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SCIENTIFIC PAPER

SIDE-STREAM SLUDGE TREATMENT USING FREE AMMONIA FOR REDUCING SLUDGE PRODUCTION

Article Highlights

• An innovative approach for achieving sludge reduction was applied by adding free ammonia
• Sludge production rate was significantly reduced by 21% after FA treatment
• Treatment performance and sludge properties were not negatively affected by the FA-treated sludge

Abstract

Much attention has been paid to reducing of excess sludge production in the activated sludge process, due to high treatment and disposal costs. In this study, an innovative approach for achieving sludge reduction, which featured recirculating a portion of the activated sludge through a side-stream sludge treatment unit, was applied by adding free ammonia (FA, i.e., NH3). The results showed that sludge production was significantly reduced after FA treatment, while the sludge production rate was decreased by 21%. Meanwhile, the treatment performance and the sludge properties were not negatively affected by the FA-treated sludge during the experiment (e.g. effluent quality, nitrification activity, sludge settleability). Economic analysis also indicated that the FA treatment approach would be an economically favorable technology, and the sludge treatment costs could be cut by 16.6%.

Keywords: Free ammonia, sludge reduction, treatment performance, economic analysis, excess sludge.

The activated sludge process has been widely used for wastewater treatment because of its high efficiency in nutrient removal [1-3]. However, large quantities of excess sludge produced from the activated sludge process are also generated simultaneously, which leads to high costs of treatment and disposal [4-11]. Therefore, the reduction of excess sludge production has become a main challenge for the operation of sewage treatment plants (STPs).

There are several traditional sludge reduction methods that were reported from existing literature. For example, ozonation had been reported to enhance biological degradation of the activated sludge effectively, where the sludge degradation could be improved by 41% at 0.1 gO3/g-SS (SS: suspended solids) after 15 days in the aerobic condition [12,13]. Saby et al. also reported a chlorination method for sludge reduction, which could reduce sludge production by 65% [14]. Camacho et al. reported that the sludge reduction rate was up to 60% using the combination of thermal treatment and the activated sludge process [15]. Ultrasound had also been applied to improve volatile solid destruction by up to 30% [16]. However, these technologies are usually energy-intensive, and were either applied in the sludge treatment line to enhance aerobic or anaerobic digestion, or in the sludge return line to improve sludge degradation in the wastewater treatment process [6]. Obviously, the key point of sludge reduction was to decrease the sludge production during the wastewater treatment process and thereby decrease the
subsequent sludge management cost. As an alternative technology to reducing the sludge production directly, high-pressure jet device (HPJD) had been widely reported and studied in Japan [17-19]. However, HPJD needed additional equipment to achieve sludge production and had to be maintained continuously by electric energy.

More recently, free ammonia (FA, i.e., NH₃) was found to inhibit the metabolism of the microorganisms existing in the activated sludge process. Meanwhile, several advantages of FA application in the activated sludge system were shown [20-32]. For example, FA-based pretreatment could enhance phosphorus release/recovery, hydrogen production and short-chain fatty acid production from waste activated sludge [21-24]. Compared with the enhancement of sludge degradation by HPJD, FA-based technology did not rely on additional equipment and could be obtained directly from anaerobic digestion liquor, which contained an ammonium (NH₄⁺) concentration at around 1.0-2.0 g N/L associate with a pH of 7.5-8.6 and a temperature of 33 °C, resulting in an FA level of 30-560 mg NH₃-N/L [25,26]. FA had also been reported to enhance the anaerobic degradation of sludge. Wei et al. demonstrated pretreatment of primary sludge using FA for 24 h at 85-680 mg NH₃-N/L could enhance anaerobic methane production by 5-15% [27]. Wei et al. also showed that anaerobic methane production from secondary sludge could be enhanced by 20-30% under the same FA pretreatment conditions [32]. Wang et al. demonstrated that the sludge concentration in the mainstream reactor decreased after incorporating FA pretreatment in the sludge recycling line [28].

These findings allowed us to hypothesize a technology that using FA treatment on the return sludge to attain sludge reduction. In order to confirm this assumption, a pilot-scale sequencing batch reactor (SBR) fed with synthesized wastewater was operated during different phases. Phase I acted as a control, while phase II and phase III served as experimental phases. While half of the return sludge was treated at an FA concentration of 350 mgN/L for 24 h and subsequently returned to the SBR. The mixed liquor suspended solid (MLSS) and mixed liquor volatile suspended solid (MLVSS) concentrations in all the three phases were measured, and the sludge production rates during different phases were also calculated. Meanwhile, the effluent quality, sludge volume index (SVI), ammonium oxidizing bacteria (AOB) activities and nitrite oxidizing bacteria (NOB) activities during phase I and phase III were also evaluated and compared.

