Alternative Treatment of Crew Wastewater Using a Hybrid Membrane Technology

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Environmental Control and Life Support Systems (ECLSS) of future long-duration, deep-space human exploration missions should treat all "waste" streams for recovery and ideally by near closed-loop. Onboard the International Space Station (ISS), the Water Recovery System (WRS) does not treat urine and gray water to recover elements beyond water and utilizes physical-chemical technologies that operate with single-use and hazardous consumables. Urine offers a renewable source of nitrogen and other trace elements that can support sustainable crop production. In response to the lack of flight ready technologies capable of treating urine and gray water for water and nutrient recovery, a Suspended Aerobic Membrane Bioreactor (SAMBR) is under development between the University of South Florida and Kennedy Space Center. SAMBR is optimized for an early planetary base/partial gravity habitat and serves as a hybrid alternative to currently utilized urine treatment technologies and support closing the resource recovery loop. With its ECLSS minded form factor and modular design, SAMBR's operation can be customized to suit the treatment objectives (i.e., nitrogen conversion) at that time. This proceeding presents preliminary research pertaining to: 1) design challenges in maximizing hydraulic throughput while minimizing mass and volume of the assembly; 2) capabilities for treating high nitrogen waste under steady and non-steady state conditions; and 3) measured performance parameters such chemical oxygen demand (COD), nitrogen conversion, nutrients, turbidity, and system

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throughput. Future research and development pertaining to further optimization on system safety, reliability, and expanded treatment capabilities will also be presented.

Nomenclature

BLSS	=	Bioregenerative Life Support System
C	=	Carbon
COD	=	Chemical Oxygen Demand
CRS	=	Cargo Resupply Mission
EC	=	Exploration Capabilities
ECLSS	=	Environmental Control and Life Support Systems
EXPRESS	=	EXpedite the PRocessing of Experiments to the Space Station
HEOMD	=	Human Exploration and Operations Mission Directorate
IRTD	=	Independent Research & Technology Development
ISS	=	International Space Station
KSC	=	Kennedy Space Center
N	=	Nitrogen, elemental
NASA	=	National Aeronautics and Space Agency
NN	=	Nitrate Nitrogen
OPA	=	Organic Processor Assembly
P	=	Phosphorus
PFD	=	Process Flow Diagram
PGH	=	Partial Gravity Habitat
SAMBR	=	Suspended Aerobic Membrane Bioreactor
TN	=	Total Nitrogen
TRL	=	Technology Readiness Level
USD	=	US Dollars
USF	=	University of South Florida
Veggie	=	Vegetable Production System
WRS	=	Water Recovery System
WPA	=	Water Processor Assembly

I. Introduction and Background

THE Artemis program, which aims to land the first woman and first person of color on the Moon, marks another progressive step within the Space Age[2]. These missions will establish a long-term lunar presence, pioneer the way to Mars, and maintain long-duration space exploration and habitation[2]. This ambitious undertaking creates a new push for the research and development for innovative technologies to meet new programmatic requirements. The goal of achieving long-duration, deep-space human exploration presents NASA and its collaborators with some of the most trying technological challenges encountered since the Space Race. Many of these challenges stem from the harsh and dynamic environments encountered within space, on the Moon, and Mars. Current crewed space operations center primarily around the International Space Station, 220 miles above Earth, where support and resources are hours away and communication is instantaneous[3]. In comparison, a one way trip to the Moon is about three days, while the same for Mars is estimated to range from seven months to over a year and communication is expected to be delayed by approximately 20 minutes[4, 5]. With little to no resources readily available to support human life, artificial habitats for crew members in these environments will need to be robust, independent, and provide all the basic requirements to support life that is naturally granted on Earth, including the air we breathe and food we eat.

Environmental Control and Life Support System (ECLSS) technologies used aboard the International Space Station (ISS) are not optimized for long-duration, deep-space human exploration. As ECLSS technologies aboard the ISS are currently dependent on the regular resupply of consumables, continued use of such technologies in an extraplanetary habitat would likely result in significant financial, logistical, and operational burden. The same instantaneous communication, support, and resupply currently relied upon will no longer be a viable option. In the case of a 30-month mission, a single crew member will require 2250 kg of water, 1359 kg of food, and produce over 5678 kg of metabolic waste[6]. With a current payload cost of approximately 10,000 USD/lb. (~4,535 USD/kg), the cost to provide the food and water for a single astronaut, during the 30-month mission, exceeds 16 million USD[7]. This shift to sustainable and regenerative technologies pertains to NASA's Technology Taxonomy, TX06.1, Environmental

Control and Life Support Systems and Habitation Systems and it's listed goal to: "maintain an environment suitable for sustaining human life throughout the duration of a mission."[8].

The Urine Processor Assembly (UPA) and Water Processor Assembly (WPA) are the primary subsystems that make up the Water Recovery System (WRS). Prior to entering the UPA, urine is pretreated with a hazardous pretreatment chemical, hexavalent chromium, to prevent the precipitation of uric acid and inhibit biological growth [9]. Upon entering the UPA, the pretreated urine is subjected to Vapor Compression Distillation (VCD) to separate the water from the brine solution and recovers approximately 85% of the water found in the urine [6, 10]. The WPA achieves approximately 85% recovery while the future goal is 98% and utilizes consumables including disposable filters and stored oxygen [6].

