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Treatment of a Slaughterhouse Wastewater using Sequencing Batch Reactors at a Shortened Operating Cycle

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Abstract

This laboratory-scale study employed sequencing batch reactor (SBR) technology to investigate the effect of two operational parameters [i.e. solids retention time (SRT) and anoxic time ratios] regarding the treatment of a slaughterhouse wastewater. Results indicated that organic matter removal, expressed as chemical oxygen demand (COD), was very high, consistently exceeding the 95 % level. In addition, the total nitrogen (TN) removal ranged between 82 and 94 %, while total phosphorus (TP) removal fluctuated between 88 and 94 %. In general, the reactors exhibited a high degree of operational stability during treatment. Although the investigated range of the two operational parameters appeared to have a minimal effect on the process performance (expressed as % carbon or nutrient removal), the corresponding COD and TN specific consumption rates were noticeably affected by the variation in the anoxic time ratios. Furthermore, the operating cycle length of 8 h employed in this study resulted in improved performance, in terms of nitrogen removal, compared to other studies conducted at longer operating cycles.

Keywords: biological nutrient removal; slaughterhouse wastewater; sequencing batch reactors; operation cycle

1. Introduction

Thailand generates a wide variety of industrial high-strength organic wastewaters, with one of the most important originating from the slaughterhouse industry. According to the Department of Industrial Works, 433 slaughterhouses were registered in Thailand in 2015; the processing and export of pork meat products generated a total income of $US 78 million (Ministry of Industry, 2016). In addition, from 2008 to 2015, Thailand was one of the top pork exporters in the world, with pork production increasing steadily from 9800 t/yr in 2008 to 17080 t/yr in 2015 (Ministry of Agriculture and Cooperatives, 2016). Slaughterhouse wastewaters typically contain a large concentration of biodegradable organics which can be mainly attributed to the presence of lipids and proteins (Massé and Masse, 2000). In addition, nutrients in the form of nitrogen and phosphorus as well as total suspended solids (TSS) are generally found in large amounts in slaughterhouse effluents (Fongsatitkul *et al*., 2011; Sunder and Satyanarayan, 2013). Some typical concentrations of abattoir wastewaters reported in the literature are shown in Table 1. It is evident that apart from the wide fluctuation of the various parameters displayed, the treatment of such wastewaters can be challenging, due to not only their organic strength but also to their high nutrient level, since it is well known that nitrogen and phosphorus can cause eutrophication in receiving water bodies. In order to meet the pertinent discharge standards of the regulatory authorities, slaughterhouses need either to incorporate on-site treatment facilities and/or pay surcharges for the right to discharge their effluents into the domestic sewer system.

Sequencing batch reactors (SBRs) have been widely considered as an effective technology for achieving simultaneous removal of carbon, nitrogen and phosphorous. The major advantage of an SBR system is its flexibility of operation, which allows for the selection of a sequence of different oxygen tensions [i.e. anaerobic, anoxic and aerobic (oxic) conditions] in an appropriate order to achieve the removal of the targeted pollutants (Ma *et al*., 2005). Consequently, this approach has resulted in high removal efficiencies for organic matter and nutrients during the treatment of a variety of wastewaters (Fongsatitkul *et al*., 2008; Li *et al*., 2008; Wu *et al*., 2013; Sathian *et al*., 2014).

