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# Nitrogen and phosphorus removal in an anaerobic (UASB)-aerobic (ABF) sewage treatment system

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ABSTRACT

Anaerobic sewage treatment process using upflow anaerobic sludge blanket (UASB) coupled with aerated biofilter (ABF) was tested for the removal of nitrogen and phosphorus by recycling the final effluent and by adding alum to the influent. TCOD Removal efficiency was about 60% in UASB without recycling of the ABF effluent, while it increased to 90% at recycling ratio of 3. Complete denitrification had occurred in the UASB, and removal efficiencies of both total nitrogen (TN) and $NH_4^+$-N were also improved to 74 and 96%, respectively, by recycling the nitrified ABF effluent. Total phosphorus (TP) removal was not improved by recycling of the ABF effluent. TP and soluble phosphorus were effectively removed in UASB by adding alum to the influent. 90% removal of TP was possible with alum dose at Al/P mole ratio of 2.6. In the final effluent, concentrations of TCOD, TN, and TP were below 14.0, 7.0, and 0.27 mg/L, respectively, in the UASB-ABF sewage treatment system at recycling ratio of 3 with alum.

*Keywords:* Anaerobic sewage treatment; UASB; ABF; TN and TP removal

## 1. Introduction

A large number of anaerobic digesters have been built and operated for high-strength wastewater treatment. Among the anaerobic digesters, high-rate digesters are considered for low-strength sewage treatment. Unlike the conventional low-rate anaerobic digesters such as anaerobic ponds and septic tanks, high-rate anaerobic reactors are designed to operate at short hydraulic retention times (HRT) and long solids retention times to incorporate large amount of high active biomass [1]. Sequential anaerobic–aerobic processes has been suggested for alternative domestic wastewater treatment that exploited many advantages compared to conventional aerobic technologies, such as less energy consumption, less excess sludge production, less carbon dioxide generation, and less complex in operation [1–3].

Higher contribution of the up-flow anaerobic sludge blanket (UASB) reactor to the TCOD removal in an anaerobic–aerobic system can reduce aeration energy and sludge production in a subsequent aerobic process. An et al. [4] achieved 98% TOC removal and

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48.1–82.8% total nitrogen (TN) removal with 50–800% recycling ratios in the combination of the UASB reactor and an aerobic membrane filtration. Pontes et al. [5] demonstrated that over 93% contribution of the UASB reactor was possible by recycling the trickling filter sludge with about 1% recycling ratio of the influent. Jun et al. [6] could have 95% contribution of the UASB reactor by recycling the aerated filter (AF) effluent with 100% recycling ratio. They stated that recycling of the nitrified effluent of AF might enrich the heterotrophic micro-organisms (denitrifiers) who improved biofloc-culation of the particulate COD in the UASB reactor. They also reported TN removal efficiency was about 70% in the UASB-ABF system that showed similar efficiency as other biological nutrient removal processes.

Even though UASB reactors are the most robust high-rate anaerobic reactors for sewage treatment and there have been more than 1,000 UASB reactors installed worldwide [7,8], their low-removal capacity of nitrogen and phosphate still remains detrimental disadvantages [8,9] for the stringent local effluent standards. This has triggered many researches on post-treatment options of UASB for N and P removals [9–12]. Li et al. [13] applied ferrous sulfate into preanoxic reactor prior to biological aerated filter with positive result. The objectives of this paper are to remove nitrogen and phosphorus in the UASB-ABF sewage treatment system by applying anaerobic denitrification as well as chemical precipitation.

## 2. Materials and methods

### 2.1. Experimental set-up

Fig. 1 shows the schematic diagram of the laboratory scale UASB-ABF system consisted of an UASB and an aerated biofilter (ABF). UASB was gently agitated by the paddle installed at bottom of the reactor to prevent sludge rising and channeling effects due to gas production. ABF was packed with half inch pal rings to inoculate high concentration of nitrification micro-organisms. Coagulant (poly aluminum chloride, PAC) was optionally applied to the influent and agitated for phosphorus removal in the mixing tank in front of the UASB reactor. The UASB was seeded with settled activated sludge from the local sewage treatment plants.

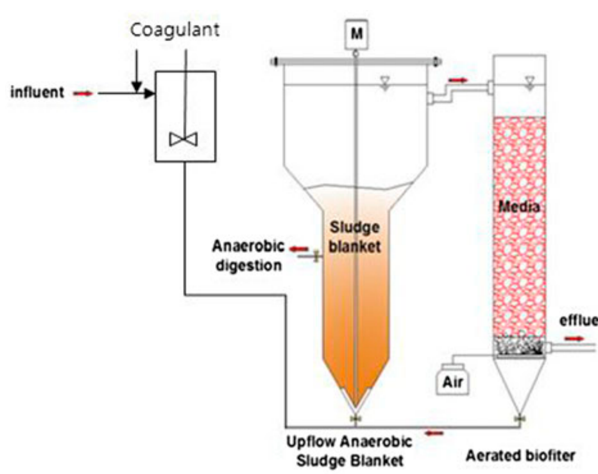


Fig. 1. Schematic diagram of lab-scale UASB-ABF system.

