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Sludge reduction and nutrient removal from an anaerobic/anoxic/oxic(A2/O) process coupled with a modified oxic-settling-anaerobic process

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ABSTRACT

There is little research that focused on both nutrient removal and sludge reduction based on an anaerobic/anoxic/oxic(A2/O) process. In this study, two systems that consisted of an A2/O process combined with a modified oxic-settling-anaerobic (MOSA) reactor were run for 200 d at the lab-scale to evaluate their effect on sludge reduction and their influence on nutrients removal. The MOSA reactor was run a hydraulic retention time of 5 d and interchange rate of 10%. Our results showed that A2/O-MOSA system performed as well as an A2/O system for removing Chemical Oxygen Demand (COD), ammonia, total nitrogen, and total phosphorus. The A2/O-MOSA system removed an average of 92% of the influent COD, slightly higher than that in the A2/O (90%) system. As for sludge reduction efficiency, the A2/O-MOSA process achieved a sludge reduction of 24%and sludge decay contributed 58% to this sludge reduction.

Keywords: Anaerobic; A2/O-MOSA process; Sludge reduction; Sludge; Municipal sewage

1. Introduction

Activated sludge treatment processes and their derivative processes have been widely used in municipal sewage treatment throughout the world for their high organic matters removal efficiency and low operating cost. However, they produce a large amount of excess sludge that contains complex organic material, heavy metals (HMs), viruses, bacteria and other microorganisms [1]. Furthermore, the treatment and disposal of sewage sludge comprises more than 50% of the total wastewater treatment plants (WWTP) cost [2]. Therefore, technologies addressing sludge reduction from the source has been a hot topic around the world.

In recent years, oxic settling-anaerobic process (OSA) processes and anaerobic side-stream reactor (ASSR) processes have shown great effectiveness in sludge reduction with little negative effects on sludge settling or effluent quality. In these processes, all or part of return sludge flow through an anaerobic tank in sludge return line.

Previous studies about these processes mostly considered combination with sequencing batch reactors (SBR). Chen et al. [3] studied possible causes of excess sludge reduction in the OSA process by making all the return sludge flow through a large-volume anaerobic tank with. Chon et al. [4] achieved 49% sludge reduction using an SBR-ASSR process. Sun et al. [5] showed that sludge reduction can reach 77% when the sludge interchanged 4 times.

The modified oxic-settling-anaerobic (MOSA) process has been used to reduce sludge production in WWTPs effi-

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ciently by inserting ananaerobic tank in sludge return line. The MOSA process developed from the OSA process. In the MOSA process, part of the return sludge flows through the anaerobic tank and the rest returns to the activated sludge stage, similar to the ASSR process and to some OSA-SBR processes [3,6,7]. The difference between the MOSA process and ASSR is that the return sludge treated by the anaerobic tank in MOSA process returns to the aeration tank while in ASSR it returns to denifitrification [7].

Nutrient removal in OSA-like processes have been researched based on some type of conventional activated sludge. Wang et al. [8] showed that the OSA process achieved better performance on Chemical Oxygen Demand (COD), total phosphorus (TP) and total nitrogen (TN) removal than a conventional activated sludge (CAS) process. Wang [9] showed from a MOSA process based on the UNITANK system (considered as modified sequencing batch reactor (SBR) [10]) at the pilot scale (120 m^3/d) that the MOSA-UNITANK system led to 38% sludge reduction and did not influence contaminant removal, except for total TP removal, which reached about 46.34% in the UNITANK but only 26.27% in the MOSA-UNITANK. Tan [11] achieved a 35% sludge reduction in a MOSA-A/O system (at a pilot scale of 10 m^3/d) and had similar effluent quality as the A/O process, except that TP removal in the A/O process (24.4%) was slightly lower than in the A/O process (28.9%).

Despite the fact that the A2/O process is one of the most common technologies in China [12], there are few studies on nutrient removal in A2/O-OSA-like processes. This study mainly focused on effluent properties, sludge settle ability and sludge reduction from the A2/O-MOSA process undertaken at a lab-scale and fed by a soluble synthetic wastewater, in order to lay a foundation for applying the MOSA process at full-scale.

