Unleashing the Power of Anaerobic–phototrophic Membrane Bioreactors for Sustainable Bioregenerative Life Support

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Using the core ideals of bioregenerative life support, an anaerobic–phototrophic membrane bioreactor (APMBR) has been designed and operated at NASA's Kennedy Space Center to treat complex wastewaters with the goal of closing water and nutrient cycles on early planetary bases. The system combined the previously operated anaerobic membrane bioreactor and the phototrophic membrane bioreactor that have been detailed in presentations at previous ICES conferences. This newly combined system is able to treat complex wastewater with completely automated controls on a small footprint. The treatment of wastes in this APMBR is as follows: (1) the waste enters the anaerobic subsystem, where solids are hydrolyzed and carbon is removed via anaerobic digestion, (2) an ultrafiltration membrane is used to separate the solids and the recovered water, (3) the effluent from the anaerobic subsystem is fed to the phototrophic subsystem on command, (4) the algae–bacteria consortium aids in nitrification in the recovered water, and (5) an ultrafiltration membrane is used to separate the algae and the final recovered water. The recovered water from the APMBR is rich in nutrients, making it a sustainable source of fertilizer for downstream hydroponic systems. This conference paper will detail the design and operation of the APMBR as a bioregenerative alternative to physical–chemical systems or bag and storage systems. In this paper, data will be presented on subsystem water quality, membrane performance, and effluent quality. Overall, the APMBR has the ability to treat wastewater using a combination of biological and filtration technologies that allow for higher removal efficiencies, low consumable use, and small footprint.

Nomenclature

AnMBR = Anaerobic Membrane Bioreactor
AP = Anaerobic permeate

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APMBR = Anaerobic Phototrophic Membrane Bioreactor
BT = Buffer tank
CO_2 = Carbon dioxide
COD = Chemical oxygen demand
COPAS = Complex organic particulate artificial sewage
HRT = Hydraulic retention time
IF = Influent feed tank
IT = Intermediate tank
L/d = Liters per day
PMBR = Phototrophic Membrane Bioreactor
PLC = Programmable logic controller
PP = Phototrophic permeate
R1 = Reactor tank 1
R2 = Reactor tank 2
SRT = Solids retention time
UF = Ultrafiltration
TOC = Total organic carbon
TMP = Transmembrane pressure
TSS = Total suspended solids
WWTP = Wastewater treatment plant

I. Introduction

IN the pursuit of sustainable space exploration and colonization, the development of bioregenerative life support systems has emerged as a crucial area of research. Bioregenerative life support is no new concept and has been studied for uses in space since the early 1950's.[1] The challenges of sustaining human life in the hostile environments of space pose formidable obstacles. Among the critical requirements for prolonged space missions and planetary colonization is the development of sustainable life support systems capable of providing essential resources, such as oxygen, water, and food, in closed-loop environments. Unlike traditional physical and chemical life support systems that rely on expendable resources and external resupply missions, bioregenerative systems utilize biological processes to recycle and regenerate essential resources within closed-loop environments. By harnessing the power of photosynthesis, microbial metabolism, and ecological interactions, these systems aim to mimic the natural cycles of nutrient cycling and waste recycling found in terrestrial ecosystems. Among the innovative technologies designed to achieve this goal, the anaerobic–phototrophic membrane bioreactor (APMBR) represents a significant advancement in bioregenerative life support systems.

At NASA's Kennedy Space Center, in collaboration with the University of South Florida, researchers have pioneered the design and operation of the APMBR to address the challenge of treating complex wastewater and closing water and nutrient cycles on early planetary bases. Building upon the previous advancements with our separately developed anaerobic and phototrophic membrane bioreactors, the APMBR integrates these subsystems into a single, compact system with fully automated controls. The APMBR is divided into two subsystems: the anaerobic subsystem (AnMBR) and the phototrophic subsystem (PMBR). The main objective of the AnMBR is to process high-strength solids and complex organics found in fecal and inedible food waste and produce an effluent capable of further downstream treatment that would otherwise overload downstream systems.[2] The anaerobic subsystems' biological components utilize anaerobic digestion, a process involving various microorganisms working together to break down organic matter from waste streams without additional inputs. The byproducts of anaerobic digestion include biogas and a nutrient-rich liquid permeate. The physical component of the anaerobic subsystem consists of a tubular ultrafiltration (UF) membrane that separates water and nutrients from the microbiome, ensuring pathogen rejection and biological washout.[3] The phototrophic subsystem is a treatment system designed to process effluent from an upstream AnMBR to produce a fertilizer solution for downstream fertigation systems.[4]

The generation of the combined fecal waste and flush water for a crew of four is estimated to be 2.5 Liters/day (L/d) and was therefore a parameter considered when designing the subsystems of APMBR.[5] The APMBR system at KSC is fed a complex organic particulate artificial sewage (COPAS) fecal simulant at a 5% solids concentration to mimic that of a real fecal and flush water mixture. COPAS was used because it is an easy-to-use and reliable surrogate for fecal waste.[6] COPAS is made by grinding Friskies Seafood Sensation cat food to a fine size and mixing it with tap water, providing carbon concentrations similar to those found in human fecal waste. At the time of this publication,

the APMBR has been continuously running for over 140 days while processing 2.5 L/d of COPAS feed. This paper will describe how this multi-stage bioreactor system treats complex wastes as a bioregenerative alternative to physical–chemical systems or bag and storage systems.

II. Design and Operation of APMBR

A. APMBR Design

Both the AnMBR and PMBR systems ran independently for multiple years prior to their integration for individual testing and optimization. Both of these systems have been thoroughly described in previous ICES papers therefore this paper will only provide detail on improvements made during their full integration and testing. A preliminary integration test was performed where these two subsystems were connected in series to run continuously together, however, not within the same skid confinements. There were many lessons learned from this initial partial integration test such as the need for robust system-to-system communication as well as the need for a primary overview software on both subsystems. Prior to their complete integration, AnMBR ran on a control system that was based on a programmable logic controller (PLC) utilizing Crouzet-Soft automation software whereas the PMBR's electrical, control, and monitoring system utilized Opto 22 control and monitoring hardware and software. In that preliminary configuration, there was no connection between each of the subsystem's control and monitoring systems. From a logic standpoint, these systems did not communicate or send information to one another and the only way these two systems interacted was from a tertiary perspective via the high and low-level sensors on the intermediary tank between the two systems. Therefore, it was decided to house the APMBR under one control and monitoring software so that efficient communication could take place between the subsystems to circumvent off-nominal event effects on the other subsystems biology. Opto 22 was chosen as the controlling and monitoring software due to its robust capabilities. The transition to one primary overview control and monitoring system drastically improved overall system performance compared to the preliminary in series integration.

