Long Term Biological Treatment of Space Habitation Waste Waters in a One Stage MABR: Comparison of Operation for N and C Oxidation With and Without Simultaneous Denitrification

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Aerobic biological stabilization has been previously demonstrated for full size MABR's (CoMANDR 1.0, CoMANDR 2.0, and R-CoMANDR) over operating periods of ~1 year. These systems have successfully treated a variety of possible habitation waste streams including an ISS (urine + flush and humidity condensate) and Early Planetary Base (EPB) wastewater (urine, flush water, hygiene wastewater, and laundry). Biological stabilization has a number of advantages including: 1) elimination of hazardous pre-treat chemicals; 2) production of NO_x species (that can be easily rejected by evaporative or membrane systems); 3) elimination of volatile organic constituents; 4) a low pH effluent that facilitates membrane and distillation processes; and 5) a effluent that produces a better quality and less hazardous brine for water recovery. Previous work has primarily evaluated aerobic operation in which organic carbon and nitrogen is converted to CO_2 and NO_x^-, respectively. An alternative to aerobic operation would be to include anoxic operation to promote denitrification and production of N_2 gas. This allows for production of make-up gas as well as reduces the O_2 demand and can increase ammonia oxidation efficiency. We evaluated the operation of a full scale (2 crew/day) MABR operated to perform oxidation of organic carbon and nitrogen with and without simultaneous reduction of oxidized N to N_2 gas, simultaneous nitrification denitrification (SNDN). The system was challenged with a variety of space habitation wastewaters ranging from an ISS composition to a possible EPB waste stream under both continuous and on-production feeding modes. The system has been operated for over 2.5 years. We report on an overall comparison of aerobic oxidation and SNDN operational regimes to evaluate the system with the best overall attributes to support recycling of space habitation waste streams.

Nomenclature

LEO = Low Earth Orbit
HC = Humidity Condensate
MABR = Membrane Aerated Bioreactors
CoMANDR = Counter Diffusion Membrane Aerated Nitrifying Denitrifying Reactor

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ISS = International Space Station
C = Continuous
P = Pulse (On Production)
EPB = Early Planetary Base
N = Nitrogen
N_2 = Nitrogen gas
$NO_2^{- -}$ = Nitrite species (aqueous)
NO_3 = Nitrate
NH_3 =Ammonia (aqueous)
TN =Total Nitrogen
DOC =Dissolved Organic Carbon
SNDN = Simultaneous Nitrification Denitrification
DO =Dissolve Oxygen

I. Introduction

The ability to reliably provide adequate potable water is a critical requirement for human habitation beyond earth's surface. Strategies include both resupply and reuse and there are numerous sometimes conflicting studies on the relative merits of resupply of water, beyond low Earth orbit (LEO). The water recovery systems designed or proposed outside of LEO must have a very high reliability. In addition, to maximize sustainable habitation over long periods and for very distant locations (e.g. Mars) water recovery systems must be able to achieve very high rates of closure. The ISS has utilized water recovery for years in order to supply or supplement its potable water. The system recovers pre-treated urine and flush water by distillation. The distillate is combined with humidity condensate (HC) after which a series of expendable filtration beds (ion exchange and activated carbon) and a catalytic oxidizer are used to remove additional organic carbon and dissolved ions before as series of final polishing beds and disinfectant addition. The system has been very successful but does require a number of consumables including replacement beds, O_2, and the hazardous pretreat solution. Water recovery from urine + flush is limited to ~85% but the addition of the brine processor (Kelsey et al., 2017) may increase this to nearly 100% in the near future. For future missions, the number of wastestreams may increase in conjunction with the addition of additional facilities such as showers, laundry, and other hygiene operations. These wastestreams will have different characteristics and will increase the demand for consumables, as well as possibly require new treatment processes.

Biological pretreatment is one process that has been evaluated to reduce the costs of recycling habitation wastewater. Biological treatment alone cannot produce potable water but can greatly reduce the organic carbon content and free ammonia (NH_3) concertation by both converting organic N to oxidized forms (NO_2^- and NO_3^-) and lowering the pH to convert the volatile ammonia form to ammonium (NH_4^+). Biological treatment can also convert NO_2^- and NO_3^- to N_2 gas, a useful product. Advantages of biological treatment include: elimination of hazardous pre-treat chemicals, possible increased desalination efficiency due to a reduction in strong mineral acids (chemical pretreat), stabilized wastewater to prevent downstream biofouling (e.g. HC tank and downstream valves), reduced loads on mixed beds and catalytic oxidizer in the WPS, produce a higher quality brine, and ability to incorporate membrane separation systems. In addition, biological effluent is compatible with plant growth systems. Biological systems have some costs including power consumption for recycle pumps and O_2 consumption.

Biological reactors as components of habitation wastewater processing systems have been actively developed for almost two decades (Pickering et al., 2001). Over the past 10 years efforts have focused on developing and demonstrating a micro-gravity compatible design. These biological systems utilize Membrane Aerated Bioreactors (MABR) that can support biological growth with bubble free oxygenation. Studies have demonstrated their ability to treat ISS, Transit, and EPB (Early Planetary Base) waste streams over long periods (~2 years). This includes operating in continuous mode or on production mode, where wastewater is fed directly to the bioreactor as they are generated (citations). In this configuration the biological reactor replaces a feed tank. Most recently, full scale systems (2-4 crew/day) have been evaluated as well as their ability to integrate into an overall wastewater processing architecture (Pickering et al., 2013). In general, these systems can achieve DOC removal of ~80-90%, organic N oxidation of 50-60%, and produce an effluent pH 6-7 with complete urea hydrolysis. Reaction rates are dependent upon waste stream and specific surface area but in general 3-4 day hydraulic retention times (HRT) are required. Some studies have evaluated incorporating denitrification (McLamore et al., 2004; Jackson et al., 2004).

Denitrification in addition to producing N_2 gas can also reduce O_2 demand and increase organic N oxidation but adds additional complexity. Denitrification can be included by the addition of a separate reactor or by changing the operation to the MABR to transfer less O_2 producing anoxic regions in the biofilm (Landes et al., 2011).

In order to continue to advance bioprocesses as part of an overall habitation wastewater processing system, an optimized design is required that maximizes the benefits while minimizing the cost and complexity. While denitrification does offer some benefits, these must be traded with impacts on sizing, performance, and complexity. In order to allow such a trade, we evaluated a pilot scale (1-2 crew/d) MABR which was operated in two modes, fully aerobic and anoxic. We evaluated the treatment rate, efficiency, complexity, and reliability for each mode when treating ISS, Transit, and EPB waste streams both for continuous and on-production modes of operation. This study compares the performance and requirements of each operational mode in order to determine which configuration is best suited for further development in long term habitation architectures.

II. Methods

A. Reactor Specifications

The details for the biological reactor, (rCOMANDR) have been previously described but are summarized here (Sevanthi et al., 2016). The reactor is a MABR with overall dimensions of L= 89cm, W= 51cm, and H= 51cm and a total volume of 0.23 m^3(Figure 1). It consists of a liquid compartment (0.11m^3) and two air plenums (0.006m^3 each) on opposite sides of the reactor that are connected by 1600 siloxane tubes (OD=0.55cm) which pass from one plenum through the liquid compartment and into the opposite plenum. There is an inlet and outlet zone at each end of the liquid compartment that is separated from the membrane section by baffle walls to distribute flow. The liquid flow enters and exits through two 2.54cm ports in each zone. The inlet and outlet are connected by a recycle line (2.54cm) and centrifugal pump (~4 l/min). There is a HACH Hydrosonde multi-probe for online measurements of DO, pH, TDS, and temperature located in the recycle line. The inlet air header is supplied at a constant rate (0.6L/min) by compressed gas cylinders (O_2 and air) and the flow rates of each gas controlled by mass flow controllers. Wastewater(s) is pumped to the reactor using a peristaltic pump(s) and enters the recycle line. Effluent is displaced from the outlet zone.

