Wastewater Effluent Polishing Systems of Anaerobic Baffled Reactor
Treating Black-water from Households

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Abstract
This paper presents the outcomes of pilot-scale experiments on anaerobic baffled reactor (ABR) and polishing systems for the treatment of domestic blackwater, aimed at determining the treatment performance of different integrated low-cost wastewater treatment systems, comprising one ABR as first treatment step followed by three polishing steps operated in parallel, namely an anaerobic filter an intermittent sand filter and a vertical flow constructed wetland. A mixture of septage and domestic wastewater was used as influent wastewater, resulting in influent chemical oxygen demand (COD) and biochemical oxygen demand (BOD) concentrations of 1,000 and 300 mg/L, respectively. The ABR system operated at a HRT of 48h could achieve average COD, suspended solids (SS) and total nitrogen (TN) removal efficiencies of 90%, 93% and 50%, respectively. The highest treatment performances in the sand filter and constructed wetland units were reached at HLR of 7 – 10 and 6 – 10 cm/day, respectively, while HRT in the range of 3 - 4 days led to the highest treatment efficiencies in the anaerobic filter. The national effluent standards of Thailand were respected by all systems in terms of average TSS and BOD concentrations. Rather than concluding which system is the most appropriate, the paper discusses specific fields of application for the different systems.

Keywords: Anaerobic baffled reactor, Anaerobic filter, Constructed wetland, Decentralized wastewater treatment, Sand filter

Introduction
The discharge of untreated wastewater into the aquatic environment is worldwide the main cause of diarrhea diseases, with annual 3.5 billion infections, out of which 3.3 million end deadly. Most governments in developing countries are aware of the need to increase sanitation coverage, but they are powerless given the huge demand for investments and the available range of technical options. The Royal Thai Government for instance invested about 1.5 billion USD since 1992 for the construction of wastewater collection and high-tech treatment systems in 85 municipalities, out of which more than 60% are malfunctioning (Koottatep et al. 2003). Recognizing their inability to cope with the problem especially in small-scale communities, the Thai Pollution Control Department (PCD) requested the assistance of the Asian Institute of Technology (AIT) to conduct a comparative study on different low-cost systems for the decentralized treatment of domestic wastewater.

Decentralized wastewater management represents a valuable alternative in developing countries because this approach enables to treat and dispose both the solid and liquid fractions of domestic wastewater.
close to point of origin. Decentralized management may employ a combination of cost effective solutions and technologies, which are tailored to the prevailing conditions in the various sections of the community. Decentralized treatment processes can be tailored to the quality of the wastewater stream generated from each household or neighborhood and to the requirements towards effluent quality. Decentralized management increases wastewater reuse opportunities by keeping wastewater as close as practical to the generating community.

However, one of the restrictions of the large-scale implementation of decentralized systems is the limited access to knowledge on appropriate technologies. For example, although the conventional septic tank is commonly used as onsite/small-scale system for treating domestic wastewater in most developing countries, the effluent from this system does not meet effluent standards. There is a clear need for alternative decentralized wastewater treatment systems enabling the treatment of domestic wastewater up to National effluent quality standards. Two stage processes were investigated in this research project, consisting of: (i) an anaerobic baffled reactor (ABR) with an anaerobic filter, (ii) an ABR with an intermittent sand filter and (iii) an ABR with a constructed wetland. The objective was to determine the treatment potential, the range of application and the optimum operating conditions of these systems for household blackwater treatment.

**Materials and methods**

**Experimental system**

The experiments have been undertaken by using pilot-scale units at the Environmental Research Station of the Asian Institute of Technology (AIT) in Bangkok, Thailand, as shown in Figure 1. Influent wastewater was firstly fed into the ABR unit (reinforce concrete) with a volume of 6.7 m$^3$ sub-divided in 4 up-flow chambers. The ABR was operated at a HRT of 2 days following the recommendations of Wanasen (2003) and Khumkhom (2004). The effluent of the ABR was fed into three polishing units: an anaerobic filter, a sand filter, and a constructed wetland. The anaerobic filter was divided in 3 up-flow chambers with a total volume of 5.4 m$^3$ (1.8 m$^3$ per chamber). Polyethylene with a specific surface of 105 m$^2$/m$^3$ was used as filter media. The anaerobic filter was operated at HRT in the range of 2 to 4 days. The sand filter (l:w:h = 3m:1.5m:2m) was operated at HLR of 5 – 10 cm/d following the findings of USEPA (2002) who observed that HLR of 4 – 8 cm/d are suitable but rather conservative and may be subject to increases as more quality-assured data becomes available. The vertical flow constructed wetland unit (l:w:h = 3m:1.5m:2m) was operated at HLR of 6, 10 and 20 cm/d following the design criteria of PCD (2004). The filter bed consisted of different layers: 0.8 m of hollow block at the bottom, 0.4 m of coarse gravel (diameter of 2.5-5.0 cm) at the middle, 0.15 m depth of fine gravel (diameter of 1.25-2.5 cm) at the upper part and 0.1 m of the fine sand (diameter of 0.30-0.75 mm) on the top. Cattail was used as wetland plants (8-12 bulb/m$^2$).

