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Biosolids reduction by the oxic-settling-anoxic process: Impact of sludge interchange rate

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HIGHLIGHTS

- Effect of SIR on OSA was studied using unsettled and settled sewage.
- SIR of 11% by volume achieved the highest sludge reduction.
- OSA performance was linked to nitrification/denitrification in the external reactor.
- Sludge reduction by OSA was more evident at higher influent sCOD.
- Effluent suspended solids and nutrients were unchanged with all SIRs studied.

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ABSTRACT

The impact of sludge interchange rate (SIR) on sludge reduction by oxic-settling-anoxic (OSA) process was investigated. The sludge yield of an OSA system (a sequencing batch reactor, SBR, integrated with external anoxic reactors) was compared to that of a control (an SBR attached to a single-pass aerobic digester). SIR (%) is the percentage by volume of sludge returned from the external reactor into the main bioreactor of the OSA, and was varied from 0% to 22%. OSA achieved greater sludge reduction when fed with unsettled sewage (sCOD = 113 mg/L) rather than settled sewage (sCOD = 60 mg/L). The SIR of 11% resulted in the highest OSA performance. At the optimum SIR, higher volatile solids destruction and nitrification/denitrification (*i.e.*, conversion of destroyed volatile solids into inert forms) were observed in the external anoxic and intermittently aerated (*i.e.*, aerobic/anoxic) reactors, respectively. Denitrification in the aerobic/anoxic reactor was inefficient without SIR. Effluent quality and sludge settleability of the main SBR were unaffected by SIR.

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1. Introduction

The worldwide trend of increasing environmental standards, particularly in sewer coverage, also entails the production of excess sludge, an inevitable by-product of biological wastewater treatment. The EU, the USA, and China each produce 6–11 million tons of sludge as dry solids (DS) per year (Fytili and Zabaniotou, 2008; Semblante et al., 2014; Yang et al., 2015). Australia also produces a significant amount of DS (*ca.* 0.3 million tons) each year (Semblante et al., 2014). The production of excess sludge is problematic because sludge volume is notoriously difficult to reduce due to its unique biological properties (Mowla et al., 2013; Ratanatamskul and Saleart, 2015), and there are only a few options for sludge disposal (e.g., landfilling, incineration, agricultural reuse) (Tchobanoglus et al., 2003). Landfilling is heavily restricted especially in countries with limited space. Incineration removes only 70% of DS and creates ash with high metal content (Fytili and Zabaniotou, 2008). The agricultural reuse of stabilised and dewatered sludge called "biosolids" has been encouraged to enable nutrient recycling. However, the transport of biosolids to end users is potentially costly (Semblante et al., 2014). Furthermore, biosolids may contain trace organic compounds, such as pharmaceuticals, pesticides, and industrial chemicals, which have long-term effect on the environment and human health (Clarke and Cummins, 2015; Semblante et al., 2015b). Therefore, to decrease the costs and risks associated with sludge treatment and disposal, it is imperative that sludge production is reduced. Research efforts

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have generated innovative strategies such as the use of advanced oxidation processes (AOPs) to destroy biomass (Wang et al., 2015), chemical addition to disrupt metabolic processes (Fang et al., 2015; Feng et al., 2014), and sludge cycling in alternating redox conditions through the oxic-settling-anoxic (OSA) process (Semblante et al., 2014). Although the use of AOPs and chemical addition has shown potential to reduce sludge, they require high capital investment (Foladori et al., 2010) and/or may introduce undesired products in treated water (Mahmood and Elliott, 2006). In contrast, OSA offers a potentially cost-efficient and low-impact alternative to sludge reduction.

OSA reduces sludge production by temporarily holding activated sludge in an external anoxic and substrate-deficient reactor, then recirculating it to the main bioreactor. Several mechanisms of sludge reduction in OSA have been hypothesized. They include enhanced cell lysis, extracellular polymeric substance (EPS) degradation, and selection of slow-growing bacteria (Navaratna et al., 2014; Semblante et al., 2014). A few OSA configurations including those that involve external anaerobic (Chon et al., 2011; Chudoba et al., 1992) or anoxic (Coma et al., 2013; Saby et al., 2003) reactors have been discussed in the literature. Laboratory-scale OSA fed with synthetic wastewater have shown promising sludge reduction (*e.g.*, 50–80%) (Chon et al., 2011; Saby et al., 2003; Sun et al., 2010). However, these high sludge reduction values have not been realized in full-scale systems (Coma et al., 2013). In a previous study, 30% reduction in the sludge yield was achieved by a laboratory scale OSA system using real sewage (Semblante et al., 2015a). OSA performance is influenced by different operation conditions, such as oxidation reduction potential (ORP), sludge retention time (SRT), and sludge loading rate of the external reactor (Coma et al., 2013; Saby et al., 2003; Ye et al., 2008). To date, the manipulation of these parameters have only resulted in variable and inconsistent success (Coma et al., 2013; Saby et al., 2003; Ye et al., 2008).

To improve OSA performance and ensure reliable performance for the water industry, it is essential to elucidate the impact of operation conditions such as sludge interchange rate (SIR) and influent chemical oxygen demand (COD) on sludge reduction. Changing SIR varies the residence time of sludge in aerobic/anoxic regimes and may have important implications on sludge reduction mechanisms. However, current information in the literature is inadequate to pin-point the optimum SIR value or range for sludge reduction.