A new technology, termed the Brine Processor Assembly (BPA), aims to treat the concentrated brine emerging from the UPA has been delivered to the ISS for initial testing since March 2021. Utilizing forced convection from ambient air coupled with membrane distillation, water is separated from the brine as vapor. This water is recovered from the existing condensate system while the brine is stored for disposal. Preliminary results indicate that the BPA increases the water recovered from urine from 85% to >90% [1]

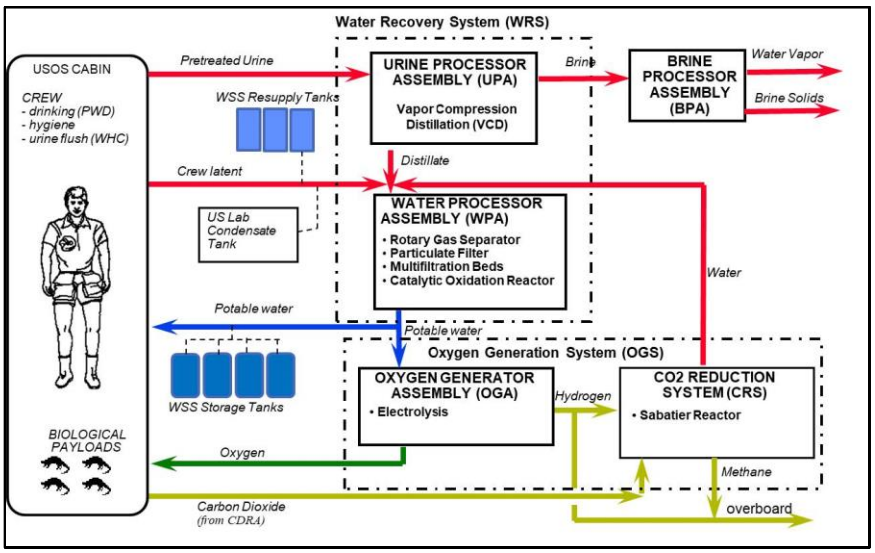

Figure 1. Schematic of water recovery and management for the ISS US segment[1].

While efficient, reliable, and well documented, current ECLSS technologies are still being investigated for improved recovery, broader treatment capabilities, and reduced consumable inputs to achieve a near closed-loop architecture. The hazardous pretreatment chemical for urine creates safety concerns and prevents any possibility of recovery of additional resources. Constant use of consumable inputs (i.e., chemical pretreatment, disposable filters, etc.) take up valuable cargo space, require expensive resupply missions, and create waste that requires disposal. Requirements of ECLSS technologies in PGH include 98% water recovery and the capability of treating all forms of waste for recovery in sustainable approaches[6]. To achieve these mandated goals, alternative treatment technologies, including bioregenerative, need to be explored to reduce consumable inputs, expand resource recovery beyond water, and maintain a similar level of efficiency and reliability.

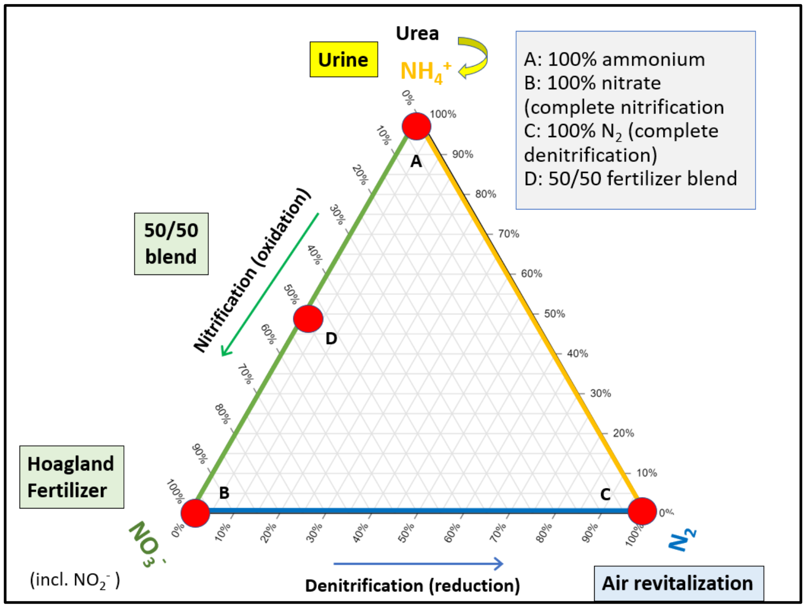

Figure 2. Chemical Oxygen Demand profile throughout SAMBR.

