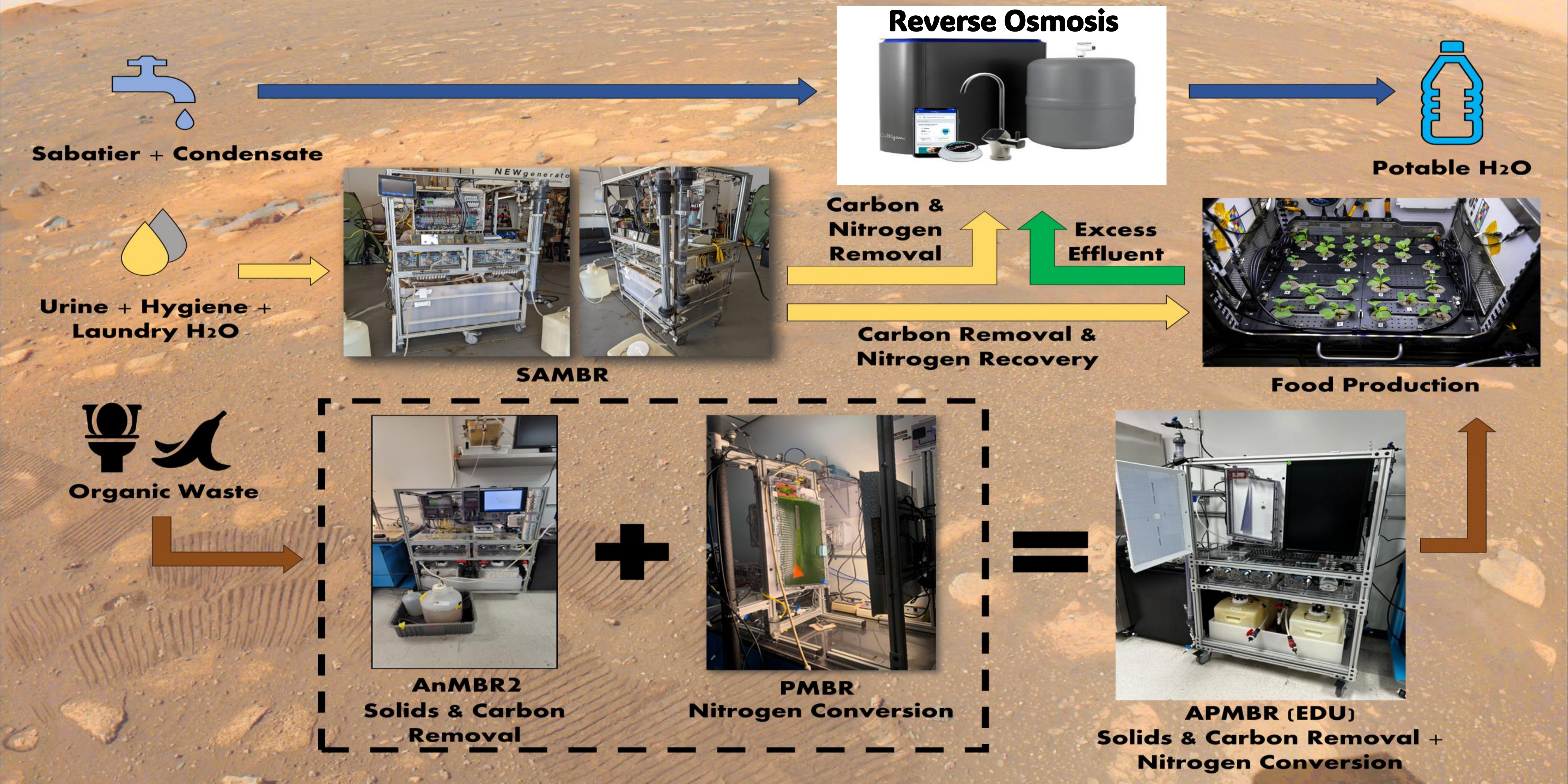
*Notes*: First two rows denote streams currently not addressed by technologies on ISS
Relative concentration: Very High (4) High (3), Medium (2), Low (1), Trace (0)
COD = chemical oxygen demand




Source: Pickett, M., L. Roberson, J. Calabria, T. Bullard, G. Turner, D. Yeh. 2020. Regenerative water purification for space applications: Needs, challenges, and technologies towards 'closing the loop'. *Life Science in Space Research, 24: 64-82.*

# Water Science Work Area

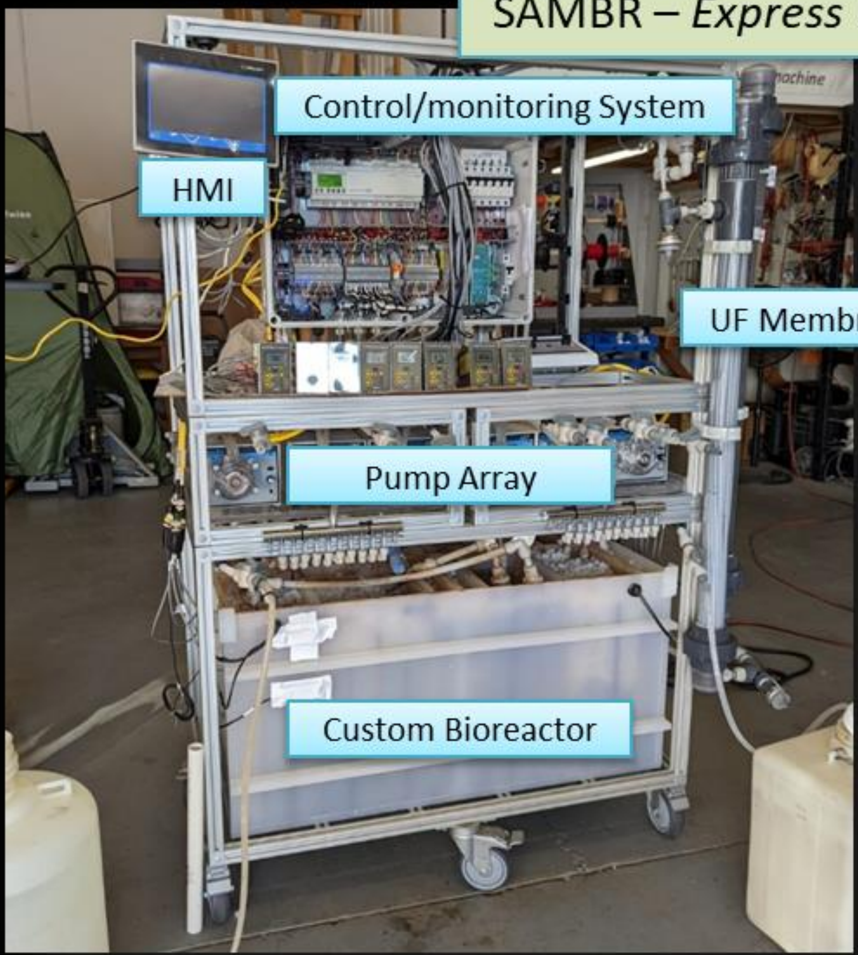
## Bioregenerative Water and Resource Recovery