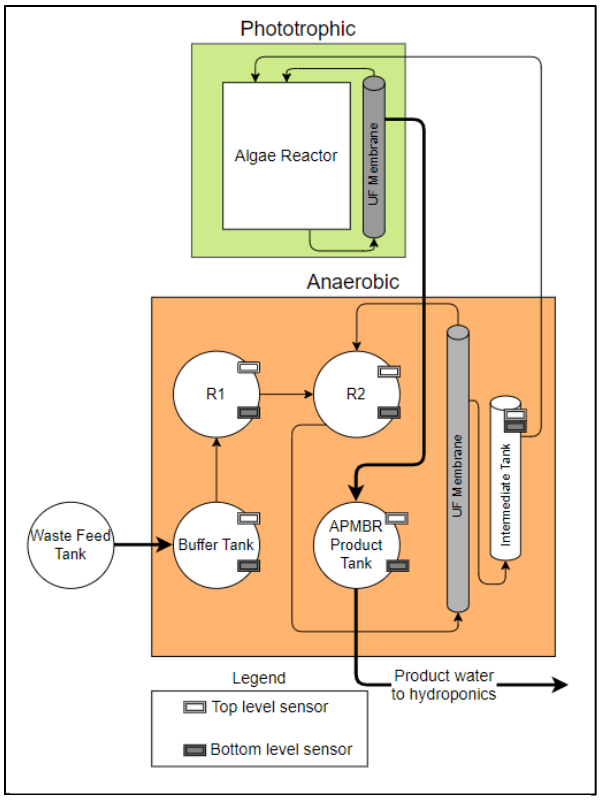

Figure 1. APMBR Flow Diagram

Figure 1 shows APMBR's flow diagram and illustrates how liquid moves through the system. The process flow of AnMBR is broken into optimal treatment stages for processes selection of anaerobic digestion. This is done by breaking AnMBR up into three 20L bioreactors that make up the treatment volume. By employing these subsequent treatment stages, the microbiome of each individual bioreactor cultivates conditions favorable to acetogenesis followed by the ideal conditions of methanogenesis.[3] The COPAS feed was continuously mixed inside a refrigerator cooled to 5℃ to overcome the unevenness in consistency of the fecal material and to prevent settling. The cooler temperature helps inhibit bacterial proliferation as the feedstock is not sterilized prior to integration into the feed tank. The feed is first introduced into the buffer tank, which was designed to absorb shock loading events due to mission overlap periods and allow for the process of solids hydrolysis to begin. After the hydrolyzed liquid leaves the buffer tank, it flows into the stage 1 reactor (R1) that is inoculated with anaerobic sludge from a local wastewater treatment plant (WWTP). R1's slightly acidic environment rapidly breaks down the complex organic fractions of the waste into volatile fatty acids. From here the stream travels into the Stage 2 Reactor (R2), which assimilates the volatile fatty acids undergoing methanogenesis in the process.[3] R2 is also inoculated with the same anaerobic sludge from the local WWTP. The contents within R2 are recirculated through a membrane loop and a concentrate is returned to R2 post membrane. After leaving R2, the contents are sent through a UF membrane with a pore size of 0.03um. The UF membrane separates the water and biologically solubilized nutrients from the microbiome of the reactor allowing them

to filter through it, while rejecting the solids portion, keeping it contained to the confines of reactor 2. The filtered permeate then leaves the membrane and is stored in an intermediate tank (IT) between the two subsystems. That completes the anaerobic processing of the APMBR. As stated earlier, biogas is one of the byproducts of anaerobic digestion. All of these carboys have a headspace that routes to a gas line and a wet-tip meter. A tedlar bag in that gas line allows users to pull various gas samples for further analysis. The gas that runs through the wet-tip meter is quantified and Opto 22 the associated values in real-time to track daily and overall biogas production.