B. Reactor Operation

rCOMANDR was challenged with 3 wastestreams (EPB, Transit, and ISS) for 2 loading conditions (continuous and on-production), and for two operational conditions (aerobic and anoxic). Aerobic operation was defined by producing a bulk liquid DO >3 mg/l, while anoxic operation was produced by maintaining a bulk DO ~0.5-2 mg/l. Each test point is summarized with the flow rate, duration, waste stream, and loading regime (Table 1). Continuous feed is produced by mixing each waste stream (urine, plush, laundry, shower, hygiene, HC) into a single feed tank each day which is then fed to the reactor over 24 hours. On-production is produced by feeding each waste stream to the reactor as it is produced (Figure 1). Details of the number of events, volume/event, and rate of feed are detailed in Table 2. For urine and flush water we assumed 6 events (330 ml/event) per crew member day over a 16 hour wake period. Hand wash wastewater was assumed to be produced over 7.5 events per crew day 6 of which correspond to urination events. We assumed one shower per crew at the start or end of wake period. Oral hygiene wastewater was produced twice per crew day and occurred at the same time as each shower event. Shaving was assumed to occur at a rate of 1 event per crew every 2 days which occurred during the shower event. Laundry wastewater was produced at the end of each sleep cycle at a rate of 1 event per crew-day. Finally, HC is continuously pumped into the system as it is generated continuously. The composition of each wastewater component has been previously described (Verostko et al., 2004). In this study we used donated urine and increased the volume produced per crew (0.3L) and reduced the flush water in order to simulate the more concentrated urine on ISS. Laundry was produced using an ultralow washing machine and washing soiled clothes with a detergent (7^{th} Generation). Other wastestreams were prepared using published ersatz recipes or by volunteer donation using approved products (Arm and Hammer Toothpaste, Neutrogena Shaving cream, No-Rinse Shampoo). System maintenance was confined to external system components (feed tank or effluent tank) and sensor calibration. We did not perform any line maintenance or solids removal from the reactor. We periodically cleaned the feed tank as its design was not part of our system test but no influent tubing was changed other than peristaltic pump tubing.

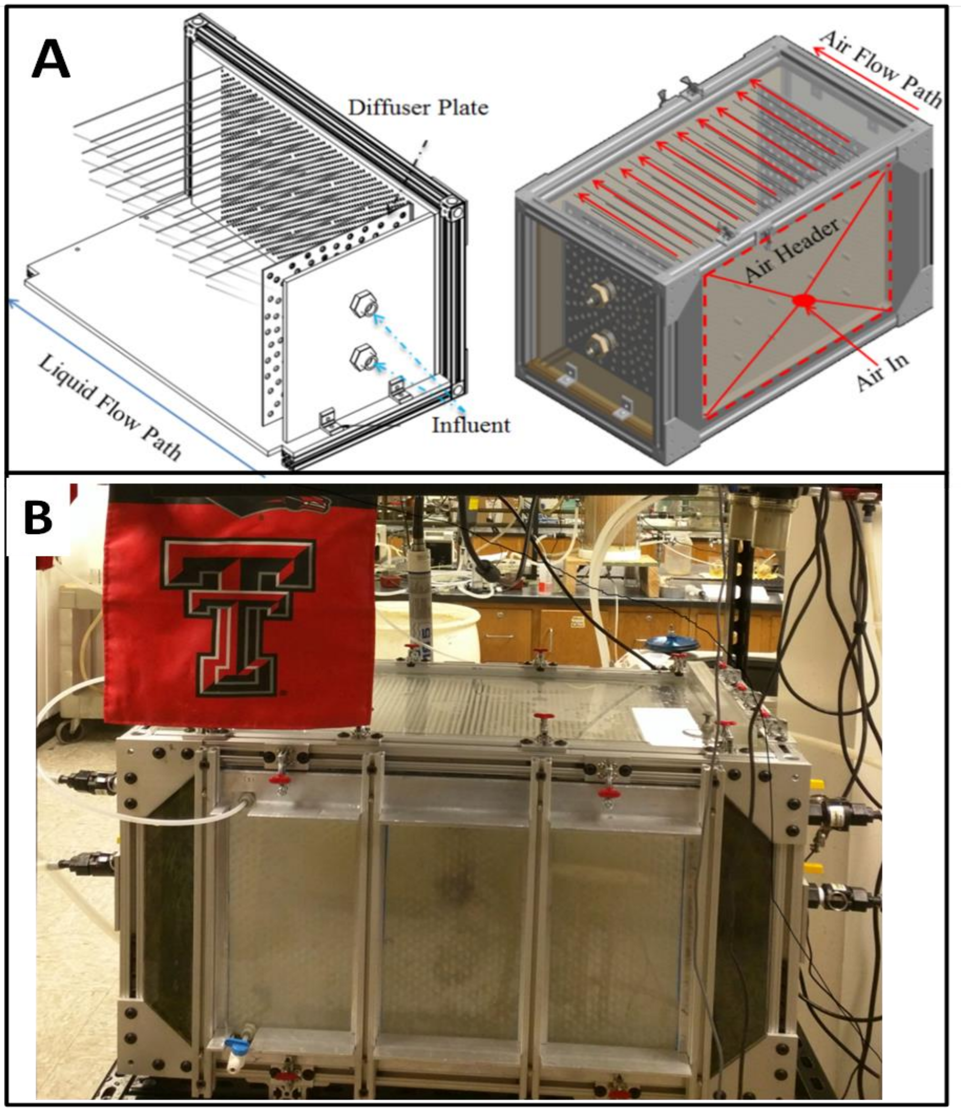

Figure 1. A) Schematic of rCOMANDR and B) Photograph of rCOMANDR prior to operation. (Sevanthi et al., 2016)

C. Sampling and Analysis

For all test points, pH, DO, T°, and TDS were evaluated continuously at a rate of 1 reading per minute. Influent and effluent water samples were taken daily. Influent samples were taken from the influent tank or mixed proportionally to their overall daily volume from each separate wastewater. Effluent samples were removed daily from the effluent tank. We evaluated reactor influent and effluent for TN, DOC, NH_3/NH_4^+ NO_2^-, and NO_3^- using previously described methods (Landes et al., 2011). The effluent gas stream composition was measured multiple times per week using an in-line gas analyzer (Quantek 902P).

For most test points we additionally tested the stability and distillation potential of each effluent multiple times. Stability of each effluent was tested by placing multiple vials of effluent taken directly form the effluent tank and placing on a lab bench in a flask open to the atmosphere. One flask was sacrificed each week and tested for pH, TN, DOC, and NO_X^-, and TSS in order to evaluate any changes in water quality or microbial growth over the 3 week period. In addition, we evaluated the distillation potential of wastewater from each test point by distilling multiple samples of effluent in a rotary vacuum distiller. The condensate and brine were tested for TN, DOC, NOx, and pH and recovery.