### 2.2. Operating conditions

Table 1 shows the detail specifications and operating conditions of UASB and ABF. Hydraulic residence times of UASB and ABF are 25 and 2.4 h, respectively, on the basis of incoming flow rate. Three different recycling ratios (1, 2, and 3) were applied for verifying the effectiveness of the recycling on the removal of organic matters and nitrate in UASB. Phosphorus removal was achieved by adding coagulant in UASB. Al/P molar ratio of 2.6 was adopted from the previous results [6]. DO was kept above 5.0 mg/L in ABF, and operating temperature was kept around 20 ± 3℃.

Table 2 shows the characteristics of the raw sewage used in this study. Total $COD_{Cr}$ of influent sewage was about 263 mg/L, and soluble $COD_{Cr}$ was as low as 67 mg/L. TN and ammonia nitrogen were 35 and 23 mg/L, respectively, so the resultant TCOD/TN ratio was about 7.5.

## 3. Results and discussion

### 3.1. COD removal

Fig. 2 shows the TCOD removal trends at each stage of the reactor system at different recycling ratio of the ABF effluent. The reactor system was started at recycling ratio of 1 for 25 d, and it increased to 2, and 3. Alum was added after 70 d operation, at recycling ratio

Table 1
Specifications and operating conditions of UASB and ABF

| Parameters | UASB | ABF |
|---|---|---|
| Flow rate (mL/min) | 6.5 | 6.5 |
| Volume (L) | 9.8 | 0.9 |
| HRT (h) | 25.0 | 2.4 |
| Recycling ratios (%) | 100, 200, 300 | |
| DO (mg/L) | <0.2 | >5.0 |
| Temperature (℃) | 20 ± 3 | |
| Coagulant (Al/P mole ratio) | 2.6 | |

Table 2
Characteristics of the domestic raw sewage used in this study

| Parameters | Range | Average |
|---|---|---|
| $TCOD_{Cr}$ (mg/L) | 180–482 | 263 ± 40 |
| $SCOD_{Cr}$ (mg/L) | 40–129 | 67 ± 40 |
| SS (mg/L) | 20–80 | 42 ± 38 |
| TN (mg/L) | 25–44 | 35 ± 10 |
| $NH_4^+$-N (mg/L) | 20–28 | 23 ± 5 |
| pH | 6.8–7.8 | 7.3 ± 0.5 |
| Alk. (as $CaCO_3$) | 80–180 | 140 ± 60 |
| No. of samples, $n = 104$ | | |

of 3 for 210 d. After 280 d operation, the reactor system was operated without recycling and without addition of alum. The final operation mode was simulated for anaerobic sewage treatment in UASB coupled with ABF. With recycling of the ABF effluent to the front of UASB, above 90% of TCOD was removed in UASB, and it was kept about 30 mg/L at recycling ratio of 3. At first 25 d start-up period with 100% recycling of the ABF effluent, 80% of TCOD was removed, while 15% of SCOD was removed in UASB (Fig. 2). At this stage, the reactor system was not fully developed with adequate micro-organisms. High TCOD in the final effluent of 72 mg/L approved the adaptation process of progressively reaching at steady state on the operating conditions. Low SCOD removal also indicated that anaerobic and/or anoxic microbial activity was low in the UASB. Nitrate input via recycling of the ABF effluent was not enough to oxidize organic matter due to low nitrification efficiency at the first stage in ABF as shown in Fig. 3.

Nitrification efficiency increased after 25 d operation and it fully developed after 50 d operation at recycling ratio of 3 (Fig. 4). COD removal accompanying nitrate reduction could yield some biomass that might be another solid load to UASB. Under the assumption of anoxic yield as 0.32, about 30 g/m$^3$ of dry-based biomass could be generated. On the other hand, removal of organic carbon in the UASB might reduce the organic load on the subsequent aerobic filter, which resulted to increase nitrification rate by eliminating competition for DO between nitrifying micro-organisms and the typical heterotrophic micro-organisms.

Removal of particulate COD in UASB decreased at final stage without recycling of ABF effluent. Removal efficiency of TCOD in UASB was about 60% at final stage without recycling. The low removal efficiency of TCOD might be the result of decrease in heterotrophic activity in UASB. Since UASB was operated in strictly anaerobic condition at the final stage, 42% removal of SCOD was contributed by the anaerobic digestion.

