Kinetic Rates and Mass Balance of COD, TKN, and TP Using SBR Treating Domestic and Industrial Wastewater

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Objective: To assess the performance of SBR to treat three different types of wastewater from domestic, hospital, slaughterhouse and investigate the kinetic rates of active biomass. Mass balance calculation of COD, TKN and TP was further performed to explain the mechanisms of the biological nutrient removals processed in the SBR system. The measured kinetic rates were in turn used to evaluate the process performances under different types of wastewater.

Material and Method: Experimental research involving 3 similar SBR lab-scales were installed and operated at the Sanitary Engineering Laboratory. The reactors were seeded with sludge biomass obtained from the Sri-Phraya Domestic Wastewater Treatment Plant in Bangkok. The slaughterhouse, hospital and domestic wastewaters were treated by SBR system for biological organic carbon (COD), nitrogen (TKN) and phosphorus removals. Biological methods for kinetic rates evaluation were conducted in five replicated batch tests.

Results: The removal efficiencies of COD and TKN were greater than 90% for all three types of wastewater while the biological phosphorus removal for domestic and hospital wastewaters were less than 60% and phosphorus removal for slaughterhouse exceeded 95%. The kinetic rates of nitrification and denitrification of hospital wastewater was lower than those the domestic and slaughterhouse wastewaters. Phosphorus release and uptake rates of slaughterhouse wastewater were high but domestic and hospital wastewaters were very low.

Conclusion: The result of system removal efficiency and batch test for kinetic rates confirmed that the domestic and hospital wastewaters were in deficiency of organic carbon with respect to its ability to support successful biological phosphorus removal.

Keywords: Domestic wastewater, Industrial wastewater, Sequencing batch reactors, Kinetic rate, Biological nutrient removal

Discharges of wastewater with organic carbon and nutrient (nitrogen, and phosphorus) can lead to adverse effects in water bodies. Nitrogen and phosphorus are the essential nutrients for the growth of algae and cyanobacteria. Where both nitrogen (N) and phosphorus (P) are plentiful, algal blooms can occur extensively which may produce a variety of nuisance condition. This could be harmful to the aquatic life and related public health problems. Contamination of nitrate nitrogen in public water supplies as an example often causes methemoglobinemia (Blue baby syndrome) in infants and cancer in man. Simultaneous removal of organic carbon and nutrients can be achieved through a biological nutrient removal (BNR) scheme. The primary characteristics of BNR system is the alternate conditions of anaerobic, anoxic, and aerobic environments to stimulate the growth of autotrophs, heterotrophs, and phosphorus accumulating organisms (PAOs). However, full-scale BNR facilities are normally characterized by significant land requirements and operational complexity. Sequencing batch reactor (SBR) technology can serve...
as an attractive alternative solution, particularly when
land availability as well as flexibility and simplicity of
operation are of concern(7-9). Domestic, hospital, and
slaughterhouse have also produced high quantities of
wastewater with their major pollutants are organic
carbon substances, nitrogen, and phosphorus(10,11).
All three different types of wastewater were treated
by SBR(12,13) system for biological COD, TKN and
phosphorus removals. The main objectives of this
research were to (i) assess the performance of SBR
system; (ii) investigate the effect of wastewater type
on the kinetic rates of active biomass, and (iii) explain
the fate of COD, TKN, and TP in the system. The result
of kinetic studies and fate of COD, TKN, TP can be
used to justify the feasibility and effectiveness of
SBR as an alternative for the BNR system.

Material and Method

Experimental procedure

Biological treatment was accomplished using
three identical SBR systems. Cylindrical reactors were
made of plastic (acrylic) material with 14.3-cm diameter
and 38-cm height. Each reactor had an actual volume
of 5 l, equipped with cover plate, rubber stopper, air
diffuser, and stirrer. Other accessories included feeding
pumps, influent and effluent containers, valves, air
compressors, and microprocessor time controllers. The
systems were sealed to prevent any air entrapment
during the non-aerated periods. The operation patterns
of SBR performed under anaerobic static fill and reacts
mode, consisting of anoxic/oxic/anoxic/oxic condition
(AnA²/O² SBR).

The reactors were seeded with biomass
obtained from the Sri-Phraya Domestic Wastewater
Treatment Plant in Bangkok. The slaughterhouse
wastewater was collected from the Pork Traders Co-
noperative of Bangkok Limited while hospital and
domestic wastewaters were taken from Rajavithi
Hospital Wastewater Treatment Plant and Huay Kwang
Wastewater Treatment Plant in Bangkok, respectively.
A summary of important influent characteristics was
presented in Table 1.