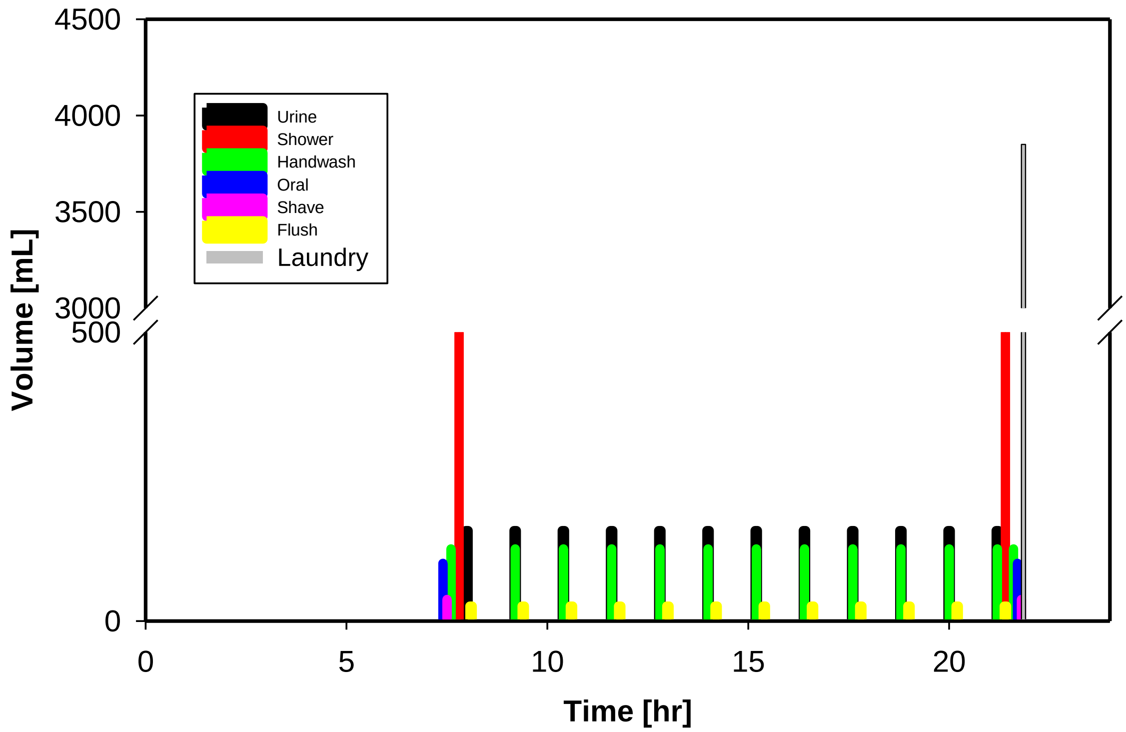

Figure 2. On production feeding schedule and rate.

Table 1. Composition and input mode and rate for all test points.

Waste Stream and Mode	Loading Rate (L/C-d)							Total Flow (L/C-d)
	U +F	Hygiene				Laundry	HC	
		O	HW	S	SH			
	1.8	0.2	0.95	6	.075	3.75	1.95	
	Input Rate: C=Continuous (l/C-d)); P=Pulse (Number of events (E) per time period per day)							
ISS-C	C						C	4.05
ISS-P	6 P/16 hr						C	4.05
Transit-P	6 P/16 hr	2 P/16hr (t= 0,16hr)	6 P/16 hr	2 P/16hr (t= 0,16hr)	2 P/16hr (t= 0,16hr)		C	11.5
EPB-P	6 P/16 hr	2 E/16hr (t= 0,16hr)	6 P/16 hr	2 P/16hr (t= 0,16hr)	2 E/16hr (t= 0,16hr)	1 E/d (t= 0)	C	15.25
EPB-C	C	C	C	C	C	C	C	15.25

U=Urine; F = Flush; O= Oral Hygiene; S= Shower; SH = Shavine; HW = Hand Wash

Table 2. Overview of all test points.

Date	Waste Stream	Feeding Mode	Days Operated	Loading	Volume Treated (L)
Start Up-Aerobic Operation					
7/20/2015	Urine	Batch			
8/4/2015	EPB	C	6	10	60
8/10/2015	EPB	C	20	20	400
8/30/2015	EPB	C	47	2 C-d (28.6 L/d)	1410
10/16/2015	Variable	C		Variable	
		Aerobic Operation			
11/30/2015	EPB	C	25	2 C-d (28.6 L/d)	715
12/14/2015	ISS	C	39	2 C-d (6.9 L/d)	269
1/24/2016	ISS	P	37	2 C-d (86.9 L/d)	255
2/22/16	Transit	P	48	2 C-d (21 L/d)23	1008
4/11/2016	EPB	P	41	2 C-d (28.6 L/d)	1172
5/23/2017	Hibernation				
6/5/2016	EPB	C	18	2 C-d (28.6 L/d)	514
Anoxic Operation					
6/24/2016	EPB	C	41	2 C-d (28.6 L/d)	1172
8/7/2016	EPB	C	37	1.5 C-d (21 L/d)	791
9/13/2016	EPB	C	30	1 C-d (14.3 L/d)	429
10/14/2016	ISS	C	66	1 C-d (6.9 L/d)	455
12/20/16	Hibernation				
1/10/2017	ISS	C	28	2 C-d (6.9 L/d)	193
2/7/2017	ISS	P	76	2 C-d (6.9 L/d)	524
4/24/2017	Transit	P	83	2 C-d (21 L/d)	1743
7/17/2017	Transit	P	80	1 C-d (10.5 L/d)	871
10/6/2017	EPB	C	37	1 C-d (14.3 L/d)	986
12/18/2017	Hibernation				
1/19/2018	EPB	C	72	1 C-d (14.3 L/d)	328
2/26/2018	EPB	P		1 C-d (14.3 L/d)	

III. Results

The rCOMANDR was continuously operated for almost 3 years over which it has treated more than 11,000 liters of habitation wastewater. The reactor was operated in both aerobic and anoxic modes in order to evaluate the rate and treatment efficiency with and without denitrification (TN removal). Each operational mode included treatment of ISS, Transit, and EPB wastewater. We also evaluated the impact of continuous loading for EPB and ISS waste water simulating an architecture where waste is collected and stored prior to treatment as well as on-production feeding where wastewater is pumped into the bioreactor as it is produced. For each operational condition, we also evaluated the overall removal of C, oxidation of organic N, removal of N, and pH. In addition, we evaluated the rate of conversion with respect to loading and removal. Details are presented below for each operational mode.

A. Treatment of EPB Wastewater

Carbon Oxidation-During aerobic operation DOC removal for continuous wastewater input ranged from 85-95% with effluent values ~110 mg/l or less (Table 3, Figure 3). This degree of carbon removal is typical of past studies on cylindrical MABRs treating EPB wastewater (Sevanthi et al., 2014; Christenson et al., 2015). The percent carbon removal was lower for on production operation mode where wastewater is input into the reactor as it is produced; however, effluent DOC concentration was similar to continuous input and the drop in percent performance is only a function of a lower average DOC influent concentration. Variations in wastewater influent concentrations are typical due to the use of donated urine and small pool of donors.

DOC removal during anoxic tests was reduced (62% and effluent DOC ~280 mg/l) at a continuous loading rate of 2 crew/d (Table 2, Figure 3). Decreasing the flow rate equivalent to a 1 crew/d load increased performance (80~90% removal) with effluent DOC ranging from 40-140 mg/l slightly higher than aerobic test points even with twice the loading. Anoxic operation in conjunction with on production wastewater input produced similar results as continuous input.

