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Short communication

Startup strategy for partial nitritation treatment of anaerobically digested effluent of swine wastewater in a sand filter

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ABSTRACT

This research investigated the startup of the partial nitritation (PN) process in a sand filter at ambient room temperature (5.5–27 °C) to produce an effluent suitable for the subsequent anaerobic ammonium oxidation (anammox) process. A naturally ventilated sand filter was used to treat anaerobically digested effluent of swine wastewater. Startup strategy of gradual step increases in the influent ammonium nitrogen concentration and pH successfully achieved the PN process. The principal cause for nitrite accumulation was high free ammonia concentration (up to about 20 mg L^{-1}). An effluent with a nitrite-to-ammonium ratio of 1.02 was obtained, with the optimal influent ammonium nitrogen concentration of 600.0 mg L^{-1} and pH of 8.09. Overall, the PN process can be maintained in a sand filter without forced aeration, and coupling with the subsequent anammox process to achieve completely unpowered autotrophic nitrogen removal.

1. Introduction

Anaerobic digestion technology has been widely applied in the treatment of swine wastewater for generating biogas (Massé et al., 2008; Vanotti et al., 2007). However, its digested effluent is usually characterized by high concentrations of organic pollutants, in particular ammonium nitrogen (Deng et al., 2008). Because land spreading of digested effluent has been restricted in some regions by insufficient spread-lands around pig farms, effective post-treatments for nitrogen removal have been recommended to facilitate management of this material (Waki et al., 2008; Zheng et al., 2012).

Generally, conventional nitrification-denitrification (NDN) is the most popular biological nitrogen removal (BNR) technology being applied in the treatment of digested effluent. Nevertheless, the performance of the NDN process in treating anaerobically digested effluent of swine wastewater has been poor, with a low nitrogen removal rate (Deng et al., 2008). The poor nitrogen removal may be attributed to the lack of biodegradable organic matter serving as an electron donor, and to the shortage of alkalinity (Deng et al., 2008; Obaja et al., 2005; Yang et al., 2015).

Innovative BNR technologies based on anaerobic ammonium oxidation (anammox) have been increasingly applied in treating ammonium-rich wastewaters (Daverey et al., 2013; Li et al., 2014). The anammox process, which directly converts ammonium to nitrogen gas using nitrite as an electron acceptor, is considered a promising technology for enhanced nitrogen removal with the advantages of less oxygen demand and no added carbon (Kartal et al., 2010; van der Star et al., 2007). Significantly, the anammox process requires the availability of both ammonium and nitrite, the latter of which is not common in real wastewaters but can be generated by partial nitritation (PN) (Daverey et al., 2013). Therefore, prior to anammox, most wastewaters can be subjected to the PN process as a pretreatment step to generate nitrite, thereby producing a suitable influent (with 1:1 nitrite-to-ammonium ratio) for the anammox process (Kong et al., 2013).

As for energy consumption, Riaño and García-González (2014) reported that the NDN unit consumed 96% of total power used, due to the intensive aeration required for ammonium oxidation. Obviously, compared to complete nitrification, the PN process requires lower oxygen demand, but forced aeration is necessary for ammonium oxidizing bacteria (AOB) to convert about half of the ammonium into nitrite, and results in both high energy consump-

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tion and operational costs (González-Martínez et al., 2014; Zheng et al., 2012). Therefore, a cost-effective post-treatment alternative without forced aeration for PN process should be sought, and attention was drawn to the sand filters (Song et al., 2015; Tonon et al., 2015; Zheng et al., 2012). Using natural ventilation, sand filters can introduce oxygen into the treatment process without forced aeration. Thus, if coupled with the PN process in sand filters, the subsequent anammox process may achieve completely unpowered autotrophic nitrogen removal.

The objective of this study was to evaluate the feasibility of operating the PN process in a naturally ventilated sand filter at ambient room temperature, for producing a suitable influent for the subsequent anammox process. A startup strategy for initiating the PN process was investigated that involved step increases in influent ammonium nitrogen concentration and pH with periodic suspension of the sand filter operation.

2. Materials and methods

2.1. Wastewater and sand

Anaerobically digested effluent used in this study was provided by a biogas plant treating swine wastewater in central Sichuan Province, China. The characteristics of the anaerobically digested effluent were as follows: pH 6.99–8.26, chemical oxygen demand 350.0–879.6 mg L^{-1}, ammonium nitrogen (NH_4^+-N) 292.2–629.9 mg L^{-1}, nitrite nitrogen (NO_2^--N) 0.1–5.8 mg L^{-1}, nitrate nitrogen (NO_3^--N) 1.0–2.2 mg L^{-1}.

The sand (0.1–1.5 mm particle size) used in the experiment was obtained from Guanghan, Sichuan Province, China. The selected sand was washed with distilled water to remove the mud, soaked for 12 h in deionized water and dried by a thermostat oven at 90 °C before use. The porosity of the selected sand was found to be 11.90%. Additionally, the main mineral in the sand was quartz (SiO_2, 64%), while the main accompanying mineral was calcium-rich albite ((Na, Ca)Al(Si, Al)$_3$O$_8$, 22%) (Zheng et al., 2011). The element present in the greatest abundance in the sand was oxygen (O, 55.1%), followed by silicon (Si, 23.1%), aluminum (Al, 7.15%), carbon (C, 4.26%), calcium (Ca, 3.34%), iron (Fe, 2.13%), sodium (Na, 1.71%), potassium (K, 1.36%) and magnesium (Mg, 1.27%).