Table 1. Typical characteristics of slaughterhouse wastewaters

COD (mg/l)	BOD (mg/l)	TKN (mg/l)	TP (mg/l)	TSS (mg/l)	NH_3-N (mg/l)	Source
1371	n/a	140	24	538	n/a	Boonfruang, 2003
1898	n/a	184	22	479	n/a	Kasawayut, 2005
5163	n/a	1057	217	1742	50	Cassidy and Belia, 2005
1600	n/a	370	n/a	879	136	Filali-Meknassi *et al*., 2005
4672	2895	356	29	1403	342	Li *et al*., 2008
27800	16680	920	78	n/a	308	Sunder and Satyanarayan, 2013

n/a: not available

Regarding the treatment of slaughterhouse wastewaters, previous research using SBRs has revealed that although phosphorus removal [(expressed as total phosphorus (TP)] was consistently between 82 and 94%, the nitrogen removal [(expressed as total nitrogen (TN)] fluctuated between 60 and 92%, at operating cycles ranging between 12 and 24 h (Boonfruang, 2003; Warodomrungsimun, 2011). The lack of consistency in the removal of nitrogen can be attributed to the overall length of the operating cycle, which may interfere with the denitrification process (Tsuneda *et al*., 2006). It has become apparent that the length of time allocated to each sequence as well as that of the total operating cycle constitute an optimization strategy, normally particular to the type of wastewater treated (Mees *et al*., 2014). This study therefore aims to: i) explore the role of varying the relative anoxic time ratios and solids retention time (SRT) on the performance of the treatment process and ii) comment on the effect of shortening the operation cycle on the optimization of nitrogen removal.

2. Materials and Methods

2.1 Wastewater and seed characteristics

The raw wastewater was sourced from the equalization tank of the Pork Traders Cooperative of Bangkok Limited industrial wastewater treatment facility, located in Klong Toei, Bangkok, Thailand. The wastewater was collected by grab sampling once a week and stored at 4 ^{o}C in 20 l containers. The influent characteristics of the raw wastewater are summarized in Table 2, indicating that the wastewater contained a large concentration of organics and nutrients, as mentioned in the introduction section. The seed used in this study was obtained from the activated sludge system of the Din-Daeng Domestic Wastewater Treatment Plant in Bangkok, and was concentrated to a target mixed liquor suspended solids (MLSS) concentration of approximately 4000 mg/l.

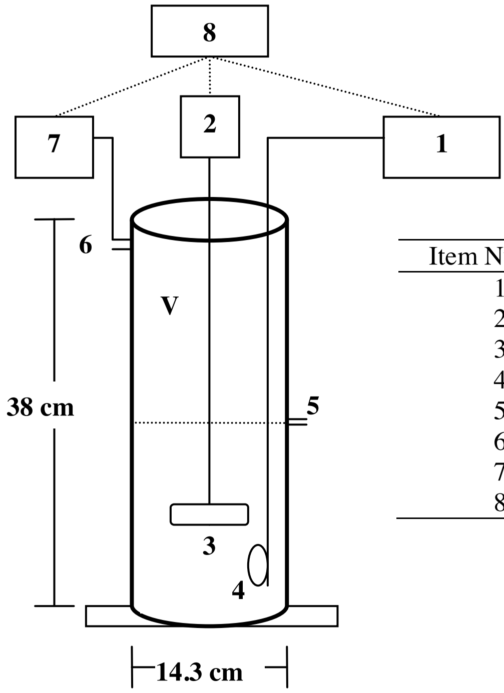
2.2 Bioreactor set-up and operation

The experimental part involved the use of three identical SBR systems operating in parallel. The reactors were constructed of acrylic material with an internal diameter of 0.143 m, a height of 0.38 m and a liquid volume of 5 l (Fig. 1). The bioreactors were sealed to prevent air entrainment during non-aerated periods.

Three runs using three reactors per run were conducted with varying the two independent variables; namely, the ratio of the first anoxic (Anoxic I) to the second anoxic (Anoxic II) period and SRT. The length of the non-aerated period (and by association that of the aeration period) affects both nitrogen and phosphorus removal (Mees *et al*., 2014), while SRT is a parameter that influences the operational stability and performance of any biological wastewater treatment process (Wu *et al*., 2013). The SBRs in this study were operated on an 8-h cycle, with the sequence of operating conditions illustrated in Table 3.

