Evaluation of WAS reduction efficiency using kinetic parameters in pilot-scale SBR operated with anaerobic sludge holding tank

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ABSTRACT

By evaluating microbial kinetic parameters of a pilot sludge blanket reactor (SBR) plant operated with an anaerobic sludge holding tank (SHT), it was found that the sludge production was reduced by 63.5%. According to the theory of uncoupling metabolism, the microorganisms were induced to the initial stage of the endogenous phase in SHT, which resulted in the reduction of yield coefficient. For the determination of optimal retention time in SHT without causing a significant decay of microorganisms, ammonia concentration was monitored with time at specific temperature and mixed liquor suspended solids concentrations. In a long-term (> 1 yr) operation of the pilot plant, no deterioration of the effluent water quality was observed. Considering phosphorus removal, an extended sludge retention time of 60–70 days (due to the reduced yield coefficient) did not significantly affect the efficiency relative to typical biological nutrient removal (BNR) processes. According to the findings of this study, anaerobic SHT can be applied for BNR processes with reduced production of sludge, and this will help to minimize environmental and economic problems pertaining to the final disposal of sludge.

Key words | kinetic parameter, SBR, sludge holding tank, sludge reduction

INTRODUCTION

Treatment and disposal of waste activated sludge (WAS) has become one of the major concerns in the sewage treatment field. WAS is organic waste produced from the synthesis of microorganisms in bio-reactors, using organics and nutrients present in wastewater. In Korea, the WAS generation rate was 8,292 ton/day in 2009, and it will be increased to 10,936 ton/day by 2013 (KMOE 2011). In addition, WAS comprises 19% of the total amount of industrial waste production, which causes a big burden environmentally as well as economically. Although ocean dumping has been the major disposal method of WAS in Korea, an appropriate alternative is required due to the prohibition of ocean dumping.

Most methods for WAS yield reduction are dependent on post-treatments of the sludge produced, such as mechanical solubilization, heat treatment, chemical oxidation, and biological hydrolysis. The pre-treated sludge is returned to the bio-reactor as additional substrate for microbial growth. It was reported that reduction of WAS production can be effectively attained with these methods by lowering total yield of sludge production (Ødeggard 2004). However, these methods require the installation of an additional unit process in the sludge handling procedure, which, in turn, requires a relatively high amount of energy consumption. On the other hand, studies have been carried out to develop proactive methods which reduce WAS production in treatment processes by manipulating microbial metabolism. The oxic–settling–anaerobic (OSA) process is one of the typical proactive methods utilizing an anaerobic sludge holding tank (SHT) installed in the sludge recycle line (Chudoba et al. 1991, 1992a, b). Low & Chase (1999) also showed this yield reduction method to be effective.

Although studies have been carried out to elucidate the possible mechanisms for sludge yield reduction of the OSA process, the changes in microbial metabolism caused by the SHT have not been studied yet. Uncoupling metabolism, changes in $S_0/X_0$ ratio, microbial decay, domination of microorganisms with low growth rate, and involvement of predators have been proposed as possible mechanisms of yield reduction in the OSA process (Low & Chase 1999; Ødeggard 2004). However, these methods require the installation of an additional unit process in the sludge handling procedure, which, in turn, requires a relatively high amount of energy consumption. On the other hand, studies have been carried out to develop proactive methods which reduce WAS production in treatment processes by manipulating microbial metabolism. The oxic–settling–anaerobic (OSA) process is one of the typical proactive methods utilizing an anaerobic sludge holding tank (SHT) installed in the sludge recycle line (Chudoba et al. 1991, 1992a, b). Low & Chase (1999) also showed this yield reduction method to be effective.

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Chen et al. 2001, 2005). Of these possible explanations, uncoupling metabolism has been studied widely as the most plausible mechanism (Low & Chase 1999; Chen et al. 2005); microorganisms are induced to the initial stage of the endogenous growth phase in reductive anaerobic conditions in SHT with little substrate available, and, then, recycled to the bioreactor, which possesses a relatively high amount of substrate. Due to this change in environments, inhibition of microbial metabolism occurs, which results in yield reduction while maintaining substrate uptake rate. It can also be explained by the reduction of adenosine triphosphate production in microbial cells mainly due to the abrupt change in growth environments. In similar studies on yield reduction by metabolic inhibition, chemicals are often added directly into a bioreactor to intentionally cause the inhibition. Yang et al. (2003) also reported the yield reduction by the organic protonophore of metabolic uncouplers, i.e., chlorophenol, nitrophenol.

