A Pilot Scale Evaluation of Membrane Aerated Biofilm Reactor (MABR) technology for BNR Process Intensification

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Introduction

The MABR is a promising biological nutrient removal intensification technology. In an MABR oxygen is delivered to a biofilm growing on the outside of membrane surface by diffusion through the membrane wall (Figure 1). The substrate is delivered from the opposite direction from the bulk liquid (or mixed liquor) into the biofilm. The introduction of oxygen and substrate from opposite directions into the biofilm results in a so-called *counter-diffusional biofilm*. Oxygen is consumed within the biofilm with minimal transfer to the bulk liquid. Indeed, effective control of the air flow rate into the lumen and therefore the supply of oxygen supply into the biofilm theoretically results in a biofilm with an aerobic biofilm layer adjacent to the lumen and an unaerated biofilm layer adjacent to the bulk liquid (as illustrated in Figure 1). When an MABR is placed in an anoxic zone of a suspended growth bioreactor, ammonia diffuses into the aerobic biofilm layer promoting nitrification. The nitrate (and any nitrite) produced through nitrification diffuses towards the bulk liquid and denitrification occurs in the unaerated (here anoxic) biofilm layer. As a result, the use of an MABR enables efficient simultaneous nitrification-denitrification within the biofilm when the bulk liquid surrounding the MABR is anoxic. In this way, a hybrid MABR-suspended growth system can be used as an intensified Biological Nutrient Removal (BNR) process. While the concept and principles of an MABR process have been extensively evaluated at the lab-scale for over three decades, commercially available MABR technologies are relatively recent (Martin and Nerenberg, 2012). Our research aims to evaluate MABRs in real-world applications under a wide range of influent and operating conditions treating primary effluent.

Research Objective

Our previous modeling efforts suggested the hybrid MABR-suspended growth (MABR-SG) system supports a higher ammonia oxidizing bacteria (AOB) fraction at lower SRTs compared to the suspended sludge process (Martin et. al., 2016). Intensification of BNR process with an MABR results in nitrification occurring in the bulk-anoxic zone in addition to the bulk aerobic zone with traditional fine bubble diffusers. Consequently, the theoretical SRT required for complete nitrification in the hybrid MABR-SG system is lower than that for a conventional activated sludge (CAS) system (Figure 2). These modeling results motivate the hypothesis that the MABR can effectively intensify a BNR process. Our research aims to test this hypothesis at the pilot scale using a pilot hybrid MABR-suspended growth system at a range of SRTs – below, at and above typical AOB washout conditions.

Methodology and Implementation

A 170 gallon (645 L) hybrid MABR-suspended growth pilot is located at the Hayward Water Pollution Control Facility (Hayward WPCF) in Hayward, California (Figure 3). The pilot is fed primary effluent. A suite of online probes (pH, temperature, DO, ammonia, nitrite and MLSS), are used for process performance monitoring. Influent, bioreactor, and effluent samples are routinely analyzed for chemical oxygen demand (COD), ammonia, total kjeldahl nitrogen (TKN), total phosphate, alkalinity, nitrate, nitrite, TSS VSS. The biofilm and suspended mixed liquor microbial communities are elucidated using high throughput 16s-rRNA sequencing.

This study is a collaboration between Black & Veatch, Suez North America and the City of Hayward.

Preliminary Results and Discussion

Reactor operation commenced in late 2017. The pilot influent (i.e., primary effluent) ammonia concentration is in the range of 41 ± 8 mg-N/L and soluble COD concentration is 242 ± 57 mg/L (Table 1). Initial operation of the reactor was at a fixed flow, rather than a diurnal pattern; at a suspended growth SRT of approximately 4 days (i.e., SRT calculated only using the mixed liquor inventory, waste sludge flow and effluent TSS). Results indicate effective nitrogen removal at the lowest flow rate achieving a Total Inorganic Nitrogen (TIN) of 10 mg-N/L (Figure 4). TIN removal across the process deteriorates at higher flow (and loading) rates. While there is a deterioration in the overall nitrogen removal performance of the process as the flow is increased above 0.3 gpm, the ammonia removal performance did not deteriorate when the flow was increased by 17% from 0.3 gpm to 0.35 gpm. The ammonia loading rate to the pilot has been in the range of ~30 – 65 gN m^3 d^{-1} with ammonia removal rates of between 50% and over 95% (Figure 5). Reactor profile results suggest that the MABR contributes between 35% - 50% of the ammonia removal in the bioreactor. Results also indicate the occurrence of simultaneous nitrification-denitrification in the MABR biofilm. Typical effluent total inorganic nitrogen concentration is in the range of 10-15 mg-N/L with only a 1Q RAS and no internal mixed liquor recycle.