Table 2. Influent characteristics of the raw slaughterhouse wastewater

Parameter	Mean ± STD	Range
pH	7.6 ± 0.1	7.0 – 8.4
COD (mg/l)	1046 ± 186	742 – 1465
TKN (mg/l)	140 ± 34	98 – 240
TP (mg/l)	6.3 ± 3.2	2.3 – 19
TSS (mg/l)	194 ± 95	60 – 395
Alkalinity (mg/l as $CaCO_3$)	514 ± 101	250 – 700



Item Number	Detail
1	Air supply
2	Motor
3	Paddles
4	Air diffuser
5	Effluent port
6	Influent port
7	Peristaltic pump
8	Timer

Figure 1. Schematic of experimental apparatus

Table 4 indicates the experimental design followed as a function of the two independent variables investigated. Each experimental run lasted for approximately two months, including a brief acclimation period. It should be mentioned that the SRT range selected for this study (i.e. 60 to 80 d) appears to be at the higher end of the spectrum regarding SBR operation. However, due to the high organic content of the wastewater (Table 2), a "conservative" approach was followed to allow biomass build-up to facilitate treatment as per previous experience (Fongsatitkul *et al*., 2008). SRT control was achieved by wasting daily an appropriate amount of mixed liquor suspended solids (MLSS). Furthermore, a hydraulic retention time (HRT) of 48 h was maintained by decanting a supernatant volume of 2.5 l during the Draw period. All experiments were conducted at an ambient liquid temperature of 30 ± 2 °C while the dissolved oxygen (DO) concentration was maintained between 2.0 and 4.0 mg/l throughout the aerated periods.

At the beginning of the operation a step-feeding approach was followed to minimize any adverse effect on the biomass due to the high organic and nitrogen content in the influent (Table 2), as well as to enhance the biomass' potential for acclimation. In this respect, stepfeeding involved adding only a fraction of the total wastewater volume during the Fill period of each cycle, starting from 25% and then progressively increasing to 50%, 75%, and finally 100% of the SBR's capacity. Acclimation was rapid, as COD removal in excess of 90% was achieved within 2 d for each incremental step-feed.

Table 3. SBR operating conditions

Parameter	SBR		
	Reactor 1	Reactor 2	Reactor 3
Fill (h)	0.5	0.5	0.5
Anoxic I (h)	0.9	0.65	0.5
Oxic I (h)	1	1	1
Anoxic II (h)	3.6	3.85	4
Oxic II (h)	0.5	0.5	0.5
Anoxic I: Anoxic II ratio	1:4	1:6	1:8
Total reaction time (h)	6	6	6
Settle (h)	0.5	0.5	0.5
Draw (h)	0.5	0.5	0.5
Idle (h)	0.5	0.5	0.5
Total cycle length (h)	8	8	8

Table 4. Experimental design matrix

Run (reactors)	SRT (d)	Anoxic I: Anoxic II ratio
1 (1,2,3)	60, 70, 80*	1:4
2 (1,2,3)	60, 70, 80	1:6
3 (1,2,3)	60, 70, 80	1:8

*Referring to reactors 1, 2, and 3, respectively

2.3 Sampling and analytical methods

Sampling was performed three times a week on the influent and the settled effluent from the SBRs. On selected occasions, track studies were conducted by sampling from each reactor. In general, samples were analyzed for chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), and TP, with influent and effluent values determined on unfiltered samples. In addition, nitrite (NO_2^- -N) and nitrate (NO_3^- -N) measurements were performed on filtered samples. The reactor DO, pH and temperature were recorded on a daily basis, while the MLSS content (measured as TSS) was determined twice a week.

Analytical determinations for COD, TKN, TP, NO_2^- -N, NO_3^- -N and total suspended solids (TSS) were conducted in accordance with Standard Methods (APHA, 2005) while commercially available membrane and glass electrodes were used for DO and pH determination. Further details for all analytical procedures are available elsewhere (Saikomon, 2012).