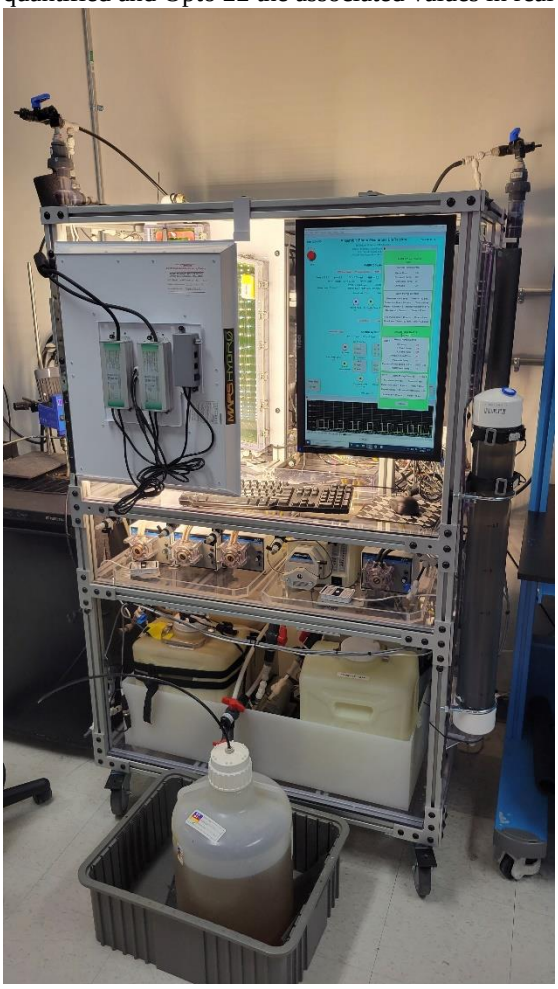

Figure 2. APMBR

During APMBR startup, the PMBR was inoculated with an algal–bacterial culture with *Chlorella sorokiniana* as the dominant algal species, a microalgae species that has a high tolerance for ammonia and sodium chloride. The PMBR is a 6L flat panel bioreactor and like the AnMBR system, it also has the addition of membrane filtration to allow for decoupling of the solids retention time (SRT) and the hydraulic retention time (HRT). The effluent of the AnMBR has a high concentration of ammonia, which is unfavorable for fertigation because of its propensity to volatilize and affect the pH. The PMBR is able to convert the ammonia into nitrate, a more stable form of nitrogen for fertigation, due to the presence of symbiotic nitrifying bacteria in the microbial community. The PMBR is able to reach higher removal rates with higher concentrations of biomass within the reactor.[4] Additionally, Carbon dioxide (CO_2) was bubbled into the reactor continuously to allow for full conversion of CO_2 to dissolved oxygen via algal photosynthesis, providing the oxygen needed for nitrification. The PMBR is fitted with a float level sensor that activates a pump between IT and the PMBR when the liquid level drops below the required high-level set point. Once the liquid leaves IT it enters the PMBR and is introduced into the main tank of the reactor. The liquid is then recirculated in PMBR's main tank and then it is sent through a membrane recirculation line similar to how AnMBR's membrane recirculation line works. A permeate pump pulls off a liquid fraction from the recirculating contents and distributes it into a final product tank that can then be used for downstream plant fertigation or other purposes. The remaining concentrate liquid is sent back into the reactor for further processing.

An Opto 22 control box controls all of the APMBR's peristaltic pumps and monitors all the capacitance level sensors, membrane pressure transducers, and probes within the system. The final permeate pump on PMBR is what drives the entire system contents to move at a specific flow rate through the system. Therefore, the PMBR's permeate pump is set to dispense 2.5 L/d of permeate into the final product tank and all upstream pumps cascade to that flow rate. As previously mentioned, CO_2 is bubbled into the PMBR and is also controlled by the Opto 22 hardware/software. The system has various leak detectors placed in strategic locations throughout the skid that would trigger specific alarms and put the system into various programmed modes depending on where the leak occurs.

One improvement in the design architecture was made when testing APMBR to reduce the IT volume between the anaerobic subsystem and the phototrophic subsystem. The previous IT had a volume of 20 liters which drastically increased the HRT of liquid moving downstream. It was observed that if any off-nominal event occurred upstream of the IT in the anaerobic subsystem, the large volume of IT would prolong the processing of these events to work their way through the downstream system. For example, if an overload of feed event occurred, this would cause an excessive amount of carbon to build up before it can properly be processed and digested in the anaerobic system and then stored in IT. As seen in Figure 2, the IT was replaced with a cylindrical design and had a reduced volume of roughly 3 liters. Therefore, the HRT was reduced and allowed for faster liquid movement from the anaerobic system to the phototropic system instead of having an increased lag time within IT and a larger volume size.

B. Operations

Inoculation of the APMBR system began with first inoculating the AnMBR subsystem which occurred in the middle of October 2023. Anaerobic sludge from the South Cross Bayou Advanced Water Reclamation Facility was acquired and delivered to KSC. A total suspended solids (TSS) measurement was performed on the sludge to help determine the correct solids to water ratio for inoculating the anaerobic sludge into R1 and R2 tanks. Once TSS data was evaluated, a 5% solids dilution (anaerobic sludge/water) was prepared and distributed into each of the reactor tanks, R1 and R2. COPAS feed was also prepared at a 5% solids solution and was distributed in the feed tank and the buffer tank. The anaerobic subsystem was turned on before the inoculation of PMBR to make enough effluent needed to feed the PMBR in continuous operation. Meanwhile, a stock algal–bacterial culture of *Chlorella sorokiniana* had been growing in a continuous fed-batch fashion in the lab that was used to inoculate PMBR. After enough liquid accumulated in IT, PMBR was inoculated and its permeate pump was set to produce 2.5L/d.

The systems' two membrane modules were outfitted with 3 pressure transducers each to help monitor their integrity and performance. Each module has a feed, concentrate, and permeate pressure transducer that records pressures in real-time. These pressures are used to calculate transmembrane pressure (TMP) which helps indicate membrane performance. Furthermore, for each of the modules, the permeate pump is engineered to reverse flow to allow for backwashing events to help remove any fouled residues on the inner walls of the individual membrane tubes within the module. Additionally, a specific permeate-relaxation-backwash schedule was established for each membrane module to ensure proper functionality and optimization of membrane integrity. The membrane modules have 3-way valves outfitted on each end to allow for membrane cleaning events utilizing exterior pumps and solutions if needed.

The Opto 22 control and monitoring software was coded and programmed to align the various scenarios that the system would encounter under both nominal and off-nominal processing operations. The control software turns peristaltic pumps on and off to move contents downstream and recirculate them through the membrane modules. The software was also programmed to send various alarms and notifications to the users for specific events and anomalies if and when they occurred. Code was written to send the system into different 'safe mode' states and alarm the users that these events occurred. Users have the ability to remotely log into the program from an internet browser and view the various conditions of the system as well as make changes remotely if needed.

III. Sample Collection and Testing

One of the main objectives of running the APMBR system is to determine how the feed is processed throughout the system and how the water chemistry changes during the overall process. Therefore, the APMBR system was designed so that sampling of the individual tanks and membranes could be pulled for analysis at the various stages of