Prior to start the continuous operation of
sequencing batch reactor, the reactors were seeded
with sludge biomass to achieve an initial mixes liquor
suspended solids (MLSS) concentration of approxi-
mately 6,000 mg/l for each reactor. To allow the biomass
to get acclimatized with the wastewater, a step-by-step
feeding approach was followed during acclimatization
period, starting with an active volume of 2.5 l. Each
system was allowed to achieve at least 80% COD
removal under a reasonably stable operation (i.e. no
more than 10% fluctuation in the removal values) prior
to any further increase in flow rate of about 20%. This
incremental addition was (without any liquid wastage)
made until the targeted operating volume of 5 l was
accomplished.

Batch test for kinetic rate evaluation

After the system reached the steady-state
(of about 4 months) as mentioned earlier, batch test of
nitrification rate (NR), denitrification rate (DNR),
phosphorus release rate (PRR), and phosphorus
uptake rate (PUR) of the sludge were determined under
different characteristics of sludge biomass at steady
state condition of SBR. Kinetic rates were characterized
by bacterial functional group and determined by a
specific process rates. Reactor batch experiments of
1 L were set up to monitor the NR, DNR, PRR, and PUR
separately for all three types of wastewater. Numerous
batch tests were conducted on different dates. Each
batch experiment was performed in five replicated tests.

In the NR and DNR tests, the linear profile of nitrate
concentration in batch experiment was determined. In
the PRR and PUR test, the linear profile of phosphorus
concentration in batch experiment was determined. To
evaluate the specific nitrification rate (SNR), specific
denitrification rate (SDNR), specific phosphorus

<table>
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<th>Domestic</th>
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<td>pH</td>
<td>7.4 ± 0.1</td>
<td>7.3 ± 0.14</td>
<td>7.2 ± 0.1</td>
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<td>COD (mg/l)</td>
<td>1468.0 ± 234.0</td>
<td>300.0 ± 44.3</td>
<td>290.0 ± 30.0</td>
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<td>TKN (mg-N/l)</td>
<td>186.0 ± 23.5</td>
<td>45.8 ± 3.9</td>
<td>52.1 ± 7.5</td>
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<td>TP (mg-P/l)</td>
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Table 1. Wastewater characteristics of different types of wastewater
release rate (SPRR), and specific phosphorus uptake rate (SPUR), the rates were calculated by the slope of the graph (linear) divided by the mixed liquor volatile suspended solids (MLVSS) in the batch reactor as illustrated in Fig. 1.

**Analytical methods and sampling schedule**

Monitoring studies conducted in SBR system involve the sampling for Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN), and Total phosphorus (TP) analyses. The Dissolved Oxygen (DO) concentration was measured with a DO electrode (YSI 550DO), measurements of COD, nitrate (NO₃⁻N), mixes liquor suspended solids (MLSS), and mixed liquor volatile suspended solids (MLVSS) were conducted according to those procedures in Standard Methods for the Examination of Water and Wastewater\(^{(14)}\). Throughout the study, influent and effluent sampling were collected from each SBR three times a week and analyzed for COD, TKN, and TP while the reactor MLVSS, MLSS, DO, and pH were measured on a daily basis.

**Results**

**System Performance**

Designated conditions of the experiment were carried out after the seeding and acclimatization processes till reaching the pseudo-steady state condition. The overall system performances were presented in terms of COD, TKN, and TP removal efficiencies as shown in Table 2. High removal efficiencies of COD and TKN were exhibited in all systems. But removal efficiency of phosphorus taken from the domestic and hospital wastewater were 44.7%, and 65.1%, respectively while that of the slaughterhouse wastewater was in good performance. These indicated that the characteristics of different types of wastewater have an effect on the biological phosphorus removal process (BPR).

**Kinetic rates evaluation**

The specific nitrification rates (SNR) and specific denitrification rates (SDNR) of three types of wastewater are presented in Table 3, according to the results of nitrification test from five replicated tests. The average nitrification rate of domestic, hospital, and slaughterhouse wastewater were found to be 1.99 ± 0.42, 0.93 ± 0.18, 2.66 ± 0.37 mg NO₃⁻N/g-VSS/h, respectively. The SDNR trends of three type of wastewater were similar to those of the SNR and the average denitrification rate of hospital wastewater was lower than those of domestic and slaughterhouse wastewaters. The specific phosphorus release rates (SPRR) and specific phosphorus uptake rate (SPUR) were shown in Table 3. The results of SPRR and SPUR from domestic and hospital wastewater are very low, but those of the slaughterhouse wastewater are very high.
Mass balance of COD, N, and P