3. Results and Discussion

3.1 Reactor performance

A summary of the reactors' performance including all corresponding runs is presented in Table 5. It can be seen that a very high COD removal was achieved throughout this study, exceeding the 95 % level. This is an indication that the slaughterhouse wastewater was successfully biodegraded under the conditions investigated. Regarding TN [defined as the sum of TKN and NO_x^- -N (i.e. NO_2^- -N plus NO_3^- -N)] removal, a moderate improvement was observed at SRTs longer than 60 d, while a similar pattern was also noticed in connection with TP removal. It should be mentioned that there was no apparent effect of the variation of the anoxic time ratios on the SBR performance.

In order to obtain a detailed picture of the behavior of the bioreactors, a representative example of the removal efficiency profiles for all three parameters analyzed (i.e. COD, TN and TP) is illustrated in Figs. 2 to 4. The COD removal efficiency profile depicted in Fig. 2 demonstrates, apart from a high degree of operational stability, a superior treatability from an organic carbon removal perspective. Furthermore, the TN and TP profiles (Figs. 3 and 4) exhibit a high removal potential (mostly within the 85 to 95 % range) as well as a reasonably stable pattern with limited fluctuations. This can be attributed in part to a favorable influent COD to TKN ratio of 7.5:1 (Table 2). It has been reported that a minimum COD to TKN ratio of 7:1 is required for abattoir wastewaters to achieve satisfactory nutrient removal (Cassidy and Belia 2005; Mittal, 2006). It is obvious therefore that with respect to carbon and nutrient removal, the slaughterhouse wastewater was readily biodegraded in the SBRs employed.

Table 5. Percent COD, TN and TP removal

Parameter	SRT (d)	Anoxic I / Anoxic II ratio		
		1:4	1:6	1:8
COD (%)	60	97.3 ± 1.3	97.4 ± 1.2	97.3 ± 1.2
	70	95.7 ± 1.6	95.7 ± 1.1	95.9 ± 0.9
	80	97.1 ± 1.2	97.2 ± 1.2	97.1 ± 1.3
TN (%)	60	82.6 ± 12.5	83.2 ± 14.2	88.2 ± 6.7
	70	91.7 ± 5.0	92.4 ± 3.2	90.0 ± 6.2
	80	90.1 ± 9.2	93.1 ± 4.1	93.5 ± 2.8
TP (%)	60	88.3 ± 5.1	86.7 ± 7.4	87.9 ± 4.7
	70	92.7 ± 5.4	94.2 ± 2.5	93.6 ± 3.6
	80	91.2 ± 1.2	91.3 ± 5.7	90.6 ± 6.2

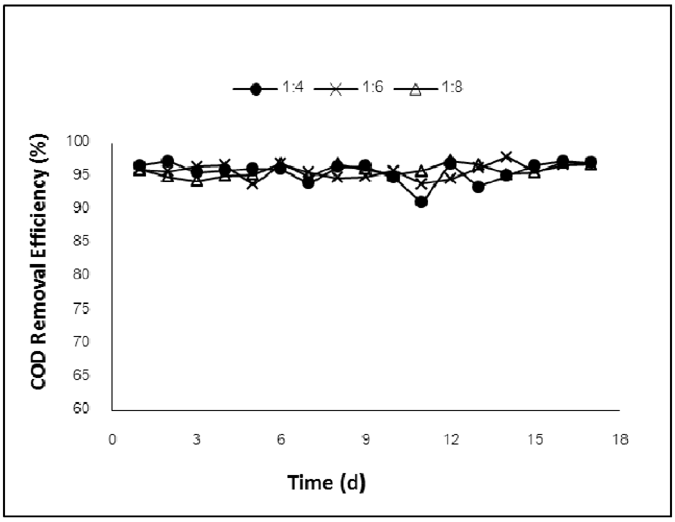


Figure 2. COD removal efficiency at first anoxic to second anoxic time ratios of 1:4, 1:6, 1:8 and SRT of 70 d