Organic N Oxidation-Aerobic operation with continuous or on production operation resulted in similar organic N oxidation efficiencies (50-60%). Increases in organic N oxidation appear to be related to increased DO concentrations (Figure 3). Similar to DOC removal, Organic N oxidation was reduced (50%) for anoxic operation for loads of 2 crew/d but increased to 60% at reduced loading rates (1 crew/d), which were even higher than those during aerobic operation. However, on production wastewater input did decrease (48%) organic N oxidation slightly.

N Removal- As expected N removal was very low (10-20%) for aerobic operation regardless of waste water input mode, as the elevated concentrations of DO (4-11 mg/l) inhibits NO_x^- removal due to denitrification. Switching to anoxic operation (DO <2 mg/l) slightly increased N removal (26%) for a 2 crew/d load but with a decrease in loading rate to 1 crew/d N removal increased to ~50% for one test point while two similar test points (anoxic operation, Continuous input, 1 crew/d) had N removal ~30-40% but DO for these test points exceeded the 2 mg/l goal. N removal with on production feeding was lower than continuous for anoxic operation even with DO < 2mg/l.

D. Treatment of Transit Wastewater

Transit wastewater was only evaluated for on production feeding. DOC removal was similar for aerobic or anoxic operation (85-86% removal; effluent DOC 130-140 mg/l) as well as reduced wastewater loading during anoxic operation (2crew/d to 1crew/d) (Table 3, Figure 4). Nitrification was similar (~60%) for aerobic and anoxic operation (2 crew/d load) but increased (80%) for anoxic operation at reduced loading (1 crew/d) which also corresponded to DO slightly above the 2 mg/l goal. As for the EPB waste stream, N removal was very small for the aerobic operation mode but was much higher than the EPB waste stream for both loading rates (2 and 1 crew/d) under anoxic conditions. The transit waste water is more concentrated (e.g. higher DOC) which combined with the longer residence time may have led to increased N removal.

E. Treatment of ISS Wastewater

Carbon Oxidation-ISS wastewater was evaluated for both continuous and on production feeding for both aerobic and anoxic conditions. DOC removal was similar for aerobic or anoxic operation (90-95% removal) although effluent DOC concentrations were more variable for anoxic conditions (100-320 mg/l) compared to aerobic conditions (100-150 mg/l) (Table 3, Figure 5). It should be noted that effluent concentrations of DOC are similar to other waste stream effluents, the influent DOC concentration is much higher 1900-2600 mg/l compared to the transit (900-1000 mg/l) or EPB waste water (600-800 mg/l). There was no clear effect of on production feeding for either the aerobic or anoxic condition.

Organic N oxidation- Similar to the transit waste stream 60-65% of the organic N was oxidized for the aerobic condition irrespective of feeding mode. Anoxic operation resulted in a consistent increase in N oxidation (~70%) even though the DO was < 2 mg/l in the bulk solution. The pH was similar for all aerobic and anoxic conditions (6-7). The increase in nitrification for anoxic conditions may be due to the decrease in NO_2^- (due to N loss, see below) and therefore HNO_2 which has been shown to inhibit N oxidation (Citation). We propose that the much longer retention time (14.5d) for the ISS wastewater compared to the EPB (3.6d) or Transit (4.5d) for a 2 crew-d load or even for a 1 crew-d load (7.2 and 9 d, respectively) may allow for increased N oxidation.

N Removal- For aerobic conditions little N removal (~13%) occurred for either continuous or on production input similar to the Transit and EPB waste streams. DO was very high (>10 mg/l) for both test points. N removal increased and was similar (50-55%) for both continuous and on-production input for anoxic operation, corresponding to the reduced DO (<2 mg/l).

Table 3. Overview of influent and effluent water quality and volume treated.

Waste Stream	Mode	Operation	C/d	Q (L/d)	Volume Treated (L)	Concentration (Standard Deviation)							pH
						Influent (g/m3)		Effluent(g/m3)					
						DOC	TN	DOC	TN	NO_x^-	NH_4^+	DO	
EPB	C	Aerobic	2	28.6	715	750(270)	780 (240)	30(6)	710 (50)	350 (28)	410 (140)	3.7 (0.2)	6.2(0.8)
EPB	C	Aerobic	2	28.6	514	722 (190)	880 (260)	110 (79)	740 (80)	370 (27)	730 (140)	10 (3.2)	6.8 (1)
EPB	P	Aerobic	2	28.6	1172	580 (80)	660 (70)	110 (22)	540 (60)	280 (52)	340 (140)	11 (3.6)	6.2 (0.5)
EPB	C	Anoxic	2	28.6	1172	630 (110)	720 (120)	240 (79)	520 (50)	35 (19)	610 (300)	1.7 (0.8)	7.1 (0.3)
EPB	C	Anoxic	1.5	21.4	792	610 (90)	700 (80)	110 (48)	520 (42)	90 (36)	370 (110)	1.7 (0.6)	6.9 (0.2)
EPB	C	Anoxic	1.0	14.3	429	590 (70)	690 (80)	40 (9)	350 (35)	140 (23)	220 (33)	1.2 (0.13)	6.5 (0.3)
EPB	C	Anoxic	1.0	14.3	987	780 (120)	830 (120)	140 (30)	560 (45)	370 (51)	320 (70)	2.3 (0.4)	6.0 (0.8)
EPB	C	Anoxic	1.0	14.3	328	730(160)	810 (110)	140 (60)	570(73)	290 (90)	320 (37)	3.9 (3.0)	6.4(1.1)
EPB	P	Anoxic	1.0	14.3	In progres s								
Transit	P	Aerobic	2	21	1008	990 (410)	590 (190)	130 (16)	780 (320)	380 (32)	43 (18)	13 (2.6)	5.6 (0.2)
Transit	P	Anoxic	2	21	1743	1000 (240)	1500 (520)	140 (40)	670 (180)	120 (69)	480 (230)	0.75 (3.2)	6.7 (0.5)
Transit	P	Anoxic	1	10.5	872								
ISS	C	Aerobic	2	6.9	269	2200 (380)	2100 (340)	100 (30)	1800 (130)	1100 (66)	1000 (110)	12 (2.5)	7.1 (02)
ISS	P	Aerobic	2	6.9	255	2500 (620)	2900 (790)	150 (20)	2400 (210)	1200 (250)	1200 (240)	13 (2)	6.2 (0.5)
ISS	C	Anoxic	2	6.9	455	1900 (470)	2500 (550)	90 (30)	1100 (330)	420 (140)	540 (160)	1.9 (1.9)	6.3 (0.3)
ISS	C	Anoxic	2	6.9	193	2700 (500)	3100 (240)	290 (60)	1400 (76)	520 (30)	952 (170)	1.7 (0.7)	6.9 (0.5)
ISS	P	Anoxic	2	6.9	524	2100 (380)	2900 (340)	320 (130)	1400 (270)	540 (130)	840 (160)	1 (1.8)	6.3 (0.5)

Table 4. Summary of reaction rates and influent and effluent loading for all test points.