The mass balance of organic matter, nitrogen and phosphorus will help to visualize the picture of system removal efficiency. For Stoichiometric calculation in mass balance, the Yield observe (\(Y_{ob}\)) value from domestic, hospital, and slaughterhouse wastewaters were 0.25, 0.23, and 0.3 g/d respectively. Stoichiometric coefficient of the COD-biomass was calculated as 1.42 g COD/g Biomass. This value obtained from the empirical formula represented the composition of active biomass, \(\text{C}_5\text{H}_7\text{O}_2\text{N}^{(15)}\), which were in accordance with the following theoretical oxidation equation of the biomass:

\[
\text{C}_5\text{H}_7\text{O}_2\text{N} + 5\text{O}_2 + \text{H}^+ \rightarrow 5\text{CO}_2 + 2\text{H}_2\text{O} + \text{NH}_4^+ \quad (1)
\]

In addition, the nitrogen and phosphorus content of cell biomass was reported to be 12.3% and 2.6 %, respectively. This the value of phosphorus content did not include the amount of the storage of poly-phosphate of PAO\(^{(16)}\). Based on the experimental results and the above assumptions of calculating the composition of nitrogen and phosphorus in cell biomass, the mass distribution of COD, TKN, and TP was finally calculated. The values of influent and effluent were obtained directly from the chemical analysis. The removal value was achieved from the difference between inflow (Influent), out flow (Effluent) and yield. The value of the yield was estimated through the \(Y_{ob}\), biomass production and the stoichiometric coefficient. The yield sludge biomass of the SBR system treating the domestic, hospital, and slaughterhouse were 0.352, 0.34, and 2.15 g-sludge biomass/d, respectively.

Table 4 shows that approximately 41.7% of the organic carbon (COD), 28.1% of the nitrogen and 59.5% of the phosphorus of the raw slaughterhouse wastewater were turned into the biomass yield. About 56.2% of the organic carbon was removed from this system in form of carbon dioxide, 63.7% of the nitrogen was removed in form of nitrogen gas, and 36.2% of the total phosphorus was removed as poly-phosphate incorporated with waste sludge. In addition, trend of COD and TN were removed from the systems treating with domestic and hospital wastewater in terms of carbon dioxide and nitrogen gas were similar to those of slaughterhouse wastewater.

Fate of COD TKN and TP in SBR treating slaughterhouse wastewater

Fate of COD, TKN, and TP could be used to illustrate and clearly visualize the removal pattern of the AnA\(^2\)/O\(^2\) SBR process. A representative plot profile curve for slaughterhouse wastewater was presented in Fig. 2. Calculation of mass distribution of COD, TKN, and TP through the react-processes of SBR was presented in Table 5.

Fate of COD and TP

The overall COD and phosphorus removals at steady state were greater than 97% and 95%, respectively. The removal characteristic of organic

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**Table 2. Effluent and removal efficiency of organic and nutrient using SBR**

<table>
<thead>
<tr>
<th>Wastewater</th>
<th>COD Effluent (mg/l)</th>
<th>COD Removal efficiency (%)</th>
<th>TKN Effluent (mg/l)</th>
<th>TKN Removal efficiency (%)</th>
<th>TP Effluent (mg/l)</th>
<th>TP Removal efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>28.0 ± 7.8</td>
<td>91</td>
<td>2.34 ± 1.14</td>
<td>95.5</td>
<td>3.81 ± 0.71</td>
<td>44.7</td>
</tr>
<tr>
<td>Hospital</td>
<td>26.9 ± 8.9</td>
<td>91.6</td>
<td>1.63 ± 0.59</td>
<td>95.7</td>
<td>1.95 ± 0.43</td>
<td>65.1</td>
</tr>
<tr>
<td>Slaughterhouse</td>
<td>30.0 ± 11.6</td>
<td>97.9</td>
<td>4.14 ± 1.44</td>
<td>97.7</td>
<td>0.85 ± 0.32</td>
<td>95.5</td>
</tr>
</tbody>
</table>

**Table 3. Biomass kinetic rates of different types of wastewaters**

<table>
<thead>
<tr>
<th>Wastewater</th>
<th>SNR mgNO(_3)-N/g VSS/hr</th>
<th>SDNR mgNO(_3)-N/g VSS/hr</th>
<th>SPRR mg-P/g VSS/hr</th>
<th>SPUR mg-P/g VSS/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>1.99 ± 0.42</td>
<td>1.20 ± 0.59</td>
<td>0.18 ± 0.05</td>
<td>0.27 ± 0.19</td>
</tr>
<tr>
<td>Hospital</td>
<td>0.93 ± 0.18</td>
<td>0.67 ± 0.26</td>
<td>0.09 ± 0.01</td>
<td>0.05 ± 0.01</td>
</tr>
<tr>
<td>Slaughterhouse</td>
<td>2.66 ± 0.37</td>
<td>1.99 ± 0.82</td>
<td>1.99 ± 0.51</td>
<td>1.66 ± 0.31</td>
</tr>
</tbody>
</table>