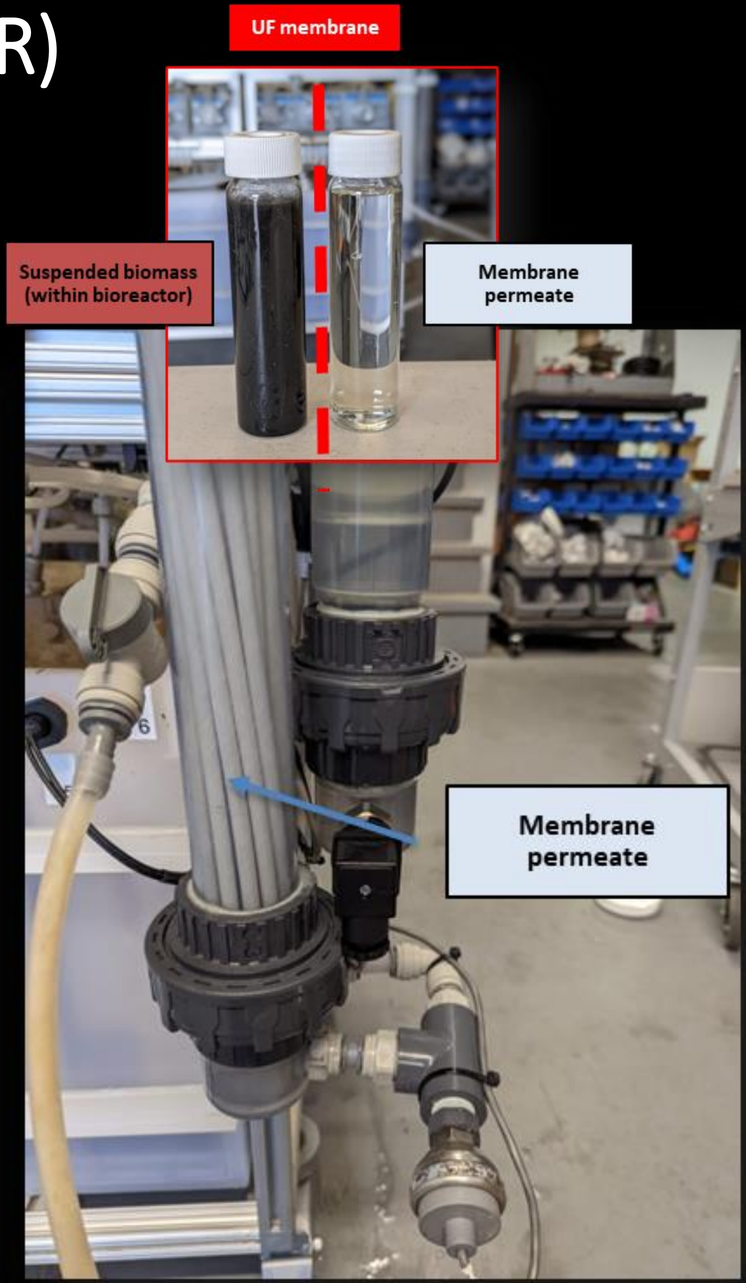


# Suspended Aerobic Membrane Bioreactor (SAMBR)

<u>Function:</u> to process **urine** and **hygiene water** for a crew of 4
** alternative to the urine processor assembly (UPA) **

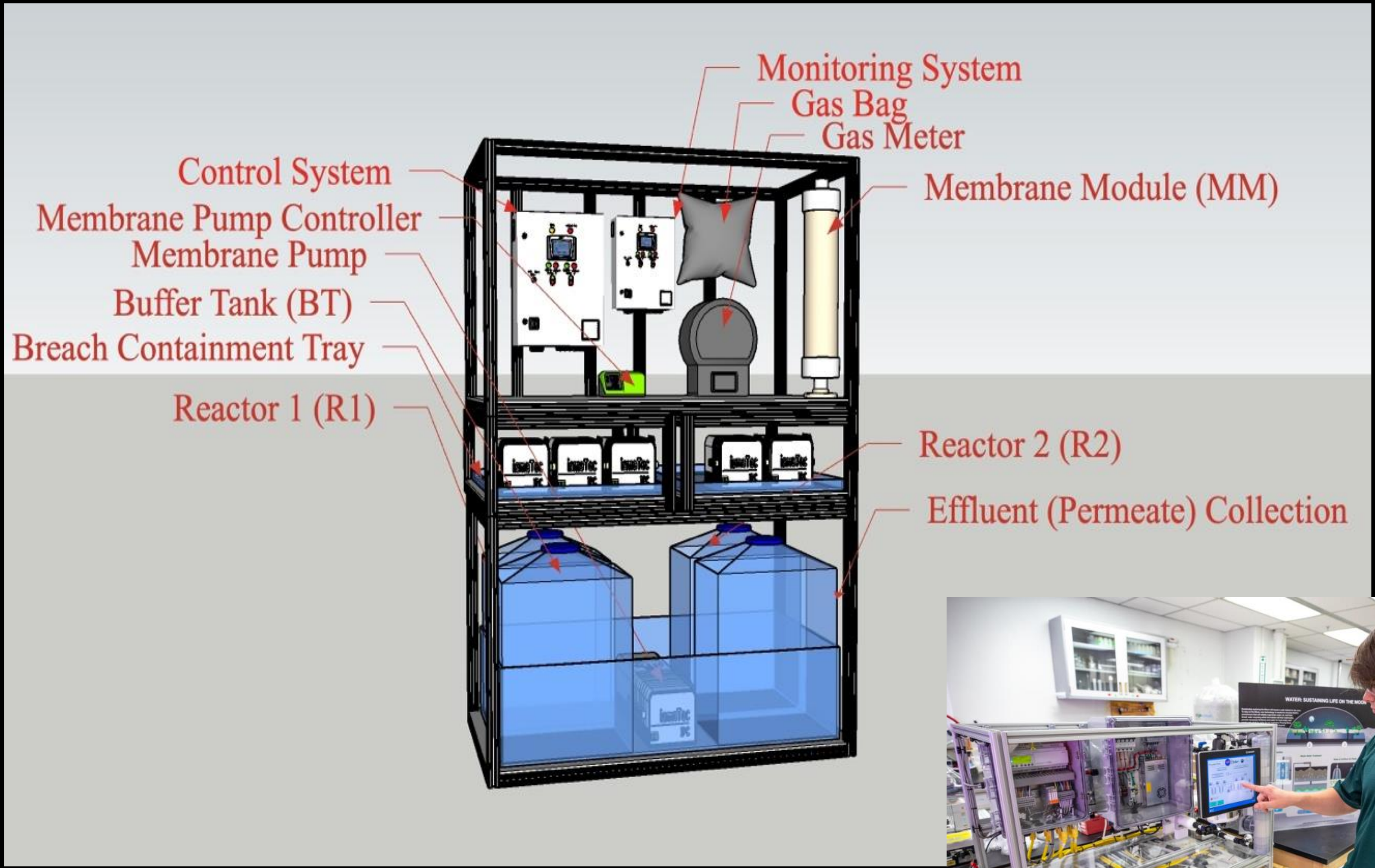
SAMBR – *Express Rack system*




Bullard, Roberson, Yeh, et al. *Alternative Treatment and Resource Recovery of Crew Urine and Gray Water Using a Hybrid Membrane Technology*. ICES-2022-353.