Waste Stream	Mode	Operation	C/d	Loading (g/d)				Percent Transformation (Standard Deviation			Reaction Rate (g/m^3-d)		
				Influent		Effluent		DOC	N Oxidation	N Removal	DOC	N Oxidation	N Removal
				C	N	C	N						
EPB	C	Aerobic	2	21	22	1	20	95 (2)	51 (10)	8	207	200	19
EPB	C	Aerobic	2	20	25	3	21	86 (6)	58 (6)	14 (15)	176	150	42
EPB	P	Aerobic	2	17	19	3	15	81 (4)	60 (8)	17 (12)	134	110	33
EPB	C	Anoxic	2	19	21	7	15	62 (10)	35 (10)	26 (15)	113	70	60
EPB	C	Anoxic	1.5	13	15	2	11	80 (10)	38 (10)	26 (11)	108	60	40
EPB	C	Anoxic	1.0	8	10	0.5	5	93 (2)	69 (4)	50 (10)	78	70	49
EPB	C	Anoxic	1.0	10	12	2	8	82 (4)	70 (20)	30 (11)	90	92	40
EPB	C	Anoxic	1.0	10	12	2	8	85 (10)	68 (40)	38 (27)	84	75	34
EPB	P	Anoxic	1.0	9	10	1.5	8	83 (11)	48 (7)	24 (12)	77	49	24
Transit	P	Aerobic	2	21	12	3	16	85 (4)	63 (9)	16 (14)	180	81	
Transit	P	Anoxic	2	22	31	3	14	85 (6)	62 (10)	59 (11)	190	190	165
Transit	P	Anoxic	1	10	15	2	8	86 (10)	80 (25)	55 (30)	85	105	75
ISS	C	Aerobic	2	15	14	1.0	12	95 (2)	65 (6)	13 (13)	150	95	23
ISS	P	Aerobic	2	17	20	1.0	16	94 (2)	59 (19)	13 (31)	160	120	35
ISS	C	Anoxic	2	13	17	0.6	7	95 (2)	73 (9)	56 (15)	125	130	100
ISS	C	Anoxic	2	18	21	2.0	10	89 (2)	69 (5)	56 (4)	158	152	120
ISS	P	Anoxic	2	14	20	2.2	9.5	85 (5)	70 (7)	51 (9)	120	140	110

F. Loading and Reaction Rates

Carbon Oxidation- Influent loading rates of organic carbon for test points evaluating a 2 crew-d influent rate generally varied from 16-22 g C/d regardless of waste stream as urine is the largest contributor to the carbon load and is present in all waste streams, although Transit and EPB are slightly higher (Figure 6; Table 4). Loading rate scales directly with flow rate so test points with lower inflow (1.5 and 1 crew-d) have corresponding lower influent loading rates. Effluent loading rates were generally low (1-3 g/d) and similar for all waste streams and flow rates. However, there was a clear increase (7 g/d) in effluent loading for treatment of the EPB waste stream for 2 crew-d flow rate under anoxic operation and the effluent loading for the ISS waste stream was generally lower (1-2 g/d) than other waste streams at similar flow rates regardless of operating conditions. The lower effluent loading could be related to the lower influent C loading or may suggest that an organic component in the hygiene or laundry is not biodegradable.

Carbon oxidation volumetric reaction rates are highest for test points with higher influent C loading rates (Figure 6). This is largely due to the similarity of effluent C loading rates, suggesting that for most operating conditions evaluated the bioreactor is over sized with respect to C oxidation. C oxidation rates for anoxic treatment of transit and ISS waste streams were similar to aerobic oxidation rates but anoxic treatment of EPB resulted in lower oxidation rates. Factoring in the impact of influent C loading, there did not appear to be any impact on feeding mode (continuous or pulse) on reaction rates. For aerobic operation or for lower daily volumetric wastewaters, the reactor is thus capable of treating higher influent loading rates, whether they are due to increased concentration or additional flow rate (e.g. more crew day). The overdesign is with purpose as it allows the system to operate with low excess growth (long mean cell residence time) and provides a safety factor for off nominal events, but is mainly due to the reactor sizing being primarily dependent on N oxidation, the rate controlling step. One exception as mentioned above was for the anoxic treatment of EPB wastewater for 2 crew-d, (for which the reaction rate was much lower), compared to the influent loading rate, suggesting a residence time limitation. Carbon oxidation rates are similar to previously reported rates for sub-scale and pilot scale MABRs treating EPB or ISS waste water (2 crew-d) regardless of membrane surface area (100-250 m2/m3) (Christenson et al., 2015 and Sevanthi et al., 2016). These studies also supported the strong relationship between influent carbon loading and volumetric reaction rate supporting the excess processing capacity of the reactor. The rectangular configuration of the rCoMANDR incorporated lower SSA (~100 m^2/m^3) to prevent preferential flow due to biofilm bridging.

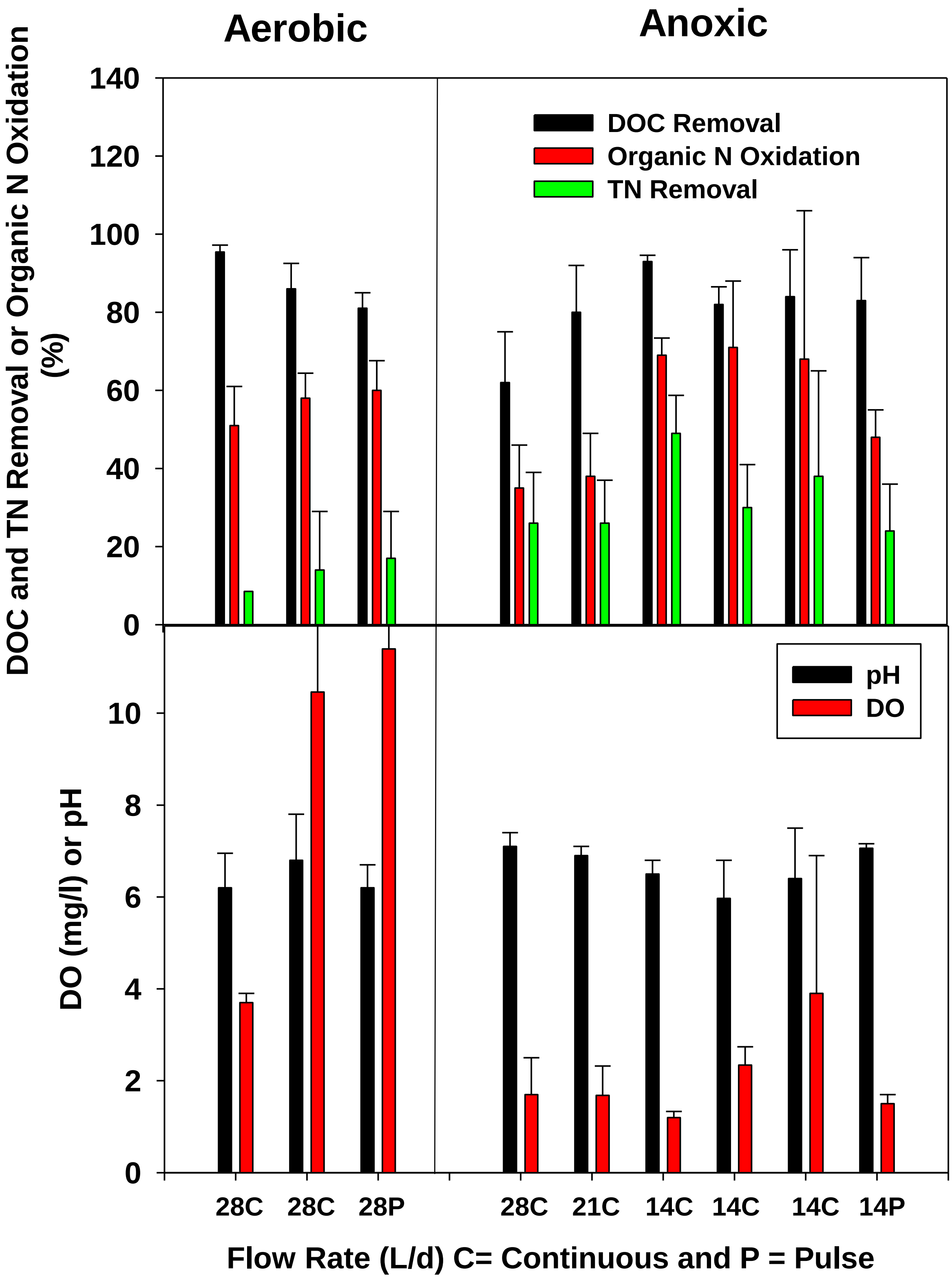

Figure 3. Impact on transformation potential for EPB waste e water of continuous and on production feed mode and aerobic and anoxic operation.