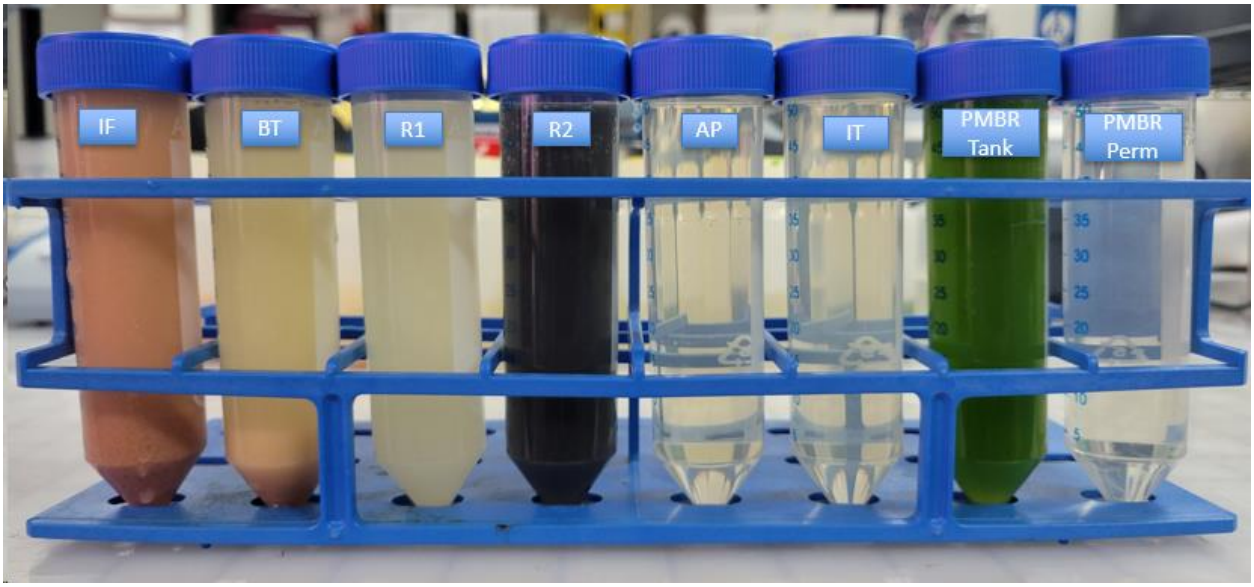

Figure 3. APMBR Samples pre-centrifugation. From left to right: Influent tank (IF), Buffer Tank (BT), Reactor Tank 1 (R1), Reactor Tank 2 (R2), Anaerobic Permeate (AP) Intermediary Tank (IT), PMBR tank, and PMBR Permeate (PP).

the bioprocessing. At the beginning of each week, samples from the influent feed tank (IF), BT, R1, R2, anaerobic permeate (AP) from the membrane module, IT, PMBR's main tank, and phototropic permeate (PP) from the membrane module were pulled. Some of the collected liquid was kept for total determinations while 50 mL aliquots of each of those pulled samples were centrifuged in an IEC Centra GP8R centrifuge for 15 minutes at 3400 RPM with the supernatant being kept as the soluble fractions for analysis. Daily samples were pulled from R1 and R2 to measure pH and oxidative reduction potential, a metric to determine anoxic environments for the anaerobic microbes. Those two tests indicate whether the environment within those reactor tanks is favorable for anaerobic digestion.

A. Carbon Testing and Biogas Data

One of the main purposes of APMBR's anaerobic subsystem is to reduce the amount of carbon going to downstream processes. Chemical Oxygen Demand (COD) is widely used as a surrogate measure for carbon bioavailability. Compared to the biochemical oxygen demand (BOD) test, which requires days, the COD test is designed to yield results in a much shorter time.[7] Both total and soluble fractions of the weekly samples were tested for COD. COD was tested by using a high-range HACH test and tube digestion solution kit coupled with a spectrophotometer for total COD concentration determination. Additionally, total organic carbon (TOC) was also used to track the removal of carbon throughout the bioprocessing stages. Only soluble sample fractions were tested for TOC and their removal rates were calculated. TOC was performed using an OI Analytical Aurora 1030 TOC analyzer with a calibration curve developed from measurements of 10, 50, 100, and 200 mg/L of standardized TOC. Additionally, biogas production is one of the main indicators of active anaerobic digestion as the microbes digest the organic matter and process it into CO_2 and other gases (methane and hydrogen sulfide). Therefore, the biogas production data was tracked via the Opto22 monitoring software and could be pulled by the user and analyzed. These three tests, coupled together, gave valuable insight into how well the APMBR system was performing in regards to reducing overall carbon entering and leaving the system.

B. Nitrogen Testing

Mentioned earlier, tracking nitrogen throughout the system is very important when one of the main considerations of APMBR's end product permeate is to be used as a fertilizing source for plants. Therefore, total nitrogen and total ammonia testing was performed on all of the soluble sample fractions. Total nitrate was also performed however only on the soluble permeate fractions (AP and PP) and the PMBR tank itself. All three of these tests were done by using HACH test and tube kits coupled with a spectrophotometer to determine total concentrations.

C. Suspended Solids Testing and Membrane Data

In regards to monitoring suspended solids and their migration through the system, total suspended solids (TSS) measurements were taken weekly from all 8 sample locations previously mentioned. TSS is a good indicator of how solids are solubilized throughout the system as well as a good metric to monitor membrane performance. TSS was performed by dispensing a known liquid amount onto an Environmental Express ProWeigh Filter (47 millimeter diameter) and vacuum filtered. The filter was dried overnight at 100°C and weighed on an analytical scale. Membrane data was monitored via the pressure transducers.

D. Ion Chromatography Methodology

Lastly, the ionic composition of the final permeates from both the anaerobic subsystem and APMBR's final product was determined via Ion Chromatography with a Dionex ICS-2100 Ion Chromatography System with an anion and cation module. It employed a 25 mL sample loop with an AG11 4x50 guard column and AS11 4x250 analytical column in the anion module, and CG12A 4x50 and CS12A 4x250 guard and analytical columns for the cation module. The flow rate for the sample was 1 mL min^{-1} using a potassium hydroxide program for the anions and a 1 mL min^{-1} methanesulfonic acid cartridge program for the cations. The anion module contained an ADRS 600 Suppressor, while the cation module had a CDRS 600 Suppressor. A calibration curve was developed from measurements of 0.50, 1.0, 5.0, 10, and 15 ppm for each of the cations and anions. The cell and column temperature for the 15-minute run times was 30°C. A 50x dilution was used for both the AP and PP fractions so that the ions would fall within the calibration range.