# THE ANAEROBIC MEMBRANE BIOREACTOR



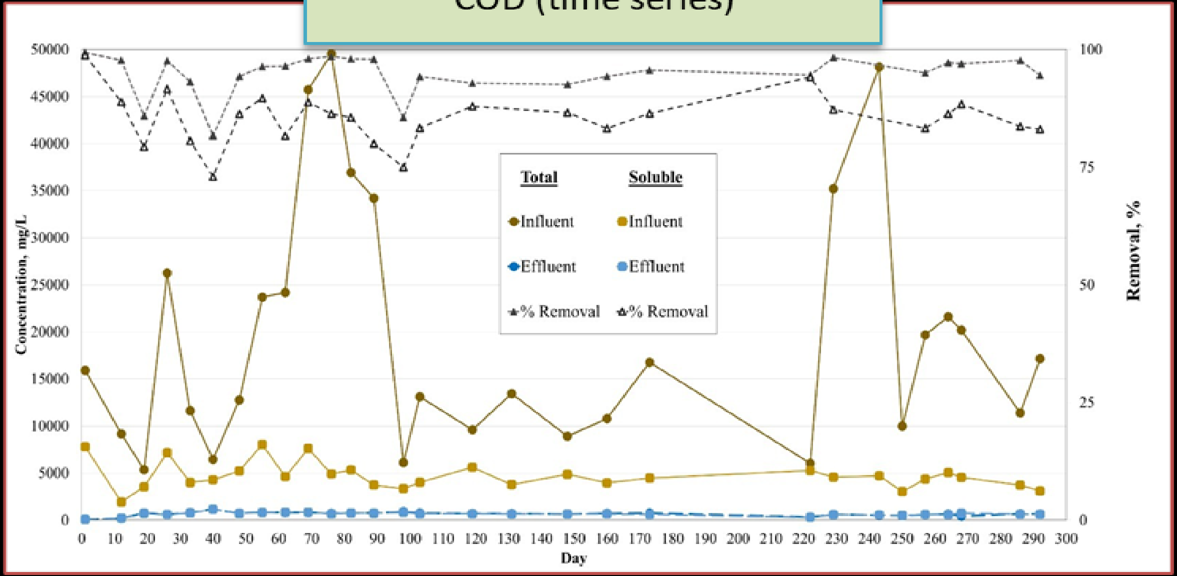


Bullard, Roberson, Yeh, et. al. “A Prototype Early Planetary Organic Processor Assembly (OPA) Based on Dual-Stage Anaerobic Membrane Bioreactor (AnMBR) for Fecal and Food Waste Treatment and Resource Recovery.”2020. ICES-2020-323.

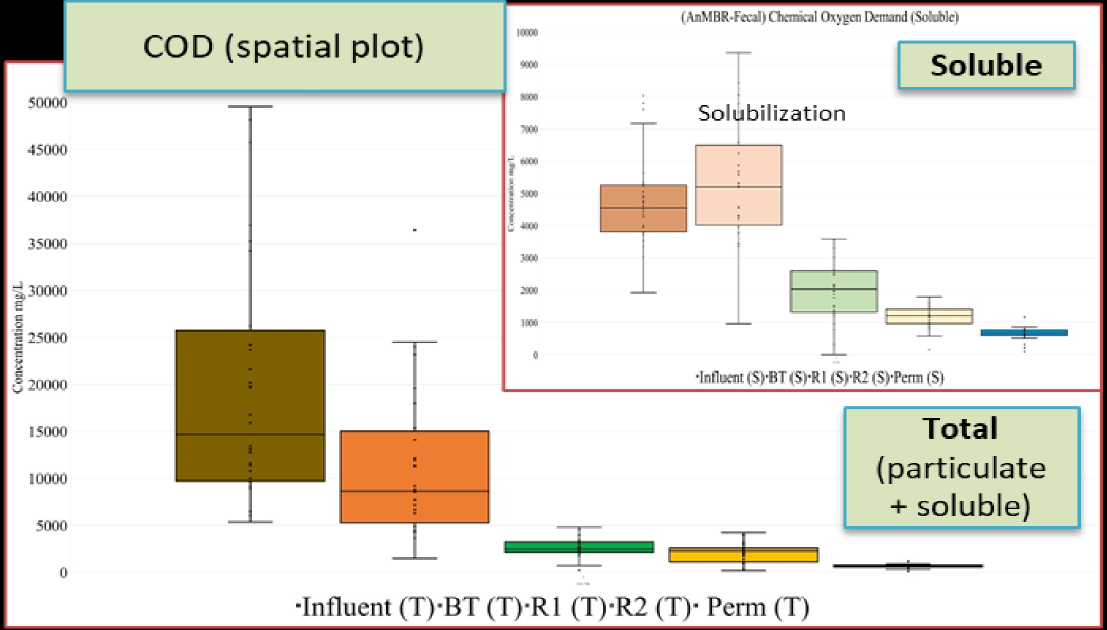
# AnMBR 1 (influent: canine fecal waste, 5%)

Smith, Roberson, Yeh, et. al. "Management of fecal and food waste utilizing a hybrid anaerobic membrane bioreactor. International Conference on Environmental Systems." ICES-2022-272

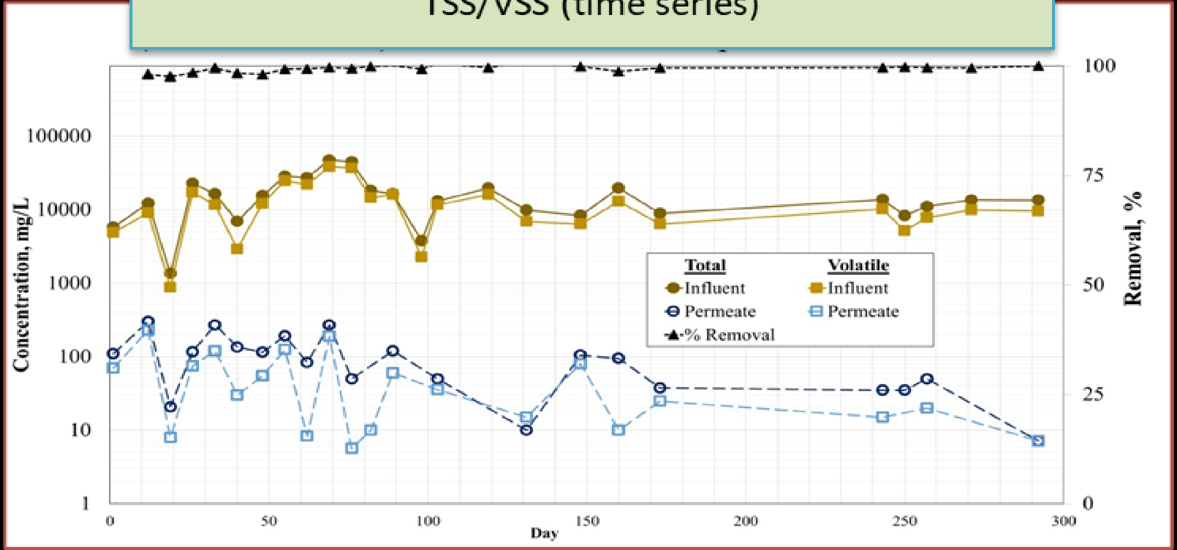
## COD (time series)