2. Materials and methods

2.1. Sludge cultivation

The cultivated sludge came from the A2/O process at the Zhenan municipal WWTP in Foshan, China, which offered similar operating parameters to both lab-scale systems. The sludge production and effluent quality in two systems became stabilized, indicating that both systems started up successfully.

2.2. Experimental equipment

Two A2/O processes (100 L/d) were established in laboratory, consisting of an anaerobic tank, an anoxic tank and an aerobic tank. The hydraulic retention times (HRTs) of the anaerobic tank, aerobic tank and aeration tank were 1.3 h, 2.2 h and 5.3 h, respectively. The mixed liquid suspended solids (MLSS) and the dissolved oxygen (DO) were about 2000–4000 mg/L and 2.0–4.0 mg/L, respectively.

The A2/O-MOSA process (Fig. 1) contained an extra anaerobic holding tank (MOSA reactor,). The HRT and interchange rate (IR, the percent of sludge mass inter changed between the activated sludge stages and the MOSA reactor on daily basis) in the anaerobic tank of A2/O-MOSA process were 5 d and 10%, respectively. Sludge in the MOSA reactor was interchange for four times by pumping from the settling tank and flowing into the aeration tank (once for sludge mixed liquor, three times for sludge supernatant) every day. The amount of wasted sludge was calculated according to the growth of the sludge in the aeration tank. To retain a good anaerobic environment, intermittent mixing was used in the MOSA reactor. The sludge retention time (SRT) calculated in the MOSA reactor was about 15 d.

The SRT in the MOSA reactor is as follows:

$$SRT_{MOSA} = \frac{TSS\ mass\ in\ MOSA\ Reactor}{TSS\ mass\ extracted\ per\ day} = \frac{X_{in} \times Q_{in} \times HRT}{Q_{ef} \times X_{ef}} = \frac{X_{in}}{X_{ef}} \times HRT \quad (1)$$

where the of the MOSA Reactor was designed to be 5 d; X_{in} is the average MLSS concentration (mg/L) of flow

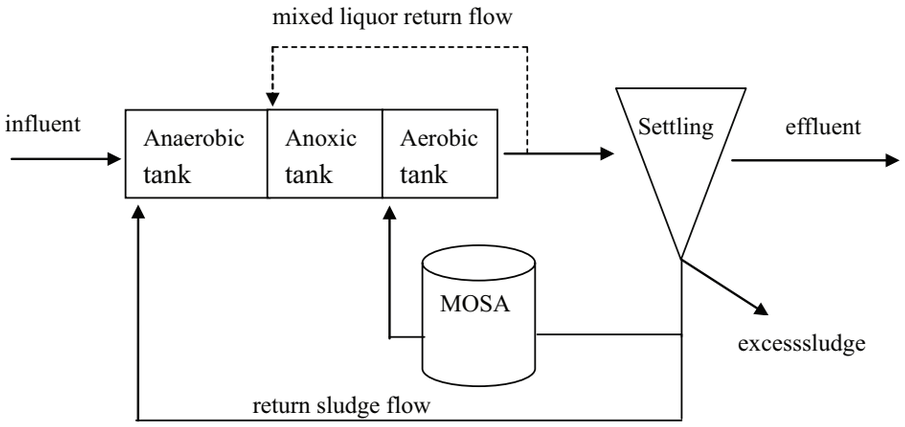

Fig. 1. Schematic diagram of the A²/O-MOSA process.

into the MOSA Reactor (four times of pumping sludge from the settling tank every day); Q_{in}, Q_{ef} is the daily sewage inflow and outflow (L/d) of the MOSA reactor, and $Q_{in} = Q_{ef}$; X_{ef} is the average MLSS concentration (mg/L) of flow extracted from the MOSA reactor (once for sludge mixed liquor, three times for the sludge supernatant every day)