**Experimental conditions**

The experimental setup aimed at investigating the optimum operating conditions of each unit system based on hydraulic retention time (HRT) and hydraulic loading rate (HLR) as shown in Table 1. Samples were collected twice a week from five different sampling points and analyzed for pH, BOD, COD, total suspended solids (TSS), total kjedahl nitrogen (TKN), ammonia nitrogen (NH$_4$-N) and total phosphorus (TP), according to Standard Methods for Examination of Water and Wastewater (APHA-AWWA-WPCF, 1998).
A mixture of Bangkok septage and AIT wastewater at the ratio of about 1:20 was used as raw wastewater. The characteristics of the influent wastewater can be categorized as high-strength domestic wastewater, with average chemical oxygen demand (COD) and biochemical oxygen demand (BOD) concentrations of 1,000 and 300 mg/L, respectively. The wastewater contained high levels of non-biodegradable organics, as indicated by the COD:BOD ratio of about 3:1.
Results and Discussion

Treatment performance of the anaerobic baffled reactor

At a HRT of 2 days, the ABR unit could produce an effluent with average BOD, TSS and TKN concentrations of 55, 65 and 45 mg/L, respectively (Figure 2). An average BOD removal rate of 83% was observed, in the same range as observed in lab-scale investigations conducted by Wanasen (2003) who obtained 86% average BOD removal efficiencies. COD removal efficiencies averaging 90% were monitored, confirming the results of Garuti et al. (1992). Even if achieving average BOD, TSS and TKN removal efficiencies as high as 80 - 90%, the effluent is still exceeding the Thai domestic wastewater effluent standards (PCD, 2000), making clear that a polishing step is required before the treated blackwater can be discharged to the environment.

![Graphs showing effluent quality](image1)

Figure 2: ABR effluent quality in comparison with Thai domestic wastewater effluent standards

Treatment performance of the polishing units

The anaerobic filter, the sand filter and the constructed wetland were fed with the effluent wastewater from the ABR unit at different HRT and HLR, as shown in Table 2.

The anaerobic filter was operated at HRT of 2, 3 and 4 days. The results reveal that the treatment performances in terms of BOD, TSS and TN for the different operating conditions are not significantly different at 95% confidence. Given the direct correlation between HRT and reactor costs, a HRT of 2 days is most appropriate for the operation of the anaerobic filter. This is in the range of 1-4 days suggested by Reyes O. et al. (1999) for the treatment of low-strength wastewater.

The sand filter was operated at HLR of 5, 7.5 and 10 cm/d. The BOD and TSS removal efficiencies at the different HLR were not significantly different at 95% confidence. The highest TN removal rates were reached at HLR of 10 cm/d (44%), whereas TN removal at HLR of 5 and 7.5 cm/d were 20% and...
29%, respectively. USEPA (2002) suggests HLR in the range of 4 - 8 cm/d for intermittent sand filter treating domestic wastewater. The sand filter investigated in these experiments achieved acceptable removal efficiencies even at higher loading rates (HLR of 10 cm/d) and produced an effluent of good quality satisfying the effluent standards in Thailand. Moreover, the application of high rate filtration results in significant cost savings.

The vertical flow constructed wetland was operated at HLR of 6, 10 and 20 cm/d. The highest removal efficiencies in terms of TSS, BOD and TN were observed at HLR of 6 cm/d. However, even at HLR 10 and 20 cm/d the Thai effluent standard for TSS, BOD and TKN could be met (PCD, 2000).

