Chemosphere 169 (2017) 586–595

Contents lists available at ScienceDirect

Chemosphere

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

Oxygen transfer dynamics and activated sludge floc structure under different sludge retention times at low dissolved oxygen concentrations

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HIGHLIGHTS

- Oxygen diffusion feature was explored in microenvironment of floc by microelectrodes.
- Activated sludge properties in combination with nutrient removal efficiency were investigated under different SRTs at low DO conditions.
- Reactors with long SRTs were less sensitive to low DO concentrations.
- EPS increased the oxygen mass transport resistance in the floc.
- Settling performance of activated sludge improved with longer SRTs.

ARTICLE INFO

Article history:
Received 8 November 2015
Received in revised form
16 October 2016
Accepted 31 October 2016
Available online 27 November 2016

Handling Editor: Y Liu

Keywords:
EPS
SRT
Floc structure
Settling performance
Low DO

ABSTRACT

In activated sludge systems, the aeration process consumes the most energy. The energy cost can be dramatically reduced by decreasing the operating dissolved oxygen (DO) concentration. However, low DO may lead to incomplete nitrification and poor settling performance of activated sludge flocs (ASFs). This study investigates oxygen transfer dynamics and settling performances of activated sludge under different sludge retention times (SRTs) and DO conditions using microelectrodes and microscopic techniques. Our experimental results showed that with longer SRTs, treatment capacity and settling performances of activated sludge improved due to smaller floc size and less extracellular polymeric substances (EPS). Long-term low DO conditions produced larger flocs and more EPS per unit sludge, which produced a more extensive anoxic area and led to low oxygen diffusion performance in flocs. Long SRTs mitigated the adverse effects of low DO. According to the microelectrode analysis and fractal dimension determination, smaller floc size and less EPS in the long SRT system led to high oxygen diffusion property and more compact floc structure that caused a drop in the sludge volume index (SVI). In summary, our results suggested that long SRTs of activated sludge can improve the operating performance under low DO conditions.

1. Introduction

Energy conservation is an essential issue in wastewater treatment plants (WWTPs). In the typical activated sludge process of WWTP, aeration usually accounts for approximately 50% of the total energy consumption (McCarty et al., 2011). Therefore, decreasing the operating dissolved oxygen (DO) concentration can reduce energy consumption. Activated sludge processes are the most widely used biological solutions in WWTPs worldwide. In recent years, a number of innovative nitrogen removal processes have been developed to reduce operational costs, such as shortcut nitrification–denitrification, simultaneous nitrification/denitrification (SND), and anaerobic ammonium oxidation (anammox) (Zeng et al., 2014). Shortcut nitrification–denitrification follows the ammonia-nitrite-nitrogen gas path for the removal of ammonia. SND implies that nitrification/denitrification or nitritation/denitritation occur concurrently in one reactor under aerobic conditions. Anammox is an anaerobic–autotrophic biochemical reaction

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http://dx.doi.org/10.1016/j.chemosphere.2016.10.137
0045-6535/

that can convert ammonium to nitrogen gas using nitrite as the terminal electron acceptor (Strous et al., 2006). In comparison with traditional nitrification/denitrification, these processes are under low DO conditions, which require less oxygen demand and lower energy costs.

However, there are some adverse effects of reduced DO concentrations. One problem caused by low operating DO concentrations is poor nitrification. It has already been proved that low DO concentrations inhibit the growth rate of nitrifiers and lead to incomplete nitrification (Park and Noguera, 2004). To reach effluent quality standards, actual operating DO concentrations in most WWTPs should be maintained at high levels. However, researchers have found that high DO concentrations do not strengthen the nitrification (Satoh et al., 2004). Therefore, there is no need to waste energy to maintain high level of DO in the aeration tank. Moreover, good nutrient removal efficiency can be obtained through traditional nitrification processes, even at low DO concentrations. Park and Noguera (2004) demonstrated that an activated sludge system could achieve good nitrification even with DO concentrations as low as 0.12 mg/L because the type of ammonia oxidizing bacteria (AOB) was able to adapt to low DO operating states. Liu and Wang (2013) also found that long-term low DO conditions resulted in lowering endogenous decay rate of nitrifiers, increasing sludge nitrification capacity and reducing the adverse effects of low DO on overall nitrification performance. These studies indicate that operation of the traditional nitrification process under low DO is feasible.