Two systems operated for 200 d in total and data were collected during this time. At first, two identical A2/O processes (A2/O-1 and A2/O-2) were operated. After a 48-d cultivation, a MOSA reactor was inserted into A2/O-2, which forming the complete A2/O-MOSA system. The A2/O-MOSA system was in the debugging period from day 49 to day 87. However, filamentous activated sludge bulking began in day 88, with SVI value exceeding 200 in the aeration tank and finally ended by adding a sodium hypochlorite solution. In the period of sludge bulking and adjusting, which ran from day 88 to day 172, there wasn't a large difference in the waste water treatment capacity ratio of mixed liquor volatile suspended solids(MLVSS) to MLSS between the A2/O system and the A2/O-MOSA system. From day 173 today 200, the SVI value dropped below 150, following a good anaerobic environment in the MOSA reactor, which had an Oxidation-Reduction Potential (ORP) value of 350–400 mV and a ratio of MLVSS/MLSS of about 0.74. This steady running period was maintained for 28 d.

2.3.Synthetic influent

The compositions and characteristics of synthetic wastewater fed into each setup are shown in Table 1.

2.4. Analytical methods

COD, ammonia nitrogen (NH_4^+-N), TP, TNMLSS and MLVSS, were measured according to the Chinese State Environmental Protection Administration Standard Methods [13]. Turbidity was measured as a surrogate measure of suspended solids (SS). A pH meter (PHSJ-3F, Shanghai Leici, China) was used to measure pH in the effluent.

Table 1
Chemical composition of synthetic wastewater

Components	Concentration (mg/L)
Peptone	30
Urea	30
Glucose	150
CH_3COONa	150
NH_4Cl	63
$KHSO_4$	22
KH_2PO_4	13
$CaCl_2$	105.5
$MgSO_4$	26.4
$FeCl_3{\cdot}6H_2O$	13.8
$Al_2(SO_4)_3{\cdot}18H_2O$	25.9

3. Results and discussion

3.1. Effluent quality

3.1.1. COD removal

Fig. 2 depicts the COD removal in both systems during the operational period. High organic matter removal in effluent was seen, despite some fluctuations. Before day 47 (without the MOSA reactor), the average COD removal in A2/O-1 and A2/O-2 were maintained at 91% and the average COD concentrations in the effluent of both systems were around 19 mg/L. From day 88 to day 172, filamentous activated sludge bulking occurred, which affecting the sedimentation and thickening processes. Although several approaches were attempted, COD concentrations in the effluent remained below 50 mg/L most of the time. From day 173 to day 200, the activated sludge sedimentation performance of activated sludge improved. Average COD removal from the A2/O-MOSA and A2/O-2′ system was 92% and 90%, respectively (COD in the effluent was 17 mg/L and 21 mg/L, respectively), meaning that both systems operated steadily. Sludge from the MOSA reactor might prolong the denitrification stage in theA2/O process.Since heterotrophic denitrifiers require an organic carbon source to reduce nitrate [14], denitrification activity in the A2/O-MOSA system consumed more COD. As a result, compared to reference system, inserting a sludge holding tank into wastewater treatment process would have high COD removal [15].

Here, COD removal in both systems had been up to more than 90% when running steadily, and little difference was found between the two systems. This means that the A2/O-MOSA has good capacity to remove COD, as well as A2/O, and the MOSA reactor would not have an adverse effect on COD removal.

3.1.2. Nitrogen removal

Nitrogen removal contains two processes: nitrification and denitrification. In the nitrification process, NH_4-N was converted into nitrate in the aerobic tank. From Fig. 4, ammonia concentrations in the effluent of both systems were all below 2 mg/L with little fluctuation, showing a high removal rate of more than 95%. DO is an important parameter for nitrification. Low DO values (2.5 mg/L) would impact nitrification efficiency [16]. DO levels in the aeration tanks of two systems was controlled at 2~4 mg/L, thus providing enough oxygen for growth of nitrite-oxidizing bacteria (NOB) and nitrifying bacteria. Villaverde [17] and Jetten [18] reported that the optimum pH value for the growth of nitrifying bacteria is 7.4–8.3, which means the pH in the systems provided a good environment for nitrification. NH_3-N concentrations in the A2/O-MOSA system effluent were about 0.4 mg/L, showing that the MOSA reactor did not have adverse effect on NH_3-N removal.