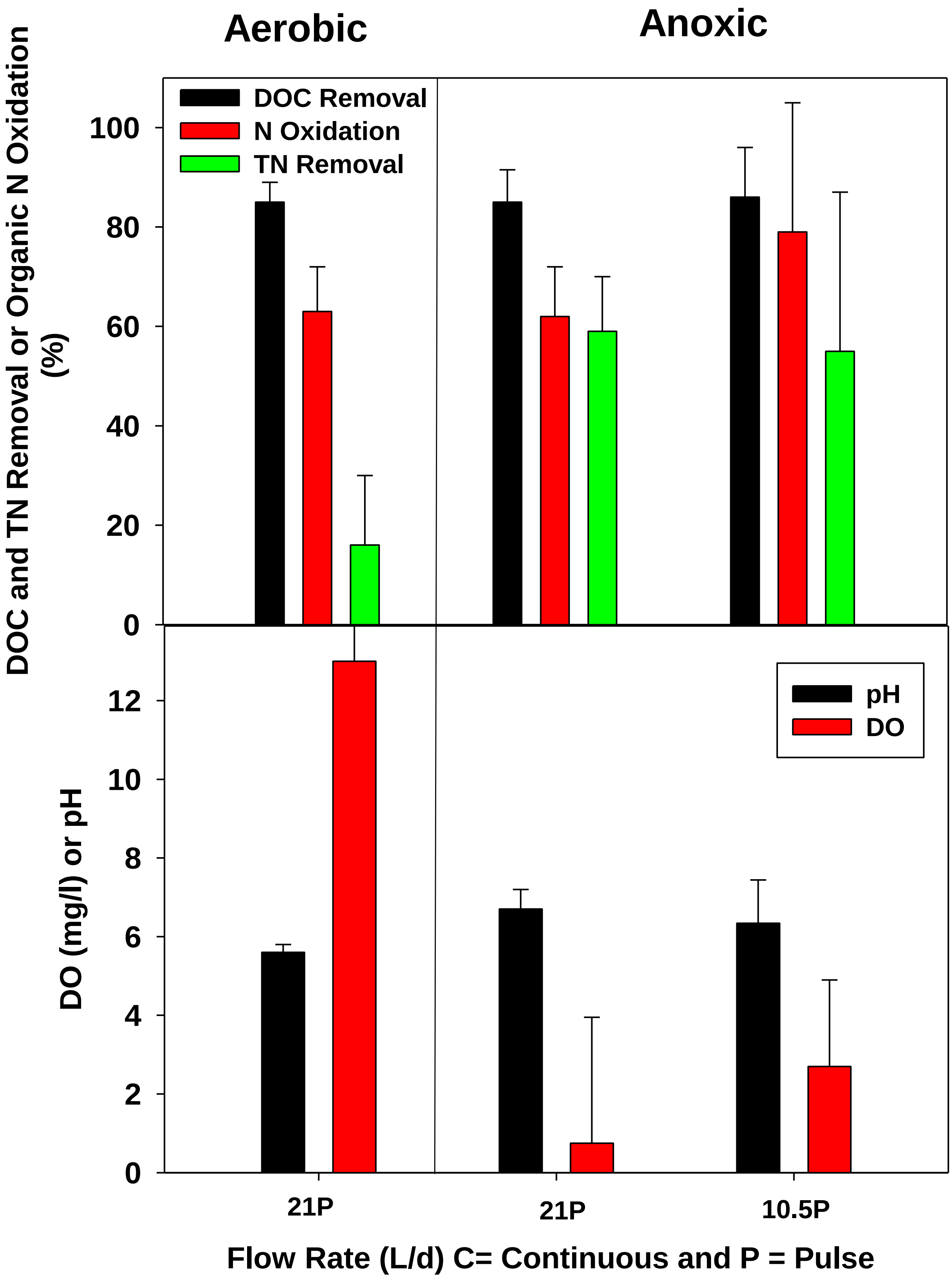

Figure 4. Impact on transformation potential for Transit waste e water of continuous and on production feed mode and aerobic and anoxic operation.

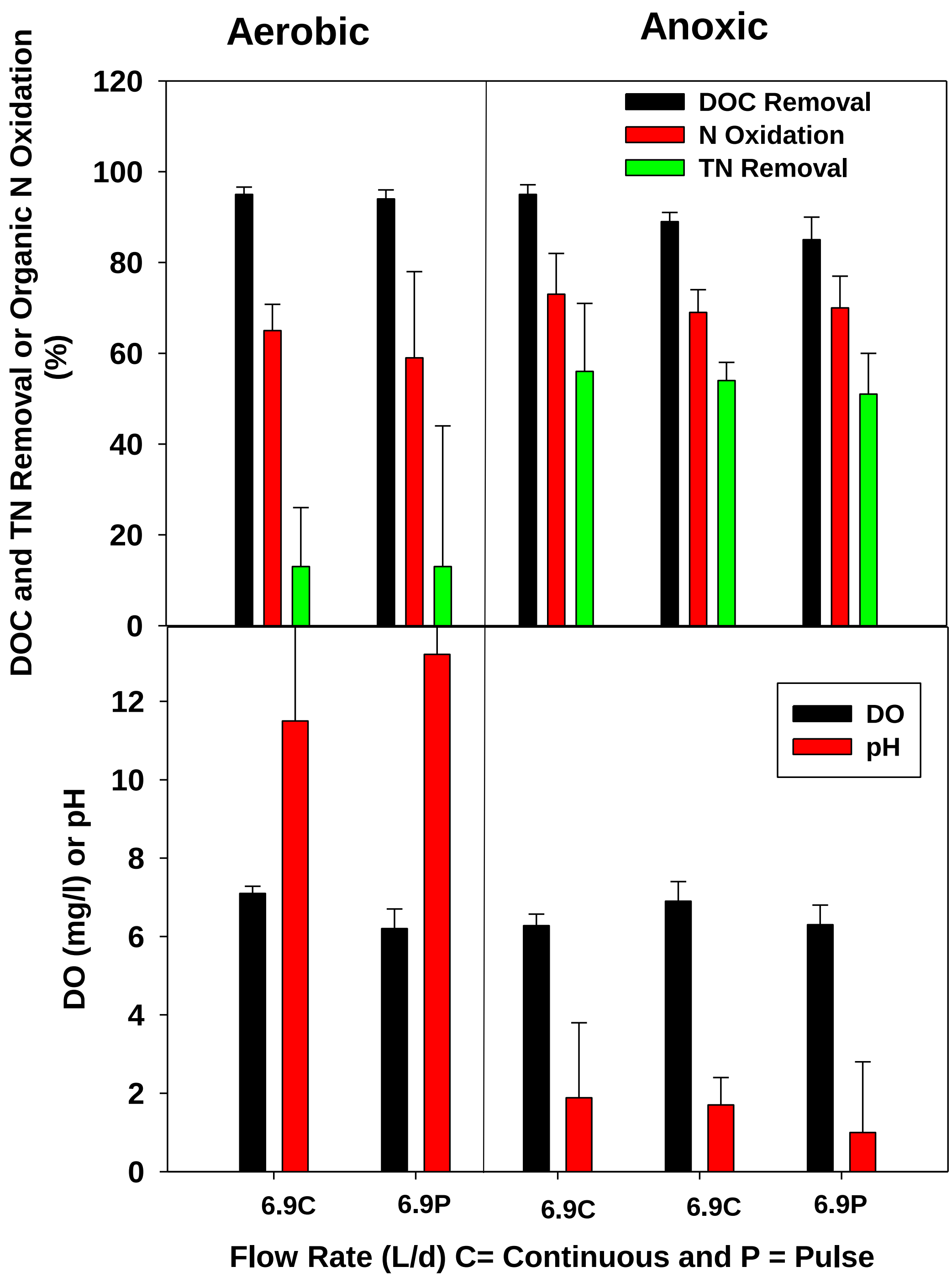

Figure 5. Impact on transformation potential for ISS waste e water of continuous and on production feed mode and aerobic and anoxic operation.