TCOD applied to the UASB might be oxidized by both nitrate and DO in recycled effluent, which resulted higher TCOD removal and reduced the fluctuation of TCOD in the UASB effluent as shown in Table 3. Finally, UASB reduced the organic and

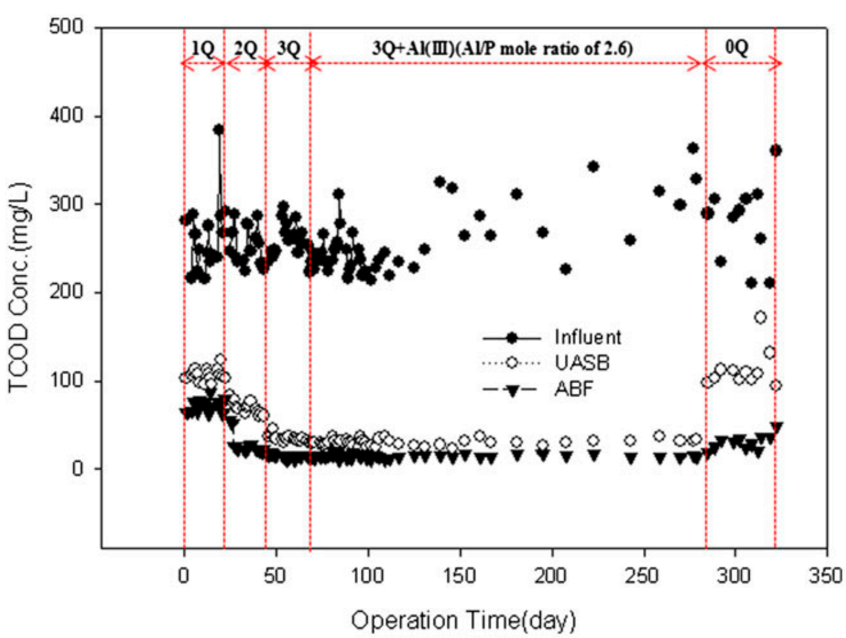


Fig. 2. TCOD removal patterns in UASB-ABF system at different recycling ratios.

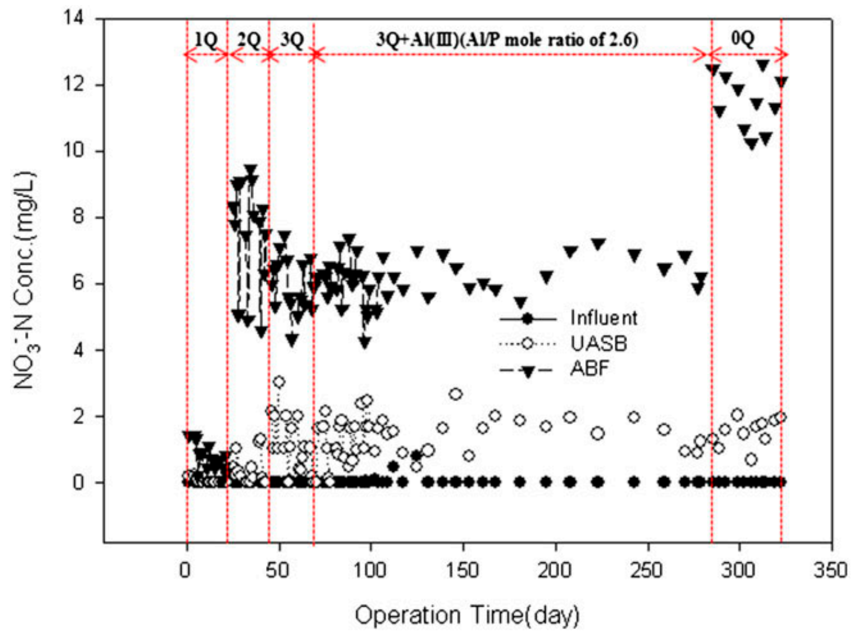


Fig. 3. $NO_3^-$-N removal patterns in UASB-ABF system at different recycling ratios.