MATERIALS AND METHOD

Lab-scale reactor setup and operation

A lab-scale SBR was used in this study with a volume of 7.5 L. The SBR was operated for 6 hours as one cycle, consisting of anoxic feeding (10 min), anoxic reaction (70 min), aerobic reaction (223 min), sludge wasting (7 min), settling (45 min) and decanting (5 min) periods. During each cycle, 2L of synthesized wastewater was injected into the SBR by the pump within the 10 min of feeding stage, giving rise to a theoretical hydraulic retention time of 22.5 h. During the control phase, 125 ml of mixed biomass was discharged every cycle, which resulted in a sludge retention time (SRT) at 15 days.

The reactor was mixed at 250 rpm in the first four steps (anoxic feeding, anoxic reaction, aerobic reaction and sludge wasting). pH was monitored without controlling, which was between 7.2 and 7.5 during one typical cycle. During the aerobic period, an on/off dissolved oxygen (DO) controller was used to keep DO in the range between 1.5 and 2.0 mg/L. The air flow rate was kept as 1.2 L/min while the DO controller was automatically turned on. The temperature of SBR was controlled at around 23 °C in an air-conditioned room.

The SBR was operated for about 5 months, and three phases were divided (Phase I acted as a control phase and Phases II and III acted as the experimental phases):

Phase I (Day 45-0). The SBR was run under the above-mentioned operating conditions for 45 days to achieve steady state, which operated as baseline phase. SRT in the reactor was set as 15 days.

Phase II (Day 0-45). During the experimental phase, approximately 500 ml of waste sludge was pumped out every day, with 50% of it (i.e., about 250 ml) being centrifuged to 100 ml. Afterwards, the concentrated waste sludge was transferred into an FA treatment unit every four cycles. An ammonium stock solution (80 g/L) was dosed into the FA treatment unit to gain a total ammonia nitrogen (TAN, i.e., NH₃-N+NH₄⁺-N) concentration of 900 mg N/L. pH was then controlled at 9.0±0.1 during a 24 h treatment period. The FA concentration was determined as 350 mg N/L by the following formula: $STAN \times 10^{30}/(Kf/Kw + 10^{38})$, in which $STAN$ is the TAN concentration, $Kf$ is the ionization constant of the ammonia equilibrium equation, and $Kw$ is the ionization constant of water [33]. The $Kf/Kw$ value was determined using the formula $Kf/Kw = e^{6.344(273+T)}$ (T = 26 °C in this experiment) [33]. The selected FA concentration in this study was based on previous studies [27,28].
Phase III (Day 46-100). The operating condition in this phase was mainly similar to that in phase II, except for the following differences. Because of the recirculation of the FA-treated wasted sludge in the steady state of phase II, the final MLSS concentration during the experimental phase (phase II) was significantly higher than the MLSS concentration during the baseline phase (phase I). In order to make the similar MLSS concentration between the experimental phase and baseline phase, the volume of wasted sludge from the experimental phase was increased, with about 750 ml waste sludge being pumped out on a daily basis. Similar to phase II, half of the waste sludge (around 375 ml) was concentrated to 100 ml by centrifugation and then pretreated with FA and recirculated to the SBR, giving rise to a SRT of 20 d in this phase.

Wastewater preparation, monitoring, sampling and analysis method

The synthesized wastewater was composed of milk powder, starch, sucrose, peptone, NH₄Cl, acetate, yeast extract and trace elements to mimic real municipal wastewater. The composition of synthesized wastewater was: 110 mg/L milk powder, 81 mg/L starch, 80 mg/L sucrose, 16 mg/L peptone, 60 mg/L CH₃COONa, 38 mg/L yeast extract, 153 mg/L NH₄Cl, 13 mg/L K₂HPO₄, 14 mg/L KH₂PO₄, 600 mg/L NaHCO₃. The trace elements were as follows: 2.5 mg/L FeSO₄·7H₂O, 0.06 mg/L MnCl₂·4H₂O, 0.06 mg/L ZnCl₂, 0.19 mg/L NaMoO₄·2H₂O, 0.04 mg/L NiCl₂·6H₂O, 0.13 mg/L CoCl₂·6H₂O, 0.44 mg/L CaCl₂, 0.06 mg/L CuSO₄·1.19 mg/L MgCl₂, 0.06 mg/L H₃BO₃.