Another problem of operating under low DO conditions is the poor settling performance of activated sludge flocs (ASFs) in the secondary clarifier. Poor settling performance causes serious operational problems, such as ineffective return of sludge, excessive activated biosolid loss in the aerobic tank, and poor standard of suspended solid (SS) of the effluent. The settling ability of ASF is determined by various floc characteristics such as structure, growth of filamentous bacteria, and chemical composition (Wilén et al., 2008). Extracellular polymeric substances (EPS) produced by sludge microorganisms play an important role in sludge flocculation. Different floc constituents are bound together by EPS because of the electrostatic forces described by the Derjguin Landau Verwey Overbeek (DLVO) theory (Zita and Hermansson, 1994). However, it has already been proved that excessive EPS produce high negative charge densities causing the disintegration of flocs (Liao et al., 2001). Therefore, EPS have different effects on sludge flocculation. The change in EPS properties is mainly due to the changes in operating conditions, microbial community structures, and chemical make-up. Considerable research studies have only focused on individual factors influencing floc characteristics such as organic loading, DO concentrations, and sludge retention time (SRT) (Wilén and Balmér, 1999).

On the basis of the literature, it is evident that EPS and floc structures are two key parameters for energy conservation in both innovative and traditional nitrification processes. In addition, sludge filamentous bulking control is crucial under low DO operating states. ASF characteristics affect the settling performance, treatment properties, and effluent quality, and are closely related to the internal microscopic mass transfer properties such as oxygen within sludge flocs. Results obtained using microelectrode techniques have shown that DO concentration distributions were distinct in flocs of different particle sizes (Han et al., 2012). Concentrations of pH, NH_4^+, and NO_3^- were also found to decrease from the surface to the center of activated sludge aggregates with particle sizes ≥1000 μm (Wang et al., 2011). However, integrative studies under low DO conditions, combining EPS compositions, floc structures, mass transfer properties, and settling performances, are very limited. Therefore, we believe that microenvironmental conditions of different floc characteristics affect oxygen mass transfer efficiency and bacterial diversity.

In this study, microelectrodes were applied to analyze oxygen transfer properties in the ASF microenvironment. The relationship between floc properties and settling performance at different SRTs was explored using a two-dimensional (2D) fractal dimension. Experimental results provided important insights for developing a control strategy to improve the operating performance of WWTPs under low DO conditions.

2. Material and methods

2.1. Reactors and operating conditions

Four sets of activated sludge system were operated in parallel at 20 °C. Each system comprised a glass column with a working volume of 3.5 L (H = 0.3 m, ø = 0.15 m, effective water depth = 0.15 m). Each column was coupled with a secondary settler with a working volume of 4.5 L (H = 0.55 m, W = 0.09 m) (Fig. 1).

Reactors were operated as continuous stirred-tank process (CSTP). Influent flow and return sludge were pumped by peristaltic pumps. Ceramic discs with 0.04 m diameter were used as fine bubble diffusers. Mixing was performed by propeller stirrers (propeller diameter = 5 cm; speed of stirring = 150 rpm). The O_2 concentration was determined using an LDO fluorescent DO electrode (Tengue Instrument Co., Ltd., Beijing) and adjusted to a target value by an air meter.

Hydraulic retention time (HRT) of one complete process was 6 h. Return sludge was pumped continuously from the settler to the aeration tank, with a ratio of 100% of the influent flow. Reactors were set up at four SRTs: 10, 17.5, 25, and 35 d. To achieve a target SRT, excess sludge was withdrawn directly from the aeration tanks daily. Each setup was run for at least three SRTs to establish steady state conditions.

Four sets of lab-scale reactors were operated at different DO conditions with different SRTs; each DO concentration was operated with at least one SRT period. DO concentration was monitored daily by using the DO electrode. To obtain a good biological nitrification effect, low DO condition of 0.5 mg/L was maintained at least three times of SRT.

2.2. Wastewater and seed sludge

The lab-scale reactors were fed with synthetic wastewater mainly consisting of glucose (Sinopharm Chemical Reagent Co., Ltd, 10010518, Analytical Pure), NH_4Cl (10001518, Analytical Pure), and KH_2PO_4 (10017608, Analytical Pure) as the carbon source, nitrogen source, and phosphorus source, respectively. The chemical oxygen demand (COD), NH_4^+–N, and PO_4^{3-}–P were controlled at 180–250, 30–40, and 6–8 mg/L, respectively. To control the COD, NH_4^+–N and PO_4^{3-}–P in the stable range, glucose, NH_4Cl and KH_2PO_4 dissolved and mixed in a water bucket were added daily at a constant dose, and two duplicate samples of about 50 mL were taken for monitoring of COD, NH_4^+–N, and PO_4^{3-}–P every two days. The nutrient solution contained $MgSO_4 \cdot 7H_2O$ (5.6 mg/L), $ZnCl_2 \cdot 2H_2O$ (0.0018 mg/L), $FeCl_3 \cdot 6H_2O$ (0.88 mg/L), $CaCl_2 \cdot H_2O$ (1.3 mg/L), and $MnCl_2 \cdot 4H_2O$ (0.19 mg/L).

Seed sludge was taken from the aeration tank of Qin He WWTP in Beijing that uses a typical anaerobic–anoxic–aerobic (A^2O) process to treat municipal wastewater, with good performance of complete nitrification, and COD and NH_4^+–N removal rates are above 95%.