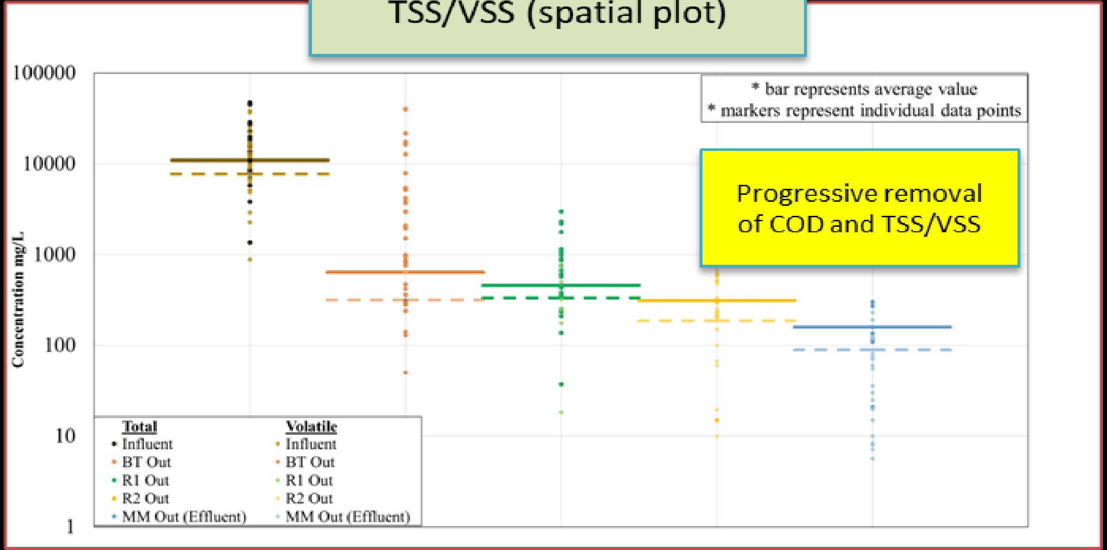

## COD (spatial plot)



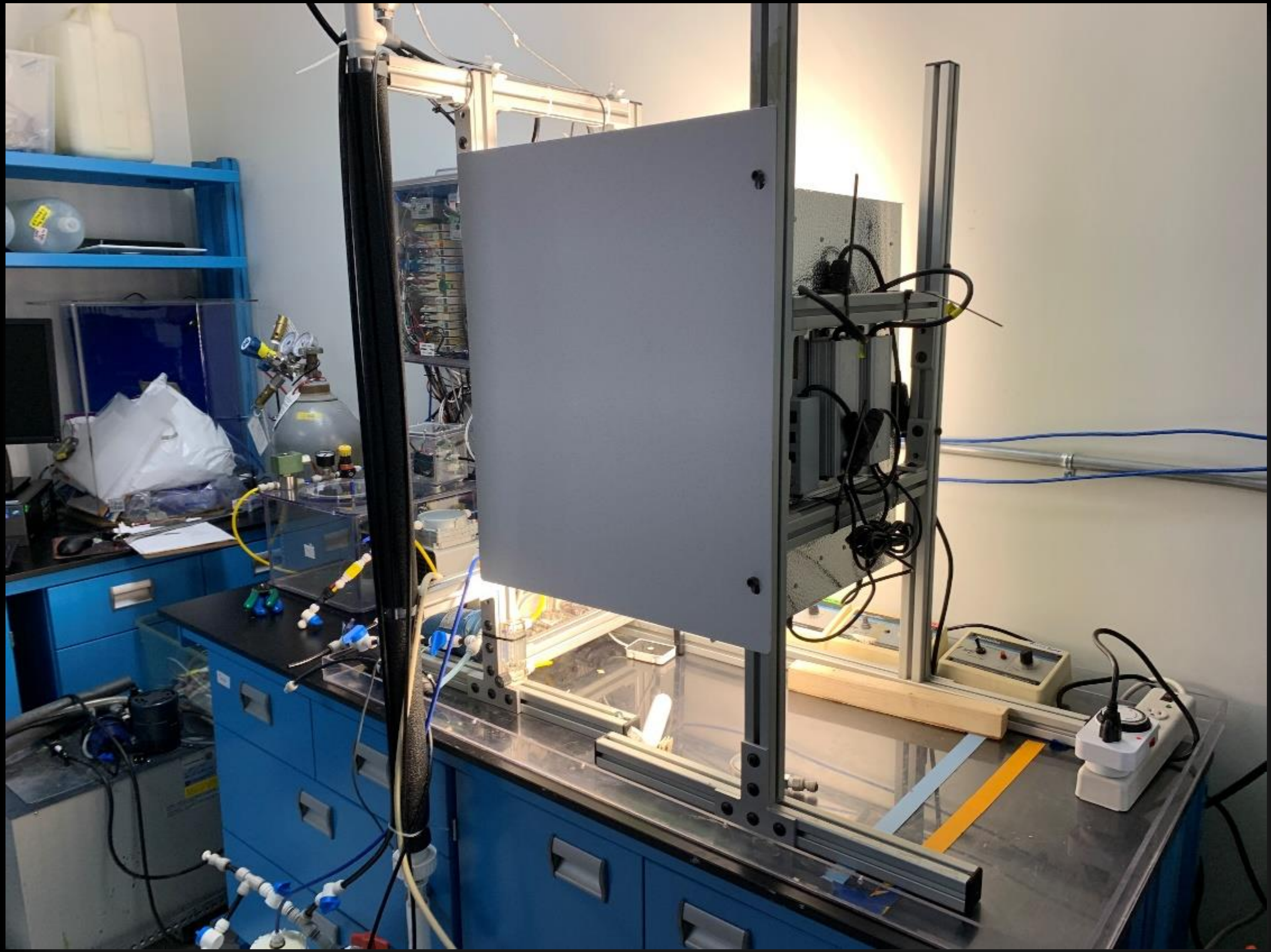

## TSS/VSS (time series)

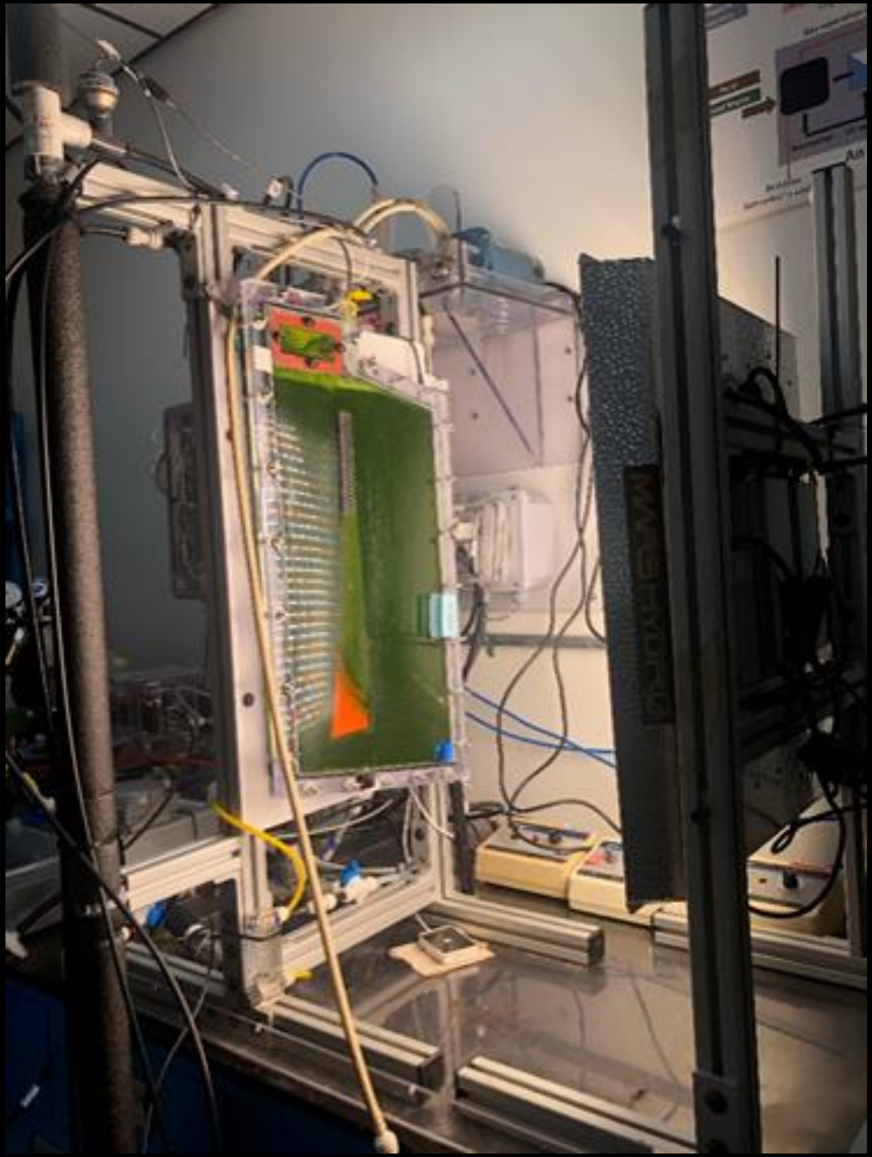



## TSS/VSS (spatial plot)



# PhotoMembrane Bioreactors (PMBR) for wastewater and BioMFG

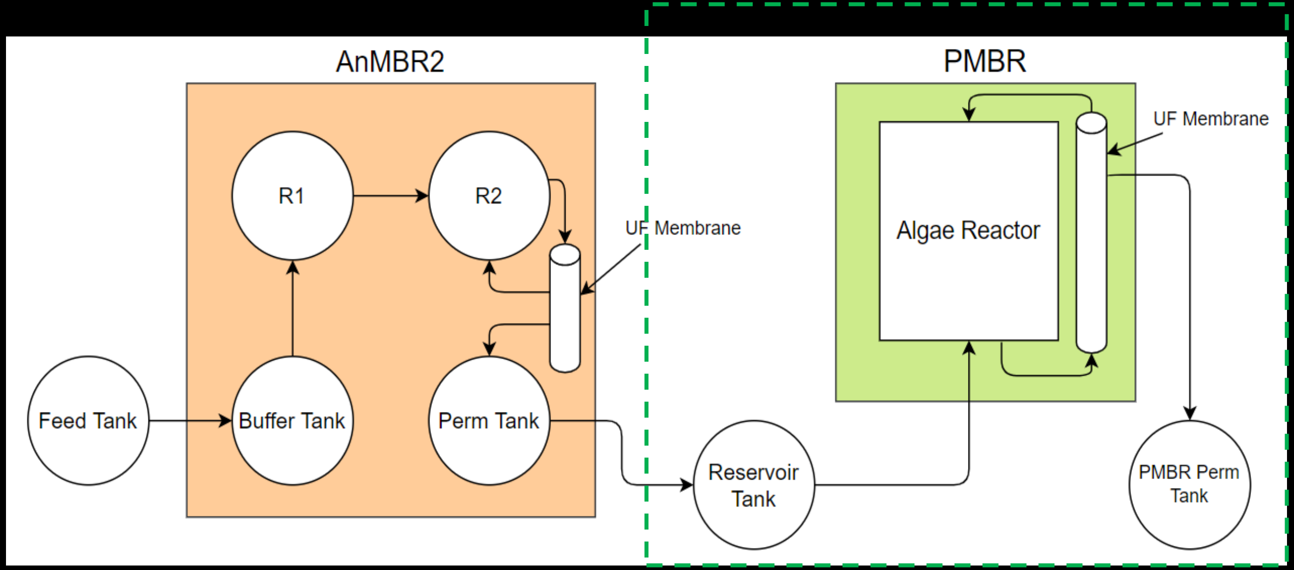


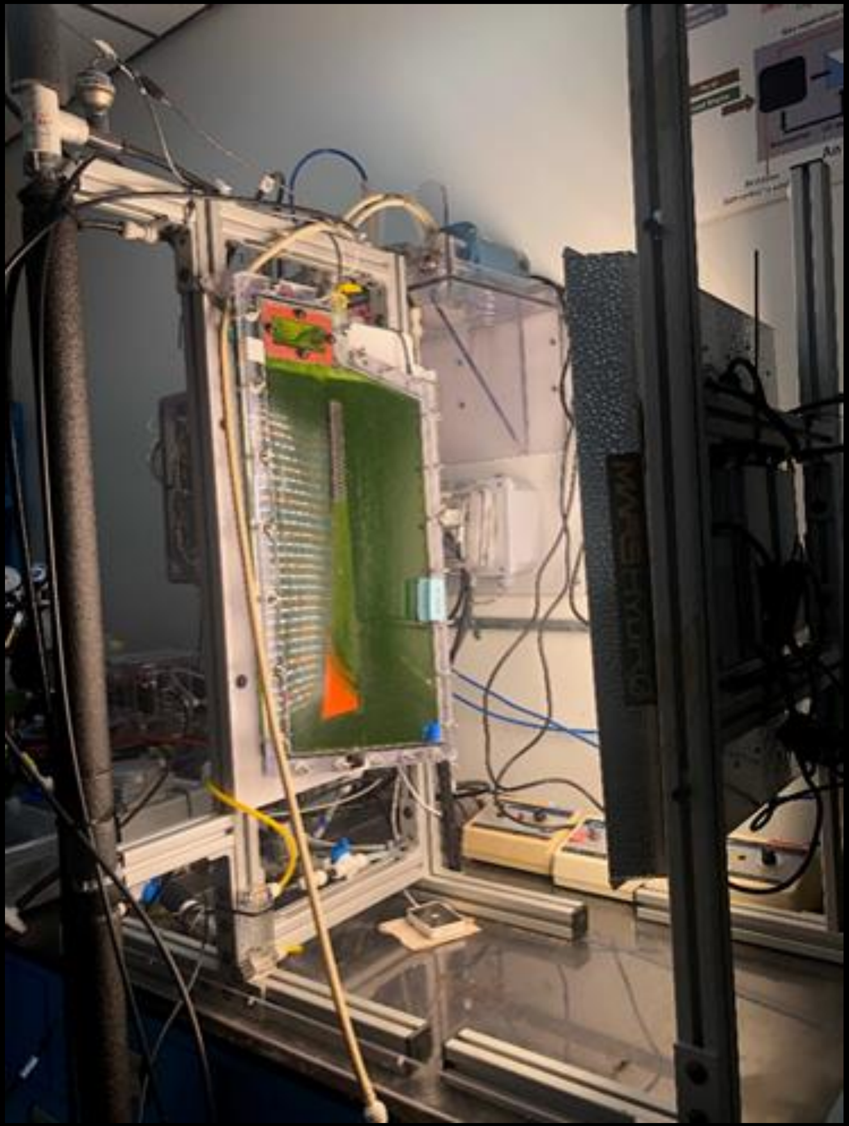


Saetta, Roberson, Yeh, et. al. "Design and operation of Photomembrane Bioreactor (PMBR) to balance nitrogen in high-ammonia wastewater treatment effluents. International Conference on Environmental Systems." ICES-2022-202.