The concentrations of MLSS and MLVSS in the reactor were measured one or two times per week during phase I, each day during phase II, and every other day during phase III. Thereby, the sludge reduction rate was calculated by subtracting the quantity of sludge production in the control phase to that in the experimental phase (Table 1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control phase</th>
<th>Experimental phase</th>
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<tbody>
<tr>
<td></td>
<td>Steady state I</td>
<td>Steady state II</td>
</tr>
<tr>
<td>MLSS (mg/L)</td>
<td>1654±19</td>
<td>2050±21</td>
</tr>
<tr>
<td>MLVSS (mg/L)</td>
<td>1585±20</td>
<td>1912±15</td>
</tr>
<tr>
<td>Sludge production rate</td>
<td>827±10</td>
<td>513±3</td>
</tr>
<tr>
<td>(mg MLSS/d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sludge reduction (%)</td>
<td>Not applicable</td>
<td>(827-513)/827 = 38%</td>
</tr>
<tr>
<td>MLVSS/MLSS (%)</td>
<td>95.8±0.1</td>
<td>93.3±0.2</td>
</tr>
</tbody>
</table>

Mixed biomass samples were filtered by disposable Millipore filter units (0.45 μm pore size) to analyze nitrite, nitrate, ammonium and soluble chemical oxygen demand (SCOD). The concentrations of nitrite, nitrate and ammonium were analyzed by ion chromatography (ICS-90, Dionex, CA USA). The SCOD, total chemical oxygen demand (TCOD), SVI, MLSS and MLVSS concentrations were measured by standard methods [34].

Nitrification batch tests

In order to evaluate the maximum activities of AOB and NOB in the reactor, nitrification batch tests were conducted in the steady state during phase I and phase III. At the end of an aerobic period, mixed biomass (100 ml) was sampled from the reactor and then transferred to an Erlenmeyer flask. Afterwards, the calculated stock solutions were then added to the Erlenmeyer flasks, which resulted in an ammonium concentration of 25 mg N/L and nitrite concentration of 20 mg N/L. pH in the Erlenmeyer flask was manually controlled in the range of 7.0 and 7.5 with dosing of 0.5 mol NaOH and 0.5 mol HCl, which was the same as the range of pH variation in the SBR reactor. Air was aerated to ensure that DO was not limiting (DO > 4 mg O₂/L) when the batch tests were conducted. The batch tests were conducted in triplicate. The mixed biomasses were sampled every 15 min for nitrate and nitrite analysis. At the end of each test, the MLVSS concentrations in the Erlenmeyer flasks were then measured. AOB activities were calculated by NOX⁻ (NO₂⁻ + NO₃⁻) production rates, which divided the corresponding MLVSS concentration. Similarly, NOB activities were determined by NO₃⁻ production rates and also divided the corresponding MLVSS concentration.

RESULTS AND DISCUSSION

Excess sludge production in different phases

A long-term experiment was conducted to assess the feasibility of FA treatment to achieve sludge reduction, which was divided into a control phase and experimental phases. During each phase, the MLSS concentration, MLVSS concentration, and sludge production rates in the reactor were measured and calculated. Therefore, the sludge production rate with/without FA treatment could be investigated and compared.

As shown in Figure 1, when MLSS concentration in the SBR reactor achieved steady state during the control phase, FA-treatment of the side-stream sludge began. After recirculating FA-treated sludge to
the SBR reactor, the concentrations of MLSS and MLVSS increased slowly between day 0 and 11 and then kept stable for the rest of phase II. Likewise, the concentrations of MLSS and MLVSS of the reactor in phase III decreased during the first week because of the decreased SRT. After that, the concentrations of MLSS and MLVSS reached steady state and were kept at a similar concentration to those in the control phase.