Khursheed et al. (2015) observed that increasing the ratio of sludge exposed to anaerobic and aerobic conditions (0–8.24 g $MLVSS_{anaerobic}$/g $MLVSS_{aerobic}$) in OSA enhanced sludge reduction (0–39.8%). Saby et al. (2003) investigated the impact of SRT in the external anoxic reactor of OSA over a range of 11–17 days and observed 23–58% reduction in biosolids production under longer SRTs or smaller SIRs. The SRT of the anoxic reactor in the study of Saby et al. (2003) was significantly longer than that of Ye et al. (2008) (5.5–11.5 h), but similar sludge reduction has been achieved by both studies. On the other hand, Sun et al. (2010) were able to achieve an enhanced sludge reduction (from 53% to 77%) by increasing the frequency of return from once per day to four times per day while maintaining the SIR between an SBR and an external anaerobic reactor at 10%. Given the inconsistent trends reported in the literature, it is worthwhile to systematically investigate the impact of SIR on OSA performance. Additionally, influent COD concentration affects biomass growth and substrate consumption (Gómez et al., 2006), but its impact on OSA remains to be evaluated. Thus, a systematic investigation under different influent COD concentrations is essential to assess the performance of OSA in plants with and without primary sedimentation.

To address the aforementioned research gaps, this study aims to systematically investigate the impact of SIR on sludge reduction by OSA at different influent strengths *i.e.*, using real sewage before and after primary settling. Volatile solids content and a range of water quality parameters including COD and nutrient concentrations of the reactors were monitored during continuous operation of the reactors over a period of 475 days to elucidate the impact of SIR on sludge reduction.

2. Methods

2.1. Wastewater characteristics

Unsettled and settled sewage (Table 1) were collected from the Wollongong WWTP fortnightly and stored at 4 °C. The former was collected at the beginning while the latter was collected at the outlet of the sedimentation channel. It is noted that due to rapid hydrolysis of readily biodegradable solid particles and the higher soluble ammonia concentration in the unsettled sewage, the soluble COD (sCOD) of the unsettled sewage was significantly higher than that of the settled sewage (113 ± 87, $n = 33$ *vs.* 60 ± 32, $n = 48$) as can be seen in Table 1.

2.2. Reactor configuration and operation

Two systems were operated in parallel: the first consists of $SBR_{control}$ (5 L) attached to a single-pass aerobic digester (2 L) forming the control system (Fig. 1a), and the second consists of SBR_{OSA} (5 L) attached to a sequential aerobic/anoxic reactor (2 L) and anoxic reactor (2 L) to form the OSA system (Fig. 1b).

$SBR_{control}$ and SBR_{OSA} were fed with real wastewater (Section 2.1), and operated at 4 cycles/day and a HRT of 12 h. Each cycle comprised of 15 min of filling, 5 h and 30 min of aeration, 1 h of settling, and 15 min of decanting. The SRT of both SBRs was maintained at 10 days by regular sludge wastage (W) (Fig. 1).

The aerobic digester of the control system (Fig. 1a) was continuously aerated using an air diffuser. The SRT of this digester was maintained at 20 days by regular sludge wastage (Q_{out}). The aerobic digester was fed with sludge from $SBR_{control}$ thickened to 5–10 g/L by centrifugation for 10 min at 3267*g* (Q_{in}). The supernatant produced by the thickening step was discarded.

In the OSA system (Fig. 1b), the aerobic/anoxic reactor was intermittently aerated (*i.e.*, 8/16 h aeration on/off) using an air diffuser placed at the bottom of the reactor, while the anoxic reactor was kept airtight using a silicone-lined cap with inlet and outlet ports. The aerobic/anoxic reactor was fed with sludge from SBR_{OSA} thickened to 5–10 g/L (q_1).

Thirty-three percent (33%) of sludge from the aerobic/anoxic reactor was transferred to the anoxic reactor (q_2), and 67% was discharged to achieve a total SRT of 20 days (q_3). The sludge discharged from the aerobic/anoxic reactor was thickened to 16–24 g/L by centrifugation for 10 min at 3267*g*. The supernatant was returned to SBR_{OSA}, and the pellet was discarded. Sludge from the anoxic reactor was returned to the aerobic/anoxic reactor (q_4) and SBR_{OSA} (q_5).

Table 1
Average properties of settled and unsettled sewage (n = number of samples).

Property	Settled sewage	Unsettled sewage
sCOD (mg/L)	60 ± 32 (n = 48)	113 ± 87 (n = 33)
TOC (mg/L)	50.6 ± 21.9 (n = 48)	49.8 ± 24.2 (n = 33)
NH_3-N (mg/L)	31.2 ± 7.5 (n = 48)	68.1 ± 31.7 (n = 33)
PO_4^{-3}-P (mg/L)	26.0 ± 12.0 (n = 48)	46.7 ± 48.2 (n = 33)
pH	5.9 (n = 42)	6.9 (n = 32)
TSS (g/L)	0.60 ± 0.12 (n = 48)	0.67 ± 0.08 (n = 33)
VSS (g/L)	0.17 ± 0.09 (n = 48)	0.19 ± 0.07 (n = 33)
VSS/TSS	0.28 (n = 48)	0.28 (n = 33)

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