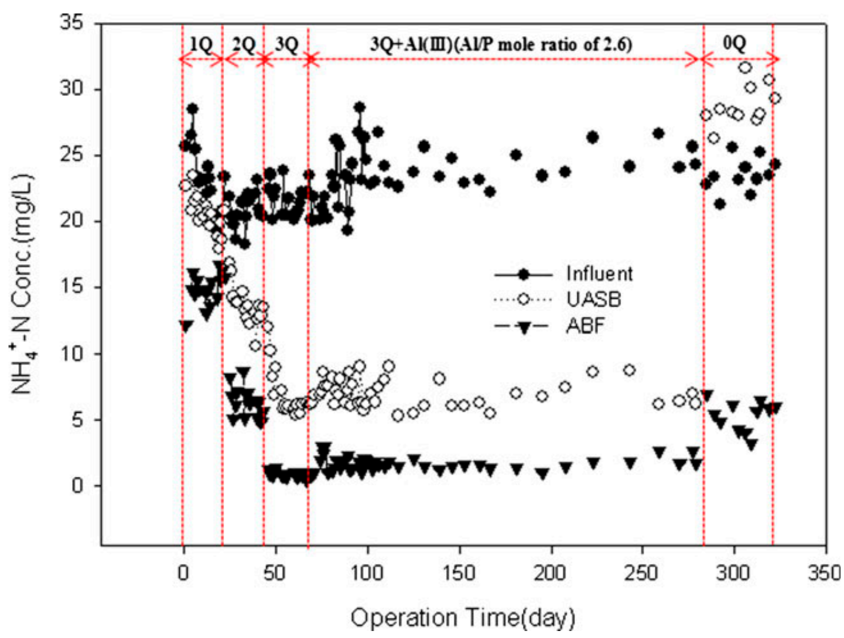


Fig. 4. $NH_4^+$-N removal patterns in UASB-ABF system at different recycling ratios.

particulate loads on the following ABF remarkably with recycling of nitrified effluent, which could improve nitrification efficiency in the subsequent ABF.

Recycling of the nitrified effluent could also improve the removal efficiency of suspended solids (SS). SS in the raw sewage fluctuated in the range of 20–80 mg/L, while SS in the UASB effluent was about 26 mg/L without recycling and 18 mg/L with 300% recycling, respectively. Influent turbidity fluctuated from 100 to 530 NTU, while effluent turbidity of the UASB was below 5 NTU at recycling ratio of 3. This result explained that nitrate in recycled effluent triggered the production of extracellular biopolymers (EPS), which might result better bioflocculation of the colloidal particles within sludge blanket.

With recycling of the nitrified effluent to the UASB, even small particulates were entrapped in sludge blanket that made clear effluent. Recycled nitrate changed the anaerobic UASB to anoxic condition where denitrifying micro-organisms were activated. These newly grown heterotrophic biomasses might be aggregated with colloidal matters in the raw sewage, then they were accumulated and formed sludge blanket in UASB. Complete denitrification occurred in the UASB as shown in Fig. 4.

### 3.2. Nitrogen removal

Figs. 3–5 show the TN, $NH_4^+$-N, $NO_3^-$-N removal patterns, respectively, in UASB-ABF at various recycling ratios. The removal efficiencies of TN were 12.9, 43.8, 74.2, and 78.1% at recycling ratio of 1, 2, 3, and 3 with coagulant, respectively. Also, the nitrification efficiencies were 34.8, 71.4, 95.5, and 91.3% at each recycling ratios. With coagulant at recycling ratio of 3, it was observed that the nitrification efficiency decreased by 4.2% compared to the results without coagulant. Stable TN removal was possible at recycling ratio of 3 at steady state after 50 d operation. Before it reached at steady state, incomplete nitrification in ABF coupled with low SCOD removal in UASB (Fig. 6). Complete nitrification at recycling ratio of 3 increased TN removal efficiency up to 75%, and it was kept stable throughout the experiment with recycling of ABF effluent. TN removal, however, decreased rapidly right after cease of the recycling. Influent TN composed of 34% organic nitrogen and 66% ammonia nitrogen (Table 2). And, particulate organic nitrogen was effectively separated in UASB with particulate COD (removed over 90%). TN oxidized to nitrate in ABF was about 7.9 mg/L at recycling ratio of 3 (Table 4).

Influent ammonia nitrogen was in the range between 20 and 28 mg/L and ammonia in UASB effluent decreased rapidly with recycling of the ABF effluent. Ammonia nitrogen in influent was diluted with the recycled flow from ABF to the level that was determined by both the recycling ratio and ammonia concentration in the recycled flow. Ammonia in UASB effluent decreased to 13 and 7 mg/L at recycling ratios of 2 and 3, respectively. At the same time, ammonia in the final effluent decreased to 6 and 2 mg/L at recycling ratios of 2 and 3, respectively, while it was as high as 15 mg/L at first stage, the recycling ratio of 1 (Fig. 4).

Nitrate recycled from ABF was denitrified effectively using the influent organic matters within sludge