To provide an sustainable alternative, the University of South Florida (USF) and NASA Kennedy Space Center developed a bioregenerative urine treatment technology, termed the Suspended Aerobic Membrane Bioreactor (SAMBR). SAMBR is a hybrid technology, coupling conventional Biological Nitrogen Removal (BNR) and ultrafiltration tubular membranes, capable of nitrogen conversion and removal for water purification and resource recovery. Adapted from a conventional MLE design, Ammonia Oxidizing Bacteria (AOB) nitrify ammonium into nitrate under oxic conditions. A anoxic zone, containing Nitrifying Oxidizing Bacteria (NOB), denitrify the nitrate into diatomic nitrogen that then off-gasses into the atmosphere. By adjusting the active oxic and anoxic zones a blend of nitrogen conversion and removal can be tailored to suit the mission objectives (Figure 2). The treated wastewater is then subjected to membrane filtration to provide a barrier of pathogens and retain active biomass. The membrane permeate produced is a high-quality, particulate free effluent that is rich in nutrients for fertigation applications or can be easily treated downstream to produce drinking water.

II. Design

Design challenges primarily stemmed from optimizing reactor geometry for optimal performance in reduced gravity and incorporating an automated control and monitoring scheme. SAMBR's design was developed over several iterations to optimize its application and operation in varying space environments, primarily PGH scenarios. The system's housing was based on NASA's EXPRESS rack and designed to be compact, easily accessible, and modular for easy integration for possible flight demonstration[11]. For the allotted volume in an EXPRESS rack, a single rectangular reactor tank was chosen as it was deemed to be the most optimal for utilization of the geometry and volume. The active reactor volume ranges from 100-110L and was primarily sized on the desired retention time and a urine and flush water generated by a crew of four at an estimated 9.2 L/d[12]. A Buffer zone increases the retention time and allows for increased treatment. A Pre-Anoxic zone denitrifies nitrate returned in the Internal Recirculation. Diffusion stones bubble air into the oxic zones for nitrification of ammonium into nitrate. A larger Post-Anoxic zone allows for the oxygen to expire and for continued denitrification that was incomplete in the Pre-Anoxic zone. Finally the treated water is pumped to the ultrafiltration membrane module and the permeate is taken as the effluent. Liquid level sensors maintain a proper volume and overflow sensors in each quadrant initiate a system stasis in the event the liquid level becomes too high. Several pumps were installed in a short loop to provide sampling and monitoring points throughout the system. An aeration pump operating at approximately 10 LPM ran to several diffusion stones throughout the oxic zone. Lastly a solids wasting pump removes biomass as needed to prevent build up at the tank outlet.

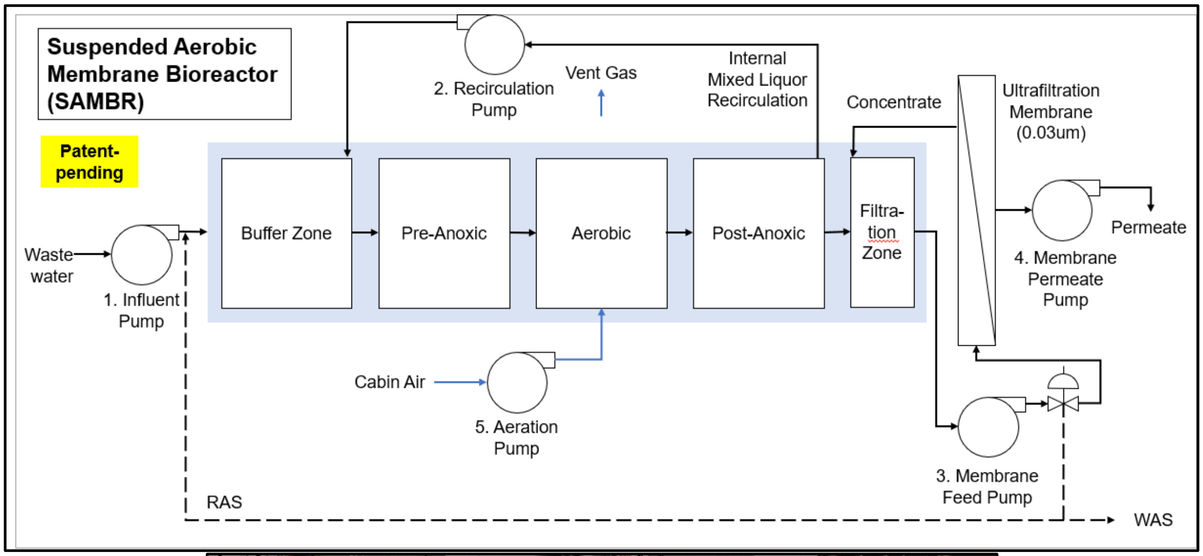

Figure 3. a). Diagram of SAMBR function and operation b.) Fabricated SAMBR system during hydraulic testing. *Patent Pending*

III. Methodology and Results

A. Sample Collection and Analysis

Samples were taken on a weekly basis at five locations throughout the system. The influent into the system, pre-anoxic zone, oxic zone, post-anoxic zone, and permeate effluent. Soluble COD, Total Nitrogen, Ammonia Nitrogen, and Nitrate Nitrogen water quality analysis was conducted on each sample point. COD provided tracking for organic substrate available primarily for denitrification. The nitrogen analyses were used to assess the system's capability to convert and remove nitrogen via nitrification and denitrification. Turbidity was used as an additional quality indicator of the effluent. pH and DO were monitored the "health" of each zone and if any correction was needed to maintain ideal conditions for each zone.