Following initial operation at a fixed flow, the pilot was operated with a diurnal flow pattern corresponding to that of Hayward WPCF, with a nominal average flow of 0.4 gpm. The suspended growth SRT was maintained at approximately 4 days with a mixed liquor suspended solids (MLSS) concentration of 1,600 mg/L. The influent ammonia-nitrogen concentration varied between approximately 30 mg-N/L and 43 mg-N/L, with the peak diurnal concentration occurring from 1300 to 1400 (Figure 6). The effluent ammonia-N concentration remained lower than 0.5 mg-N/L for 18 hours of the day. The effluent ammonia-N concentration increased to a maximum of approximately 2.5 mg-N/L. Note that the lumen process air flowrate was not actively controlled to enhance MABR nitrification performance during the course of the day. Rather it was maintained at a constant level. Overall, these data suggest that at a temperature of 18 – 19 ^{o}C, an effluent TIN concentration of less than 12 mg-N/L at a suspended growth SRT of ~4 days with a hybrid MABR-SG system.

Preliminary Conclusions

Preliminary data from this collaborative study suggests that a hybrid MABR-SG system holds value for those utilities considering intensification of BNR systems. The MABR study is ongoing and additional data, including comparisons between the biofilm microbial community and suspended growth community, will be presented.

References

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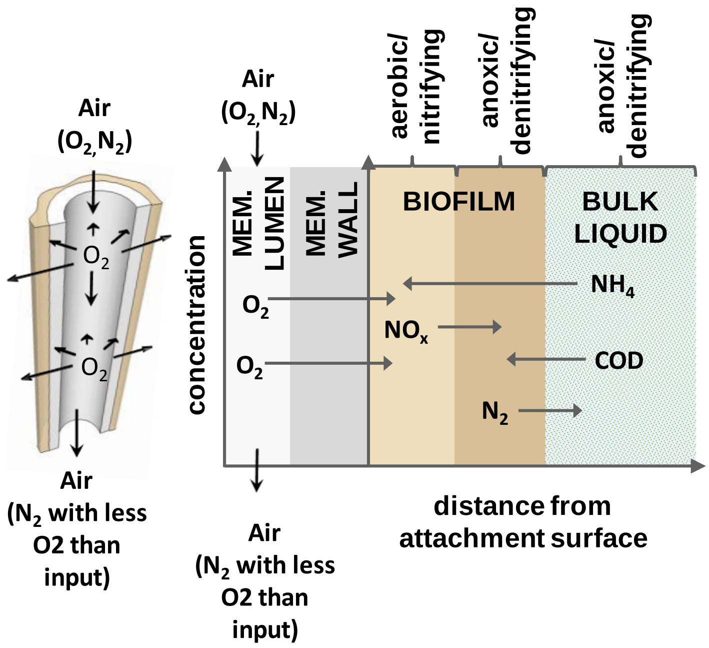

Figure 1. (L) Schematic view of an MABR membrane illustrating air input and discharge and diffusion of oxygen from within the lumen into the biofilm on the outside of the membrane. (R) Cross section of the counter-diffusional biofilm showing the transport of oxygen from the MABR lumen and diffusion of substrate (e.g., NH_4 and COD) from the bulk liquid.