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**Table 2.** Effluent and removal efficiency of organic and nutrient using SBR

**Table 3.** Biomass kinetic rates of different types of wastewaters
phosphorus distribution in the reactor was increased up to 302% at the end of the first anoxic. This mass distribution decreased from the first oxic to the second anoxic, and finally to the second oxic at 32%, and 7.1%, respectively.

Fate of TKN
The initial mass distribution of TKN from the first anoxic to the first oxic, the second anoxic, and finally to the second oxic at 86%, 18%, and 14%, respectively (Table 5). These data show that TKN reduction under anaerobic and aerobic conditions were 14%, and 72%, respectively.

Discussion
System performance
Hospital and domestic raw wastewaters used in this study were poorly characterized for biological
phosphorus removal process. Considering on the ratio of COD:TKN from the presented data (Table 1), it reveals that domestic and hospital wastewater was lower than the slaughterhouse wastewater. The result reminds that the wastewater lacks of sufficient and suitable COD to support phosphorus removal\(^{10,17}\).

**Kinetic rates evaluation**

The results reveal that the hospital wastewaters have SNR and SDNR lower than those of the domestic and slaughterhouse wastewaters. The low-rate of nitrification occurred in hospital wastewater reminded that the nitrifying bacteria quite low function when treated wastewater from hospital. Comparing the result of denitrification rates between wastewater sources, it was found that the slaughterhouse wastewater has a high quality source serving as a substrate for denitrification. Several researchers have reported that the high-rate of denitrification was referring to a high quality of organic carbon source serving as a main substrate for microorganism growth under anoxic processes\(^{18,19}\). SPRR and SPUR tests, the result indicated that the process rates are clear with the result of phosphorus removal efficiency. From this result, it suggests that slaughterhouse wastewater has sufficient and suitable COD used as carbon source for Phosphorus Accumulating Organisms (PAOs) under the process of anaerobic phosphorus release. The SPUR related to the aerobic phosphorus release process. Considering on the COD:TKN ratio, it can be calculated from wastewater characteristic (Table 1) as 8, 6, and 5 for slaughterhouse, hospital, and domestic wastewaters respectively. These results indicated that the PAOs were not able to function well under low COD:TKN ratio, this observation was agreed with those studied by Fongsatitkul\(^{17}\) as increasing the COD:N feeding ratio could significantly stimulate the growth of PAO.

**Mass balance of COD, TKN, and TP**

The result of calculated mass balance indicated that the main mechanism of COD and TKN removals in SBR were a cell-biomass growth (synthesis) and biochemical oxidation processes. In addition, phosphorus removal mechanism was classified as; (1) phosphorus served as a nutrient for biomass growth and a new cell synthesis, and (2) phosphorus was kept in form of intra-cellular storage product as a poly-phosphate.

**Fate of COD, TKN, and TP**

Fate of substrate could be used to illustrate and clearly visualize the removal pattern of the SBR process. The results suggest that the main process for COD and phosphorus removal occur within two first phase of SBR (first anoxic and first oxic). In first anoxic, the main reactions were poly-phosphate cleavage and COD consumed for phosphorus accumulating organisms (PAOs). For the first oxic phase, the main reaction was phosphorus uptake and oxidation of organic matter during the growth of PAOs. In these behaviors, it reminded that the composition of COD in slaughterhouse wastewater was in a good quality for being consumed or adsorbed by PAOs in the anoxic/anaerobic conditions. In TKN removal pattern, the result suggests that TKN reduction under anaerobic condition was assimilation for biosynthesis of bacterial cell while under aerobic condition it was a dissimilation through nitrification process. These results indicated that the main reaction of TKN removal was a nitrification process in the first oxic.

In conclusion, the SBR system employed in this research has successfully treated the three different types of wastewater, namely as domestic, hospital and slaughterhouse wastewaters. Characteristics of active biomass were investigated using a calculated mass balance and kinetic rates approaches. The COD and TKN removal efficiencies were in excess of 90% for all types of wastewater, while TP removal ranged from 44-95%. Biological phosphorus removal (BPR) process was occurred in the SBR when slaughterhouse wastewater was treated. Phosphorus removal efficiency of slaughterhouse wastewater exceeded 95%. In addition, the result of system removal efficiency and batch experiment confirmed that the domestic and hospital wastewaters were in deficiency of organic carbon with respect to its ability to support successful biological phosphorus removal.