Table 3
TCOD removal at each recycling ratio in the UASB-ABF system (mg/L)

| Parameters | Raw | | | | | UASB | | | | | ABF | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Recycling ratio | 0Q | 1Q | 2Q | 3Q | 3Q(Al) | 0Q | 1Q | 2Q | 3Q | 3Q(Al) | 0Q | 1Q | 2Q | 3Q | 3Q(Al) |
| TCOD | 278 ± 82 | 263 ± 120 | 273 ± 49 | 261 ± 36 | 257 ± 105 | 112 ± 59 | 106 ± 17 | 76 ± 16 | 35 ± 11 | 30 ± 9 | 30 ± 18 | 72 ± 14 | 32 ± 23 | 15 ± 5 | 14 ± 6 |
| SCOD | 65 ± 31 | 65 ± 21 | 76 ± 23 | 68 ± 12 | 67 ± 50 | 38 ± 45 | 59 ± 15 | 50 ± 24 | 23 ± 5 | 23 ± 5 | 21 ± 11 | 35 ± 13 | 30 ± 11 | 15 ± 11 | 12 ± 8 |
| SSCOD | 213 ± 99 | 198 ± 122 | 197 ± 33 | 193 ± 30 | 190 ± 88 | 74 ± 55 | 47 ± 25 | 26 ± 12 | 12 ± 6 | 7 ± 3 | 9 ± 8 | 37 ± 17 | 2 ± 2 | 0 ± 2 | 2 ± 2 |
| No. of samples | 16 | 15 | 16 | 46 | 11 | 16 | 15 | 16 | 46 | 11 | 16 | 15 | 16 | 46 | 11 |

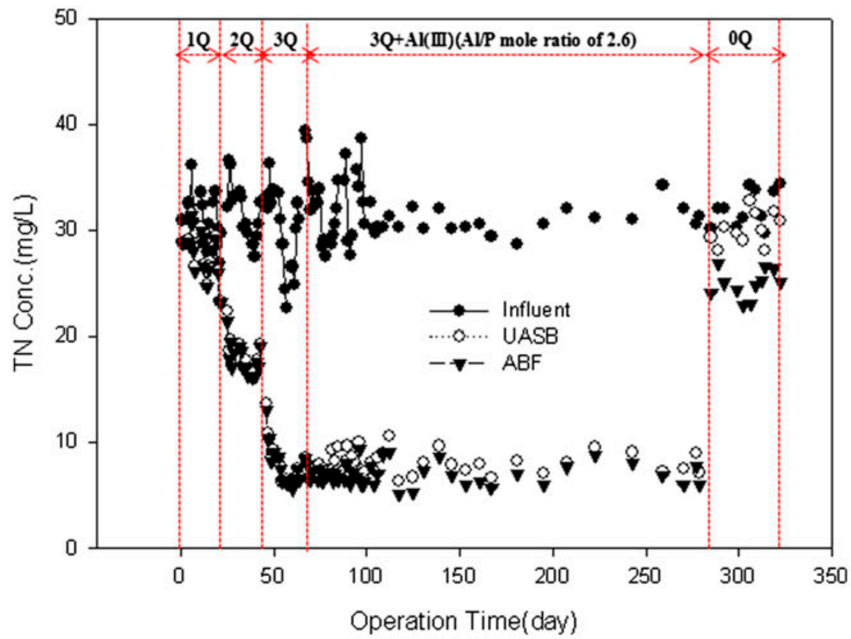


Fig. 5. TN removal patterns in UASB-ABF system at different recycling ratios.

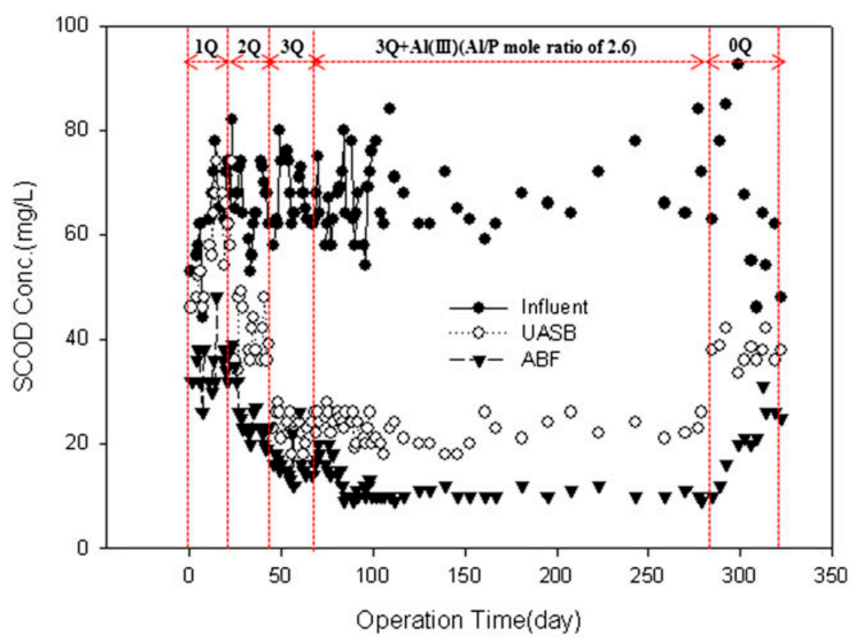


Fig. 6. SCOD removal patterns in UASB-ABF system at different recycling ratios.

blanket formed in UASB. Stable nitrification could be achieved efficiently, and excess sludge generated in ABF was negligible due to minimal heterotrophic growth with low COD level in ABF influent. And increased EPS as a result of heterotrophic growth in sludge blanket could also enhance bioflocculation of the particulate organic matter, which reduced organic and SS load on the subsequent ABF. Low COD input to ABF could increase nitrification efficiency and it could reduce the start-up period and save the aeration energy in ABF.