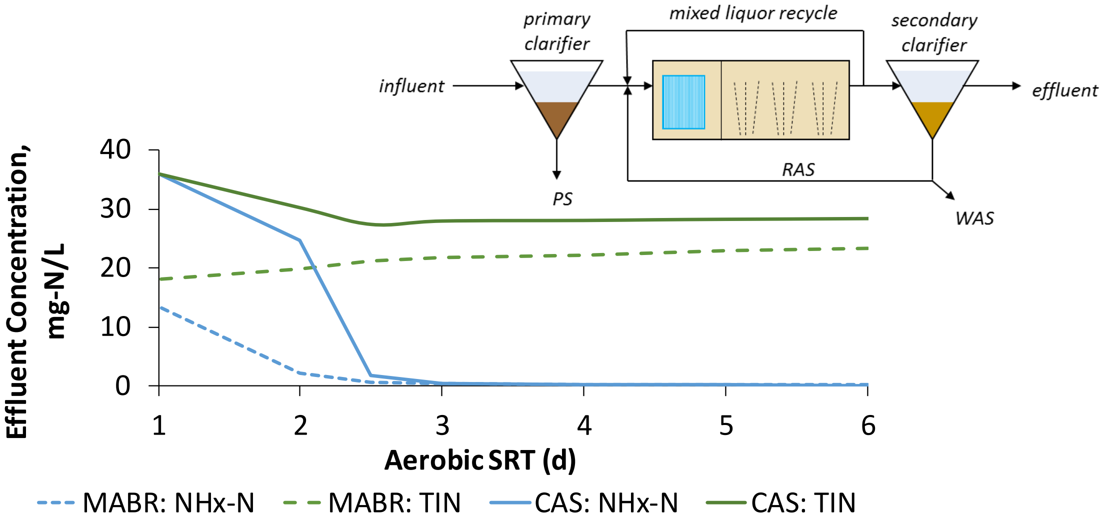

Figure 2. Process intensification of a BNR process (e.g., the MLE configuration shown in the inset) using an MABR results in a lower SRT required for complete nitrification (dashed blue line) compared to a conventional activated sludge (CAS) process. Use of MABR also results in more effective denitrification and a lower Total Inorganic Nitrogen (TIN) concentration.