IV. Results and Discussion

A. Carbon Removal and Biogas Results

Shortly after inoculating APMBR, an off-nominal overloading event occurred which caused an influx of carbon to buildup in the previously mentioned larger IT. This was caused by the AnMBR's permeate pump being set to too high of a flow rate, causing liquid to move through the system faster than the predetermined HRT. Due to IT's previous volume of roughly 20 liters, the overloaded carbon remained in IT as the HRT took around 22.5 days for those contents to be completely flushed out of the AnMBR subsystem. This was one of the main driving factors for the architectural change to the smaller IT tank. Therefore, the COD and TOC removal data shows a drastic reduction in the overall removal percentages during that time.

Table 1. Monthly average TOC concentrations throughout the APMBR system

	TOC (mg/L)							
Month	**IF**	**BT**	**R1**	**R2**	**AP**	**IT**	**PMBR Tank**	**PP**
October	1778	4529	3449	1927	2079	989	172	50
November	1761	5096	3877	2679	2644	2464	2358	2241
December	2000	5055	5436	1770	1574	1675	652	588
January	1632	5203	5227	947	812	931	112	93
February	1467	4962	4936	573	483	536	66	49

Table 1 depicts TOC concentration across the entire APMBR system. TOC concentration is highest in BT and R1 as the COPAS is hydrolyzed and then begins to be removed in R2. As mentioned earlier, splitting the anaerobic inoculum into two different tanks helped separate distinct phases of anaerobic digestion. R2's primary objective focuses around the anaerobic digestion phase of methanogenesis. The methanogens assimilate and convert carbon into biogas thus removing it from the solution. The off-nominal overload event that began around day 20 caused excess carbon to move into the PMBR and altered the biology of that reactor. The biology shifted towards a higher ratio of bacteria when typical operations call for a higher ratio of algae. As mentioned earlier, the HRT of the contents entering the AnMBR subsystem is roughly 8 days per tank. Therefore, since BT was overloaded, the cascade of these contents moving and being processed throughout the entire APMBR system took about 34 days to 'bounce back' to nominal

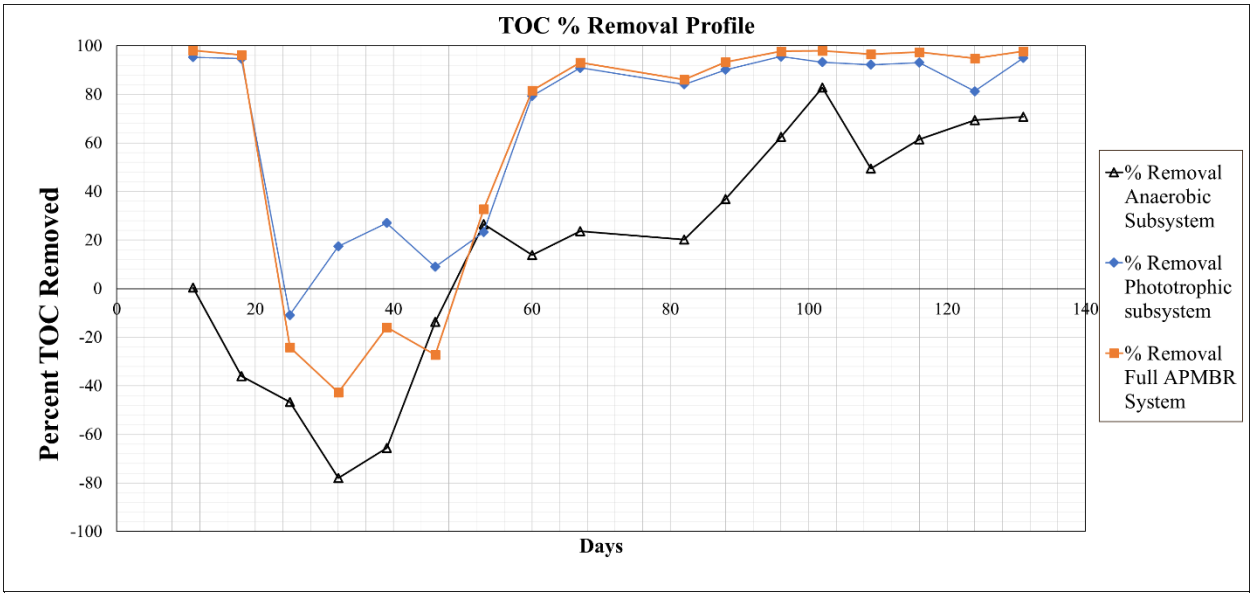

Figure 4. TOC Percent Removal Profile. The black triangle points represent the anaerobic subsystems percent removal. The blue diamond points represent the phototrophic subsystem precent removal. The orange square represents the entire APMBR system percent removal**.**

carbon removal operations. This carbon removal dip is illustrated in both the TOC and COD removal figures (figure 4 and Figure 5, respectively). During the overload event, the APMBR system was still capable of removing 86.3% COD. After the overload event worked its way through the system, the TOC removal rate averaged 95% while the COD removal rate averaged 98.9%. This indicates that the biology within both the anaerobic subsystem and the phototrophic subsystem are robust enough to withstand these off-nominal events and can rebound with time and without any external inputs.