2.2. Experimental set-up and operational mode

The experimental sand filter was cylindrical and was made of plexiglas with a height of 65 cm and an inner diameter of 15 cm. The filter bed was 50 cm high with a working volume of 8.84 L, using sand as packing material. Additionally, a depth of 10 cm pisolite (5–10 mm particle size) was placed at the bottom of the filter to support the sand and to prevent clogging. The sand filter was operated at ambient room temperature (5.5–27 °C) for 110 days segmented into four stages by "rest" periods during which operation of the filter was suspended. The main operational mode of the sand filter is listed in Table 1. Oxygen was introduced into the filter through natural ventilation without any extra forced aeration. Digested effluent was introduced intermittently by a porous distributor at the top of the sand filter without deoxygenation, allowing oxygen to penetrate deep into the sand filter bed by air diffusion.

2.3. Analytical methods

Influent and effluent samples were collected at three-day intervals and then analyzed immediately after collection. Following standard methods (APHA et al., 1998), concentrations of NH_4^+-N, NO_2^--N and NO_3^--N were measured using a UV–Vis spectrophotometer (UV-2450, Shimadzu, Japan), pH was determined by an acidimeter (PHS-3C, DAPU, China), and room temperature was measured with a mercury thermometer.

3. Results and discussion

3.1. Ammonium nitrogen removal and pH fluctuations

Based on the variations in ammonium removal and nitrite accumulation over time, the startup of PN in the present study involved four stages: the adsorption stage (days 1–28), the adaptation stage (days 51–78), the growth stage (days 85–94), and the stabilization stage (days 101–110).

During the adsorption stage, the average nitrogen loading rate (NLR) and influent NH_4^+-N concentration were maintained at 36.3 gNH_4^+-N m^{-3} d^{-1} and 320.9 mg L^{-1}, respectively. In the first 20 days, effluent NH_4^+-N concentration was consistently less than 5 mg L^{-1}, and the average NH_4^+-N removal efficiency was 99.4%. However, in the last few days of this period, the average effluent NH_4^+-N concentration began to increase from 2.2 mg L^{-1} (day 20) to 43.8 mg L^{-1} (day 28).

When the digested effluent was first introduced into the sand filter, the removal of NH_4^+-N was mainly due to ion exchange and chemical adsorption, resulting in a rapid decline in the effluent NH_4^+-N concentration (Fig. 1). Achak et al. (2009) pointed out that adsorption and ion exchange were the principal physical-chemical surface reactions occurring in sand during the transit of wastewater through this medium. The exchange reaction can be expressed as Eq. (1) (Zorpas et al., 2000):

$$[S]\,M^{n+} + nNH_4^+ ?\,[S]\,nNH_4^+ + M^{n+} \quad (1)$$

where, S is the anionic group of minerals in sand; M^{n+} represents the exchangeable cations (mainly alkali metal ions or alkaline earth metal ions), and n is the valence of exchangeable cations; NH_4^+ represents the ammonium nitrogen ions.

During ion exchange, strong alkali metal ions (Na^+ and K^+) or alkaline earth metal ions (Ca^{2+} and Mg^{2+}) of the sand were easily replaced by NH_4^+ ions (weak alkaline ions), and the exchanged metal ions entered the aqueous phase forming hydroxides, thus causing an increase in effluent pH (Achak et al., 2009; Ortega et al., 2000). This explains why the average effluent pH (7.94) was higher than the influent pH (7.36) during the adsorption stage (Fig. 1). There were abundant alkali metal ions and alkaline earth metal ions in the sand filter, thus leading to a reasonably low effluent NH_4^+-N concentration and a high effluent pH. However, as the experiment progressed, ion exchange gradually reached saturation such that effluent NH_4^+-N concentration increased while pH dropped near the end of the adsorption stage.

At the end of the adsorption stage, digested effluent delivery to the sand filter was suspended for about 20 days, then loading was resumed on day 51 during the adaptation stage with the average NLR of 105.6 gNH_4^+-N m^{-3} d^{-1} and influent NH_4^+-N concentration of 466.3 mg L^{-1}, respectively. From the very start of the adaptation stage, ion exchange and chemical adsorption remained dominating for NH_4^+-N removal. Because the 20-day suspension period led to the recovery of most of the adsorption and ion exchange sites with the exchanged NH_4^+ ions being removed by ammonia volatilization or nitrification. However, as adsorption and ion exchange sites became increasingly saturated, the nitrification process got functional, and effluent NH_4^+-N concentration slowly increased with the average effluent NH_4^+-N concentration of 229.4 mg L^{-1}. At this point, the sand filter completed the transition from adsorption and ion exchange to nitrification for NH_4^+-N removal.

Additionally, the influent pH was elevated to 7.71 at the adaptation stage. There was an appearance of a "break point" at approximately day 67 in both the influent and effluent pH pro-