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a Laboratory-scale Demonstration

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Intermittent Aeration Increases Oxygen Transfer Efficiency In Flow-through MABRs: a Laboratory-scale Demonstration

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Summary: Membrane-aerated biofilm reactors (MABRs) are an energy-efficient technology for nutrient and carbon removal; yet, a trade-off remains between their rate and efficiency of oxygen transfer. We operated nitrifying flow-through MABRs under continuous or intermittent aeration modes. The continuously- and intermittently-aerated MABRs nitrified ammonia at similar rates, even as the (calculated) absolute oxygen partial pressure on the gas side dropped to 0.05 atm during the no-aeration phase. The ammonia-oxidizing bacteria in the intermittently-aerated MABRs were dominated by Nitrosospira, previously shown to be abundant at low oxygen concentrations and provide reactor stability under changing conditions. Intermittent aeration did not affect trace organic chemical transformation, which continued under anoxic conditions and may therefore be driven by heterotrophic bacteria. Our results suggest that intermittent aeration can allow for high oxygen transfer efficiencies and high removal rates, which are facilitated by biofilm adaptation.

Keywords: Membrane-aerated biofilm reactors; Intermittent aeration; Oxygen transfer efficiency

Introduction

Membrane-aerated biofilm reactors (MABRs) have emerged as an alternative to conventional bioreactors with the potential to reduce the amount of energy required for aeration [1]. MABRs can be aerated in either a dead-end or a flow-through mode with a trade-off between the oxygen transfer rate (OTR) and the oxygen transfer efficiency (OTE) [2]. Periodic venting can increase the OTR with minimal impact on the OTE in MABRs operated in a dead-end mode [3]. However, ways to increase the OTE without decreasing the OTR in flow-through MABRs remain unexplored. Intermittent aeration is an alternative flow-through mode. It has been applied in MABR studies to allow for autotrophic nitrogen removal via the partial nitritation/anammox pathway [4-5]. Here we provide evidence on how intermittent aeration can be used to increase the OTE in flow-through MABRs without compromising their performance. Lab-scale nitrifying MABRs operated with different aeration strategies were monitored for nitrification rates (NRs) and trace organic chemical (TOrC) removal. The aeration pattern effect on the microbial community composition was also assessed.

Materials and methods

We used three lab-scale flow-through MABRs made of acrylic plates and silicone rubber gaskets. Each reactor had a volume of 280 mL and housed a flat-sheet membrane (Fluence Corporation, NY) with a surface area of 0.01 m^2 and a gas-side volume of 80 mL. The feed was supplied at a flow rate of 0.8 mL min^{-1} (hydraulic retention time = 5.8 h); it contained 50 mg NH_4^+-N L^{-1} and no organic carbon source. Two gas flow meters upstream and downstream to the gas side of the membrane were used for controlling the air flow rate and entry gauge pressure, which were set to 100 mL min^{-1} and 5 kPa, respectively. Air was supplied continuously (Rc) or intermittently (Ri1 and Ri2). Solenoid valves connected to a programmable power strip were used for controlling the duration of the aeration and no-aeration periods. Ri1 was operated in an 8-h cycle, consisting of a 4-h aeration period followed by a 4-h no-aeration period. Ri2 was operated in a 0.5-h cycle, consisting of a 0.25-h aeration period followed by a 0.25-h no-aeration period. The MABRs were operated at room temperature (19 ± 1 °C). pH was not controlled and ranged between 7.2-7.3. The MABRs were run for 385 days under the described operational conditions. The last 100 days of operation are presented.

Results and discussion

All MABRs displayed steady state behaviour for at least 100 days (Fig. 1). The dissolved oxygen (DO) concentration was typically below the detection limit (0.02 mg L^{-1}). The mean NRs of all MABRs were comparable, ranging between 2.6-2.8 g N m^{-2} d^{-1} (Fig. 2a). Comparable NRs and undetectable DO concentrations indicated similar oxygen fluxes across the membranes under all aeration regimes (11.9-12.8 g O_2 m^{-2} d^{-1}, based on nitrification stoichiometry). Therefore, the OTE of Ri1 and Ri2, which received airflow for 50% of the time, was double the OTE of Rc, which was continuously supplied with air. The absolute OTE of Rc was low (0.2%) as air was supplied at a high flow rate in relation to the gas-side volume (gas retention time < 1 min).

