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Control of partial nitrification using pulse aeration for treating digested effluent of swine wastewater

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ABSTRACT

Three sequencing batch reactors (SBRs) were used to investigate the influence of pulse frequencies on the partial nitrification (PN) process in this study. At a total aeration time of 6 min each hour, the aerated frequencies of R1, R2 and R3 were 6, 3 and 2 time h^{-1}. During the steady period (117-143d), the nitrite accumulation rates (NARs) were 90.80%, 90.71% and 90.23% in R1, R2 and R3, respectively, indicating a steady nitritation was acquired. Activity measurements of the sludge samples taken at day 138 showed the activity of nitrite oxidating bacteria (NOB) was 0, indicating NOBs were successfully suppressed. The ratio of NO_2^--N to NH_4^+-N in the effluent of R3 was 1.35, which most closely matched the influent of Anammox process. However, the energy efficiency evaluation showed that R1 had the highest actual oxygen transfer efficiency (AOTE) and dynamical efficiency (DE).

1. Introduction

Partial nitrification-anaerobic ammonium oxidation (PN-Anammox), an innovative biological nitrogen removal method, can oxidize ammonium to nitrite, and then directly use the nitrite as the electron acceptor to oxidize ammonium to N_2. It is widely used to treat low carbon-to-nitrogen (C/N) ratio wastewater because of its several advantages. First, it shortens the path of nitrogen removal (referred to as shortcut biological nitrogen removal) and decreases the oxygen demand by 60%. Second, compared with heterotrophic denitrifying bacteria, Anammox bacteria are autotrophic and, therefore, have no need of organic carbon. Hence, this greatly decreases the operating costs (Jetten et al., 2002; Wang et al., 2012). The digested effluent of swine wastewater is a typical low C/N ratio wastewater from which most of the chemical oxygen demand (COD) is removed after anaerobic digestion (Meng et al., 2016; Zhao et al., 2014). When treating the digested effluent of swine wastewater, the traditional nitrification-denitrification method exhibits a low nitrogen removal performance because of the lack of an easily degradable electron donor. Apparently, PN-Anammox brings a new perspective. The PN-Anammox process has been successfully applied to treat the digested effluent of swine wastewater on a laboratory scale in many studies (Lackner et al., 2014; Meng et al., 2016; Shuang et al., 2017; Vazquez-Padin et al., 2009). However, its application on an industrial scale has not been reported (Lackner et al., 2014). As a result, there is much work to be done before the PN-Anammox process can be applied to the digested effluent of swine wastewater.

In the PN-Anammox process, it is well known that Anammox bacteria have a long doubling time (10–14 d at 30–40 °C) and a high sensitivity to changing environmental conditions. Moreover, there is an important technical challenge in the PN process, which is nitritation (Ge et al., 2014; Jin et al., 2012; Tokutomi et al., 2010). In the literature, many options have been discussed for controlling the PN process based on the inhibition of nitrite oxidizing bacteria (NOB), including oxygen control, high temperature, high pH, free ammonia (FA), free nitrous acid (FNA) and alkali etc (Bournazou et al., 2013; Ge et al., 2015; Park et al., 2010; Tokutomi et al., 2010). However, these options increase the operational cost compared to dissolved oxygen (DO) control. Two methods have been reported for DO control in the literature. The first one is continuous aeration. Yong et al. (2009) and Zeng et al. (2010) realized nitrite accumulation by controlling DO at 0.3–0.7 mg L^{-1} (Yong et al., 2009; Zeng et al., 2010). However, the NOB inhibited by oxygen limitation easily recovered when DO ranged out of control during continuous aeration, further influencing the stabilization of the PN process (Yang and Yang, 2011). In addition, many studies showed that a low DO concentration not only weakens the activities of aerobic ammonia-oxidizing bacteria (AOB), resulting in a low nitrogen removal rate in the PN-Anammox process, but could also result

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in sludge bulking (Yang and Yang, 2011; Zeng et al., 2010). The other method of DO control is intermittent aeration. Compared to continuous aeration, it easily suppresses NOB. As AOB have a higher oxygen affinity and a stronger ability to adapt from anoxic to aerobic conditions (Kornaros et al., 2010), they can easily out-compete NOB and quickly recover their capabilities during intermittent aeration (Bournazou et al., 2013; Ge et al., 2014; Li et al., 2008). Pulse aeration is a type of intermittent aeration when the aeration frequency is higher than in general intermittent aeration. The air pulses provide a better mixture inside the reactor and maintain a suitable DO concentration (Figueroa et al., 2012). However, thus far, no studies have focused on the effects of different aeration frequencies on nitritation.

The influences of different frequencies of pulse aeration on the PN process for treating digested effluent of swine wastewater in a sequencing batch reactor (SBR) were investigated in this study, not only in order to acquire a high and stable nitrite accumulation rate (NAR) but also to obtain a high ammonium conversion rate (ACR). In addition, the characteristics of the effluent of PN process were matched with the influent of Anammox process. Moreover, the energy efficiencies of different frequencies of pulse aeration were evaluated to select the optimal aeration strategy.