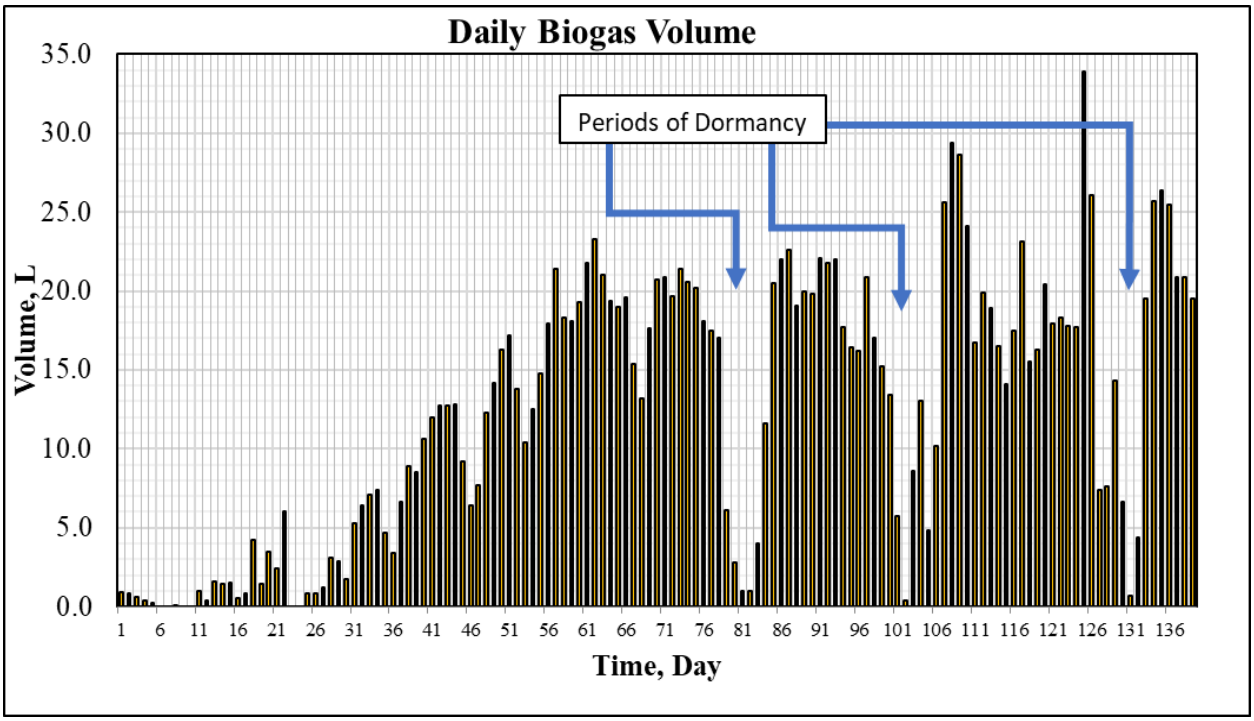

Figure 6. APMBR daily biogas production from the anaerobic subsystem.

After initial inoculation, the biology within the system takes about 30 days to acclimate to its new environment and begin proper anaerobic digestion of complex carbon molecules. Figure 6 shows the daily biogas production of the anaerobic subsystem with three periods of brief dormancy that were due to minor off-nominal events. After these brief periods of dormancy, biogas production ramps back up quickly to nominal values. Not counting the periods of dormancy, biogas production averaged 20 liters per day. The main constituents of anaerobic digestion biogas typically consist of methane (50–75%), carbon dioxide (25–50%), and smaller amounts of nitrogen (2–8%). Trace levels of hydrogen sulfide, ammonia, hydrogen, and various volatile organic compounds are also present in biogas depending on the feedstock.[8] Currently, only the volume of biogas production is measured with future plans to analyze and characterize the biogas constituents to get a more accurate ratio of what is present within APMBR biogas.

B. Nitrogen Results

Table 2. Monthly average total nitrogen concentrations throughout the APMBR system

	Total Nitrogen (mg/L)							
Month	**IF**	**BT**	**R1**	**R2**	**AP**	**IT**	**PMBR Tank**	**PP**
October	272	254	158	141	174	120	18	13
November	256	316	252	273	230	208	235	207
December	237	271	247	302	268	251	158	122
January	191	404	399	432	339	308	91	64
February	225	455	539	591	523	518	139	118

Table 2 shows the monthly average total nitrogen concentration throughout the various stages of APMBR. The influent feed has a relatively stable nitrogen concentration going into the system while the highest concentration of soluble nitrogen is found in R2. As COPAS is broken down throughout the stages of anaerobic digestion, an increasing amount of soluble nitrogen is released into the system. At this stage of the bioprocess, the majority of the soluble nitrogen is in the form of ammonia (see Figure 7). Therefore, it is sent to the PMBR subsystem for further processing and conversion.

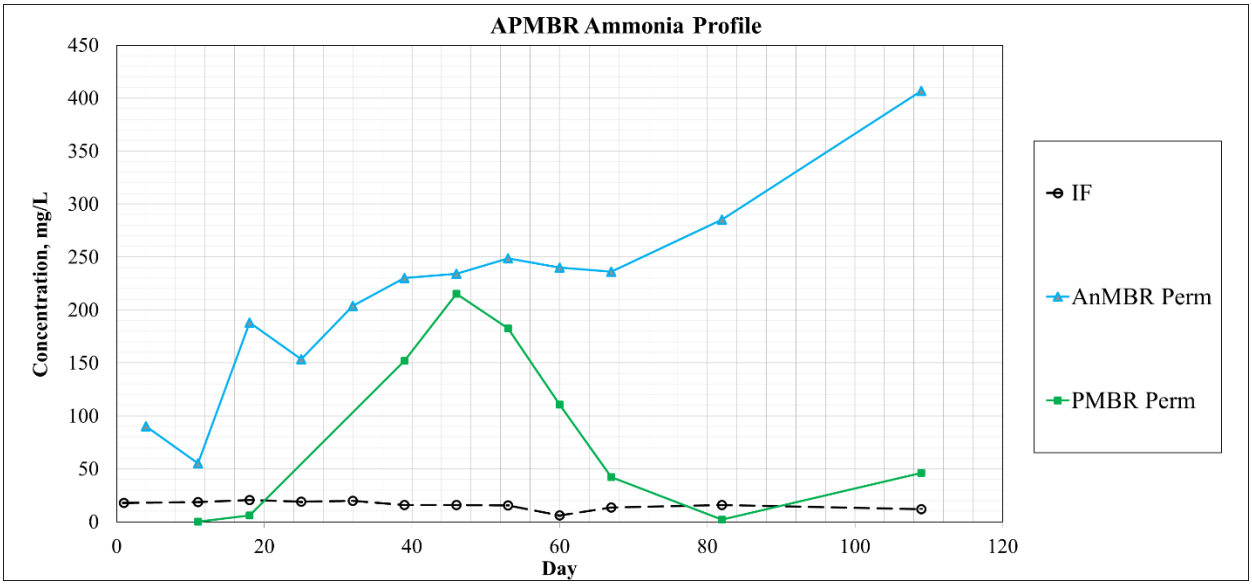

Figure 7. Total ammonia concentration in APMBR. The black circle line represents the total ammonia concentration of the influent feed (COPAS), the blue triangle line represents the total ammonia concentration of the anaerobic subsystem oermeate, and the green square line represents the total ammonia concentration of the PMBR permeate which is the final product of the APMBR system.