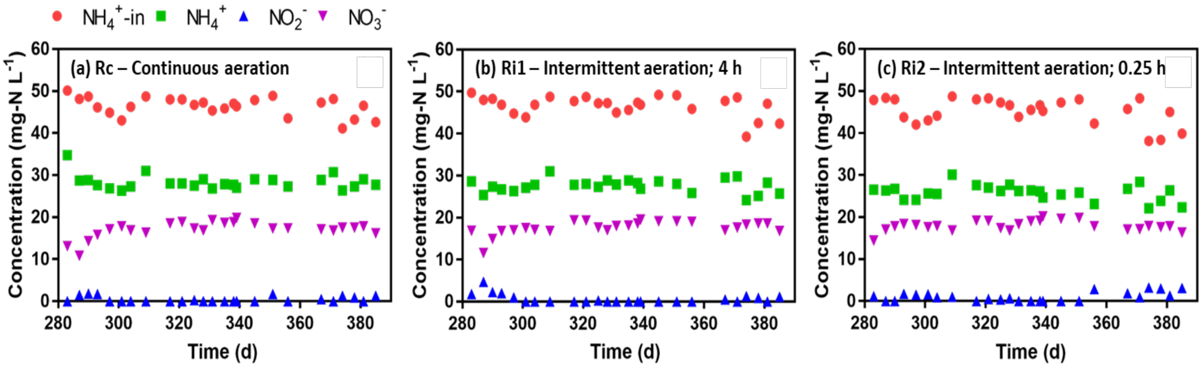

Figure 1. Effluent ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) concentrations and influent ammonium concentrations (NH_4^+-in) during the last 100 days of operation. (a) Rc; (b) Ri1; (c) Ri2.

The NRs were comparable to those often reported in MABR studies at all scales [6]. We could calculate the absolute oxygen partial pressure in the gas side at the end of the no-aeration phases. The absolute oxygen partial pressure in the gas side dropped to 0.20 atm in Ri2 during the 15 minutes in which the aeration was turned off. In Ri1 the drop was significantly higher with the absolute oxygen partial pressure reaching 0.05 atm after 4 hours of no aeration. Nonetheless, Ri1 nitrification capacity was comparable to that of Rc and Ri2. In MABR applications, a decrease of the absolute oxygen partial pressure in the gas side is typically associated with a decline in the removal rate [6]. To the best of our knowledge, this is the first time that a drop in the absolute oxygen partial pressure in the gas side of the membrane is shown not to have a negative impact on performance.

We used 16S rRNA gene amplicon sequencing to investigate the membrane-aerated biofilms. The relative abundance of ammonia oxidizing bacteria (AOB) ranged between 35-40% in all three MABRs. The composition of the AOB guild under continuous aeration was nevertheless different than under intermittent aeration. *Nitrosomonas europaea* was the dominant AOB species in Rc (Fig. 2b). By contrast, *Nitrosospira* sp. was the most abundant among the AOB in Ri1 and Ri2 (Fig. 2b).

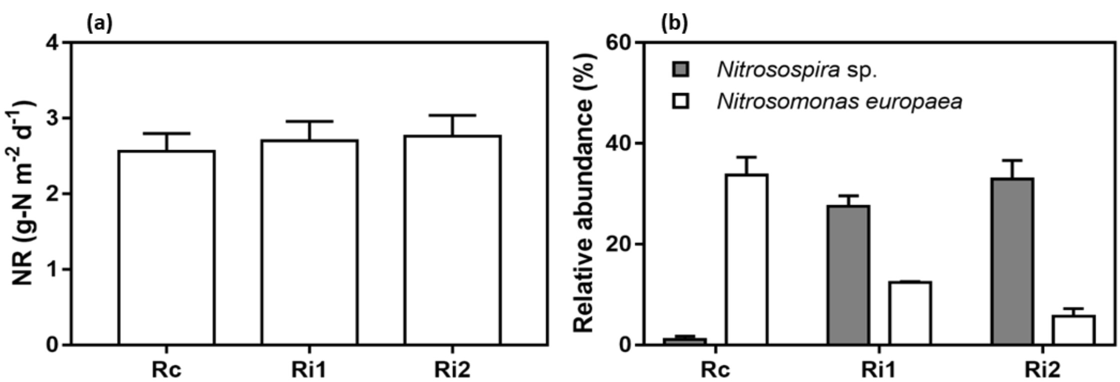

Figure 2. (a) Mean nitrification rates (NRs) in the last 100 days of the operation period. Error bars represent standard deviations; (b) The relative abundance of AOB at the species level as measured at the end of the experimental period (Mean + SD for triplicate samples).