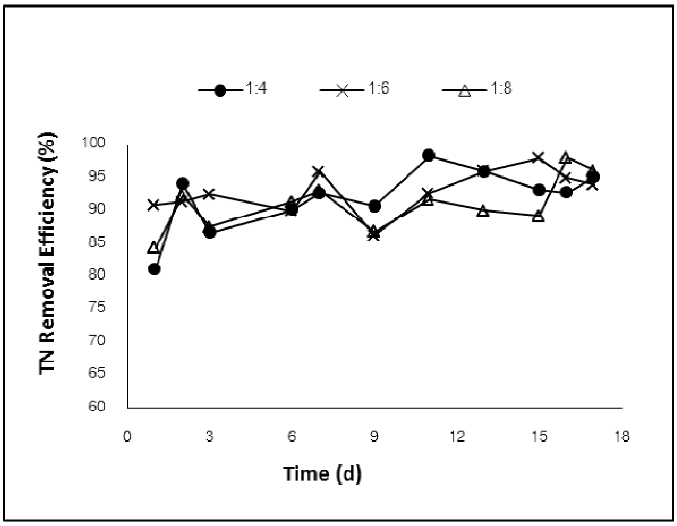


Figure 3. TN removal efficiency at first anoxic to second anoxic time ratios of 1:4, 1:6, 1:8 and SRT of 70 d

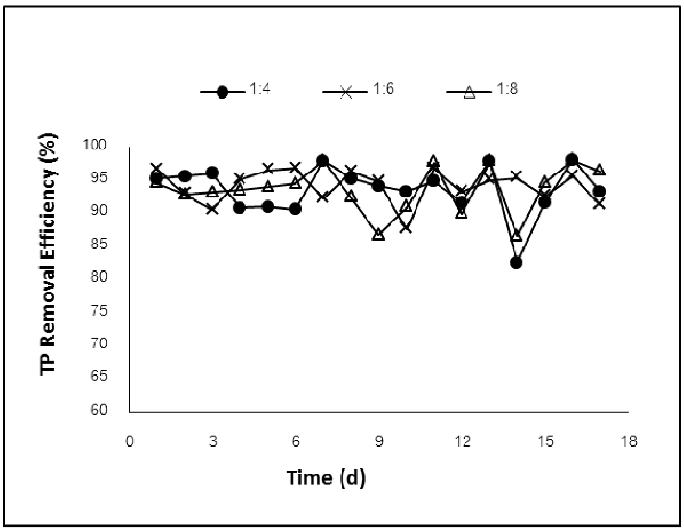


Figure 4. TP removal efficiency at first anoxic to second anoxic time ratios of 1:4, 1:6, 1:8 and SRT of 70 d

Table 6. Specific COD, TN and TP consumption rates

Parameter	SRT (d)	Anoxic I / Anoxic II ratio		
		1:4	1:6	1:8
COD (mg COD / mg MLSS·d)	60	1.077 ± 0.166	0.987 ± 0.099	0.803 ± 0.088
	70	1.075 ± 0.138	0.923 ± 0.125	0.766 ± 0.067
	80	1.050 ± 0.184	0.849 ± 0.116	0.745 ± 0.093
TN (mg TN / mg MLSS·d)	60	0.117 ± 0.019	0.104 ± 0.016	0.090 ± 0.015
	70	0.135 ± 0.022	0.110 ± 0.014	0.094 ± 0.018
	80	0.123 ± 0.025	0.095 ± 0.020	0.082 ± 0.013
TP (mg TP / mg MLSS·d)	60	0.0044 ± 0.0004	0.0040 ± 0.0006	0.0043 ± 0.0007
	70	0.0054 ± 0.0008	0.0055 ± 0.0009	0.0049 ± 0.0008
	80	0.0050 ± 0.0007	0.0053 ± 0.0008	0.0047 ± 0.0006