**Acknowledgements**

This research work was fully supported by the grant from the Centre for Environmental Health, Toxicology and Management of Chemicals (ETM) and the Science & Technology Postgraduate Education and Research Development Office (PERDO), Ministry of Education, Bangkok, Thailand.

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อัตราทางจนศาสตร์และสมดุลมวลของซีโอดี, ทีเคเอ็น, และฟอสฟอรัสโดยการใช้ SBR สำหรับการบำบัดน้ำเสียชุมชนและน้ำเสียอุตสาหกรรม

ชวลิต ไพรท์นัทธิธรรม, ประภัฏ ฟองสถิตย์

วัตถุประสงค์: เพื่อหาประสิทธิภาพของระบบ SBR ในการบำบัดน้ำเสียตามประเภทต่างกันคือ น้ำเสียจากชุมชน,โรงพยาบาล, และโรงงานฆ่าสัตว์ พร้อมกับการศึกษาอัตราทางจนศาสตร์ของมวลชีวภาพ นอกจากนี้การคำนวณสมดุลมวลของ COD, TKN, และ TP ได้ถูกใช้เพื่อดำเนินการควบคุมการกำจัดสารอาหารทางชีวภาพในระบบ SBR ซึ่งนั้นอาจชี้ให้เห็นว่าจะถูกน้ำมานำไปในการประเมินประสิทธิภาพและใช้ในการคำนวณปรับเปลี่ยนรูปแบบของระบบการรับน้ำเสียที่ต่างประเภทกัน

วัสดุและวิธีการ: เป็นการทดลองในระดับห้องปฎิบัติการด้วยชุดทดลอง SBR ที่มีลักษณะเหมือนกัน 3 ชุดที่รับน้ำเสียจากชุมชน, โรงพยาบาล, และโรงงานฆ่าสัตว์เพื่อการกำจัดสารอาหารทางชีวภาพในระบบ SBR คิดเป็นน้ำเสียจากชุมชน, โรงพยาบาล, และโรงงานฆ่าสัตว์ เพื่อการกำจัดสารอาหารทางชีวภาพในระดับห้องปฎิบัติการด้วยระบบ SBR ที่มีลักษณะเหมือนกัน 3 ชุดที่รับน้ำเสียจากชุมชน, โรงพยาบาล, และโรงงานฆ่าสัตว์ เพื่อการกำจัดสารอาหารทางชีวภาพในระบบ SBR ได้ถูกใช้ในการทดลองแบบแบตซ์ (Batch Test)

ผลการศึกษา: ประสิทธิภาพการกำจัดซีโอดีและทีเคเอ็น มีค่ามากกว่าร้อยละ 90 ในน้ำเสียทั้งสามประเภท ในขณะที่ประสิทธิภาพการกำจัดฟอสฟอรัสของน้ำเสียชุมชนมีค่ากว่าร้อยละ 70 ในน้ำเสียชุมชนและน้ำเสียโรงพยาบาล และน้ำเสียจากโรงงานฆ่าสัตว์, ค่าการต่ำกว่าร้อยละ 55 ในน้ำเสียชุมชนและน้ำเสียโรงพยาบาล และน้ำเสียจากโรงงานฆ่าสัตว์ ซึ่งมีค่าต่ำกว่าร้อยละ 80 ในน้ำเสียชุมชนและน้ำเสียโรงพยาบาล ปัจจัยที่มีความสูงน้ำเสียชุมชนและน้ำเสียโรงพยาบาลมีค่าต่ำกว่าร้อยละ 80

สรุป: จากผลการศึกษาของระบบและผลกระทบของการทดลองแบบแบตซ์ในการทดลองน้ำเสียชุมชนในระบบ SBR ได้เห็นได้ว่ามีประสิทธิภาพในการกำจัดซีโอดี, ทีเคเอ็น, และฟอสฟอรัสของน้ำเสียชุมชนและน้ำเสียจากโรงพยาบาลมีประสิทธิภาพในการกำจัดซีโอดี, ทีเคเอ็น, และฟอสฟอรัสของน้ำเสียชุมชนและน้ำเสียจากโรงพยาบาลมีค่าต่ำกว่าร้อยละ 80 ปัจจัยที่มีความสูงน้ำเสียชุมชนและน้ำเสียโรงพยาบาลมีค่าต่ำกว่าร้อยละ 80