Fig. 5 shows TN concentrations in the effluent of both systems. The influent TN fluctuated between 20–40 mg/L. At the initial operating stage, TN in the effluent was over 15 mg/L due to the initial acclimatization period and it gradually decreased through internally recycling 100% of the mixture from the anaerobic tank to the anoxic tank, where nitrogen was removed by denitrification. A2/O-1 and A2/O-2 ran similarly, with TN in the effluent at 14 mg/L

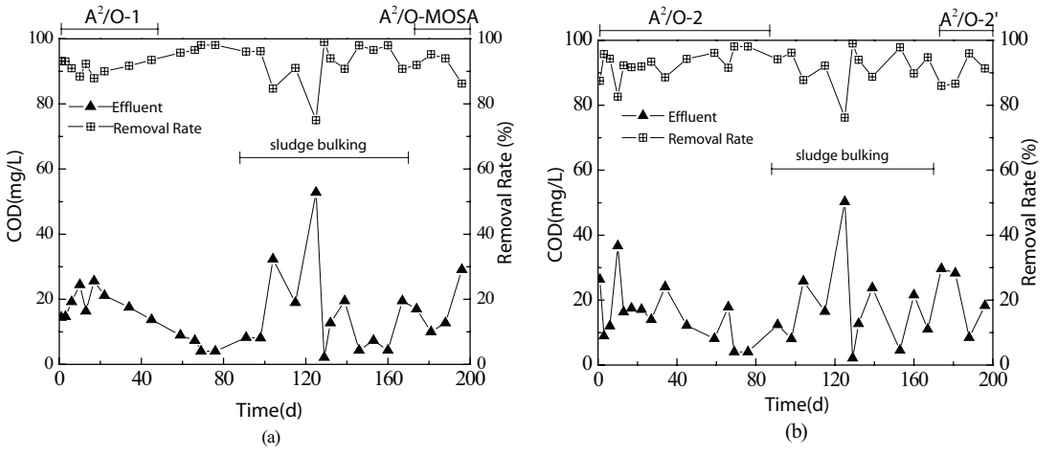

Fig. 2. Change in COD concentration over the entire operating period.

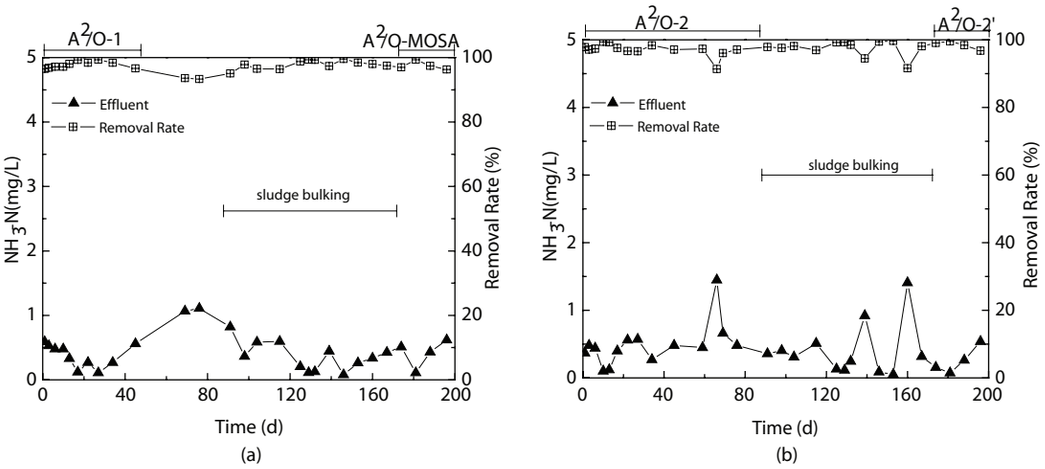

Fig. 3. Change in NH_4^+-N concentration over the entire operating period.