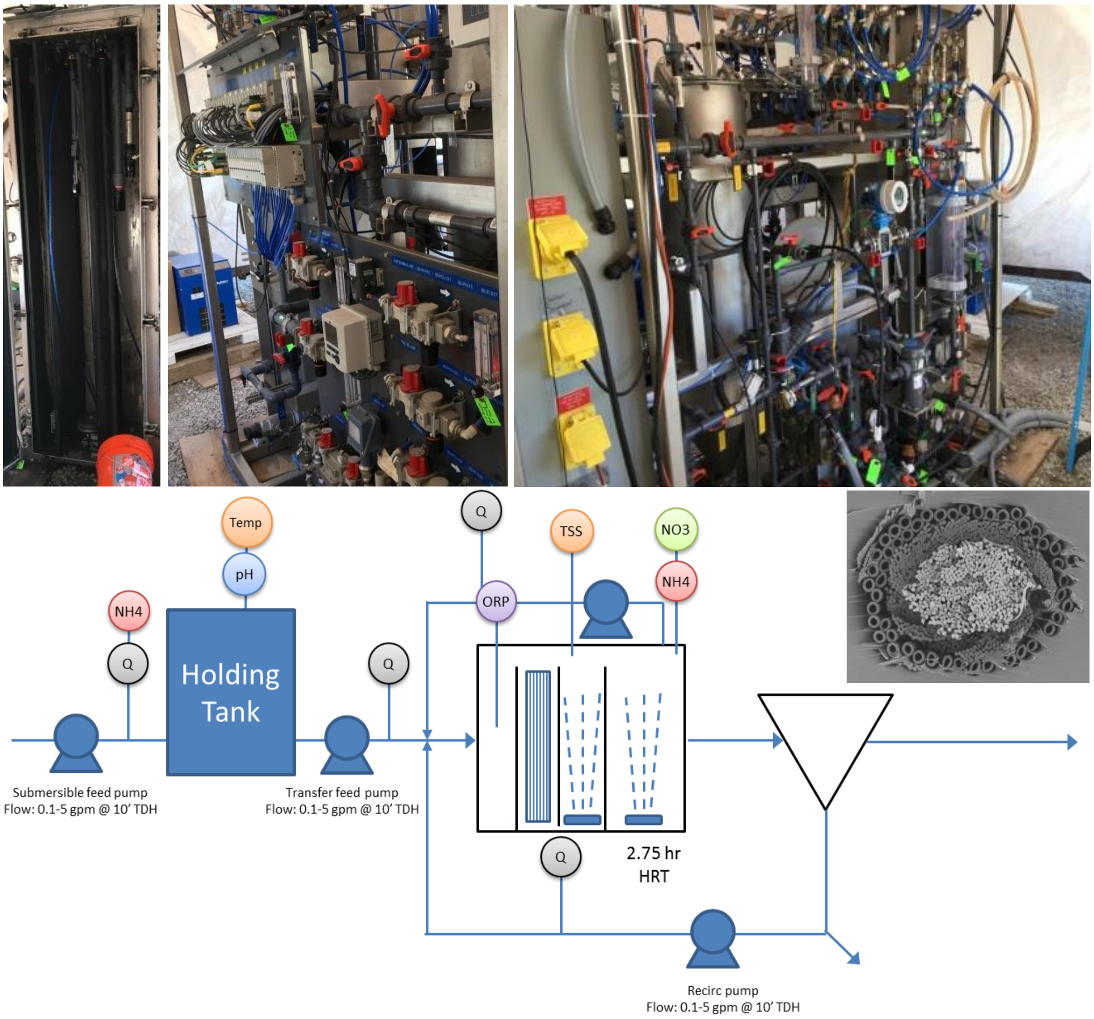

Figure 3. The MABR Pilot Unit at Hayward Water Pollution Control Facility and the schematic layout of the reactor along with online instrumentation. Inset figure shows the structure of the ZeeLung membrane cord.

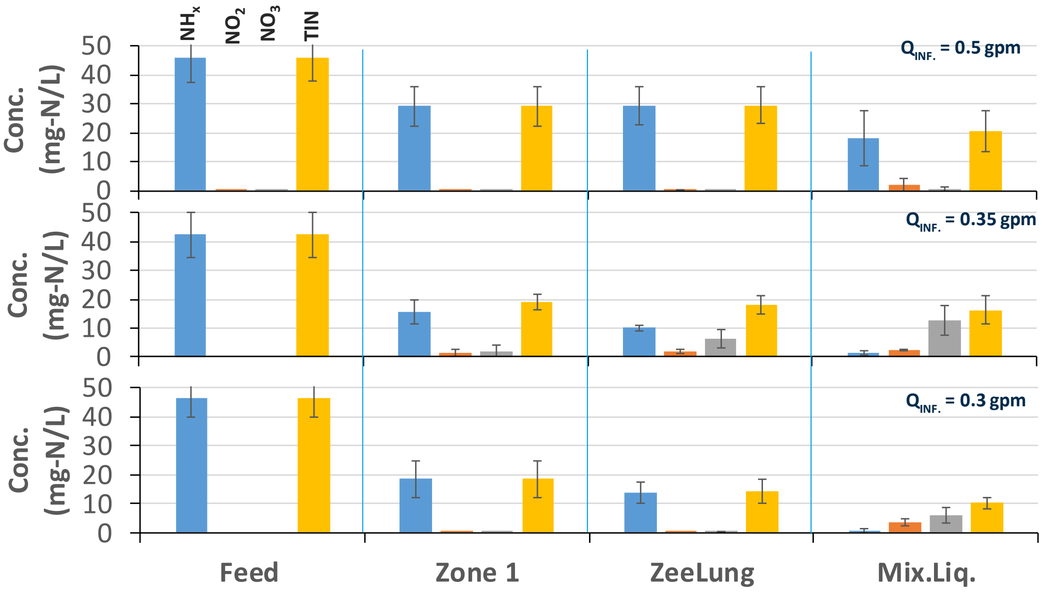

Figure 4. Fate of inorganic nitrogen species across the MABR pilot during operation of the MABR at a fixed flow with an SRT of approximately 4 days. From bottom to top, data are illustrated for operation at 0.3, 0.4 and 0.5 gpm.

