Biochemical Engineering Journal 55 (2011) 215–222

Contents lists available at ScienceDirect

Biochemical Engineering Journal

journal homepage: www.elsevier.com/locate/bej

Long-term partial nitrification in an intermittently aerated sequencing batch reactor (SBR) treating ammonium-rich wastewater under controlled oxygen-limited conditions

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ARTICLE INFO

Article history:
Received 10 December 2010
Received in revised form 21 March 2011
Accepted 5 May 2011
Available online 12 May 2011

Keywords:
Aeration control
Intermittent aeration
Nitrification
Nitrite accumulation
Molecular analysis
Online monitoring

ABSTRACT

In this study, a novel technology was developed to achieve efficient partial nitrification at moderately low temperature, which would save the aeration cost and have the capacity to treat a wide range of ammonium-rich wastewaters with low chemical oxygen demand-to-nitrogen (COD:N) ratios. At pH of 7.1–7.4 and a sludge retention time (SRT) of greater than 100 days, a laboratory-scale intermittently aerated sequencing batch reactor (IA-SBR) was operated at about 20 °C to treat synthetic wastewater containing readily biodegradable COD of 100–300 mg L^{-1} and ammonium–nitrogen (NH_4^+–N) of 300 mg L^{-1}. During the aeration periods, DO concentrations were controlled at less than 0.2 mg L^{-1}, and the aeration was terminated when on-line NH_4^+–N measurement reached 20 mg L^{-1}. During 180 days of operation, the mass ratio of nitrite–N (NO_2^-–N) to the total oxidized nitrogen was over 90% in the effluent. Molecular analyses show that ammonium oxidizing bacteria (AOB) represented up to 10% of the total bacterial population in the sludge biomass, and the ratio of AOB to nitrite oxidizing bacteria (NOB) was generally over 100. The IA-SBR quickly recovered after non-operation for 47 days. The three main factors enabling long-term stable partial nitrification in this study were: enrichment of AOB in the start-up period; controlled oxygen-limited conditions and the intermittent aeration strategy.

1. Introduction

Conventional biological nitrogen removal (BNR) comprises two successive steps: autotrophic nitrification in aerobic conditions and heterotrophic denitrification in anoxic conditions. The chemical oxygen demand-to-nitrogen (COD:N) ratio of wastewater is of great importance to the overall N removal performance. A low COD:N ratio is usually unfavorable due to limited organic carbon (C) for heterotrophic denitrification. For ammonium-rich wastewater with low COD:N ratios (e.g. <2.5), the addition of external C, such as methanol, leads to a significant increase in the operational cost.

The recently developed anaerobic ammonium oxidation (anammox) process is a cost-effective approach to treat ammonium-rich wastewater with low COD:N ratios [1]. Under anoxic conditions, the slow-growing autotrophic anammox biomass utilizes ammonium NH_4^+ and nitrite NO_2^- as main substrates to produce nitrogen gas (N_2). As shown in Eq. (1), the ideal mole ratio of NH_4^+ to NO_2^- for the anammox process is 1:1.32 [2].

$$NH_4^+ + 1.32NO_2^- + 0.066HCO_3^- + 0.13H^+ \rightarrow 1.02N_2 + 0.26NO_3^- + 0.066CH_2O_{0.5}N_{0.15} + 2.03H_2O \quad (1)$$

Partial nitrification, namely the oxidation of NH_4^+ to NO_2^-, but not NO_3^-, is needed to supply NO_2^- for the anammox process. Stable and efficient partial nitrification prior to the anammox process is essential to maintain a high N removal rate in the anammox reactor. The SHARON (single reactor system for high activity ammonium removal over nitrite) process has been successfully coupled with the anammox process to treat reject water (sludge digester liquor) at full scale [3]. High temperature (30–35 °C) is the essential factor used in the SHARON process to encourage a faster growth of ammonium oxidizing bacteria (AOB) than nitrite oxidizing bacteria (NOB). With a short sludge retention time (SRT) of 1–2 days, NOB are completely washed out of the reactor, while sufficient AOB are retained.

The majority of municipal and industrial wastewaters are discharged at ambient temperature and have moderately low temperatures, for instance, municipal wastewater in the United States having a representative value of 15.6 °C [4] and wastewater in the

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doi:10.1016/j.bej.2011.05.002

balance tank of a slaughterhouse wastewater treatment plant in western Ireland (County Mayo) having an average value of 20 °C. The anammox process has been proven to be efficient at 18–22 °C [5,6]. Till date, little research on partial nitrification at 15–20 °C to produce high NO_2^- effluent for the subsequent anammox process has been conducted. Therefore, it is desirable to explore a feasible partial nitrification process that will be efficient and cost-effective at moderately low temperature.

The aim of this study was to examine the long-term stability of partial nitrification in an intermittently aerated SBR (IA-SBR) treating low COD:N ratio, ammonium-rich wastewater at ambient temperature of around 20 °C under controlled oxygen-limited conditions.

2. Materials and methods

2.1. The partial nitrification reactor

A sequencing batch reactor (SBR) with a working volume of 2.0 L, made from a 2.5 L glass cylinder with a diameter of 120 mm, was used in this study. Two peristaltic pumps (323S, Walson-Marlow, UK) were used, one feeding the wastewater to the reactor and the other withdrawing the treated wastewater. A constant airflow for aeration was provided with a peristaltic pump through an air diffuser located at the bottom of the reactor. A mechanical mixer (Yellow-Line, IKA, Germany) with a standard four-blade shaft paddle was used to stir the liquid in the reactor at 150 rpm. The sequential operation of the SBR was controlled by a programmable logic controller (PLC) (S7-CPU-224, Siemens, Germany).