Yield reduction has also been evaluated by integrating SHT to sewer treatment processes. Datta et al. (2009) reported the effectiveness of SHT by measuring mixed liquor suspended solids (MLSS) concentrations using a bench-scale sequencing batch reactor (reactor volume of 2 L). The intermittent aerobic–settling–anaerobic process has also been proposed to achieve nitrogen removal with yield reduction (Nam 2008).

In this study, reduction of sludge production was investigated by evaluating kinetic parameters of microorganisms in a 50-m³/day pilot-scale sludge blanket reactor (SBR) process coupled with SHT, as more direct evidence than MLSS measurements. The pilot plant was operated for more than 1 year with actual domestic wastewater, and during the operation direct measurement of sludge reduction as well as nutrient removal efficiencies were evaluated.

**METHODS**

**Pilot pant**

A 50 m³/day pilot-scale SBR process coupled with SHT was operated for more than 1 year in a local sewer treatment plant located in a suburban metropolitan area of Seoul, Korea. The pilot plant was fed with raw wastewater which was pretreated with a 0.5-mm fine screen. The schematic diagram of the pilot plant is shown in Figure 1.

One operation cycle of the SBR process was 6 hours, and operated with continuous inflow-mode of wastewater. For the reaction cycle, the reactor was intermittently aerated to operate the SBR as a biological nutrient removal (BNR) system. At the return cycle, settled sludge was pumped into SHT at a flow rate that was one-half of the influent flow rate, while the sludge reacted in SHT was returned to the SBR reactor by gravitational flow. To minimize the turbulence of settled sludge, a telescope-type decanter was specially developed and employed. Table 1 shows the operation cycle of the SBR pilot plant.

Hydraulic retention time (HRT) of the SHT was 6 hours, the same as one operation cycle of the SBR system, and a reducing condition (oxidation reduction potential of about −250 mV) was maintained. In order to shorten the time required for inducing the initial stage of the endogenous phase, a heating system was installed in the SHT to maintain 30 ± 1 °C while mixing continuously.

**Evaluation of optimal HRT of SHT**

In order to evaluate the optimal HRT of SHT, samples were taken from the settled sludge and incubated in reductive anaerobic condition, while monitoring NH₃-N concentration with time. According to the theory of uncoupling metabolism, as mentioned earlier, it is critical to induce microorganisms to
the initial stage of the endogenous phase. In this study, therefore, an abrupt increase in NH$_3$-N release rate was considered as the start of the endogenous phase, and the time required for the release rate change was determined as the optimal HRT of SHT.

Before the incubation, the sludge samples were washed three times with distilled water, MLSS concentration was adjusted to 5,000 or 10,000 mg/L by centrifugation, and the samples were incubated at 30 or 35°C in cylindrical reactors equipped with a mixing device. All the incubation conditions are summarized in Table 2. For the incubation, no substrate was added, to replicate the real anaerobic SHT condition. At each experiment, a small portion of sample was taken at each hour and used to measure NH$_3$-N concentration.

### Analysis of kinetic parameters

In order to evaluate the biological kinetic parameters as direct evidence of sludge yield reduction, sludge samples were taken from the effluent line of the SHT, washed three times with distilled water, and aerated for more than 2 hours to remove residual organics. The same raw wastewater used for the pilot plant operation was filtered through GF/C filter paper, 20 mg/L of allylthiourea was added to prevent nitrification, and the wastewater was fed to the sludge with a food-to-microorganism ratio of 0.15. To evaluate the kinetic parameters at different operation conditions, SHT was operated in four different conditions (as in the experiments of HRT evaluation of SHT, Table 2), and sludge samples were taken at each operation condition for the evaluation experiments.

For yield coefficient, $Y_{1H}$, estimation, the sludge was incubated with the filtered wastewater at 20°C, while monitoring the amount of soluble chemical oxygen demand (SCOD) consumed and total COD (TCOD). The COD concentration corresponding to the biomass was calculated from the differences between TCOD and SCOD. As the ratio of biomass COD (BCOD) produced per soluble COD consumed, $Y_{1H}$ was determined as following equation.

$$Y_{1H} = \frac{\Delta \text{BCOD}}{\Delta \text{SCOD}} \quad (1)$$

The decay coefficient, $b_{1H}$, was estimated through the measurement of oxygen uptake rate (OUR) using N-CON Systems Company Inc.’s Comput-ox respirometer 4R (Crawford, GA, USA). The sludge samples mixed with the filtered wastewater were incubated in a water bath at 20°C, and dissolved oxygen consumption was monitored with time. The recorded dissolved oxygen data were plotted as OUR values (in natural logarithmic values) with time, and $b_{1H}$ was obtained from the slope. By assuming the non-active biomass fraction, $f_{p}$, as 0.08, $b_{1H}$ was determined using the following equation.

$$b_{1H} = \frac{b_{1H}}{1 - Y_{1H}(1 - f_{p})} \quad (2)$$

Sludge production, $P_{X,VSS}$, as a result of microbial substrate consumption can be expressed as Equations (3) and (4).

$$P_{X,VSS} = Y_{obs}(Q)(S_0 - S) \quad (3)$$

$$Y_{obs} = \frac{Y_{1H}}{1 + b_{1H}S_{RT}} \quad (4)$$

$P_{X,VSS}$ was estimated using the $Y_{obs}$ value determined from the kinetic parameters estimated at each SHT condition, $Y_{obs}$ is the observed yield in the system with recycle, $S_0$ is the substrate concentration in the influent (mg/L), and $S$ is the substrate concentration in the effluent (mg/L).