Table 1. SAMBR testing matrix.

Phase	Preliminary	Evaluation		Phase I Experimental					
Stage	A-1	A-2	B	C	D	E	F	G	H
Base Feed Type	Synthetic: Ammonium bicarbonate	Synthetic: Ammonium bicarbonate + carbon source		Urine (actual) and Flush					
Influent nitrogen (mg-N/L)	46	46	46	46	450	1700	3500	5000	7061
Influent COD (mg/L)	0	70	70	70	693	2617	5388	7697	10870
Influent carbon (mg/L)	0	44	44	44	431	1630	3355	4793	6769
Vol (urine + flush) as % of total influent	1%	1%	1%	1%	6%	24%	50%	71%	100%
Q (L/d)	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
HRT (d)	12	12	12	12	12	12	12	12	12
Internal recirculation (IR)	OFF	OFF	ON	ON	ON	ON	ON	ON	ON
Target duration of stage(d)	14	14	14	28	28	28	42	101	101
Cumulative duration (d)	14	28	42	70	98	126	168	269	370

B. Influent Collection and Preparation

During Stages A-1 to B a synthetic influent was used and prepared by dissolving ammonium bicarbonate and acetic acid in water to the approximate levels listed in Table 1.

During Stages C to H real urine was used as the system influent. The urine was collected from voluntary and anonymous donors and stored in sealed containers to hydrolyze for a finite amount of time. The hydrolyzed urine was then diluted corresponding to the stage of testing and mixed in with flush water and fed into the system.

C. Seeding and Operation

Activated sludge was obtained from South Cross Bayou Advanced Water Reclamation Facility and used to seed SAMBR. Operation commenced in December 2021 and has been ongoing. The system is operated at the urine and flush throughput generated by a crew of four which equates to approximately 9.2 L/d. A phased approach was favored to assist acclimating the consortia to a more concentrated urine feed compared to that it encountered treating municipal wastewater. Ammonium bicarbonate dissolved into water at approximate municipal levels was initially prepared to assess and validate the oxidation zone and that nitrification is present (A-1). Acetic acid was subsequently added to the feed mixture to provide a carbon source for denitrification in the pre- and post-anoxic zones (A-2) with the internal recirculation implemented (B) to validate the coupling of the oxic and anoxic zones. Real urine was then introduced at increasing concentrations until full strength was obtained to acclimate the consortia. Results discussed here include up to Stage F as Stage G is currently underway.

D. Results

Figures 4-11 display the water quality plots of SAMBR throughout its operation and are summarized in Table 2. A continuous decline in COD (Figure 4) indicates organic substrate is being consumed, presumably for denitrification (and a small fraction for assimilation) as there is an average removal of 66% of COD. This is further supported by a reduction in TN and AN with an average removal of 65% and 94% respectively (Figure 5 and 6) indicating denitrification is occurring and diatomic nitrogen is being off-gassed into the atmosphere. Some fraction may have off-gassed as ammonia however, since the pH was consistently lower (Figure 10) than 9.3, most of the nitrified nitrogen would be present as ammonium and therefore it is likely to be a marginal fraction.

Nitrification is evident as an increase throughout the system and at the effluent composed, on average, 83% of the nitrogen content. This remaining nitrate is valuable as a fertilizer source for crop production and hydroponics. The Dissolved Oxygen (DO) in oxic zone was consistently around 3 mg/L, and ideal level for nitrification, indicating a sufficient amount of mass transfer from the air diffusion stones such that the oxygen expired by the time it reached the Pre-Anoxic zone. The drop in turbidity from an unmeasurable level (>1000) to a single digit demonstrates a significant retention of particulates by the membrane and that a high-quality effluent, rich in soluble nutrients is being produced.