The temperature, pH, oxidation-reduction potential (ORP), DO, NH_4^+–N and NO_3^-–N concentrations in the reactor were monitored in real-time using individual probes. The pH and ORP probes (Polyplast Pro, Hamilton, Switzerland) were connected to corresponding transmitters (Eutech, Singapore) that transformed the signals from the two electrodes into 4–20 mA analog signals. A peristaltic pump was controlled by a pH controller (alpha-pH 1000, Eutech, Singapore) to dose 0.5 M Na_2CO_3 solution into the reactor to maintain pH in a specific range, if needed. A highly sensitive Clark-type mini-DO sensor, connected to a pico-ammeter (PA2000, Unisense, Denmark), was used to monitor DO in the reactor. The mini-DO sensor had a detection limit of 0.01 mg L^{-1} and a response time of about 4 s. Ion-selective membrane electrodes (VARiON, WTW, Germany) were used to online monitor NH_4^+–N and NO_3^-–N concentrations in the reactor. A data acquisition card (USB-6009, National Instruments, USA) and LabView software (V7.1, National Instruments, USA), installed on a desktop computer, were used to collect and process all online signals from transmitters. The online data were recorded every 5 s.

2.2. Synthetic wastewater

Synthetic wastewater made from tap water was used in this study. Glucose and $(NH_4)_2SO_4$ were the main organic C source and NH_4^+–N source, respectively. The NH_4^+–N concentration in the synthetic wastewater was 300 mg L^{-1}. The COD:N ratio was set at 1:1 or 1:3 by changing the influent COD to 300 mg L^{-1} or 100 mg L^{-1}. The other main components in the synthetic wastewater were: NaH_2PO_4 (31 mg P L^{-1}), yeast extract (50 mg L^{-1}) and $NaHCO_3$ (1800 mg L^{-1}). The supplement of mineral elements was after van de Graff et al. [7]. The mole ratio of NH_4^+ to HCO_3^- was 1:1. The synthetic wastewater was prepared once every week and stored at 4 °C in a refrigerator. The influent for the reactor was replaced daily by using the stored feed.

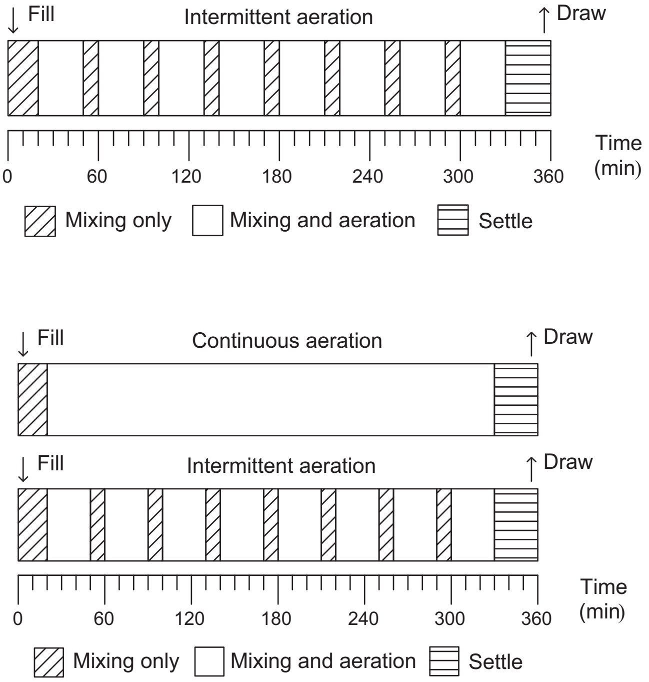

Fig. 1. Sequencing operation of the SBR.

2.3. Seed sludge

The reactor was seeded with return sludge of a local municipal wastewater treatment plant (MWWTP) in western Ireland. Initially, 1.0 L of the seed sludge and 1.0 L of the synthetic wastewater were added into the reactor, giving a mixed liquor suspended solids (MLSS) concentration of about 3000 mg L^{-1} and a volatile suspended solids (VSS)-to-suspended solids (SS) ratio of 82%.

2.4. Operation conditions of the SBR

The SBR was initially operated in a short start-up period (7 days) when a high temperature and a high DO level was applied to enhance the growth of AOB, and high free ammonia (FA) concentrations temporarily inhibited the growth of NOB. A water bath was used to maintain 25 °C in the reactor. A continuous aeration (CA) strategy was applied at an aeration rate of 200 mL air min^{-1} (Fig. 1). The NH_4^+–N concentration in the reactor was kept above 100 mg L^{-1} by manually replacing a certain amount of the supernatant with the feed during the settle phase. pH in the reactor was automatically controlled at 8.2–8.5. Thus, the FA concentration in the reactor was kept above 8.5 mg N L^{-1} during the start-up period.

An intermittent aeration (IA) strategy was applied to sustain partial nitrification after the 7-day start-up period (Fig. 1). The reactor was operated at an ambient temperature of around 20 °C. The cycle duration was 6 h. During the first 5 min of the cycle, on average, 250 mL of the synthetic wastewater was delivered into the reactor, giving a hydraulic retention time (HRT) of 2.0 days and a nitrogen loading rate (NLR) of 0.15 g N L^{-1} d^{-1}. During the aeration period, the aeration rate was set at 150 mL air min^{-1}. The aeration was automatically terminated when the online measurement of NH_4^+–N dropped to 20 mg L^{-1}. The pH controller maintained pH of 7.1–7.3 by dosing Na_2CO_3 solution into the reactor.

2.5. Batch experiments testing the activity of NOB in the biomass

Batch experiments were carried out to test the activity of NOB in the biomass under oxygen-sufficient conditions, under