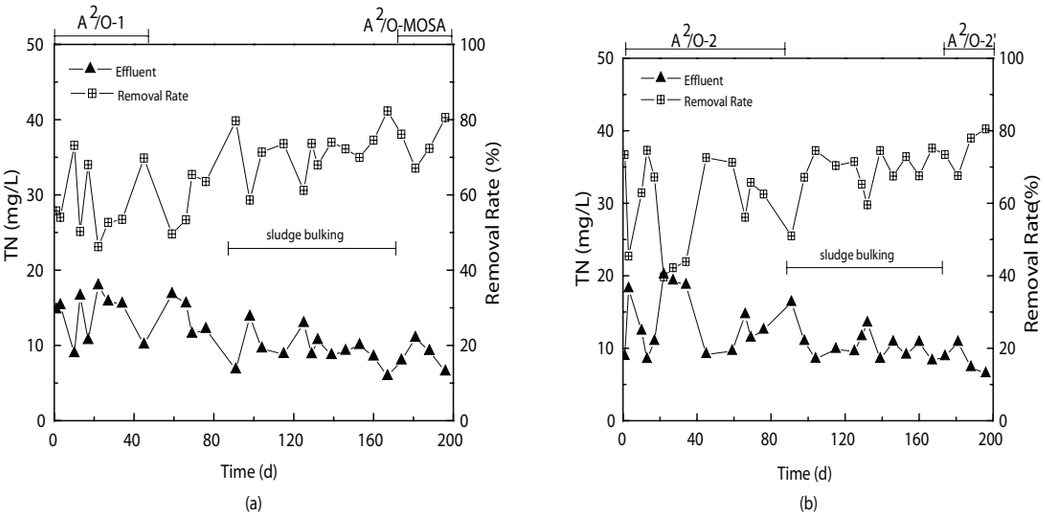

Fig. 4. Change in TN concentration over the entire operating period.

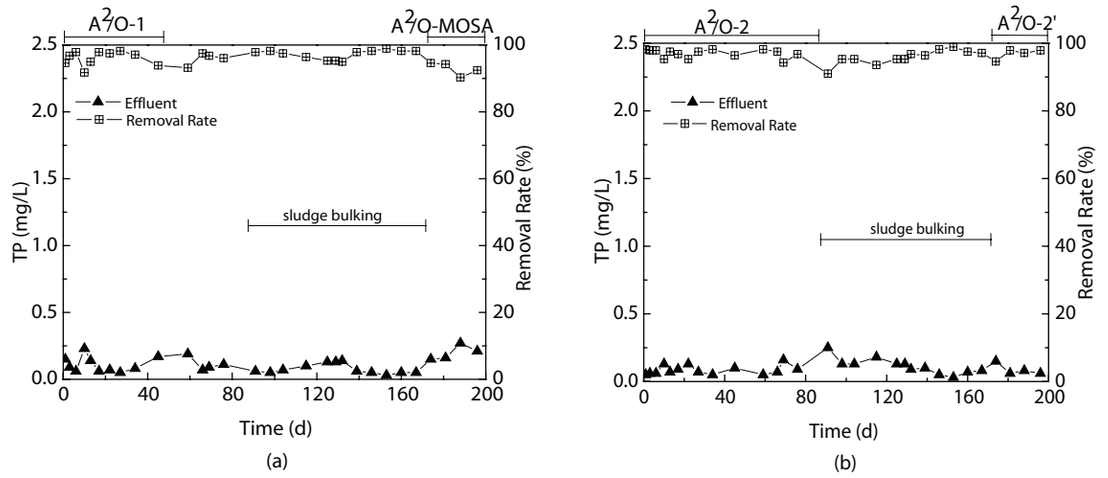

Fig. 5. Change in TP concentration over the entire operating period.