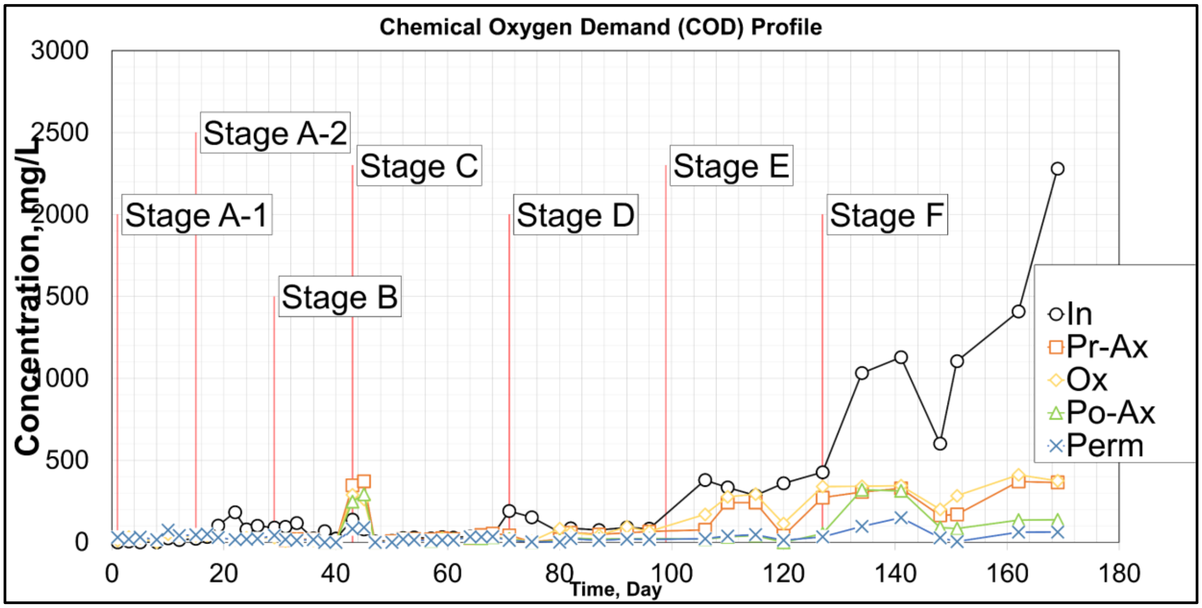

Figure 4. Chemical Oxygen Demand (soluble) profile throughout SAMBR.

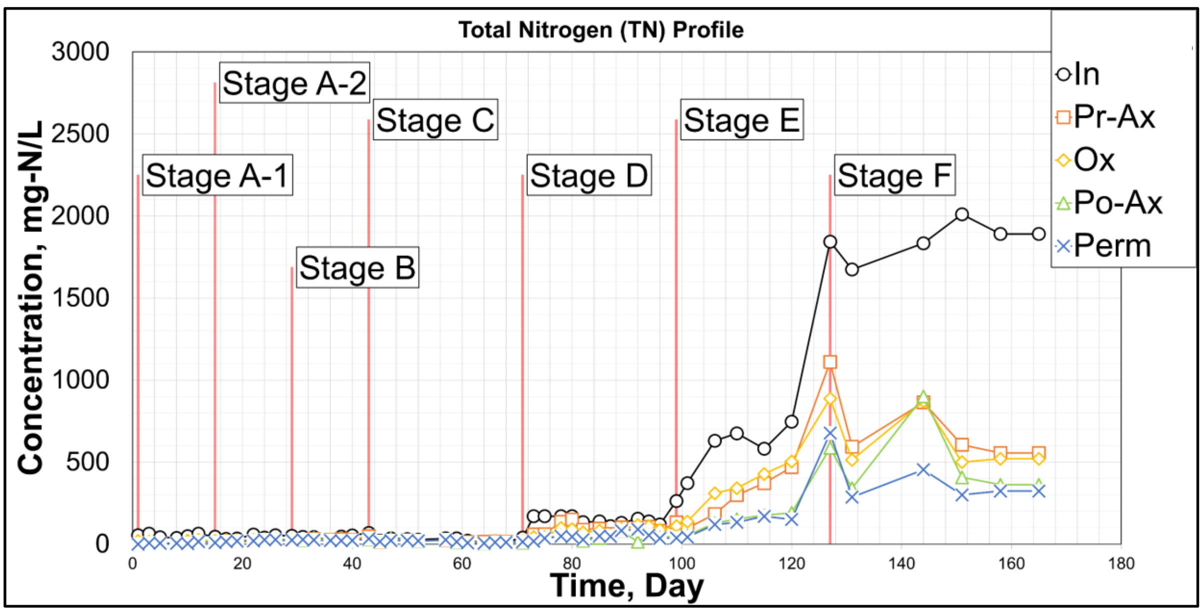

Figure 5. Total Nitrogen (soluble) profile throughout SAMBR.