# PhotoMembrane Bioreactors (PMBR) for wastewater and BioMFG

- **GOAL: Use the algae/bacteria community to balance the nitrogen cycle in the AnMBR effluent.**
- **The PMBR nitrifies the ammonia in the AnMBR effluent into nitrate, a more suitable form of plant fertilizer.**



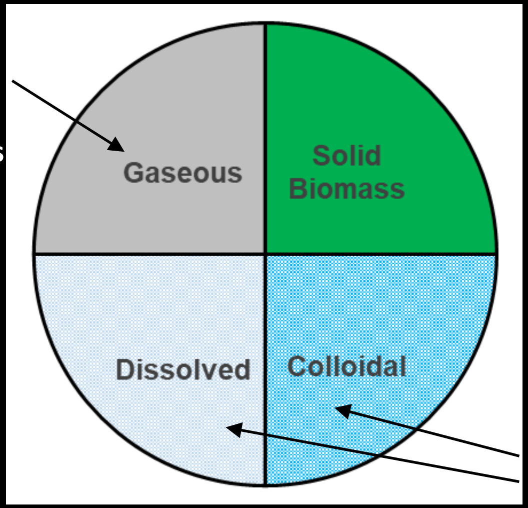
| Sampling Locations |
| --- |
| Influent (Reservoir Tank, RT) |
| PMBR Contents |
| PMBR Permeate |

| Measured Parameters | |
| --- | --- |
| Optical Density | Total Organic Carbon |
| Ammonia | Total Suspended Solids |
| Nitrate | Reservoir tank pH |
| Nitrite | pH/$CO_2$/DO on-line sensors |
| Total Nitrogen | |