Without recycling of ABF effluent ammonia in UASB increased over the influent concentration, and ammonia in the final effluent also increased to

Table 4
TN removal at various recycling ratios in UASB-ABF system

| Components | TN(mg/L) | | | | |
|---|---|---|---|---|---|
| Recycling ratio | 0Q | 1Q | 2Q | 3Q | 3Q(Al) |
| Influent | 32.1 ± 2.4 | 31.2 ± 5.0 | 31.8 ± 4.9 | 30.8 ± 8.6 | 31.7 ± 7.0 |
| UASB | 30.1 ± 2.7 | 27.5 ± 4.1 | 18.2 ± 4.2 | 8.1 ± 5.5 | 7.9 ± 2.7 |
| ABF | 24.9 ± 2.1 | 27.4 ± 4.2 | 17.9 ± 3.5 | 7.9 ± 5.2 | 7.0 ± 2.3 |
| No. of samples | 16 | 15 | 16 | 46 | 11 |

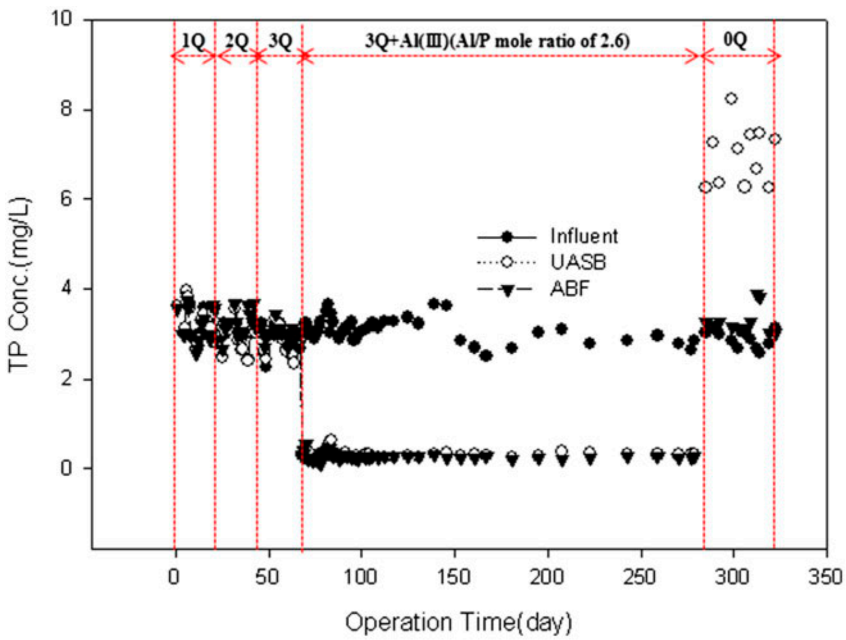


Fig. 7. TP removal patterns in UASB-ABF system at different recycling ratios.

5.4 mg/L. Fig. 3 shows the nitrate concentration at each stage. Nitrate in ABF effluent was below 2 mg/L at recycling ratio of 1, however, it increased rapidly to 9 mg/L at recycling ratio of 2, and it was kept about 6 mg/L at recycling ratio of 3. Nitrification seemed to reach at steady state after 50 d operation, then, nitrification efficiency showed stability throughout the experiment. Nitrate in UASB effluent was below 2 mg/L from the beginning of the experiment, which showed stable denitrification occurred in UASB.

### 3.3. Phosphorus removal

Fig. 7 shows the total phosphorus (TP) removal patterns in UASB and ABF at various recycling ratios. TP removal in UASB-ABF system was not efficient at any recycling ratios except for Al(III) addition as shown in Table 5. Organic phosphorus could be degraded in UASB at 25 h residence time, even though some soluble phosphorus possibly is synthesized via heterotrophic growth at recycling ratio of 3. TP removal in ABF was also ignored due to low biomass yield as mentioned earlier. TP in UASB increased to about 7 mg/L without recycling. Soluble phosphorus might be eluted from particulates at strict anaerobic condition in UASB. $PO_4^{3-}$-P also increased to 6 mg/L at recycling ratio of 0 as shown in Fig. 8. Biological phosphorus removal is not expected in this UASB-ABF system.