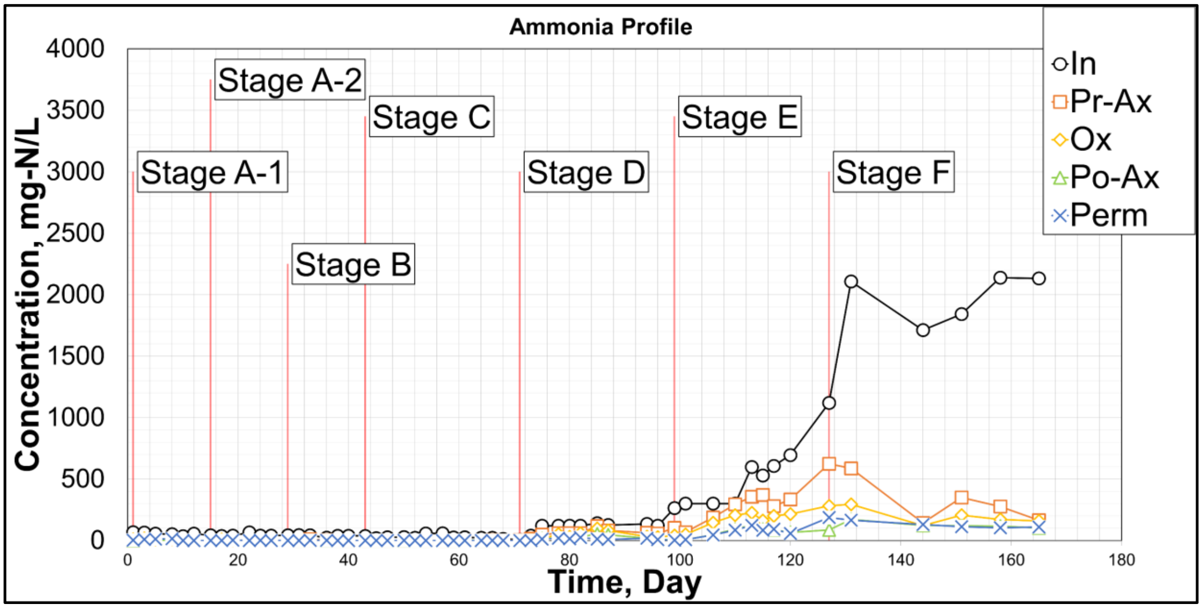

Figure 6. Ammonia (soluble) profile throughout SAMBR.

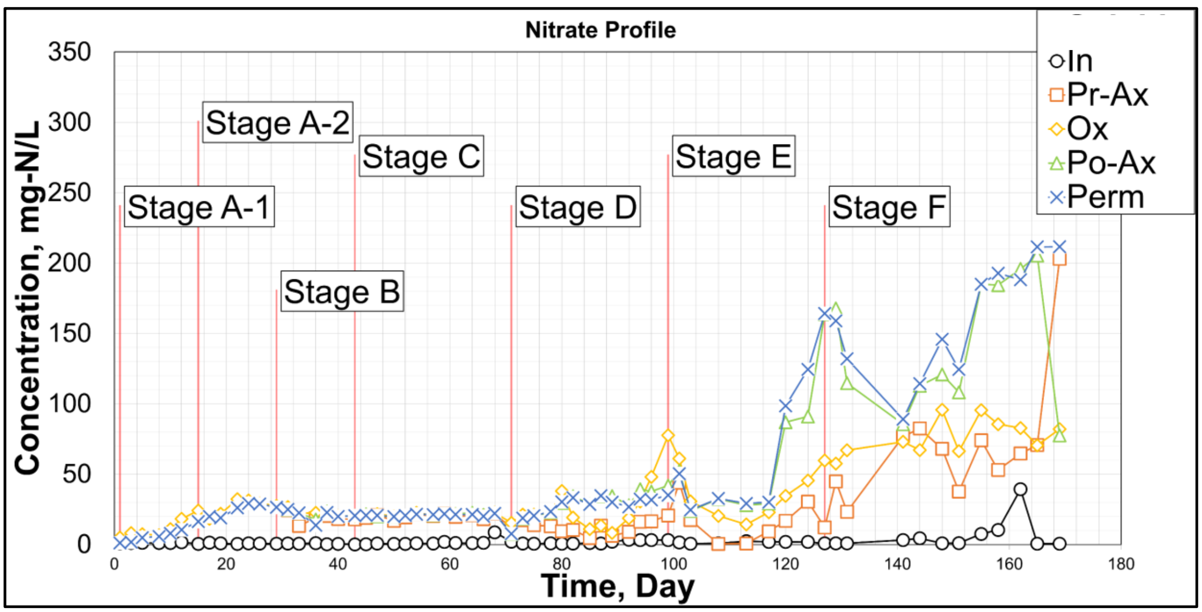

Figure 7. Nitrate (soluble) profile throughout SAMBR.