Table 1 summarized all measured and calculated data in steady states of three phases, including MLSS and MLVSS concentrations, sludge production rates, and sludge reduction percentage. In phase II, a sludge reduction of about 38% was achieved in the steady state when part of return sludge was treated by FA. This indicated that FA treatment could effectively improve sludge reduction. However, the value of sludge reduction percentage was not totally representative, because the MLSS concentration in the experimental phase (2050 mg/L) and control phase (1654 mg/L) were quite different ($p < 0.05$). Therefore, sludge wastage flow rate from the reactor was increased in phase III (i.e., decreased SRT). After reaching steady state, similar concentrations of MLSS and MLVSS were achieved between phases I and III ($p > 0.05$), while the rate of sludge production based on MLSS in phase III was 21% lower compared to that in phase I (656 mg/d vs. 827 mg/d).

The ratios of MLVSS/MLSS in the reactor in phases II and III were lower ($p < 0.05$) than in phase I, suggesting that the return of FA-treated sludge involved inorganic solids accumulation in the reactor. This is consistent with the SRT in the experimental phases (30 days in phase II and 20 days in phase III) which were higher than that in the control phase (15 days in phase I).

The reactor performance affected by FA treatment

To evaluate the reactor performance and sludge properties affected by FA treatment, effluent SCOD, TCOD, nitrogen composition (ammonium, nitrite and nitrate) concentrations were measured as the indicator for reactor performance; SVI, AOB and NOB activities were measured as the indicator for sludge properties.

Table 2 presents that there was no negative effect on effluent SCOD and TCOD concentrations in phases I and III ($p > 0.05$). Nitrogen removal rates were also similar in both phase I and phase III, which indicated that the effluent quality was not influenced by the FA treatment of excess sludge. Sludge settleability was found to be similar ($p > 0.05$) in phase I and phase III according to SVI indicators (Table 2), which suggested that sludge settleability was not affected by FA treatment. Moreover, the effects of FA

<table>
<thead>
<tr>
<th>Property</th>
<th>Parameter</th>
<th>Phase I</th>
<th>Phase III</th>
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<tbody>
<tr>
<td>Treatment performance</td>
<td>Effluent SCOD (mg/L)</td>
<td>30.5±0.4</td>
<td>29.3±0.9</td>
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<tr>
<td></td>
<td>Effluent TCOD (mg/L)</td>
<td>37.6±0.9</td>
<td>38.3±0.8</td>
</tr>
<tr>
<td></td>
<td>Effluent NH$_4^+$ concentration (mg N/L)</td>
<td>0.1±0.1</td>
<td>0.1±0.1</td>
</tr>
<tr>
<td></td>
<td>Effluent NO$_2^-$ concentration (mg N/L)</td>
<td>0.1±0.1</td>
<td>0.1±0.1</td>
</tr>
<tr>
<td></td>
<td>Effluent NO$_3^-$ concentration (mg N/L)</td>
<td>10.4±0.6</td>
<td>10.5±0.4</td>
</tr>
<tr>
<td>Sludge properties</td>
<td>SVI (ml/g)</td>
<td>136±6</td>
<td>139±5</td>
</tr>
<tr>
<td></td>
<td>Maximum activity of AOB (mg NO$_x^-$-N/(g MLVSS h))</td>
<td>5.37±0.13</td>
<td>5.75±0.17</td>
</tr>
<tr>
<td></td>
<td>Maximum activity of NOB (mg NO$_3^-$-N/(g MLVSS h))</td>
<td>4.96±0.15</td>
<td>4.74±0.12</td>
</tr>
</tbody>
</table>
treatment on nitrification activity were evaluated using maximum activities test of AOB and NOB. As summarized in Table 2, AOB and NOB activities in phase I were similar to those in phase III (p > 0.05), suggesting that FA treatment does not negatively affect the nitrification activity.

**Implication and economic analysis of FA treatment for sludge reduction**

This is the first study to use FA treatment to achieve sludge reduction, which was experimentally verified by comparing sludge production rates between two phases with/without FA sludge treatment. After recirculating half of the wasted sludge that was treated by FA at 350 mg NH₃-N/L for 24 h to the parent reactor, sludge production was found to be 21% lower than the sludge without FA treatment in phase I. Moreover, this FA treatment technology did not affect treatment performance and sludge properties, which suggested that FA-based sludge reduction technology could become a potential promising technology. The process was operated in the following way: the FA treatment unit can be added during the sludge returning line, and then the FA treated sludge returns to the bioreactor. Through this treatment, the amount of excess sludge produced from STPs could be reduced, and then save the cost for the excess sludge treatment and disposal.