3.2 Specific consumption rates

The specific rates with respect to COD, TN and TP consumption were computed (expressed as mg of substrate removed per mg of reactor MLSS per d) and the results have been tabulated in Table 6. All specific rates were calculated for the total time of the operation of each run (and reported as a mean value) to provide a better estimation of the ability of biomass to perform under the conditions explored. It can be seen that both the COD and TN specific rates were the highest at an Anoxic I: Anoxic II time ratio of 1:4 and they gradually decreased as the ratio varied, exhibiting the lowest values (by about 30 %) at a ratio of 1:8. This suggests that the biomass functioned more efficiently at a relatively shorter second anoxic time than at a longer one. It has been reported that long anoxic times may have a negative effect on nitrogen removal since they interfere with the dynamic balance between denitrifiers and phosphorus-removing bacteria (Peng *et al*., 2006). This can be particularly critical in systems which are designed and operated to remove nitrogen and phosphorus simultaneously from wastewaters such as SBRs (Tsuneda *et al*., 2006). On the other hand, the TP specific rates did not appear to be affected by the changes in the anoxic time ratios and fluctuated slightly between 0.0040 and 0.0055 mg TP per mg MLSS per d, with no apparent trend. Moreover, the effect of SRT on all specific rates was rather minimal, with minor variations observed.

3.3 Performance comparison at varied operating cycle lengths

The length of the operating cycle of an SBR is a key parameter which not only affects the overall performance of the biological system but also the potential to accommodate a larger volume of wastewater for treatment (Mees *et al*., 2014). Since this research was conducted at an operating cycle of 8 h (Table 3), relevant data from other related studies (using a similar source of wastewater and comparably-operated SBR systems) have been extracted to provide a meaningful comparison (Table 7). Results indicated that at an SRT of 60 d, there is a gradual improvement in TN removal as the length of the operating cycle is reduced from 24 to 8 h, by approximately 15 %. However, the corresponding TN specific rates increased by more than 30 % (which is statistically significant at the 95 % confidence level), reflecting the ability of biomass to perform more efficiently at such a shortened cycle. This can be mainly attributed to the improvement of the denitrification process (Galí *et al*., 2007), which is congruent with the progressively reduced effluent NO_x^- -N concentrations at shorter cycles (Table 7). The removal of TP appears to be independent of the length of the operating cycle, while COD removal was consistently high throughout the experimental runs (Table 5); therefore, it can be concluded that the operating conditions investigated in this study have resulted in an overall successful system performance.

Table 7. Performance comparison as a function of the operating cycle length at an SRT of 60 d

Parameter	Length of SBR cycle (h)		
	8	12 [a]	24 [b]
TN (% removal)	84.8 ± 9.4	76.6 ± 10.8	73.1 ± 11.5
TP (% removal)	87.8 ± 5.7	88.5 ± 4.6	85.7 ± 7.9
Effluent NO_x^- -N (mg/l)	13.4 ± 5.2	22.8 ± 9.1	28.7 ± 9.8
TN specific rate (mg TN / mg MLSS·d)	0.104 ± 0.016	0.080 ± 0.012	0.071 ± 0.015

[a] Data obtained from Warodomrungsimun (2011)

[b] Data obtained from Boonfruang (2003)

4. Conclusions

The SBR systems used in this research successfully treated the slaughterhouse wastewater investigated. In general, all runs demonstrated a high level of operational stability. COD removal was in excess of 95 %, while TN and TP removals ranged from 82 to 94 %, and from 88 to 94 %, respectively. The effect of the variation of SRT and anoxic time ratios on the process performance (expressed as % removal) was rather limited; however, the corresponding COD and TN specific consumption rates were considerably influenced by the variation in the anoxic time ratios. Lastly, the shortened operating cycle length of 8 h applied in this research resulted in higher nitrogen removal, compared to previous studies conducted at longer operating cycles.

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