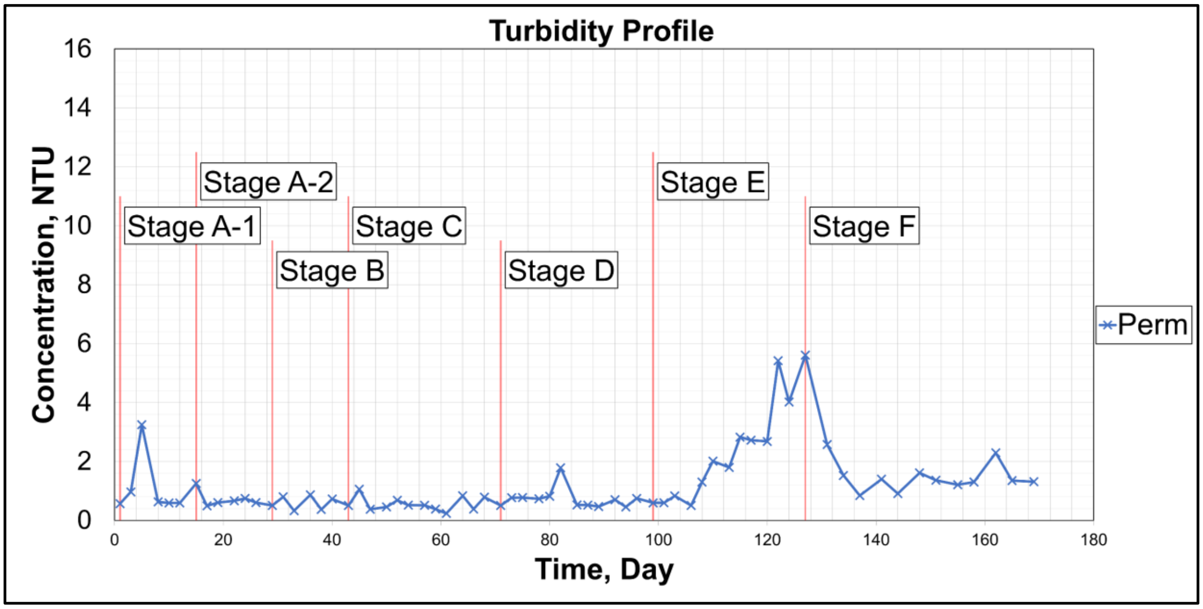

Figure 8. Turbidity profile throughout SAMBR.

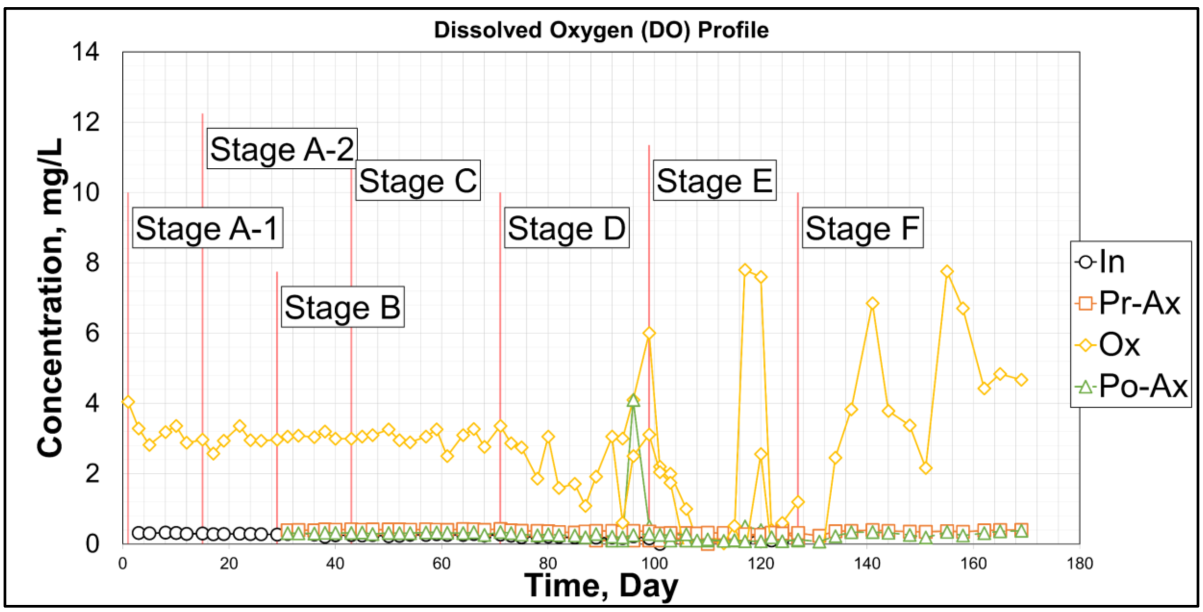

Figure 9. Dissolved Oxygen profile throughout SAMBR.