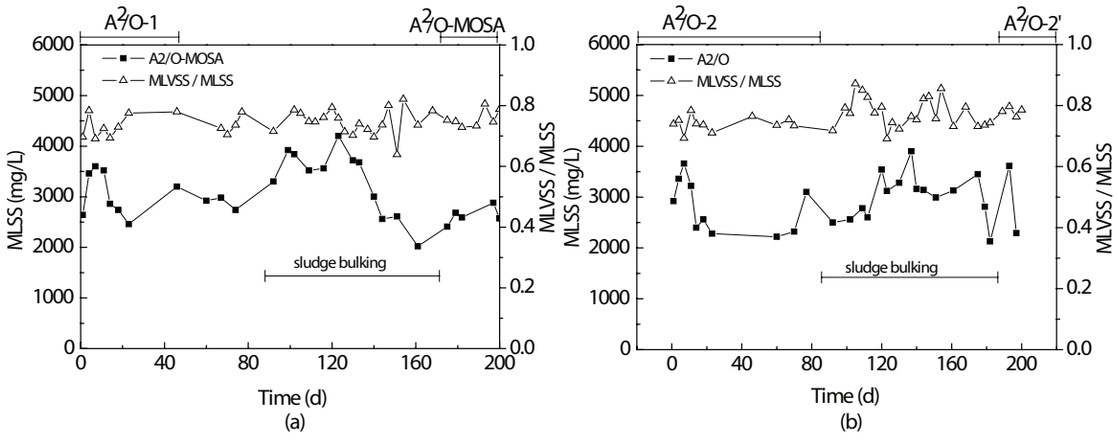

Fig. 6. Solids concentrations in the aerobic tank (a) A2/O-MOSA system (b) A2/O system.

with 58% removal. At the conclusion of A2/O-MOSA and A2/O-2, effluent dropped to 9 mg/L and 8 mg/L in A2/O-MOSA and A2/O-2, respectively, showing mean removals of 74% and 75%, respectively. For the reason that soluble COD released in the MOSA reactor provide more carbon source for denitrification process [19], the A2/O-MOSA system achieved slightly better TN removal.

3.1.4. Phosphorous removal

Inconventional activate sludge plants, phosphorous removal is achieved through the accumulation of P in bacterial cells in the form of polyphosphate (poly P) granules in excess of the levels by poly P accumulating organisms (PAO). Since phosphorous releases in anaerobic environments, PAOs convert short chain volatile fatty acids into polyhydroxy alkanoates (PHAs) with internal polyphosphate and glycogen reserves hydrolyzed to supply energy and reducing power to the cells, leading to an increase in TP or PO_4^{3-}-P concentration [20].

The different forms of phosphorous in effluent consist of soluble phosphorous and particulate phosphorous (mainly phosphate). Primary or secondary clarifiers usually remove most particulate phosphorous in wastewater treatment plants [21]. Low SS concentrations in the effluent (<5 mg/L) revealed that most particulate phosphorus was removed in both systems. Some studies has shown that OSA-like processes would have diverse effects on TP removal in wastewater treatment because of the sludge disintegration [22]. In order to solve this problem, some studies removed TP by adding metal salts as chemical precipitators [23,24]. In our study, TP concentrations in the effluent of both systems were all been below 0.5 mg/L with TP removal of more than 90% (shown in Fig. 6). The reasons for such good TP removal efficiency might be: (a) low TP concentrations in the influent (2~5 mg/L); (b) low phosphorus release in the MOSA reactor (<10 mg/L); or (c) appropriate pH values in effluent (6.5–8.5). The pH changes and COD/P ratio are important factors for biological phosphorus removal. According to Tania [14], the pH value of the effluents from both system similarly fluctuated within 6.5~8.5, close to optimum pH of 7.5–8.0. A COD/TP ratio of 9.1 is needed to achieve good biological phosphorus removal efficiency. In

the MOSA reactor, COD/TP was about 12, indicating that the MOSA reactor did not affect TP removal in the A²/O process.