Al(III) was added to the front of UASB and mixed with influent and recycled flow from ABF effluent in a mixing tank as shown in Fig. 1. Average TP decreased below 0.3 mg/L right after applying alum at Al(III)/P molar ratio of 2.6. It is difficult to find a theoretical alum dose for P removal at various pH values because $Al(OH)_3$ also precipitates. It was necessary to use twice

Table 5
TP removal at various recycling ratios in UASB-ABF system

| Components | TP(mg/L) | | | | |
|---|---|---|---|---|---|
| Recycling ratio | 0Q | 1Q | 2Q | 3Q | 3Q(Al) |
| Influent | 2.88 ± 0.31 | 3.26 ± 0.63 | 3.0 ± 0.56 | 2.85 ± 0.61 | 3.07 ± 0.59 |
| UASB | 6.96 ± 1.25 | 3.25 ± 0.70 | 2.97 ± 0.58 | 2.85 ± 0.51 | 0.30 ± 0.32 |
| ABF | 3.27 ± 0.60 | 3.15 ± 0.60 | 3.23 ± 0.58 | 3.00 ± 0.43 | 0.27 ± 0.29 |
| No. of samples | 16 | 15 | 16 | 46 | 11 |

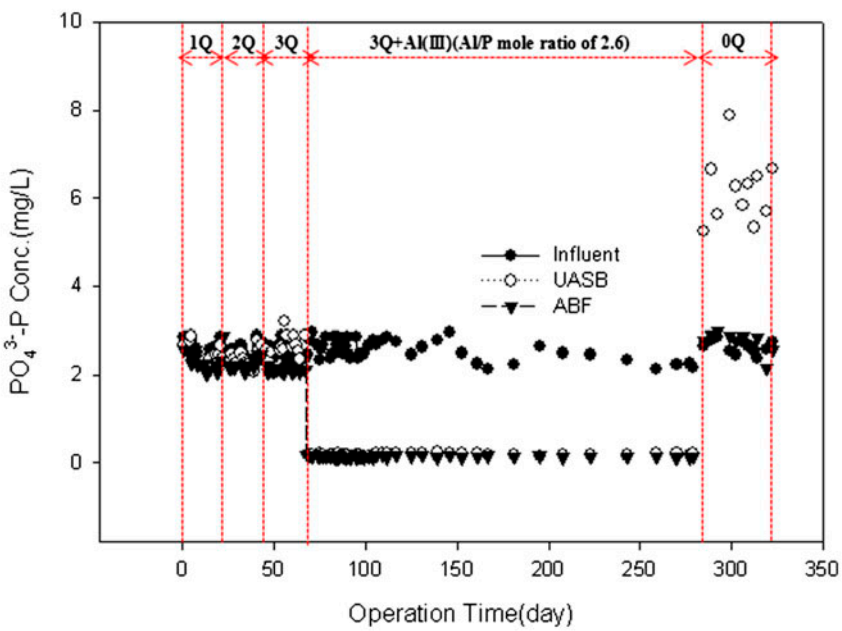


Fig. 8. $PO_4^{3-}$-P removal patterns in UASB-ABF system at different recycling ratios.

as much aluminum salt as required for phosphate precipitation at pH of 6 [14]. Since $Al(OH)_3$ are expected to dominantly precipitate at pH values above 6, molar ratio of Al/P should be larger than 1. Tian et al. [7] reported that molar ratio of Al/P was above 3 at pH 7 for P removal above 80% from domestic wastewater. Therefore, the ratio of 2.6 was adopted from the previous study [6]. Li et al. [13] used Fe/P molar ratio of 2–2.2 to avoid overdose. Even though optimum dose might be variable depending on the system, 2.6 was a reasonable dose to use in this study. Soluble phosphorus was kept below 0.13 mg/L in the UASB as shown in Fig. 8. Aluminum chloride was applied by others and it apparently enhanced granulation in UASB but did not achieve the positive effect on P removal [15]. However, from this study chemical precipitation of phosphorus proved an efficient option for removal of TP in an anaerobic sewage treatment process such as the UASB-ABF system.

In addition to removal of P, having chemical/biological additives applied during start-up and/or operation of UASB has shown various effects on COD removal [9]. In this study, additional TCOD and TN removals were also achieved with alum addition as

Table 6
Performances of UASB-ABF at recycling ratio of 3 with alum at Al/P molar ratio of 2.6

| | | UASB | | ABF | |
|---|---|---|---|---|---|
| Components | Influent (mg/L) | mg/L | % | mg/L | % |
| TCOD | 257 | 30 | 88.3 | 14 | 94.6 |
| SCOD | 67 | 23 | 65.7 | 12 | 82.1 |
| TN | 32 | 8.0 | 75.0 | 7 | 78.1 |
| $NH_4^+$-N | 23.5 | 7.0 | 70.2 | 1.7 | 92.8 |
| $NO_3^-$-N | 0 | 1.3 | – | 6.3 | – |
| TP | 3.07 | 0.30 | 90.2 | 0.27 | 91.2 |
| $PO_4^{3-}$-P | 2.56 | 0.18 | 93.0 | 0.14 | 94.5 |