### RESULTS AND DISCUSSION

#### Optimal HRT for SHT

In anaerobic SHT with no supply of substrate, ammonia nitrogen can be released from biomass decay (Equation (5)),

Table 1 | Operation cycle of the SBR pilot plant

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Agitation</th>
<th>Aeration</th>
<th>Agitation</th>
<th>Aeration</th>
<th>Settle</th>
<th>Decant</th>
<th>Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (min)</td>
<td>50</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>40</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>State</td>
<td>Anaerobic</td>
<td>Oxic</td>
<td>Anoxic</td>
<td>Oxic</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 2 | Experimental conditions for the estimation of optimal HRT of SHT

<table>
<thead>
<tr>
<th>Experimental conditions</th>
<th>Exp. 1</th>
<th>Exp. 2</th>
<th>Exp. 3</th>
<th>Exp. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLSS (mg/L)</td>
<td>5,000</td>
<td>5,000</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Temp. (°C)</td>
<td>30</td>
<td>35</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>
as Low & Chase (1999) reported that the reduction of sludge yield in the treatment process can be the cause of increased nitrogen concentration in the effluent.

\[
\text{Biomass N} \rightarrow \text{NH}_3\text{-N} + \text{Biomass debris N} \tag{5}
\]

At 30°C using 5,000 mg/L of MLSS, the release rate of NH$_3$-N increased after about 10 hours, while this was observed after 6 hours at 35°C (Figure 2(a)). On the other hand, at 10,000 mg/L of MLSS concentration, the increase in NH$_3$-N release rate was observed after 6 hours at 30°C and after 4.5 hours at 35°C (Figure 2(b)). This increase in the release rate may be caused by the increased degradation of microbial cells and, therefore, indicates the start of the full-fledged endogenous phase at each experimental condition. Since the anaerobic time required for the start of the endogenous phase can be considered as the optimal point for uncoupling metabolism, it was determined as the optimal

**Figure 2** | The concentrations of NH$_3$-N with time by incubation of the settled sludge at 30 and 35°C. (a) MLSS = 5,000 mg/L and (b) MLSS = 10,000 mg/L.

**Figure 3** | Experimental results obtained at each condition for $Y_H$ estimation: MLSS concentration of 5,000 mg/L at (a) 30°C and (b) 35°C, 10,000 mg/L at (c) 30°C and (d) 35°C.
HRT for SHT. As shown in Figure 2, the optimal HRT was shortened with increasing temperature and MLSS concentration. By considering the MLSS concentration of settled sludge in the SBR pilot plant and the cost of initial construction and operation, 6 hours was selected as an optimal retention time of the SHT operated at 30 °C.

Besides the release of NH₃-N in SHT, COD concentration may also be increased as a result of microbial cell decay, while it can be easily consumed as substrate for heterotrophic growth. Therefore, it is more reasonable to evaluate the start of the endogenous phase using the change in NH₃-N release rate.

Kinetic parameters

From the experiments of kinetic parameters estimation using sludge taken from the effluent line of SHT, the average values of \( Y_H \) and \( b_H \) were estimated as 0.27 and 0.085 day⁻¹, respectively. As shown in Figures 3 and 4, no significant differences in the parameters were observed at each SHT operation condition, and the results were summarized in Table 3.

The estimated value of the yield coefficient, \( Y_H \), corresponds to about 40% of the value typically observed in sludge of normal sewage treatment plants (0.67), which indicates the efficient yield reduction through the anaerobic SHT. On the other hand, the decay coefficient, \( b_H \), is in the range of typical values, 0.06–0.2 day⁻¹, which suggests the anaerobic treatment of microorganisms in SHT did not cause the increase in microbial decay rate, and inducing the microorganisms in WAS to the initial stage of the endogenous phase is critical to achieve the reduction of sludge yield rate. Additional increase in HRT in SHT may cause more sludge decay and reduction of sludge production. However, the excessive decay of microorganisms may result in the deterioration of treatment efficiencies of the system, and, therefore, the evaluation and maintenance of optimal retention time in SHT are critical for successful operation without negative effect on the treatment efficiencies.