3.2. Sludge properties and sludge reduction

The MLSS concentrations in the aeration tanks of both systems were maintained between 2000–4000 mg/L (Fig. 6). From day 1 to day 48, average values of MLSS in the A2/O-1 and A2/O-2 systems were 3078 mg/L and 2933 mg/L, respectively, and the mean value of MLVSS/MLSS was 0.74 in both systems. From day 88 to day 172, sludge bulking occurred with SVI values exceeding 200 (Fig. 7) in both systems, meaning that it was not the insertion of the MOSA reactor that led to sludge bulking, and was finally completed by adding a sodium hypochlorite solution. Day 173 to day 200, SVI values were maintained around 150 in both systems, and the average value in A2/O-MOSA (SVI = 151 mL/g MLSS) was slightly higher than in A²/O-2′ (SVI = 144 mL/g MLSS), showing that sludge settling was improved and remained stable. During this period, the average MLSS in A2/O-MOSA and A2/O-2′ were 3567 mg/L and 3686 mg/L, respectively, and the average value of MLVSS/MLSS was the same at 0.76, which indicating that inserting the MOSA reactor did not the nature of biomass in the aerobic tank. There is no change in MLSS/MLSS ratio in present studies [25,26] on sludge reduction using chemical pretreatment, because inorganic particulates from disintegrated cells, which come from the MOSA reactor, might be taken out of the system by discharged sludge or effluent [27] .

The observed sludge yield (Y_{obs}) was used to determine the sludge production rate in this study, usually calculated on a daily cumulative basis. Since there was a period of sludge bulking and adjusting from the day 88 to day 172, it was difficult to calculate the mean daily variation of TSS in activated sludge tanks. Thus, Y_{obs} was calculated by the absolute amount of TSS produced and COD removed in systems, calculated as follow [7]:

$$Y_{obs} = \frac{\Delta \mathrm{TSS}}{\Delta \mathrm{COD}} = \frac{\left(MLSS_t - MLSS_0\right) \times V_a + U_{eff} + W_{ss}}{\left(COD_{in} - COD_{eff}\right) \times Q \times T} \quad (2)$$

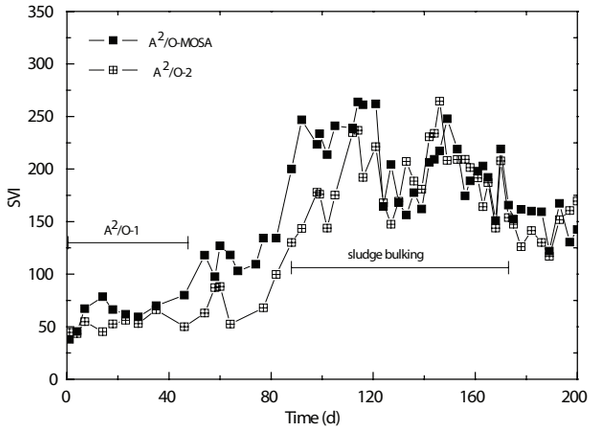

Fig. 7. Change in SVI values in the aerobic tank.

where ΔTSS and DCOD are the TSS produced and COD removed in the systems; $MLSS_t$ and $MLSS_0$ are the MLSS concentrations (mg/L) in the aeration tank during the initial and late periods of operation; V_a is the volume (L) of the aeration tank; U_{eff} is the total mass of the excess sludge (mg) from settling tank, except for returned sludge; is the mass of suspended solid (mg) escaping via effluent; COD_{in} and COD_{eff} are the average COD concentrations (mg/L) in the influent and effluent; Q is the daily sewage flow (L/d) of the system; T is the operating time (d).

The calculation f or Y_{obs} in the A2/O-MOSA process is shown in Table 2.

The reduction in sludge production was evaluated by comparing Y_{obs} in the A2/O-MOSA (0.3739 kg-TSS/kg-COD) with that in the A2/O-2′ system (0.4909 kg-TSS/kg-COD). The sludge reduction rate is about 24% in this study under the operating conditions of IR = 10%, HRT = 5d and SRT = 15 d. Though it cannot achieve as high of sludge reduction as an A2/O processes combined with chemical or physical ways [28], A2/O-MOSA system has the great advantage of much lower cost for operation. The A2/O-MOSA system also achieved less sludge reduction compared to the MOSA-A/O system in Tan′ study [10], where a sludge reduction of 35% was achieved, so the optimal operation parameters (like IR and SRT) in A2/O-MOSA still need to research.