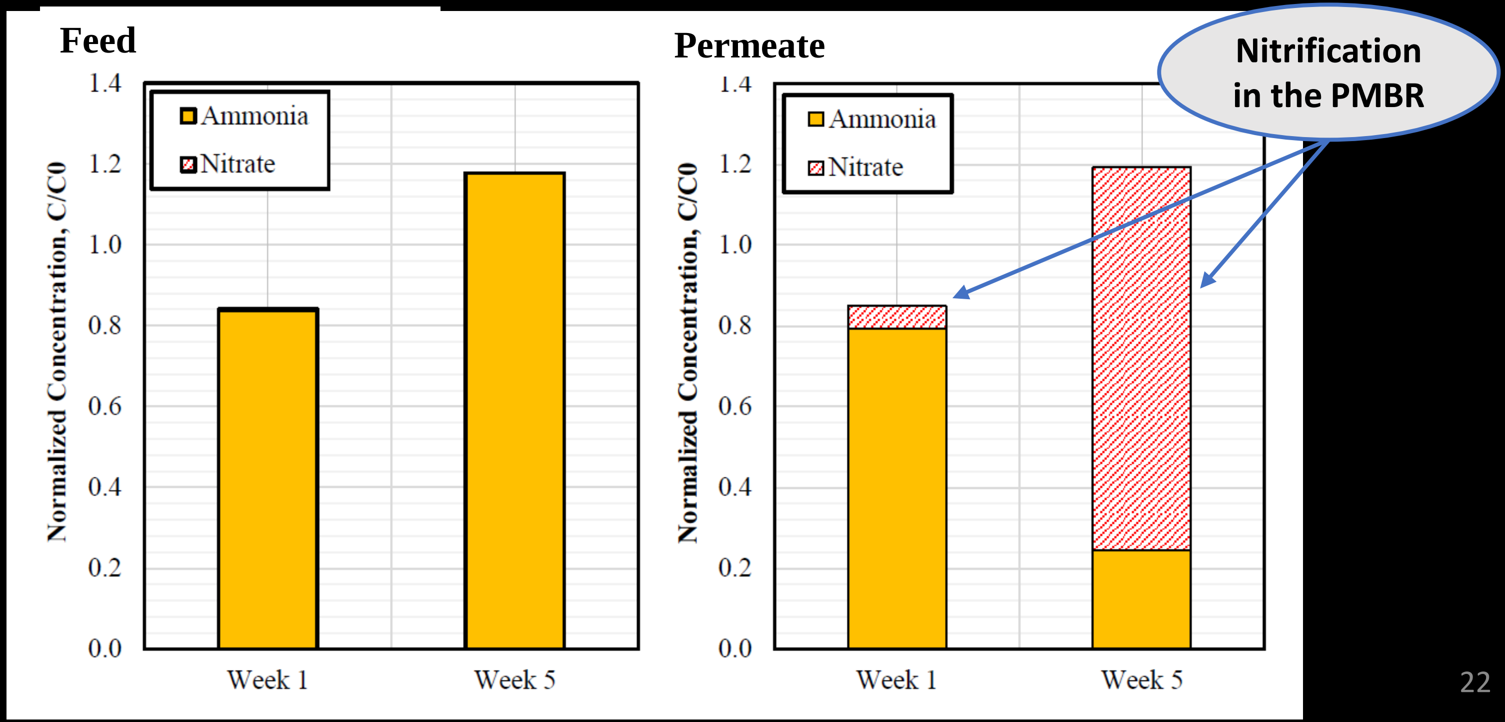
# PMBR for Nitrogen Balance

Daniella, Riley, and Jason in front of OPA 2 and PMBR

At pH < 8, gaseous nitrogen is assumed negligible

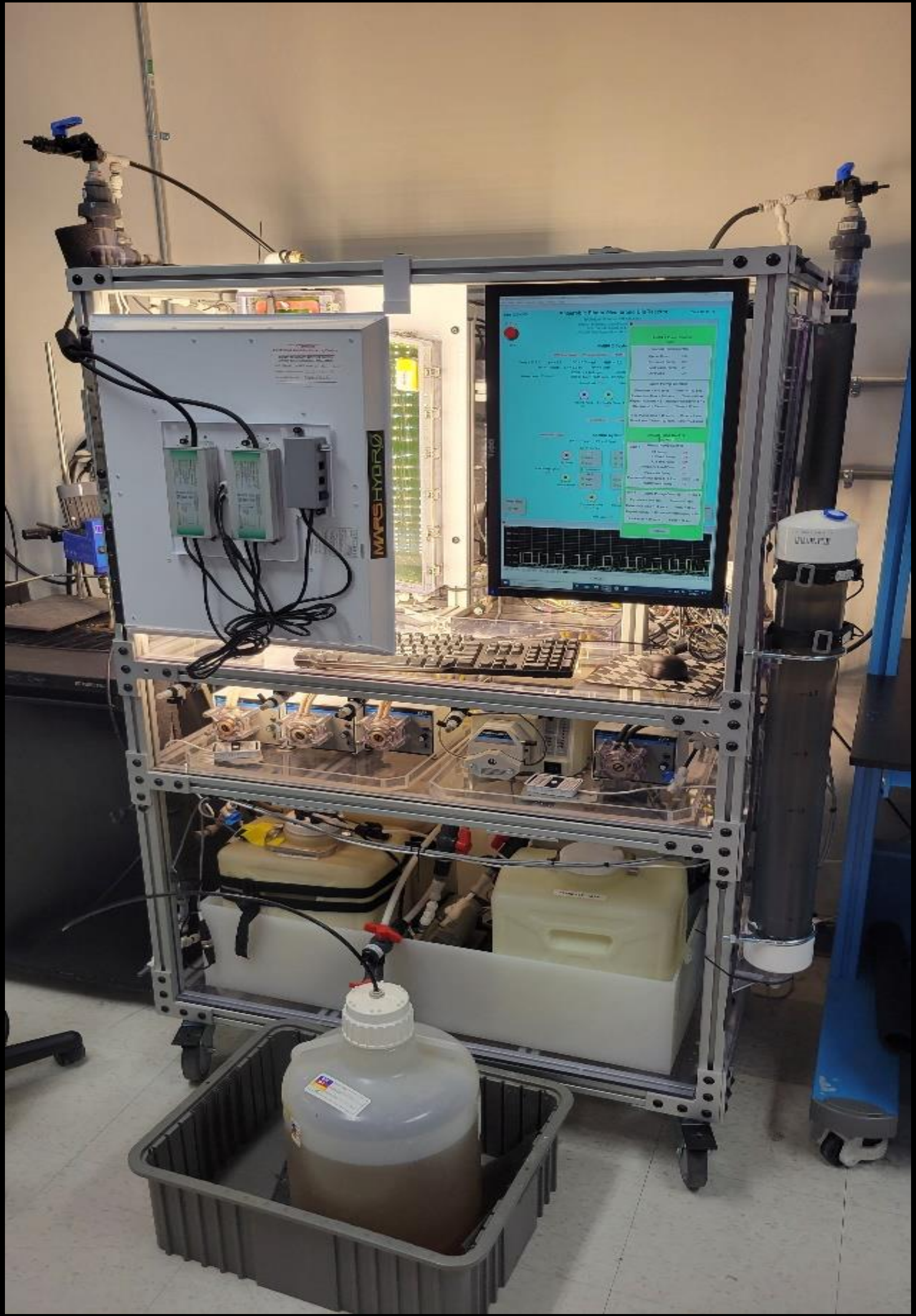


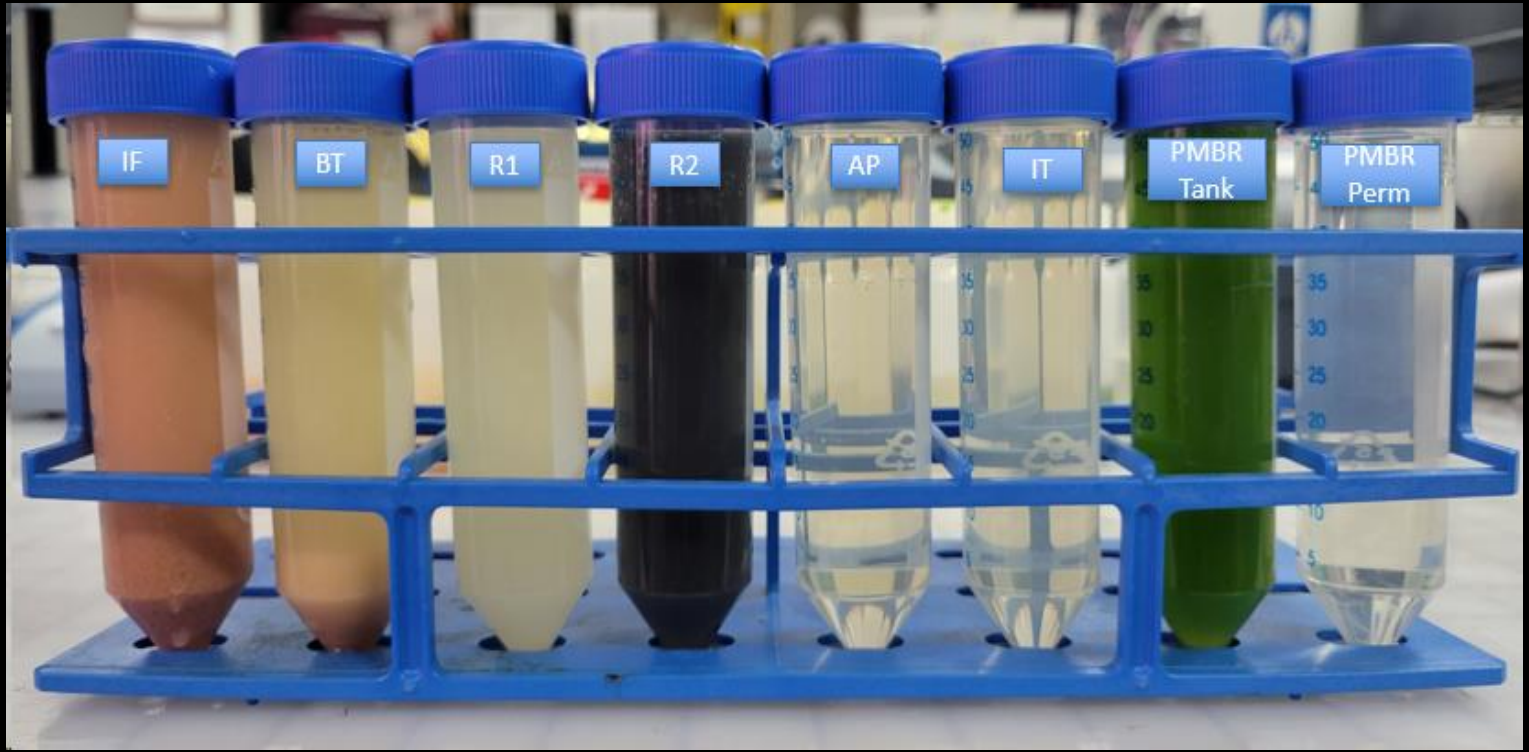

Liquid phase in PMBR, can be ammonia, nitrate, nitrite, or organic nitrogen




Saetta, Roberson, Yeh, et. al. “Design and operation of Photomembrane Bioreactor (PMBR) to balance nitrogen in high-ammonia wastewater treatment effluents. International Conference on Environmental Systems.” ICES-2022-202.