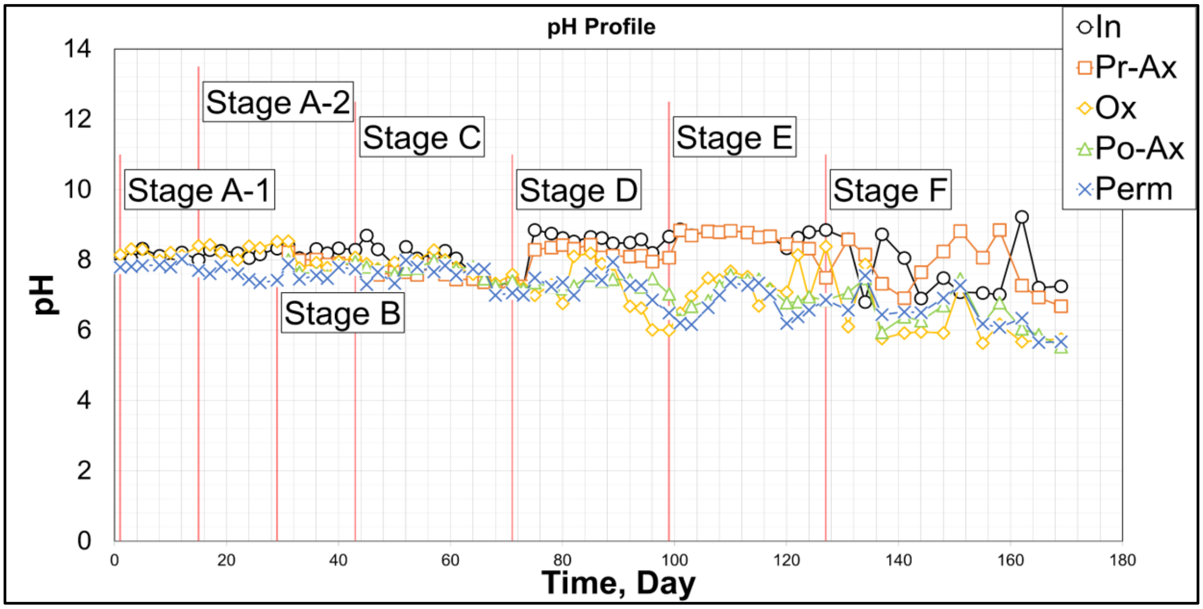

Figure 10. pH profile throughout SAMBR.

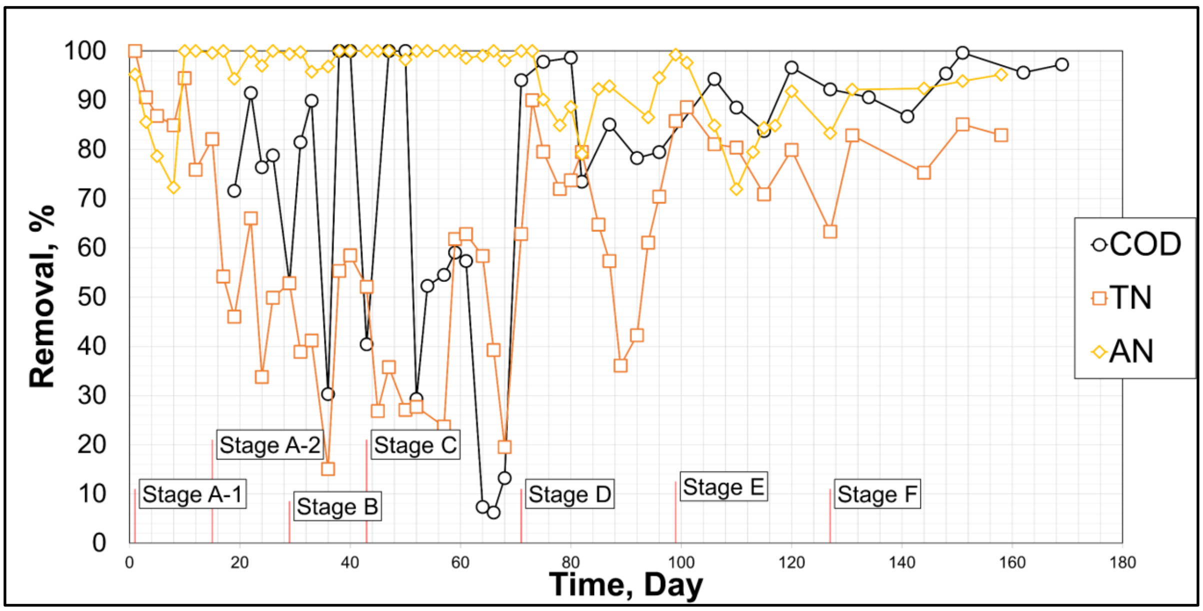

Figure 11. COD, TN, and AN removal profile throughout SAMBR.

Table 2. SAMBR influent/effluent water quality averages.

Stage	A-1		A-2		B		C		D		E		F	
Sample	In	Eff.	In	Eff.	In	Eff.	In	Eff.	In	Eff.	In	Eff.	In	Eff.
COD (mg/L)	9	37	98	29	77	21	45	23	91	12	357	30	1259	67
TN (mg-N/L)	50	6	44	21	46	25	26	15	155	47	808	215	1852	341
AN (mg-N/L)	53	5	44	1	37	0	27	0	159	14	641	104	1950	128
NN (mg-N/L)	1	7	1	25	1	21	2	20	2	29	1	69	6	159
Turbidity*	1.1		0.6		0.6		0.6		0.7		2.5		1.5	

*Influent value exceeded measurable range (>1000 NTU). Only effluent value is shown.

IV. Conclusion

The preliminary investigation of the SAMBR system demonstrates it as a promising bioregenerative alternative urine treatment technology capable of recovering nutrients in addition to water for expanded resource recovery. It's minimal need of consumable inputs and ability to remove 94% of the ammonia present and convert 83% of the remaining nitrogen into nitrate that can be used in fertigation applications, makeing it ideal for PGH in future LoDDSHE missions. Current research is focusing on operating with full-strength urine and addressing the high salinity and ammonia content. Future testing will expand to include gray water and incorporate algal assisted treatment.

Acknowledgments

This work was made possible through funding provided by NASA's Exploration Capabilities (EC) Division within the Human Exploration and Operations Mission Directorate (HEOMD) and the University of South Florida's Genshaft Family Doctoral Fellowship. Additional gratitude is extended to the numerous USF and NASA personnel who have participated in key project support, insight, and review.

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