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Simultaneous carbon and nutrient removal in an airlift loop reactor under a limited filamentous bulking state

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HIGHLIGHTS

- A stable limited filamentous bulking (LFB) state was achieved.
- The LFB promote a well-balanced aerobic and anoxic/anaerobic state.
- The LFB enhanced COD and nutrient removal in the airlift loop reactor (ALR).
- The LFB reduced the ALR height-to-diameter ratios and aeration energy consumption.
- Removal efficiencies of COD, NH_4^+—N, TN and TP were 91%, 92%, 86% and 94%.

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ABSTRACT

Airlift loop reactors (ALRs) are important bioreactors for wastewater treatment. However, few studies have investigated the application of an ALR for simultaneous carbon and nutrient removal, especially for activated sludge systems. This study evaluated the performance of integrated nitrogen, phosphorus and COD removal in an ALR with a low height-to-diameter ratio in a limited filamentous bulking (LFB) state (SVI of 180–220 mL/g). The average removal efficiencies for COD, NH_4^+—N, TN and TP were 91%, 92%, 86% and 94%, respectively. Additional research showed that only under the LFB state, the appropriate distribution of dissolved oxygen inside the ALR was established to promote a well-balanced aerobic and anoxic/anaerobic state. In addition, the macro-gradient of the substrate concentration at the inlet and the heavier bio-P sludge density compensated for the proliferation of filaments. Hence, the stable LFB state was achieved by balancing the floc-forming bacteria and the filamentous bacteria in the ALR.

1. Introduction

The excessive discharge of nitrogen (N) and phosphorus (P) nutrients to rivers and lakes can result in eutrophication. Therefore, the effluent requirements for decreasing N and P discharges are becoming more stringent. In conventional biological nutrient removal (BNR) systems, the removal of N is accomplished by aerobic nitrification followed by anoxic denitrification. In contrast, the removal of P is achieved through enhanced biological phosphorus removal (EBPR), which uses polyphosphate-accumulating organisms (PAOs) to generate alternating anaerobic–aerobic conditions. For the simultaneous removal of N and P, the operating conditions (i.e., anaerobic, anoxic and aerobic) have been achieved by varying space (the A^2O process) or time (the SBR process). However, these processes are problematic because the A^2O process requires a large amount of space and the SBR process is operationally complex.

In recent years, substantial attention has been given to integrated bioreactors. These bioreactors are cost-effective, efficient and small footprint. Thus, the airlift loop reactor (ALR) (a type of integrated bioreactor), which combines anaerobic, anoxic and aerobic conditions in a single reactor, is a valuable alternative for the simultaneous removal of N and P. Previously, ALRs have been used to treat wastewater containing nitrogen (Fujiwara et al., 1998; Guo et al., 2005; Hano et al., 1992; Jin et al., 2008; Meng et al., 2004; Walters et al., 2009), nitrite (Dhamole et al., 2009), nutrients (Bando et al., 1999), chemical fertilizer plant waste (Wen et al., 2005), and landfill leachates (Yang and Zhou, 2008).

To achieve the appropriate anoxic/anaerobic and aerobic zone volume ratios in the ALR (which is important for nutrient removal), a biological membrane system is commonly used. In a biological membrane system, the bacteria responsible for nitrogen and phosphorus removal can be immobilized on fixed materials (Guo et al.,

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2005; Meng et al., 2004), on biofilm carrier particles or on granular sludge (Jin et al., 2008; Walters et al., 2009; Wen et al., 2005). However, these immobilization processes increase the complexity of the ALR and its manufacture, machining and installation. Another option is to use an ALR with an activated sludge system. Usually, the inside of a draft tube is used as an aerobic zone, and the annulus is used as an anoxic/anaerobic zone. The circulation flow rate of mixed liquor between the anoxic/anaerobic and aerobic zones is the most important parameter of operation for nutrient removal. The circulation flow rate can be varied by changing the height of the draft tube and the flow rate of air into the draft tube. To meet the general requirements of dissolved oxygen (DO) concentrations in the aerobic zones (1.5–2.0 mg/L) and to achieve the well-balanced anoxic/anaerobic and aerobic conditions in the ALR, the height-to-diameter ratio must be greater than 10 (Bando et al., 1999; Dhamole et al., 2009; Fujiwara et al., 1998; Hano et al., 1992; Weston, 1982). However, high height-to-diameter ratios are economically undesirable because the resistance force needed for phase circulation and mixing increases with increasing reactor height mean that tall reactors have higher construction and power consumption costs.

Guo et al. (2010) were the first researches to advocate the limited filamentous bulking (LFB) theory and method. In their experiments, the LFB state was maintained with low DO concentrations (0.5 and 1.0 mg/L). In their subsequent work, Guo et al. (2012) further discussed the relationship between optimal DO concentrations and sludge loading rates for a stable LFB state. In addition, several factors that influenced the stable LFB state were also studied. Tian et al. (2011) demonstrated the use of an LFB state for stimulation of simultaneous nitrification and denitrification (SND) to enhance biological nutrient removal and effluent quality. Therefore, to employ an LFB state in an ALR with a low height-to-diameter ratio and an activated sludge system, the aerobic zone DO concentrations only need to be maintained between 0.5 and 1.0 mg/L. Then, to obtain a longer residence time in each zone during the circulation of liquid, the ALR can be operated at the lowest circulation rate required to keep the sludge in a suspended state. The aerobic and anoxic/anaerobic zones in the ALR could result in a well-balanced state that enhances nutrient removal.