Organic N Oxidation-Similar to organic C, organic N loading rates for all waste streams with similar flow rates (crew/d) were similar due to the N influent loading being dominated by urine (Figure 7). In general influent N loading was proportional to flow rate (crew-d), although there was significant variation for the transit waste stream. However, in contrast to organic C, organic N effluent loading was correlated to influent N loading. This supports the reactor design premise that volumetric sizing is limited by the nitrification rate. Also similar to C oxidation, aerobic organic N oxidation rate was proportional to influent N loading. Anoxic treatment of the EPB waste stream resulted in lower reaction rates for 1-2 crew-d flow rates. In contrast, organic N oxidation rates for anoxic treatment of ISS wastewater were higher than aerobic due to increased organic N oxidation independent of influent loading. The differences in aerobic and anoxic reaction rates for EPB and ISS waste streams is likely due to the longer hydraulic residence time for the EPB waste water even though the organic loading is similar this suggests that there is less of a kinetic limitation. The increased performance for the anoxic treatment of the ISS wastewater could be due to alkalinity generation during denitrification or a reduction in HNO2 which can inhibit ammonia oxidation (citations). There was no clear impact of continuous versus on production feeding on reaction rates. Organic N oxidation rates for subscale and early pilot scale generation MABRs treating habitation waste streams with SSA ranging from 100-250 m^2/m^3 are similar to those reported here at similar flow rates (100-150 g/m^3-d) (Christenson et al., 2015 and Sevanthi et al., 2016).

Organic N Reduction- Little N loss is expected during aerobic operation although some will occur due to areas of thick biofilm, gaseous intermediate losses (N_2O) and some N incorporation into cell mass. In congruence with N percent removal only relatively minor differences in N influent and effluent loading occurred and N removal rates were low accordingly (Figure 8). Interestingly, lowering the volumetric flow rate from 2 to 1 crew-d for EPB waste stream did not improve denitrification rates and the highest rate occurred during anoxic operation for a 2 crew-d inflow for which the system was overloaded (effluent carbon was higher and DO was less than 2 mg/l). Decreasing the volumetric flow rate lowered C but also reduced N loss, likely due to a reduction in available C to support denitrification. In contrast anoxic treatment of the Transit and ISS wastewater produced much higher N loss rates and larger reductions in total N effluent loading rates. It is unclear why the N loss rates and overall N removal were lower for EPB even when considering lower influent loading rate at reduced flow. DO was similar between anoxic operation points and effluent carbon while higher for ISS wastewater was not always so nor was it higher for transit. Further, there is little change in the C/N ratio between waste streams. One possibility is that the higher nitrification rates and efficiencies for transit and ISS anoxic test points reduce DO in the biofilm allowing a larger zone of denitrification to occur, although it is unclear why that would not result in differences in bulk DO.

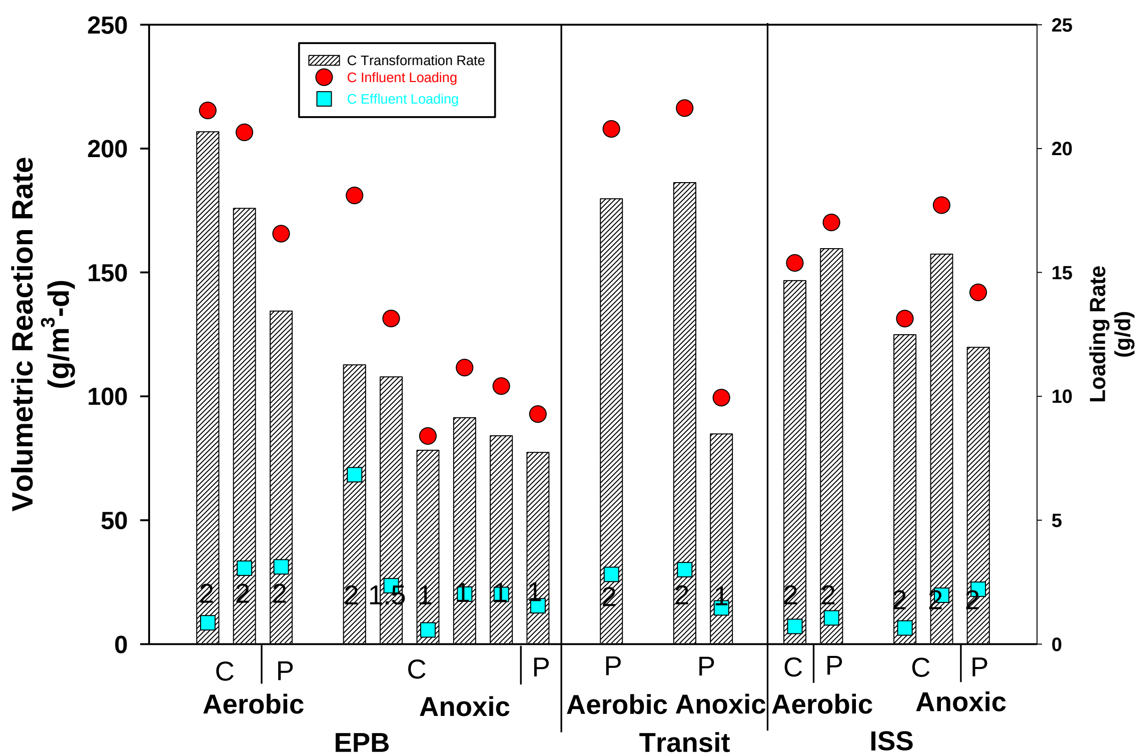

Figure 6. Organic C oxidation volumetric transformation reaction rates in comparison to influent and effluent C loading.

