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Performance and robustness of an ANAMMOX anaerobic baffled reactor subjected to transient shock loads

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ABSTRACT

The impacts of transient overloads on the performance of a laboratory-scale anaerobic ammonium oxidation (ANAMMOX) anaerobic baffled reactor was studied by increasing the substrate concentration or inflow rate to 1.5–3.0 times above normal values. These shocks, with the exception of the highest substrate shock, weakened the nitrogen removal efficiency (NRE) but improved the nitrogen removal rate by 0.01–0.18 g l^{-1} h^{-1}. The communities and the location of the sludge may be altered by distinct types of shocks. The substrate vibration data showed that the reactor was unresponsive to hydraulic shocks but sensitive to substrate shocks and the former compartments were more susceptible to the shocks. In the inhibition period, the pH and NRE of the reactor were related to the residual ammonium and free ammonia (FA) and FA was a factor in the reactor fluctuations. The Gaussian model proposed to describe the shocks response fits the experimental data well.

1. Introduction

Anaerobic ammonium oxidation (ANAMMOX) is a biological process in which ammonium (NH_4^+) is oxidized to dinitrogen gas (N_2) using nitrite (NO_2^-) as an electron acceptor, producing meager amounts of nitrate (NO_3^-) (Eq. (1)) (Strous et al., 1998). Compared with the conventional nitrification/denitrification process, the application of ANAMMOX for nitrogen removal could lead to significantly lower costs for aeration and exogenous electron donors. In laboratory-scale trials, an optimal nitrogen removal rate (NRR) has been shown to be 74.3–76.7 kg N m^{-3} d^{-1} (Tang et al., 2011), and there are several studies where an NRR above 20 kg N m^{-3} d^{-1} was obtained (Tsushima et al., 2007; Chen et al., 2010b; Tang et al., 2010; Ma et al., 2011). Given the appropriate operating conditions, ANAMMOX bioreactors have an amazing potential for high efficiency.

$$NH_4^+ + 1.31NO_2^- + 0.066HCO_3^- + 0.13H^+ \rightarrow N_2 + 0.26NO_3^- + 0.066CH_2O_{0.5}N_{0.15} + 2H_2O \quad (1)$$

For a successful and sturdy ANAMMOX process, in both laboratory-scale and full-scale reactors, the latent negative effects of the influential factors that emerge in daily operations should be studied. Variations in inflow loads, influent pH, reactor temperatures, and specific compounds, primarily exogenous toxic and inhibition compounds, lead to reactor performance deterioration (Leitão et al., 2006). Fluctuations in hydraulic and substrate loads are more common during routine work and are reported to be the responsible for losses in ANAMMOX activity. Reactors with diverse configurations make systems resilient to hydraulic and substrate shock loads. Nachaiyasit and Stuckey (1997a,b) evaluated perturbations during and after hydraulic and substance overloads in a methanogenic anaerobic baffled reactor (ABR). With a specific configuration design, the ABR has a "phase separation" characteristic that creates a sufficient buffer space for the overloads. The authors found that the reactor had a high tolerance to transient shocks and was minimally influenced by oscillations in inflow substrate concentrations and flow rates; even if such a disturbance occurred, the unit quickly recovered to the original processing level. Other researchers have shown that multi-stage wastewater treatment processes were capable of absorbing the shock loads, recovered quickly from the shocks, with recovery times proportional to the magnitude of the shock loads (Seetha et al., 2010). Jin et al. (2008) subjected three laboratory-scale ANAMMOX bioreactors to different substrate concentration and flow rate shocks. The reactors had dissimilar robustness, in accordance with the quantitative evaluation, due to the different reactor configurations. The instability indices indicated that the hydraulic shocks were less harmful than the substrate shocks.

The design of ABRs has been evolving since the early 1980s, and the ABRs currently possess several advantages over other well-established anaerobic reactors. ABRs have a better resistance to shock loads, longer biomass retention times and the ability to

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partially separate between the various phases of anaerobic catabolism (Barber and Stuckey, 1999; Shanmugam and Akunna, 2010). However, relatively few studies have examined the role of the ABR in determining both the stability and the response of the ANAMMOX pathway under unstable influent substrate concentrations or flow rate conditions. Accordingly, the objective of the present study was to elucidate the unique responses of an ANAMMOX ABR, which had been in a pseudo steady state (PSS) condition, under several substrate concentrations and flow rate shock conditions.

2. Methods

2.1. Synthetic wastewater

Ammonium and nitrite were added to the mineral medium, as required, in the form of $(NH_4)_2SO_4$ and $NaNO_2$, respectively. The mineral medium was prepared according to Jin et al. (2008).