### Table 3 | \( Y_H \) and \( b_H \) values estimated at each SHT operation condition

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Exp. 1</th>
<th>Exp. 2</th>
<th>Exp. 3</th>
<th>Exp. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLSS (mg/L)</td>
<td>5,000</td>
<td>10,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHT operation condition</td>
<td>Temp. (°C)</td>
<td>30</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>( Y_H )</td>
<td>0.27</td>
<td>0.26</td>
<td>0.28</td>
<td>0.27</td>
</tr>
<tr>
<td>( b_H ) (day⁻¹)</td>
<td>0.11</td>
<td>0.06</td>
<td>0.09</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Figure 4 | Experimental results obtained at each condition for \( b_H \) estimation: MLSS concentration of 5,000 mg/L at (a) 30 °C and (b) 35 °C, 10,000 mg/L at (c) 30 °C and (d) 35 °C.
Evaluation of sludge reduction by $P_{X,VSS}$ calculation

In order to evaluate the actual sludge production, $P_{X,VSS}$ values were calculated using Equations (3) and (4), and compared between SBR operated with SHT and conventional activated sludge (CAS) without SHT. For SBR with SHT, the estimated values of kinetic parameters were used for the calculation, while for CAS without SHT, typical values of yield coefficient and decay coefficient were used. In addition, a 15-day sludge retention time (SRT) was used for CAS, while actual SRT values of 60–70 day were used for SBR with SHT. Due to the reduced sludge yield by SHT, the amount of wasted sludge was very low, which resulted in the long SRT value.

As shown in Figure 5 for 90 days of cumulative sludge production, SBR coupled with SHT exhibited 63.5% less sludge production than conventional SBR. Datta et al. (2009) also reported similar results of reduced sludge production from their experiments using a bench-scale SBR reactor. In sewage treatment plants, the reduced sludge production can reduce the size of sludge treatment facilities and the amount of sludge required for final disposal.

Wastewater treatment in pilot plant

In order to achieve stable operation of sewage treatment plants, optimal operation and maintenance of bioreactors are essential. The decreased yield coefficient, however, may affect the treatment efficiencies, and so the treatment efficiencies of microorganisms exposed to an unfavourable environment in a starving anaerobic SHT were evaluated. During the operation period of the pilot SBR plant, treatment efficiencies were monitored, and the results are summarized in Table 4. COD$_{Cr}$ and suspended solids (SS) removal rates were greater than 95%, and the water quality was within the limit of discharge standards. The removal efficiencies for total nitrogen (TN) and total phosphorus (TP) were also within the discharge standard, and, considering the removal efficiencies (65.4% and 71.4%, respectively), SHT did not affect the BNR. Since the major pathway of phosphorus removal is microbial uptake, the long SRT of the pilot plant (60–70 days) may increase phosphorus concentration in the effluent. As mentioned, however, this was not observed during more than 1 year of operation of the plant, and SHT may be applied in BNR processes as a successful sludge yield reduction method.

<table>
<thead>
<tr>
<th>Item</th>
<th>Influent (mg/L)</th>
<th>Effluent (mg/L)</th>
<th>Average efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD$_{Cr}$</td>
<td>89.4–310.8</td>
<td>4.6–7.4</td>
<td>95.7</td>
</tr>
<tr>
<td>SS</td>
<td>74–191</td>
<td>1.8–6.8</td>
<td>96.1</td>
</tr>
<tr>
<td>TN</td>
<td>19.8–41.1</td>
<td>7.8–13.3</td>
<td>65.4</td>
</tr>
<tr>
<td>TP</td>
<td>1.7–5.0</td>
<td>0.7–0.9</td>
<td>71.4</td>
</tr>
</tbody>
</table>

Table 4 | Treatment efficiencies of the SBR pilot plant operated with SHT

CONCLUSIONS

By evaluating microbial kinetic parameters of a pilot SBR plant operated with SHT, it was found that the sludge production was reduced by 63.5%. In anaerobic SHT, the microorganisms were induced to the initial stage of the endogenous phase, which resulted in the reduction of the yield coefficient. For the determination of optimal HRT of SHT without causing a significant decay of microorganisms, ammonia concentration was monitored with time at specific temperature and MLSS concentrations. In a
long term (>1 yr) operation of the pilot plant, no deterioration of the effluent water quality was observed. Considering phosphorus removal, an extended SRT of 60–70 days (due to the reduced yield coefficient) did not significantly affect the efficiency relative to typical BNR processes. According to the findings of this study, anaerobic SHT can be applied for BNR processes with reduced production of sludge, and this will help to minimize environmental and economic problems pertaining to the final disposal of sludge.

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