The objective of this paper is to introduce the use of an LFB state in an ALR with a low height-to-diameter ratio to enhance biological nutrient removal and to achieve the optimum operating parameters for this type of ALR.

2. Methods

2.1. Reactor configuration

Fig. 1A plexiglass bench-scale ALR with a low height-to-diameter ratio is depicted in Fig. 1. The ALR consists of a reaction zone and an upright settling zone and has a working volume of 22 L. The inside diameter of the upright settling zone and the reaction zone and the overall height of the ALR were 220, 160 and 1000 mm, respectively. Two draft tubes, an upper tube with a diameter of 130 mm and a height of 160 mm and a lower tube with a diameter of 100 mm and a height of 850 mm, were concentrically placed in the ALR. For sparging gas, 120 0.5 mm diameter holes in a perforated pipe were positioned equidistantly around the circle at the middle of the riser. The air that bubbled into the draft tube was measured and controlled by an air-flow meter. The circulation flow rate of the mixed liquor between the annulus and the draft tube could be changed by varying the gas-flow rate. The influent was introduced into the ALR through one of the three wastewater inlets (bottom of the riser, middle of the riser or upper part of annulus), and the flow rates were controlled by a peristaltic pump. The effluent was withdrawn from the liquid surface in the settling zone. The ALR and tubes were periodically cleaned to avoid the proliferation of bacteria in the lines and on the walls.

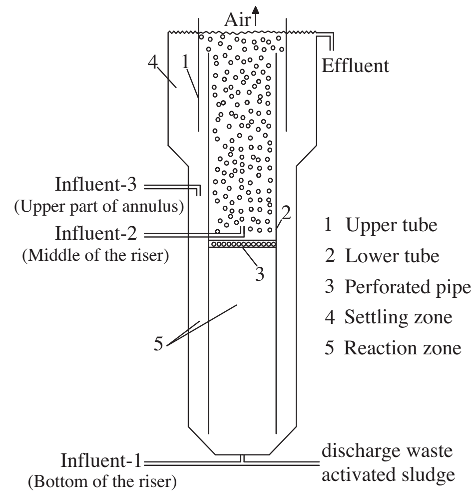

Fig. 1. Schematic structure of the ALR.

2.2. Synthetic wastewater

Synthetic wastewater of the following composition was used as the feeding solution: 384.4 mg of CH_3COONa (300 mg/L as COD basis), 30.7 mg of KH_2PO_4 (7 mg/L as PO_4^{3-}—P basis), 152.9 mg NH_4Cl (40 mg/L as NH_4^+—N basis), 90 mg $MgSO_4{\cdot}7H_2O$, 14 mg $CaCl_2{\cdot}2H_2O$ and 0.3 mL of trace element solution per liter. The trace elements solution consisted of the following compounds per liter: 1.5 g $FeCl_3{\cdot}6H_2O$, 0.15 g H_3BO_3, 0.03 g $CuSO_4{\cdot}5H_2O$, 0.18 g KI, 0.12 g $MnCl_2{\cdot}4H_2O$, 0.06 g $Na_2MoO_4{\cdot}2H_2O$, 0.12 g $ZnSO_4{\cdot}7H_2O$, 0.15 g $CoCl_2{\cdot}6H_2O$ and 10 g EDTA (Tsuneda et al., 2006).

2.3. Experimental conditions and procedures

The ALR was inoculated with mixed liquor that was obtained from a secondary clarifier from the Quyang Wastewater Treatment Plant (WWTP) (Shanghai, China). An activated sludge of mixed liquor suspended solids (MLSS) was prepared at 3.5 g/L and acclimated for two weeks, using the synthetic wastewater, to obtain a stable state. During this period, the ALR was operated with a superficial gas velocity of 0.0032 m/s, which was sufficient to maintain the biomass as a circulating suspension. The suspension's aerobic zone DO concentration was maintained at 1.5 mg/L. In this study, the reactor was maintained at a temperature of 25 °C, and the hydraulic retention times (HRTs) of the reaction zone and the settling zone and the solid retention time (SRT) were 9, 2 h and 15 d, respectively. Various investigations were conducted with different air-flow rates and feeding patterns to achieve simultaneous nitrification, denitrification, and phosphorus removal in the ALR.

2.4. Analytical methods

Levels of ammonia nitrogen (NH_4^+—N), nitrate nitrogen (NO_3^-—N), nitrite nitrogen (NO_2^-—N), total phosphorus (TP), chemical oxygen demand (CODcr), MLSS, mixed liquor volatile suspended solids (MLVSS), alkalinity and sludge volume index (SVI) were determined in accordance with APHA (1998) standard methods. The total nitrogen (TN) concentration was determined with a multi N/C 2100 (CHD) BU (Jena, Germany). The DO concentration was measured with a WTW oxi/340i oxygen probe (Germany).