Sludge reduction in this study was lower than that in other studies that researched OSA-like processes mostly based on SBRs and achieved sludge reductions of more than 40% [4,5]. Sludge reduction in OSA-like processes may partly result from sludge degradation because of the prolonged SRT [29,30]. But there are other mechanism of sludge reduction with important roles in OSA-like processes [3], including energy uncoupling, domination by slow growers, and effect of soluble microbial products.

In order to evaluate the sludge decay that contributed to sludge reduction, the sludge concentration of the MOSA reactor inflow and outflow was monitored (Fig. 8).

Because both systems ran steadily from day 173 to day 200, data from that period was selected to calculate the amount of sludge decay in the MOSA reactor as follows:

Table 2
Observed sludge yield from different periods

Parameter	A2/O-1	A2/O-2	A2/O-MOSA	A2/O-2′
(mg)	905220	905690	543200	520741
$MLSS_t$ (mg/L)	3216	3112	3373	3649
$MLSS_0$ (mg/L)	2626	2858	3362	3390
(L)	22			
(mg)	281072	272884	200016	258129
W_{SS} (mg)	5069	4858	3326	3203
(mg)	273161	272154	203100	255634
Y_{obs} (kg-TSS/kg-COD)	0.3018	0.3005	0.3739	0.4909
Reduction in Y_{obs}	–	–	24%	–

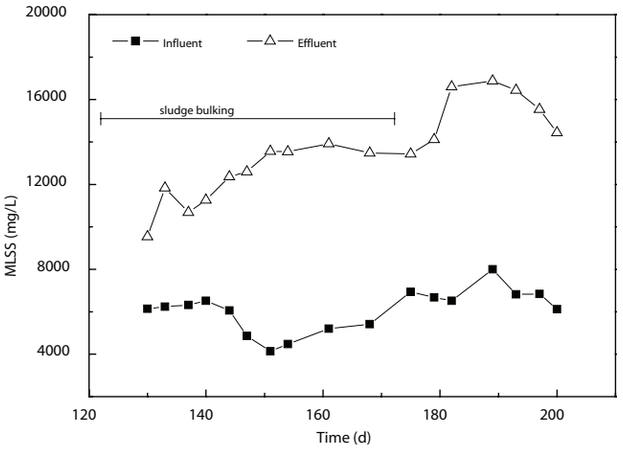

Fig. 8. Change in MLSS of the MOSA reactor.

$$\Delta M = \left(4 \times C_0 V - C_1 \cdot V - 3 \times C_2 \cdot V\right) * T \quad (3)$$

where V is the volume of influent and effluent of the MOSA reactor (0.15 L each time); C_0 is the mean value of MLSS of inflow (four times each day); C_1 is the mean value of MLSS of sludge mixed liquor flowing out (once each day); C_2 is the mean value of MLSS of sludge supernatant flowing out (three times each day); T is the operating time (28 days here).

The absolute amount of sludge decayed in the MOSA reactor was 30,372 mg, and the amount of sludge reduced between A2/O-MOSA and A2/O-2′ systems (ΔTSS) was 52,534 mg. This means that sludge decay accounted for about 58% of the total sludge reduction indicating that sludge decay is the main reason causing sludge reduction, similar to Chen's [3] study on OSA process.

4. Conclusion

Combining a MOSA reactor (IR = 10%, HRT = 5 d, and SRT = 15 d) with an A2/O process would not affect pollutant removal rates. Meanwhile, no significant worsening of sludge settle ability occurred when operating the MOSA reactor. But it will require effort to avoid sludge bulking. Yobs in A2/O-MOSA and A2/O-2′ were 0.3739 and 0.4909 kg-TSS/kg-COD, respectively, achieving a reduction of 24% in excess sludge production. For the A2/O-MOSA system, sludge decay contributed 58% sludge reduction. With the advantages of a simpler structure and lower costs in modifying an activated sludge system, MOSA-A2/O is a promising and practical technology for sludge process reduction. Further research is needed for determining the optimal operating parameters and for applying A2/O-MOSA at a pilot-scale or full-scale.

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