2. Materials and method

2.1. Set-up and operation

Three SBRs with working volumes of 4.0 L were used to acquire an optimal aeration frequency for controlling the PN process. The SBRs, which have inner diameters of 10 mm, heights of 510 mm and height-to-diameter ratios of 5.1, were fabricated using plexiglass and had thermostatted water baths to control the temperature around 35 ± 1 °C. Air distributors were fixed at the bottoms of the SBRs, and were each connected to an air pump and gas flow meter. The experiments used pulse aeration, and the DO concentration was controlled by a gas flow meter (see Table 1). At a total aeration time of 6 min each hour, the aerated frequencies of R1, R2 and R3 were set to 6, 3 and 2 times h^{-1}, namely R1 (6 times h^{-1}), R2 (3 times h^{-1}) and R3 (2 times h^{-1}). A mixing device operating at 60–80 rpm was used to keep the mixed liquor homogenous for each SBR. The digested effluent of swine wastewater was taken from a swine farm at Chengdu, China, and it contained 400–900 mg L^{-1} NH_4^+-N, 0–3 mg L^{-1} NO_2^--N and NO_3^--N, 305–1000 mg L^{-1} COD, 6.4–8.0 mg L^{-1} total phosphorous and 0.02 mg L^{-1} total solids (Shuang et al., 2017). The aerobic sludge was taken from a municipal wastewater treatment plant at Chengdu, China. The mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) were 13.24 g $L^{-1}$and 8.32 g L^{-1}, respectively. The ratio of seed sludge to digested effluent swine wastewater was 1:1. Two peristaltic pumps (Longer WT600-2J, Baoding, China) were used to feed and discharge the SBRs. The inlet and outlet pipes were set at the top and 1/4 height of the reactors, respectively. The exchange volume was 1 L $period^{-1}$ and the HRT was 2 d. The operating period was 12 h, which included 10 min of feeding, 650 min of reacting (aeration and mixing), 50 min of settling and 10 min of decanting.

Table 1
Set-up of pulse aeration in the three SBRs.

Set-up	R1	R2	R3
Aerobic time (min): Anaerobic time (min)	1:9	2:18	3:27
Aerated frequency (times h^{-1})	6.0	3.0	2.0
Aerobic time (min $time^{-1}$)	1.0	2.0	3.0
Gas flow (L min^{-1})	3.33	3.33	3.33

2.2. Analytical methods

MLSS and MLVSS were detected by the weight method (Sliekers et al., 2002). The concentrations of NH_4^+-N, NO_2^--N and NO_3^--N were detected by a continuous flow analyzer (AA3, Germany; SKALAR, Netherlands) (Sliekers et al., 2002). DO concentration was measured by a DO meter (Mettler, Toledo, Switzerland). pH was measured by a phs-3c pH meter (Shanghai Leici Equipment Factory, China).

2.3. Batch activity tests

Batch tests were conducted to determine the aerobic ammonium oxidizing activity of the AOB, the aerobic nitrite oxidizing activity of the NOB and the anaerobic denitrifying activity of the denitrifying bacteria (DB). Sludge samples were taken from the three SBR reactors at day 138 and washed with 2 g L^{-1} $KHCO_3$ until no ammonium, nitrite or nitrate was detected (at least three times). The test method was detailed by Shuang et al. (2017). Each test was performed in triplicate.

2.4. Energy efficiency evaluation

The change in DO concentration was detected each minute to compare the energy efficiencies of the three aeration frequencies during an aerated cycle (10 min in R1, 20 min in R2, 30 min in R3). The DO concentrations at the start and end were named DO_s and DO_e in the aerated cycle, and each test was performed in triplicate. The actual oxygen transfer efficiency (AOTE, Eqs. (1)–(2) and dynamical efficiency (DE, Eq. (3) were used to analyse the energy efficiency of the different aeration frequencies.

$$AOTE = \frac{(DO_e - DO_s) \times V \times 10^{-3}}{M_{o_2} \times n} \times 100\% \tag{1}$$

V: working volume of the reactor (L);
M_{O2}: the molecular weight of O_2, 32 g mol^{-1};
n: the moles of O_2 in the reactor (mol).

$$n = \frac{V_{air} \times 20.947\% \times 10^{-3} \times (P_{air} + P_{water})}{R \times T_{35°C}} \tag{2}$$

V_{air} : the air volume which was pumped into the reactor (L);
20.947%: the volume fraction of O_2 in the air;
P_{air} : atmospheric pressure at 35 °C;
P_{water} : ρgh, water pressure underwater 0.5 m;
R : ideal gas constant.
T_{35}°C: T at 35 °C (k).

$$DE = \frac{(DO_e - DO_s) \times V \times 10^{-6}}{P \times t} \tag{3}$$

P : the power of the air pump (W);
t : aeration time (h)

3. Results and discussion

Three SBRs were used to investigate the influence of different pulse aeration frequencies on the PN process for treating the digested effluent of swine wastewater. The 142 days of the experiment were divided into three periods: period I (1–35 d), adaptation; period II (36–116 d), unstable nitrite accumulation due to the accidental blockage of the air distributor; period III (117–142 d), the steady PN process.

3.1. Nitrogen conversion

3.1.1. Ammonium conversion

The NH_4^+-N concentration, ammonium conversion efficiency (ACE), pH, FA and FNA concentrations in the three SBRs are shown in Fig. 1. The three SBRs were designed to have the same aeration rate but different aeration frequencies. In period I (1–35 d), the ACEs in R1 (1:9,