Figure 7 illustrates that the high concentration of ammonia leaving the AnMBR subsystem is either assimilated into biomass, converted to other nitrogen species, or volatilized due to PMBR's pH during phototrophic processing. In the last data point in Figure 7, day 109, the ammonia concentration in the AnMBR perm equaled 407 mg/L while the PMBR perm, which is the final product of the overall APMBR system, equaled 45 mg/L which is a 9-fold reduction of ammonia. It can be assumed from Figure 7 that the biology shift within PMBR that occurred during the off-nominal overload event, roughly between days 25 and 50, favored the non-nitrifying bacteria as ammonia removal and conversion drastically reduced during this time frame. However, further genetic sequencing data would need to be acquired in order to support that assumption.

The total nitrogen concentration in APMBR's final product averages between 100 – 200 mg/L. A more thorough mass balance of the nitrogen within the system is being performed, including the nitrate concentration data, and is being considered for journal publication and will unfortunately not be shown in this ICES paper. The aim is to better understand what the ratio of nitrogen species is throughout the various stages of bioprocessing as a more thorough characterization of the nitrogen will help better understand the quality of the permeate product and its intended use as a fertilizing source.

C. TSS and Membrane Data

Not only does APMBR aim to break down complex solids into soluble fractions and biogas, but it also aims to reduce the overall total suspended solids within the contents that are processed through the system. Therefore, and as mentioned earlier, UF membranes are employed in both subsystems to help achieve this goal. The 0.03-micron porosity of the membranes allows liquid components to permeate through while blocking insolubilized fractions, bacteria, and other precipitated agents. Table 3 outlines the monthly average TSS concentrations across the stages of APMBR processing. It is easy to see that the biggest reductions in solids occur after R2 and the PMBR tank as just upstream of these tanks the contents pass through their respective membranes. It is common for these closed-looped systems to accumulate solids over time as can be seen in table 3. The COPAS feed remains relatively constant at a 5%

solids solution while BT, R1, and R2 tend to increase over time. This concept was considered when designing APMBR so that periodical 'wasting' events could take place to help decrease the solids that build up. These 'wasting' events are performed with plumbing and pumps that are already in place to help take contents out of R1 and R2. The 'wasted' contents could then be repurposed for other uses or fed back into the feed tank for further processing and breakdown.

Table 3. Total Suspended Solid Concentrations in APMBR

Month	Total Suspended Solids (mg/L)							
	IF	BT	R1	R2	AP	IT	PMBR Tank	PP
October	44242	1650	233	1067	34	101	1875	43
November	53538	11465	340	1560	210	295	780	230
December	44950	35703	490	1550	90	447	1147	147
January	54900	74250	1620	1935	165	398	2550	50
February	44800	124450	9100	3940	50	20	2240	35

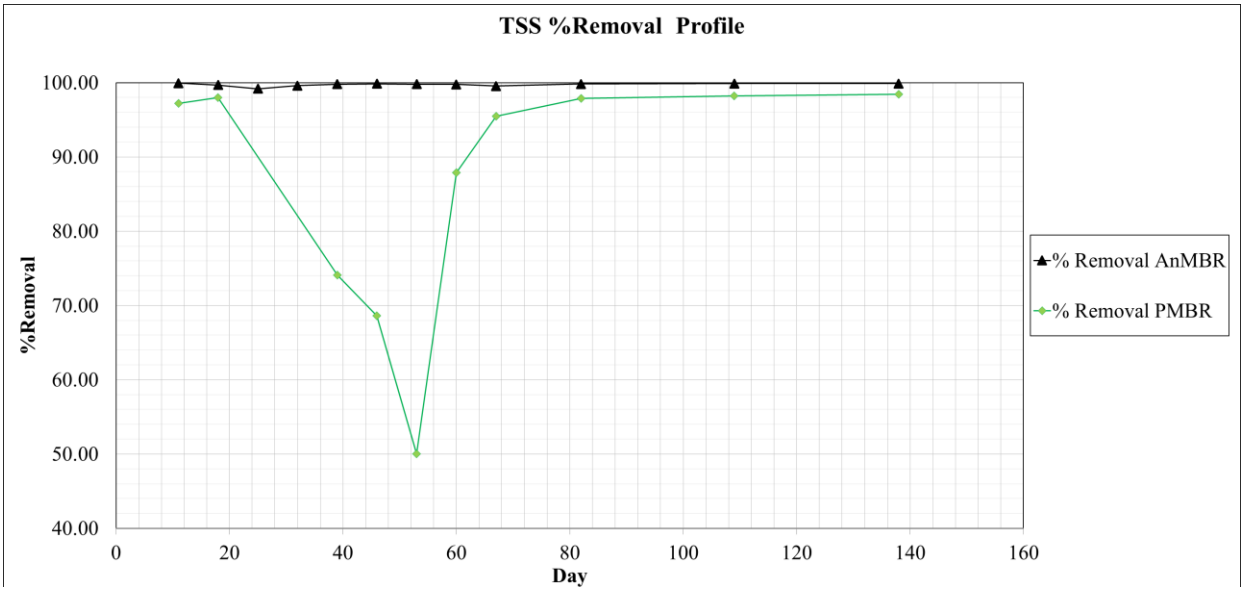

Figure 8. Total Suspended Solids Removal Profile.

Figure 8 shows the TSS removal percentage for each of the membranes in APMBR. Over the last three months of operation, the anaerobic subsystem membrane averages a 99.7% solids removal while the phototrophic subsystem membrane averages a 95.6% solids removal. The major dip in the PMBR removal profile was most likely due to precipitated solids on the permeate side of the membrane as the anaerobic subsystem had to be spiked with sodium bicarbonate to help normalize pH values in R2. It is likely that these and other byproducts precipitated post-permeation and thus increased the TSS values. Since then, the values have drastically improved and normalized.