Achieving high performance under low absolute oxygen partial pressures can be explained by the composition of the AOB community within the biofilms. Nitrosomonas and Nitrosospira coexist in wastewater treatment plants, where the balance between the two genera has been suggested to help maintain stable NRs under shifting environmental and operational conditions [7]. Furthermore, the abundance of Nitrosospira is negatively correlated to DO concentrations [8] and members of this genus are significant among AOB in aerated anoxic processes [9]. In our study, intermittent aeration could lead to the formation of a diffusive boundary layer at the membrane-gas interface once aeration was turned off. The periodic gradient could then favor the growth of AOB adapted to low DO concentrations like *Nitrosospira* spp., which could support maximal NRs not only under zero air flow but also under low absolute oxygen partial pressures.

We carried out 24-h batch experiments with nine TOrCs. The transformations of atenolol (ATN) and sulfamethoxazole (SFX) followed first-order kinetics with complete removal of ATN and partial removal of SFX (Fig. 3a-b). We observed no differences in the biomass-normalized transformation rate constants (k_{bio}) of SFX between the MABRs. By contrast, the k_{bio} of ATN varied between the MABRs with Ri2 displaying the highest value. This variation was reflected by the atenolol concentrations that were measured in the effluent. The concentration dynamics of all other tested TOrCs could not be fitted with one-phase exponential decay models nor suggested they were transformed. Nitrification proceeded similarly in all MABRs (Fig. 3c) at a rate of 1.9-2.0 g N m^{-2} d^{-1}. Total inorganic nitrogen removal was also detected at rates of 0.25-0.38 g N m^{-2} d^{-1} with no statistically significant difference between the reactors. Upon addition of allylthiourea (ATU; a nitrification inhibitor) and flushing the gas side of the membrane with N_2, nitrification ceased completely. ATN and SFX transformation kinetics, however, remained as under non-inhibiting conditions, as well as the total inorganic nitrogen removal rate (TINRR; Table 1).

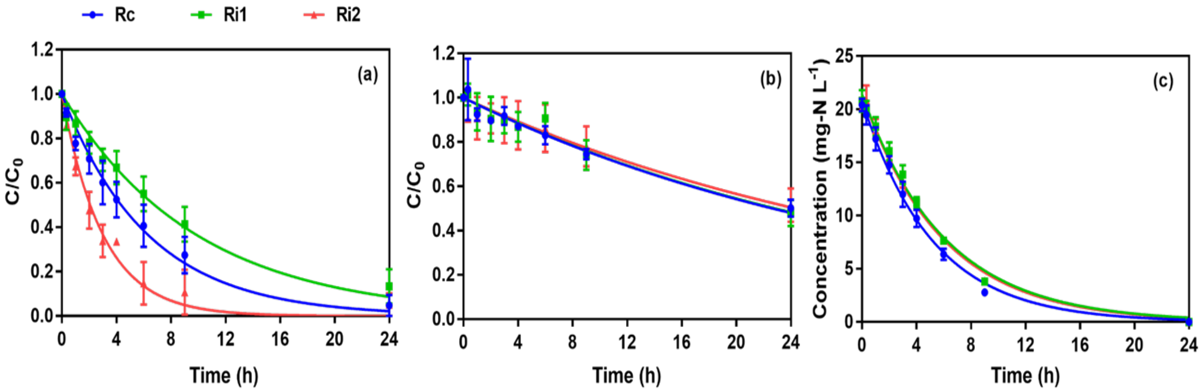

Figure 3. Measured and modeled concentrations of atenolol (a), sulfamethoxazole (b), and ammonium (c) during batch experiments. C/C$_0$ denotes the concentration normalized to the initial concentration. Error bars represent standard deviation. Data points are fitted with one-phase exponential decay models.

Table 1. k_{bio} (L gVSS^{-1} d^{-1}), NR (g-N m^{-2} d^{-1}), and TINRR (g-N m^{-2} d^{-1}) in TOrC batch experiments with (+inh.) and without (-inh.) ATU and N_2 flushing

	k_{bio}							
Treat.	ATN	95% CI	SFX	95% CI	NR[a]	95% CI	TINRR[a]	95% CI
-inh.	1.43	[1.27, 1.62]	0.37	[0.29, 0.46]	0.94	[0.7, 1.1]	0.29	[0.16, 0.41]
+inh.	1.73	[1.39, 2.08]	0.36	[0.20, 0.58]	0.04	[-0.2, 0.3]	0.23	[0.10, 0.36]

[a] calculated using linear regression at the range 0-6 hours.

In conclusion, our results imply that: intermittent aeration of flow-through nitrifying MABRs can increase the OTE by at least 100% without affecting the NR; maximal NRs are maintained despite a drop in the absolute oxygen partial pressure in the gas side of the membrane during the no-aeration phase and supported by AOB that are adapted to low DO concentrations; TOrC removal in nitrifying MABRs is not affected by intermittent aeration and is driven by denitrifying heterotrophic bacteria.

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