Table 2: Treatment Performance of the different polishing units

<table>
<thead>
<tr>
<th>System</th>
<th>Parameter</th>
<th>HRT 4 d.</th>
<th>Treatment</th>
<th>HRT 3 d.</th>
<th>Treatment</th>
<th>HRT 2 d.</th>
<th>Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HLR 5 cm/d.</td>
<td>Inf</td>
<td>Eff</td>
<td>Rem</td>
<td>Inf</td>
<td>Eff</td>
<td>Rem</td>
</tr>
<tr>
<td>Anaerobic Filter</td>
<td>SS</td>
<td>65±50</td>
<td>7±5</td>
<td>89%</td>
<td>75±45</td>
<td>15±10</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>BOD</td>
<td>55±40</td>
<td>7±5</td>
<td>87%</td>
<td>70±35</td>
<td>20±7</td>
<td>86%</td>
</tr>
<tr>
<td></td>
<td>COD</td>
<td>150±55</td>
<td>20±10</td>
<td>83%</td>
<td>120±45</td>
<td>20±15</td>
<td>83%</td>
</tr>
<tr>
<td></td>
<td>TKN</td>
<td>45±12</td>
<td>7±5</td>
<td>84%</td>
<td>30±5</td>
<td>2±1.2</td>
<td>93%</td>
</tr>
<tr>
<td></td>
<td>TN</td>
<td>50±14</td>
<td>40±10</td>
<td>20%</td>
<td>35±5</td>
<td>25±4</td>
<td>29%</td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>10±3</td>
<td>5±3</td>
<td>50%</td>
<td>4±1.3</td>
<td>2.5±1</td>
<td>38%</td>
</tr>
<tr>
<td>Sand Filter</td>
<td>SS</td>
<td>100±40</td>
<td>25±12</td>
<td>75%</td>
<td>65±50</td>
<td>15±8</td>
<td>77%</td>
</tr>
<tr>
<td></td>
<td>BOD</td>
<td>45±20</td>
<td>10±25</td>
<td>78%</td>
<td>55±40</td>
<td>20±10</td>
<td>64%</td>
</tr>
<tr>
<td></td>
<td>COD</td>
<td>170±60</td>
<td>40±15</td>
<td>76%</td>
<td>150±55</td>
<td>55±30</td>
<td>63%</td>
</tr>
<tr>
<td></td>
<td>TKN</td>
<td>40±5</td>
<td>10±4</td>
<td>75%</td>
<td>45±12</td>
<td>30±10</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>TN</td>
<td>45±5</td>
<td>15±6</td>
<td>67%</td>
<td>50±14</td>
<td>35±10</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>5±1.5</td>
<td>1.8±1</td>
<td>64%</td>
<td>10±3</td>
<td>7±3</td>
<td>30%</td>
</tr>
</tbody>
</table>

Comparison of treatment performances of the different polishing units

BOD and COD removal – The sand filter operated at a HLR of 5 – 10 cm/day produced an effluent with BOD concentrations as low as 7 – 8 mg/L, (Figure 3-i), whereas the average effluent BOD concentration of the anaerobic filter and the constructed wetland amounted to 20 and 15 mg/L, corresponding to removal efficiencies of 64% and 70%, respectively. All systems could in average reach the Thai effluent standard of 20 mg BOD/L (PCD, 2000), but in isolated cases the anaerobic filter and the constructed wetland units produced an effluent which exceeded the Thai effluent standard. Likewise, the highest COD removal efficiency of 80% could be reached in the sand filter, whereas the anaerobic filter and the constructed wetland systems could reach COD removal efficiencies of 63% and 67%, respectively.

Solids removal - The anaerobic filter, sand filter and constructed wetland units produced an effluent with average SS concentrations of 17, 15 and 23 mg/L, respectively. As shown in Figure 3-ii, the sand filter
offered the highest average SS removal efficiency of 85%, which is in the typical range of 65% to 95% as indicated Bruen and Piluk (1994). The three polishing units produced an effluent which met the Thai effluent standard of 30 mg/L (PCD, 2000).