# APMBR TREATMENT PROCESS



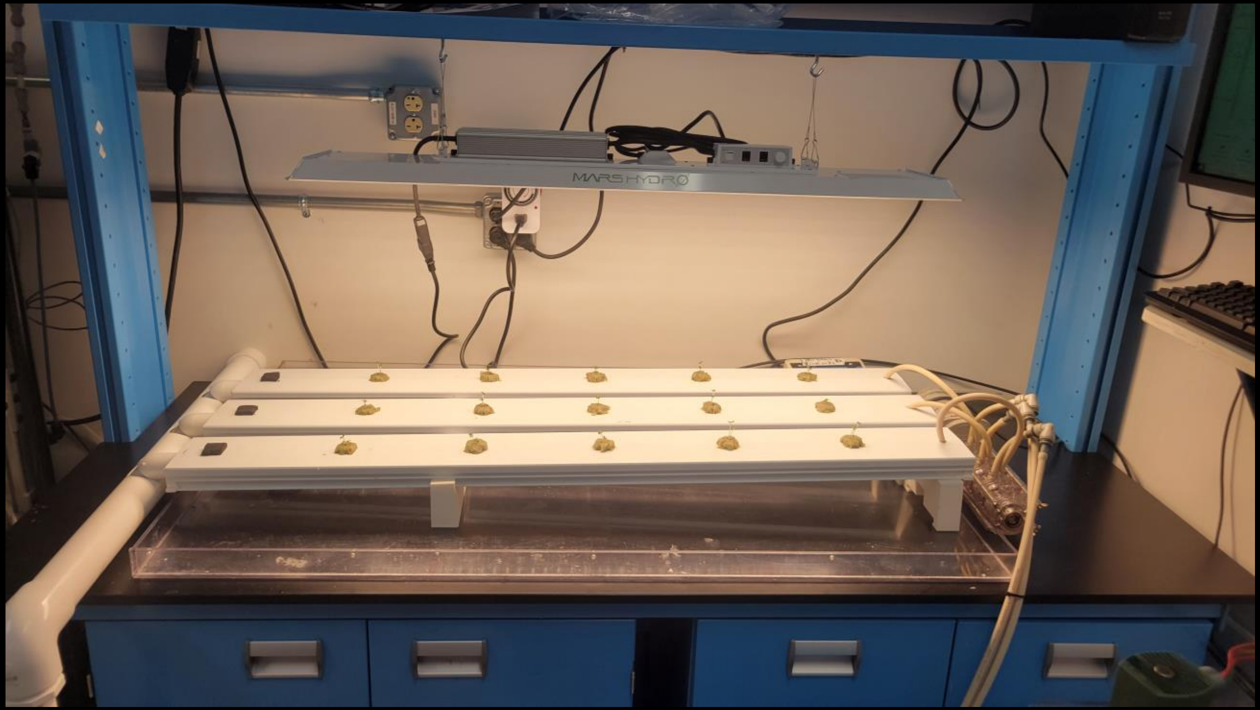

**APMBR Samples pre-centrifugation.** From left to right: Influent tank (IF), Buffer Tank (BT), Reactor Tank 1 (R1), Reactor Tank 2 (R2), Anaerobic Permeate (AP) Intermediary Tank (IT), PMBR tank, and PMBR Permeate (PP).

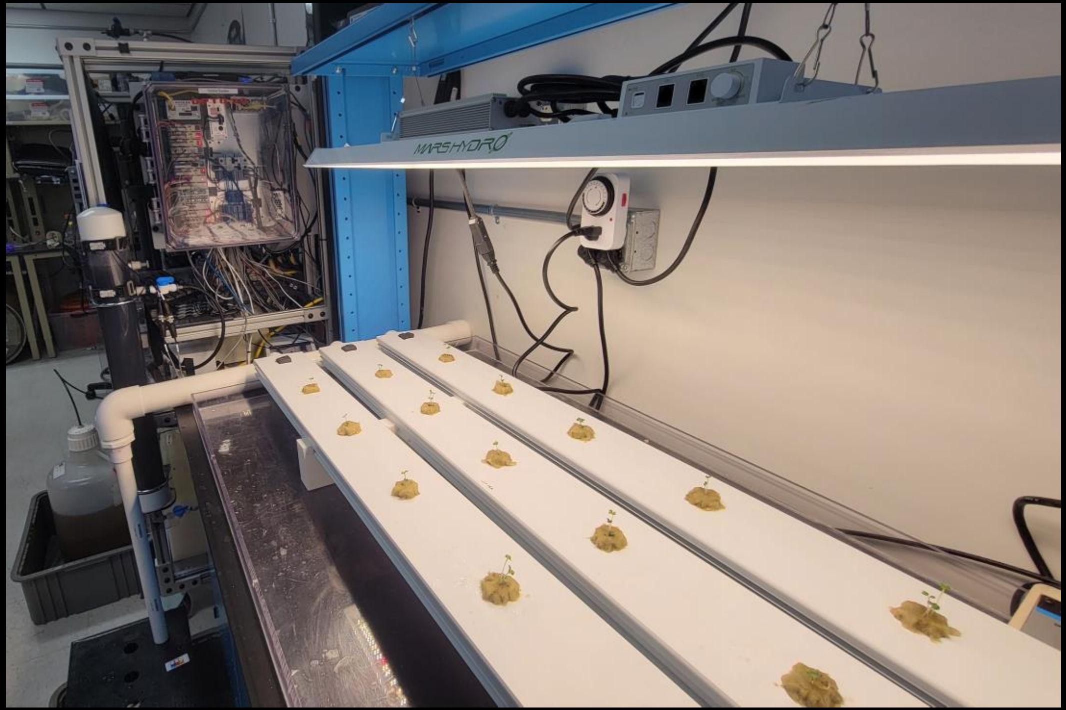
- APMBR has been in nominal operation for 180 days as of April 9th, 2024
- C/N Ratio of AnMBR perm remains close to 1 indicating proper microbial processing.