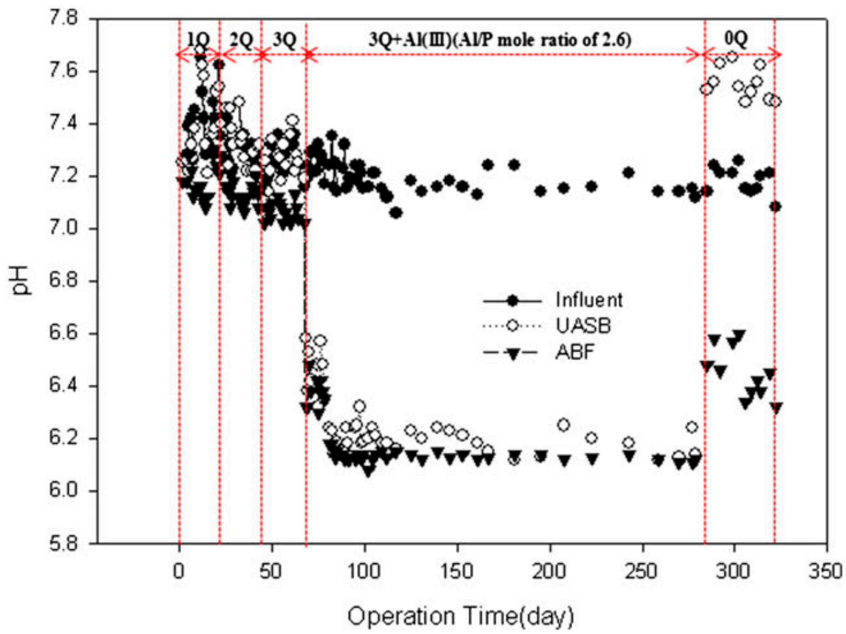


Fig. 9. pH change patterns in UASB-ABF system at different recycling ratios.

shown in Tables 3 and 4. And stable nitrification occurred regardless of alum addition due to complete separation of micro-organisms in ABF from those in UASB where alum was applied.

### 3.4. Effects of Al(III) dose on UASB-ABF system

Table 6 shows the performances of UASB-ABF sewage treatment system at recycling ratio of 3 with alum. Stable removal of organic matters and TN could be achieved with chemical precipitation of phosphorus in UASB. Recycled nitrate from ABF was successfully denitrified in UASB with no relation to Al(III) addition. Seventy-five percent of influent TN was removed in UASB, while additional 3.1% of TN removed in the subsequent ABF. With this result, it was found that the major role of ABF was to oxidize ammonia in aerobic condition and to inoculate nitrifying micro-organisms. Low COD input to the ABF could also help the efficient growth of these micro-organisms as a result of high removal of COD in UASB through physical and biological means. TP in the final effluent was below 0.3 mg/L that showed apparent improvement in phosphorus removal. Above 90% of TP was removed with organic particles in UASB by adding alum to the influent. Ninety-three percent of soluble phosphorus was also removed in UASB by chemical precipitation. And any adverse effects on the other components except for ammonia described in Table 6 were not observed after addition of alum to the UASB-ABF system. About 4.2% decrease in nitrification efficiency originated on pH drop as shown in Fig. 9. The pH in ABF effluent was lowered from 7.0 to 6.2 after applying alum at recycling ratio of 3. Otherwise, overall removal efficiencies of the other pollutants were improved as results of chemical precipitation in UASB-ABF sewage treatment process. Even nitrification efficiency showed as high as 92% at low pH of 6.2.

## 4. Conclusions

Anaerobic sewage treatment process using UASB coupled with ABF was tested for the removal of nitrogen and phosphorus by recycling the final effluent and by adding alum to the influent. UASB was gently agitated to prevent sludge rising and channeling effects due to gas production, and ABF was packed with half inch pal rings to inoculate effectively high concentration of nitrifying micro-organisms.

TCOD removal efficiency was about 60% in UASB without recycling of the ABF effluent, while it increased to 90% at recycling ratio of 3. Complete denitrification had occurred in the UASB, and removal efficiencies of both TN and $NH_4^+$-N were also improved to 74 and 96%, respectively, by recycling the nitrified ABF effluent. Low organic matter in ABF influent could improve nitrification efficiency in a subsequent ABF. TP removal was not improved by the recycling of ABF effluent. TP and soluble phosphorus were effectively removed in UASB by adding alum to the influent. 90% removal of TP was possible with alum dose at Al/P mole ratio of 2.6. In the final effluent, concentrations of TCOD, TN, and TP were below 14.0, 7.0, and 0.27 mg/L, respectively, in the UASB-ABF sewage treatment system at recycling ratio of 3 with alum.

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