2.2. Reactor and experimental setup

The ABR was fabricated from polymethyl methacrylate with an effective volume of 13.5 l and contained three vertical baffles that divided the reactor into four identical compartments. In each compartment, downcomer and riser regions were constructed with a slanted edge (45°) vertical baffle to direct the flow evenly through the riser. The volume ratio of the downcomer to riser was 1:3. Each compartment was equipped with a sampling port. The influent was fed from troughs into the reactor, and a peristaltic pump was used to control the influent feed rate to the ABR. The temperature of influent in the feed tank was heated to 30 ± 1 °C. The produced gas was discharged via portholes in the top of the each compartment. Black fabric was used to cover the entire reactor to prevent light inhibition.

After starting and operating for about 1 year, the reactor was operated under PSS conditions at a hydraulic retention time (HRT) of 8 h. The NRR of the bioreactor was approximately 0.83–0.89 $g\,l^{-1}d^{-1}$ with a 79.7–84.9% nitrogen removal efficiency (NRE). The stability of the reactor was tested for 4 h during substrate concentration or flow rate shocks, and the expected operation conditions are listed in Table 1. At the end of the overload periods, the inflow substrate or inflow rate was returned to a constant level. There was an interval duration of 20 times the HRT before manipulating the next shock.

2.3. Chemical analysis and calculations

NH_4^+-N, NO_2^--N and NO_3^--N were measured by standard methods (APHA, 1998). Temperature and pH were detected by an alcohol thermometer and a pH meter (Mettle Toledo Delta 320), respectively. Free ammonia (FA) and free nitrous acid (FNA) were calculated according to formulas provided by Anthonisen et al. (1976). The nitrogen overload caused by substrate and hydraulic shock was calculated by Eqs. (2) and (3), respectively, and the NRR of reactor in shock period was calculated by Eq. (4).

$$M_{iconc} = (N_{ov} - N_{ss})\Delta t F_{ss} \tag{2}$$

$$M_{ihyd} = N_{ss}\Delta t(F_{ov} - F_{ss}) \tag{3}$$

where M_{iconc} = the extra nitrogen applied under substrate shocks (mg); N_{ov} = the nitrogen concentration during the shocks ($mg\,l^{-1}$); N_{ss} = the nitrogen concentration under PPS conditions ($mg\,l^{-1}$); M_{ihyd} = the extra nitrogen overload under hydraulic shocks (mg); F_{ov} = the inflow rate under hydraulic shocks ($l\,h^{-1}$); F_{ss} = the inflow rate under PPS conditions ($l\,h^{-1}$); Δt = the duration of the shock (h).

$$\text{NRR under shocks} = \sum_i F^i\left[\left(\frac{N_j^i + N_j^{i-1}}{2}\right) - N_j^0\right]\Delta t^i \tag{4}$$

where i = the period of time; F^i = the flow rate during the period i; N_j^i = the nitrogen concentration of the effluent during the period i; N_j^{i-1} = the nitrogen concentration in the effluent during the period $i-1$; N_j^0 = the nitrogen concentration during PSS conditions; Δt^i = the duration of period i.

2.4. Gaussian model

The Gaussian model in this paper was used to simulate the effluent under shock condition, and the model was listed in Eq. (5).

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{5}$$

where $f(x)$ = effluent substrate concentration ($mg\,l^{-1}$); x = the period of time (h); σ = mathematical expectation; μ = variance.

3. Results and discussion

3.1. Performance of an ANAMMOX ABR under transient substrate shocks

Ammonium and nitrite, substrates of the ANAMMOX pathway, were inhibitors when their levels exceeded threshold values. Therefore, a several-fold inflow substrate change may cause a perturbation in the bioreactor. In all three substrate shocks, the effluent ammonia and nitrite concentrations from each compartment increased, in proportion to the respective influent concentrations. Following the substrate shock load initiation, the ammonium and nitrite in each compartment increased sequentially, reached a peak within 9 h, and caused a temporary deterioration of the NRE in reactor. Fig. 1 shows the effluent ammonium, nitrite and pH variations under substrate shocks.

The degree of deterioration depends on the duration and magnitude of the shocks and the adaptability of the ANAMMOX community. When the reactor was subjected to a shock load of 1.5 times higher than the normal operation level (Shock No. 1), the feedback of the reactor performance was observed. The peak value of effluent NH_4^+-N and NO_2^--N reached 94.5 and 47.8 $mg\,l^{-1}$,

Table 1
Nitrogen loading rate and flow rate applied at each loading shock.

Shock No.	Set flow rate ($l\,h^{-1}$)	Upflow velocity ($m\,h^{-1}$)	Set influent NH_4^+-N ($mg\,l^{-1}$)	Set influent NO_2^--N ($mg\,l^{-1}$)	Set nitrogen loading rate ($g\,l^{-1}\,h^{-1}$)
Baseline	1.69	0.13	175.0	175.0	0.59
1	1.69	0.13	262.5	262.5	0.89
2	1.69	0.13	350.0	350.0	1.18
3	1.69	0.13	525.0	525.0	1.77
4	2.53	0.19	175.0	175.0	0.89
5	3.38	0.26	175.0	175.0	1.18
6	5.06	0.39	175.0	175.0	1.77