D. Water Chemistry Results

The ultimate objective of the APMBR system is to treat complex organic solids and convert them into a value-added product. the APMBR will convert these solids into a nutrient-rich liquid solution that can be used for downstream space crop production or as an alternative feedstock for other processes. The space crop production group at KSC utilizes a half-strength Hoaglands fertilizer solution for the majority of their hydroponic growout studies. Therefore, the chemical makeup of that solution was used as a comparison control for the APMBR final permeate. Figure 10 represents a combination of 'test and tube' kit results coupled with ion chromatography data to produce a nutrient comparison. The data presented in this graph is an average of the past 3 months of operation. Data during the first couple of months is not shown as the system was acclimating to the new operation as well as the overload event that skewed average nominal nutrient concentrations. It can be seen that the APMBR permeate contains all of the vital

nutrients that make up the half-strength Hoaglands solution. One major note is the extremely high levels of sodium and chloride. These elevated concentrations are due to the COPAS cat food containing high levels of salt for palatability. Effluent from a sister prototype of AnMBR being run at USF is being fed canine fecal matter at a 5% solids solution and contains very little sodium and chloride. Therefore, one can assume that these two components would not be present in such high concentrations when being fed real human fecal matter. Preliminary growout studies

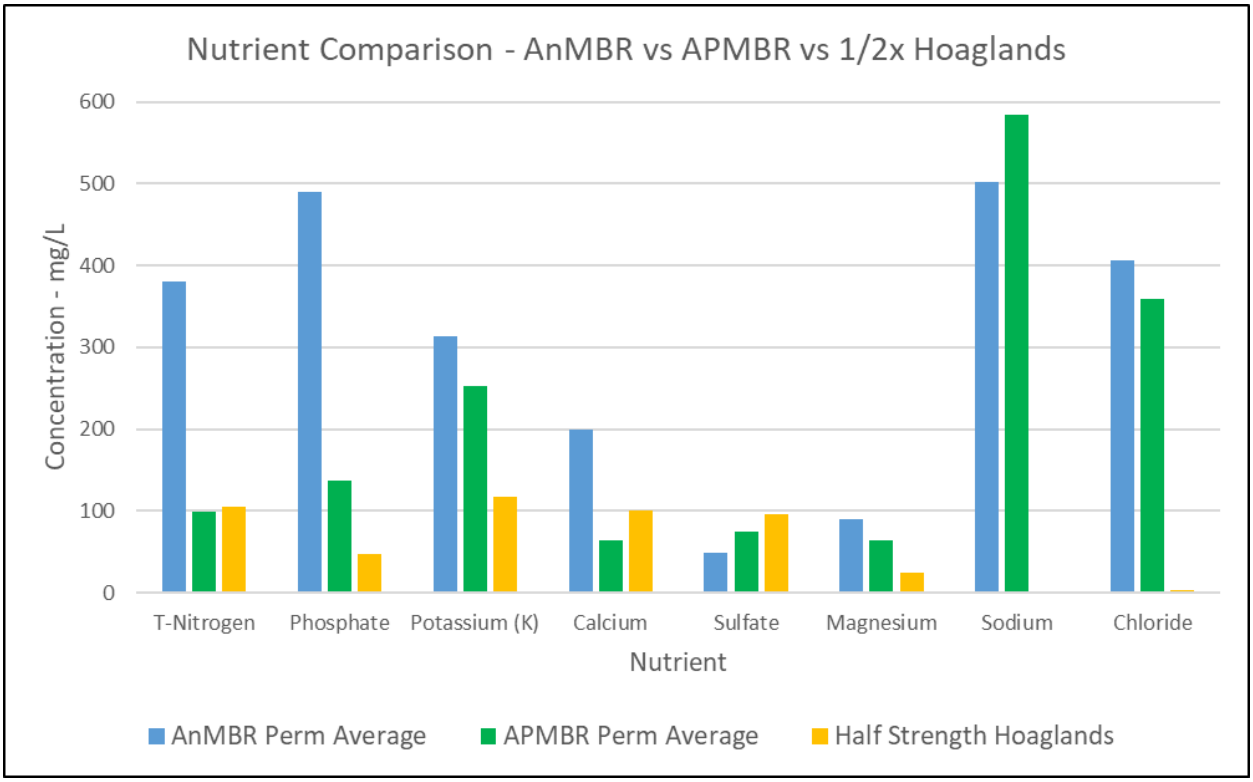

Figure 10. Nutrient comparison of the AnMBR subsystem, APMBR permeate, and a half strength Hoaglands fertilizer solution.

have already been performed growing extra dwarf pok choi microgreens utilizing AnMBR permeate, PMBR permeate, and a half-strength Hoaglands solution. The results showed exceptional growth when utilizing the PMBR permeate so future work is planned to use APMBR permeate for a full-scale growout.

Ultimately, the nutrient data and preliminary growout studies have indicated that APMBR is able to break down high-strength and complex solid wastes into a reusable nutrient solution that mimics an industry standard that is used to grow various space crops. However, future studies need to be performed to assess whether or not the overabundance of certain nutrients can lead to detrimental effects on the plants being grown on APMBR permeate.

V. Conclusion

Bioregenerative life support systems, like the APMBR, recycle resources crucial for long-term deep space exploration. The APMBR integrates anaerobic and phototrophic subsystems to treat high-strength complex waste and produce essential nutrients for reuse. After an initial overloading event in the APMBR, carbon removal efficiency decreased temporarily but eventually rebounded to nominal high removal levels. The system effectively processed nitrogen, with ammonia being converted to less volatile forms. Total solids were effectively removed from the final product by the membranes, therefore illustrating the longevity of their use which is extremely practical for deep space applications where resupply is not feasible. Additionally, membrane pressure data indicated consistent operation within acceptable limits. The final permeate from the APMBR contained essential nutrients for plant growth, similar to an industry-standard hydroponic solution. However, further studies are needed to assess potential effects on plant growth. Overall, through continuous operation and optimization, the APMBR demonstrates promising advancements in sustainable life support systems for space exploration, offering a bioregenerative alternative to traditional physical-

chemical systems. Continuous research and optimization are essential for further enhancing the efficiency and reliability of such systems in long-duration space missions and planetary colonization efforts.

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