According to the experimental results achieved in this study, a desktop scaling-up study (Table 3) was conducted to evaluate the economic benefit of proposed FA treatment technology. Two systems were used to compare the economic benefit, with one system operated serving as a control system and other as an experimental system. In the control system, SRT was operated at 20 d and sludge production was about 1 ton of dry solids every day. In the experimental system, SRT was operated at 20 d and daily sludge production was about 0.8 ton of dry solids.

The experimental system with FA technology resulted in 21% sludge reduction, compared with the control system. The costs that were required for 21% sludge reduction, with respect to the control system, were evaluated and calculated, as shown in Table 3. As shown in Table 3, the total cost for the sludge transport and disposal in the control was 146,000 $/year, whereas the cost of the experimental system with FA technology was 121,700 $/year. Therefore, sludge reduction that involved FA treatment could save 24,000 $/year, indicating that FA pretreatment is an economically favorable technology for sludge reduction. Additionally, the FA treatment unit is expected to be easily equipped with a very simple device, compared to the other current methods (mechanical, thermal and chemical technologies), which need specialized reactors/equipment to bear with some special environment (e.g., high pressure, high temperature, high mechanical forces). Moreover, FA is a very cheap chemical material that can be recycled and reused directly from waste liquor of anaerobic digestion, which contains FA concentration at around 30-560 mg NH₃-N/L, calculated from ammonium concentration of 1.0-2.0 gN/L with a pH range of 7.5-8.6 and a temperature of 33 °C in the anaerobic digestion liquor [27,28]. Therefore, the FA concentration applied in this study could be obtained from the wasted liquor of anaerobic digestion of the STPs in situ. There are also environmental advantages by substantially reducing the addition of ammonium to the FA treatment unit and alleviate the nitrogen load in the wastewater influent. Even though the small-scale STPs without an anaerobic digestion process, FA could be realized by purchasing ammonium salt and sodium hydroxide from the commercial market, which are cheap chemicals and can also be recycled. However, this needs to be verified in the full-scale STPs in the future. This study is a first step in demonstrating the proof-of-concept of sludge reduction by FA treatment technology. The optimization of the treatment (e.g., optimization of FA concentration or treatment duration) was not conducted yet and this is required to fully determine the potential for the application of the technology. Also, the effect of the FA treatment on the sludge dewaterability and nitrous oxide (N₂O) emission are still unknown. Consequently, future studies are still needed to evaluate and optimize this technology. Also, full-scale studies are required to better verify this proposed method.

**CONCLUSIONS**

The feasibility of the reduction of sludge production based on a novel sludge treatment with free ammonia (FA, i.e., NH₃) was firstly investigated through a side-stream sludge treatment unit. The results showed that 350 mg NH₃-N/L FA treatment of return sludge was effective in reducing excess sludge production by 21%, compared with a control system in this study. Meanwhile, the effluent quality, nitrification activity and sludge settleability of the system were not affected by the FA treatment. Furthermore, economic analysis shows that sludge treatment costs could be saved by 16.6% using FA treatment technology, which indicated that the proposed technology...
was an economically attractive and environmentally friendly strategy for sludge reduction.

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REFERENCES


OBRADA RECIRKULACIONOG MULJA KORIŠĆENJEM SLOBODNOG AMONIJAKA RADI SMANJENJE PROIZVODNJE MULJA

Sve veća pažnja posvećena je smanjenju proizvodnje viška mulja u procesu aktivnog mulja zbog visokih troškova obrade i odlaganja. U ovom radu je primenjen inovativni pristup za smanjenje mulja, koji uključuje recirkulaciju dela aktivnog mulja kroz jedinicu za obradu mulja u bočnoj petli, dodavanjem slobodnog amonijaka (NH₃). Rezultati su pokazali da je proizvodnja mulja značajno smanjena nakon obrade slobodnim amonijakom, dok je brzina proizvodnje mulja smanjena za 21%. Pri tome, performanse obrade i svojstva mulja (npr. kvalitet otpadne vode, aktivnost nitrifikacije, taloživost mulja) nisu bili pogoršani ovakvim tretiranjem muljem tokom eksperimenta. Ekonomski analiza je, takođe, pokazala da bi obrada slobodnim amonijakom bila ekonomski povoljna tehnologija, a troškovi obrade mulja mogli bi da se smanje za 16,6%.

Ključne reči: slobodni amonijak, smanjenje mulja, performanse obrade, ekonomski analiza, višak mulja.