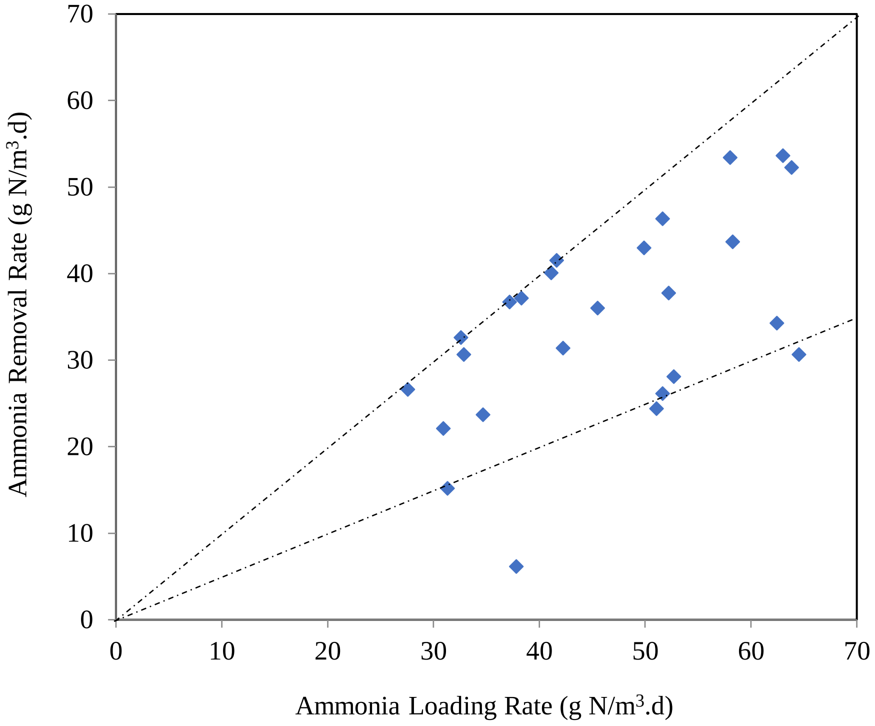

Figure 5. Ammonia removal in the pilot MABR-suspended growth reactor during the startup period.

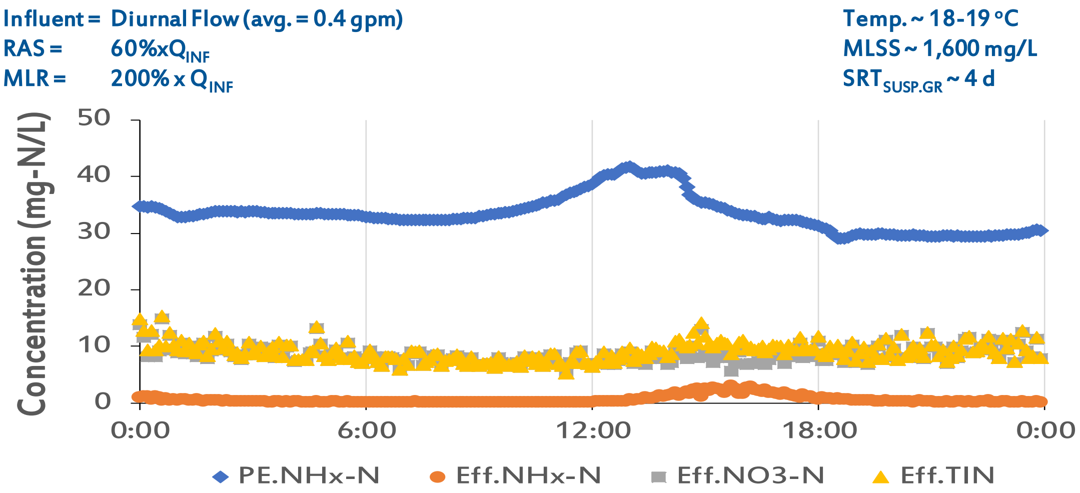

Figure 6. Diurnal influent ammonia concentration (blue), pilot effluent ammonia (orange), nitrate (grey) and total inorganic nitrogen (yellow) with the pilot operated at an SRT of approximately 4 days.

Table 1. MABR pilot influent quality summary

	TSS (mg/L)	VSS (mg/L)	Tot. COD (mg/L)	Filt. COD[1] (mg/L)	Sol. COD[2] (mg/L)	ffCOD (mg/L)	NH_X-N (mg-N/L)	OP (mg-P/L)	Alk. (mg/L as $CaCO_3$)
Count	10	8	17	18	56	2	57	51	21
Max.	322	100	946	406	406	262	60	5	373
90%ile	305	99	631	341	304	259	52	5	370
Avg.	131	84	472	262	242	247	41	3	320
SD	97	15	164	75	57	22	8	1	33
10%ile	68	71	337	180	179	234	32	2	273
Min.	63	51	294	102	96	231	24	1	272

Notes:

1. Filtered COD is the COD measured sample after filtration through a 1.2 μm filter
2. Soluble COD is the COD measured sample after filtration through a 0.45 μm filter