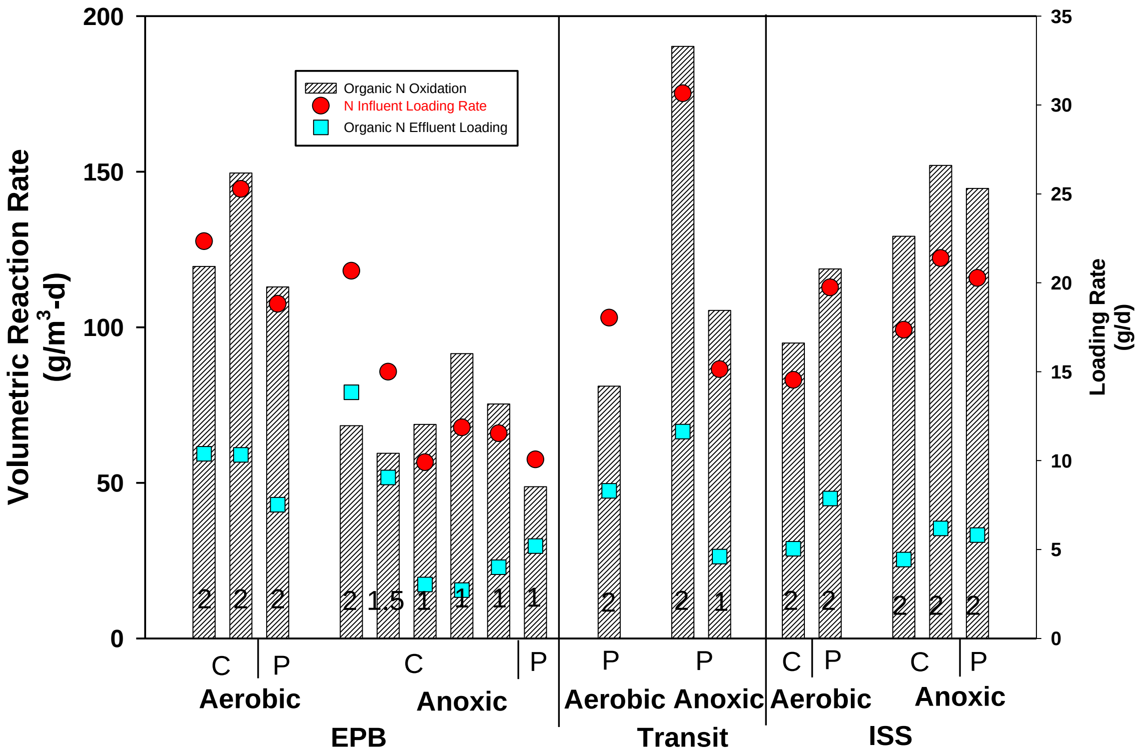

Figure 6. Organic N oxidation volumetric transformation reaction rates in comparison to influent and effluent N loading.

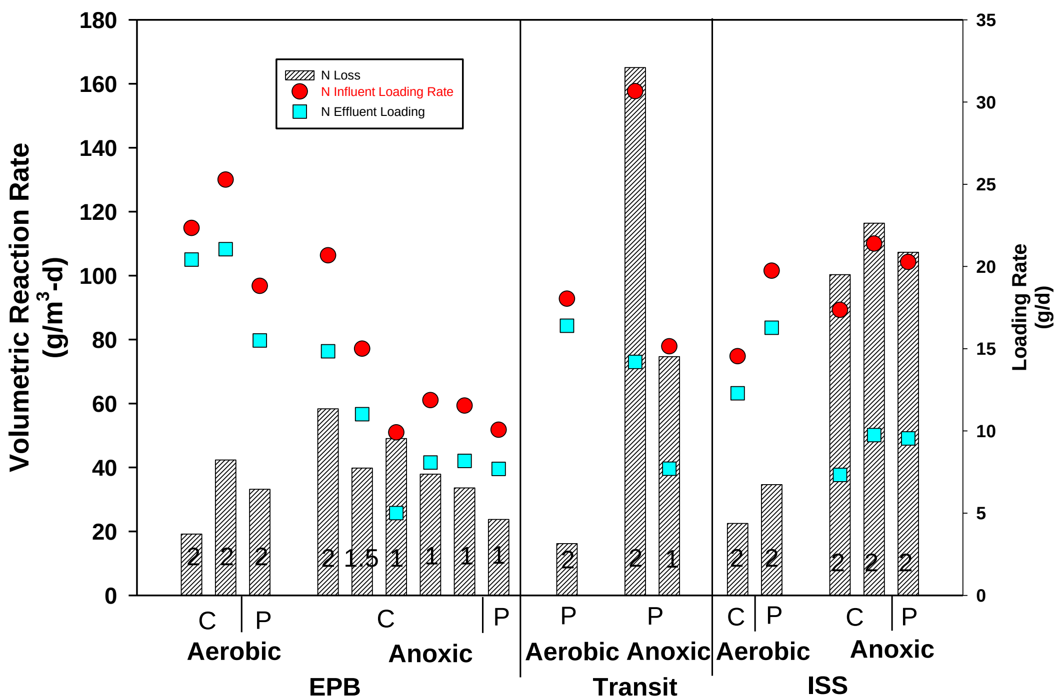

Figure 7. N loss volumetric transformation reaction rates in comparison to influent and effluent N loading.

G. Peripheral Operation Issues

Treatment efficiency and rate of treatment are not the only issues that impact evaluation of the use of biological reactors in life support systems. Operational issues are also important. The rCoMANDR was operated for almost 3 years. During that time no maintenance was performed on any part of the system excluding the in-line sensors. The system is defined as everything downstream of the influent pump to the effluent tank. For instance, no recycling tubing or effluent tubing was changed or cleaned, the recycle pump was not cleaned or replaced, and no solids were removed from the reactor. We also conducted 3 hibernation tests lasting from 2-4 weeks in which the system was placed on recycle with a minimal air flow (~50m/min). After each hibernation period the system resumed treatment at the full pre-hibernation flow rate within 0-5 days. While not included here due to space and time constraints, the effluent is very stable. Tests evaluating the subsequent changes in DOC, pH, organic N, and solids concentration recorded very little change over a 3 week period with no preservation (*results will be presented in a poster at ICES*).

IV. Conclusion

Overall, the system was able to treat a spectrum of habitation waste waters for almost 3 years with no loss of function, performance, and no failures. Performance varied depending on waste stream and O_2 availability (anoxic or aerobic) but in general most organic carbon can be removed (>80% up to 95%). Organic N oxidation is more variable but can approach 70% with adequate residence time, and up to 50% of the total N can be removed with substantial production of N_2 gas for Transit and ISS waste water. We also demonstrate that on-production feeding in which the biological reactor is used as the feed tank does not impact performance. The results of this study with respect to previous studies have a number of important outcomes. The rectangular design with cross flow results in similar performance as older designs which were cylindrical and utilized parallel flow. Membrane specific surface area at or above 100 m^2/m^3 does not limit performance as long as DO can be maintained (e.g. use of pure O_2). Anoxic operation lowers carbon oxidation capacity for short residence times (EPB flow rates) but can improve organic N oxidation. Nitrogen removal is enhanced for anoxic operation but only limited N removal occurred for the EPB waste water. Anoxic operation did reduce the maximum capacity of the system for the EPB wastewater in order to maintain DOC removal.

While we have not yet performed a detailed equivalent system mass analysis, we can propose volumetric requirements and consumable requirements. We propose that ~ 0.1m^3 of reactor volume is required per crew for aerobic treatment of all waste waters. If N_2 generation is beneficial to an overall consumable analysis, then for 1 stage treatment of EPB waste water the volumetric requirement would double. As we have shown that the biological reactor can function as the sole "feed tank" (no intermediate storage), the volumetric requirement is offset to some extent based on required sizing for separate storage tanks for Urine, HC, and hygiene and laundry. While we have not yet evaluated O_2 consumption for this study, previous work has directly measured O_2 consumption, which is in the range of ~50-60 g/d-crew (<5% of the requirement for 1 crew). The only energy consumption is due to the recycle pump. Further analysis is required to evaluate the impact of inclusion of biological reactors into habitation waste water recycling systems based on specific mission scenarios. Such analysis should also consider issues beyond mass and volume requirements but also consider issues such as reduced biofouling throughout the system, impact on brine and reduced volatile carry over to the cabin, elimination of volatile organics to polishing systems, and flexibility to treat diverse waste streams.

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