![BOD Concentration](image1)

![TSS Concentration](image2)

Figure 3: Effluent BOD and TSS concentrations

**Nutrient removal** - As expected, the three systems behaved very differently in terms of nitrogen transformation and removal. Virtually all nitrogen present in the raw wastewater is in the form of organic nitrogen or ammonium. In the anaerobic baffled reactor, organic nitrogen undergoes a mineralization process and is broken down into ammonia, resulting in effluent wastewater with nitrogen mainly in form of ammonium (75%). Given the different HRT and HLR, N loadings are different on the polishing units as shown in figure Figure 5-ii. In the anaerobic filter, which was loaded up to 135 g nitrogen per day, solely 10% of nitrogen was removed in average, mainly due to the filtration and sedimentation of org-N. The absence of oxygen disables a nitrification process, which results in similar effluent characteristics as in the influent (Figure 5-ii). The sand filter showed a great nitrification capacity but rather low total nitrogen removal performances. Ammonium is converted to nitrate, which is mobile and thus easily released in the environment. The sand filter unit showed average TN removal rates of 45%, with nitrogen mainly in form of NO3-N (92%). The highest nitrogen removal rates (67%) were observed in the constructed wetland unit operated at a hydraulic loading rate of 6 cm/d, and N loading rates of about 12.15 g/d, indicating the important role of the plants in the nitrogen transformation and removal process: Koottatep and Polprasert (1997) demonstrated that uptake of nitrogen by the plants is one form of nitrogen removal in constructed wetlands but according to Wallace (2002) only up to 10% in case the plants are harvested. According to Tanner (2001) plants primarily facilitate improved nutrient removal indirectly through their effects on other removal processes. The plants enhance key nutrient transformation processes (i.e. nitrification and denitrification) through low-level root-zone oxygen release. They supply organic matter for microbes, sequester organically bound nutrients, and buffer nutrient release. The increase of the hydraulic loading rate from 6 cm/d to 20 cm/d, with N loading rates increasing from 12.15 to 31.5 g/d, led to strongly decreased nitrification capacities in the constructed wetland, and thus to reduced nitrogen removal rates. At HLR of 20 cm/d, the average nitrogen removal rate dropped down to 26%, with nitrogen mainly in form of ammonium (70%), but with TKN concentrations still below the effluent quality standards of Thailand (35 mg/l), as illustrated in Figure 5-i. Thus, the selection of the loading rates of constructed wetlands will strongly depend on effluent TKN concentration requirements.

In terms of phosphorous, the anaerobic filter, sand filter and constructed wetland showed average TP removal efficiencies of 12 %, 20 % and 25 %, respectively. The phosphorus removal efficiency
observed in the constructed wetland unit is in the typical range of 10-40% indicated by Crites and Tchobanoglous (1998).

<table>
<thead>
<tr>
<th>TKN Concentration</th>
<th>Anaerobic Filter, HRT 2 d</th>
<th>Sand Filter, HLR 10 cm/d</th>
<th>Constructed Wetland, HLR 20 cm/d</th>
<th>Effluent Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (days)</td>
<td>1 7 14 21 28 35 42 49 56 63 70 77 84 91</td>
<td>0 20 40 60 80</td>
<td>0 20 40 60 80</td>
<td>0 20 40 60 80</td>
</tr>
</tbody>
</table>

Figure 4: Effluent Nitrogen concentrations and nitrogen compound

Conclusions

The hypothesis that the anaerobic baffled reactor is an efficient pre-treatment system for domestic blackwater could be confirmed in the pilot-scale experiments. Average removal efficiencies as high as 83% and 93% in terms of BOD and TSS, respectively, were determined. Despite the virtue of the ABR, national wastewater effluent standards of Thailand could not be reached with the ABR systems only. The post-treatment systems investigated could treat the pre-treated wastewater to a satisfactory level. The ABR with sand filter could reach average effluent BOD concentrations of 8 mg/L, which corresponds to the highest average removal efficiency observed (98%). The ABR with anaerobic filter could receive the highest organic loading rates (OLR) up to 0.075 kg COD/m³.d whereas the ABR with constructed wetland could achieve the highest nitrogen removal rates. Based on the observations done in these pilot-scale experiments, the authors recommend the following operation conditions for the treatment of blackwater: (i) Anaerobic baffled reactor: HRT = 2 days, (ii) Anaerobic filter: HRT = 2 days, (iii) Sand filter: HLR = 7 – 10 cm/d, (iv) Constructed wetland: HLR = 6 – 20 cm/d, depending on nitrogen removal requirements. The research project demonstrated that simple treatment systems could efficiently treat domestic wastewater. Rather than concluding which system is the most appropriate, it is suggested to define specific fields of application for the different systems. The ABR with anaerobic filter produced an effluent which contains high levels of nutrients (N and P) that makes it a potential treatment system in cases where wastewater irrigation is possible and wished. On the other hand the ABR with sand filter or constructed wetland produced an effluent, which always respected the effluent standards of Thailand; hence these systems could be suitable in cases where protection of aquatic systems has high priority.

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