FIscher, Yeh, Roberson, et. al. “Unleashing the Power of Anaerobic–phototrophic Membrane Bioreactors for Sustainable Bioregenerative Life Support .” ICES-2024-347

# APMBR + HYDROPONICS

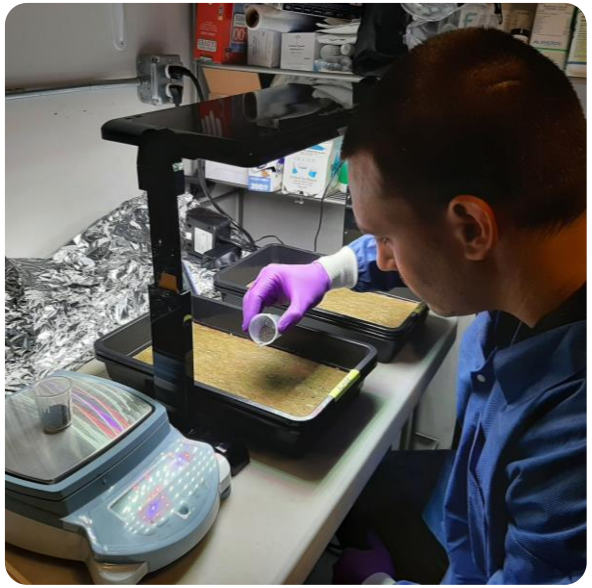




Hydroponics control grow out of Extra Dwarf Pok Choi on 1/2x Hoaglands nutrient solution started. The plants will reach maturity at 28 days at which point they will be harvested and analyzed. The nutrient solution is also being sampled and analyzed throughout the grow out to determine plants effects on water chemistry. After the control grow out, we will test the same batch of plant seeds using APMBR permeate as the nutrient solution in recirculating flow.

# HI-SEAS

- **H**awaii **S**pace **E**xploration **A**nalog and **S**imulation is an analog habitat and environment purposed to simulate manned Mars/Lunar surface missions.
- Missions take place in a dome structure that is 36 feet in diameter and has about 1150 square feet of living space. Power and heat are supplied via the solar panel farm, as well water is housed in a storage unit outside the habitat structure.
- Provides a great environment to perform feasibility studies for a variety of projects. NASA hardware such as VEGGIE has been tested at HISEAS!
- Future longer-term feasibility studies with bioregenerative purification systems at HISEAS would garner a better understanding of how these systems work in a simulated high-fidelity early planetary base-like habitat.



# CHAPEA

- **C**rew **H**ealth **a**nd **P**erformance **E**xploration **A**nalog is an analog habitat and environment purposed to simulate manned Mars/Lunar surface missions at Johnson Space Center.
- 1-year missions take place in a 3D printed structure that has about **1700 square feet** of living space. Four private crew quarters, dedicated medical and workstations, lounge areas, galley, and food growing areas.

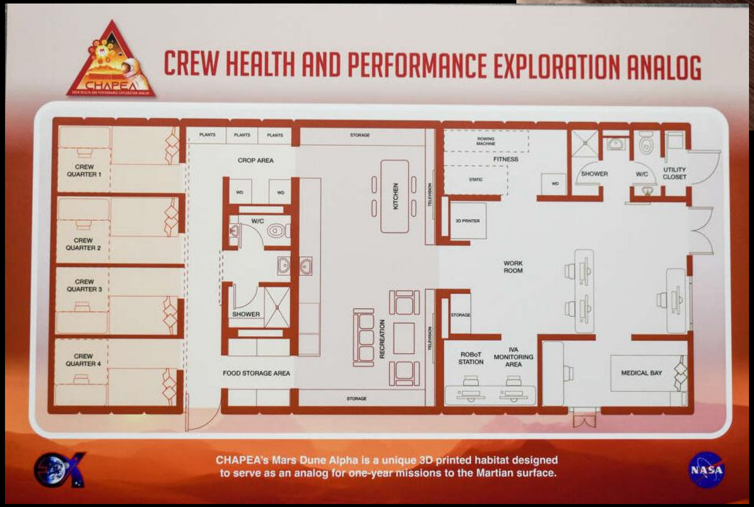


**2024-2026 Test Plan**

**Phase 1: Integrate wastewater treatment processes into CHAPEA and test their engineering constraints, performance, and capabilities. (FY25-26)**

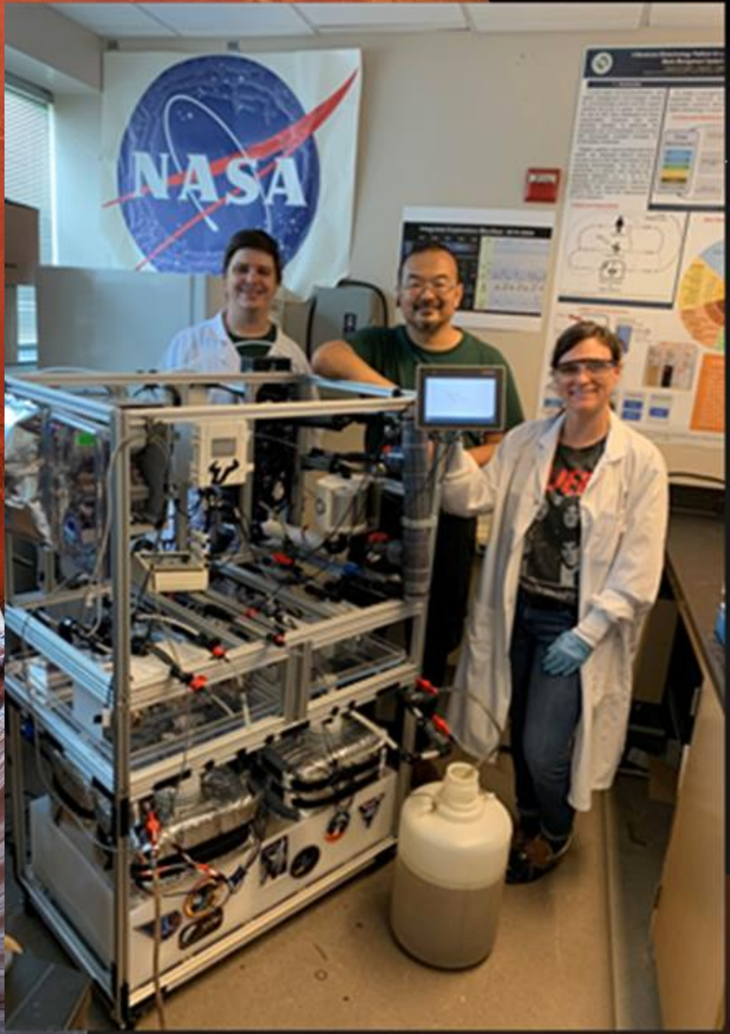
**Phase 2: Develop post-processing treatment methods that generate value added products and test for requirement conformance. (FY27)**

**Phase 3. Develop air and trash integration points for a fully sustainable architecture, integrate those systems, and test full system performance. (FY28)**





https://www.nasa.gov/humans-in-space/chapea/




# Acknowledgements