Desalination and Water Treatment
www.deswater.com

4 (2009) 274–280

Buffering capacity in an anaerobic baffled reactor treating carbohydrate–protein wastewater

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Received 10 December 2008; Accepted 10 March 2009

ABSTRACT

A 10-L working volume of an anaerobic baffled reactor (ABR) with three, six and eight compartments using an organic loading rate of 4 g COD/l-d (named as 3C-OLR4, 6C-OLR4, and 8C-OLR4 experiments, respectively) was used. COD removal efficiencies of 74%, 78% and 83% were accomplished, respectively. The effluent pH and alkalinity values were maintained around 7.9 and 2000 mg/l as $CaCO_3$, respectively, and the effluent VFA concentrations were mostly less than 500 mg/l as $CaCO_3$. This resulted in a low VFA/alkalinity ratio (less than 0.4), which indicated that the system had a high buffering capacity with only 2000 mg/l as $CaCO_3$ alkalinity concentration. Subsequently, the eight-compartment ABR was selected to further investigate the effect of organic loading rates (OLRs) of 8, 12, 16 g COD/l-d (8C-OLR8, 8C-OLR12, 8C-OLR16). The same influent alkalinity (2000 mg/l) was applied to these three OLRs. The effluent pH values of those remained in the range of 8.1–8.5 and the effluent alkalinity concentrations were around 2500 mg/l as $CaCO_3$. This signifies that the alkalinity requirement in the ABR treating carbohydrate–protein wastewater would be reduced, resulting in chemical cost reduction.

Keywords: Anaerobic baffled reactor; ABR; Alkalinity; Volatile fatty acid; VFA; SRT/HRT ratio

1. Introduction

In anaerobic degradation, the two principal pathways involved in the formation of methane gas are the conversion of hydrogen and carbon dioxide to methane and water as shown in reaction (1):

$$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (1)$$

and the conversion of acetic acid to methane and carbon dioxide gases as shown in reaction (2):

$$CH_3COOH + CO_2 \rightarrow CH_4 + CO_2 \quad (2)$$

It is a common belief that the methane gas in anaerobic degradation was mostly converted by reaction (2) [1,2]. From this equation, the production of carbon dioxide (CO_2) and methane (CH_4) gases is theoretically equal, or they should be present at about 50% each by volume in the biogas produced from the anaerobic conversion of acetic acid. However, there has never been such a 50:50 ratio of these two gases found in anaerobic biogas. This is because carbon dioxide could be dissolved into the liquid phase, resulting in a higher percentage of methane (more than 50%) in biogas. This dissolved carbon dioxide generates carbonic acid (H_2CO_3), which can adversely affect the pH value of the system. In the anaerobic process with a high efficiency of organic removal, carbonic acid from dissolved carbon dioxide plays a more important role in

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Presented at the 1st Asia-Pacific Young Water Professionals (APYWP) Conference, 8–10 December 2008, Gwangju, Korea.

decreasing pH value than volatile fatty acid from an acidogenesis step.

Generally, anaerobic processes are involved with several groups of microorganisms and their complex series of degradation steps. Process stability mainly depends on the synergism of the different microbial groups involved in the degradation. The buffering capacity (or alkalinity) for the build-up of acids in the process is required to maintain neutral pH for methanogenic bacteria. For neutral pH operation, Li and Sutton [3] reported that the alkalinity requirement was mostly for buffering carbonic acid caused by dissolved carbon dioxide in biogas, especially in the single-phase anaerobic process.

An anaerobic baffled reactor (ABR) contains a series of vertical baffles creating a compartmentalized structure, which is helpful in spatially separating acidogenic and methanogenic populations. This advantage maintains a more sensitive population, methanogens, from the front of the reactor where exposure to unfavourable high organic loading may occur, resulting in organic removal efficiency enhancement with shorter HRT [4]. The successful operation of ABR in treating domestic, industrial and agricultural wastewater with the removal efficiency higher than 90% has been reported [5–8]. This article aims to report the buffering capacity happening in the ABR process treating carbohydrate–protein wastewater.

2. Material and methods

2.1. Reactor design

Three laboratory-scale ABRs with three, six and eight compartments and a working volume of 10 L were used in this study. A schematic diagram of the experimental set-up is shown in Fig. 1. Each compartment was equipped with a vertical baffle that directed the liquid flow alternately downward and upward. The ratio of downflow and upflow widths in each compartment is 1:3 as recommended by Dama et al. [6]. Also, the 45° slanting baffle was recommended to reduce the region of dead space and direct the flow to the center of the upflow region [6]. The wastewater flows from one compartment to the next through a window cut on the acrylic partition.

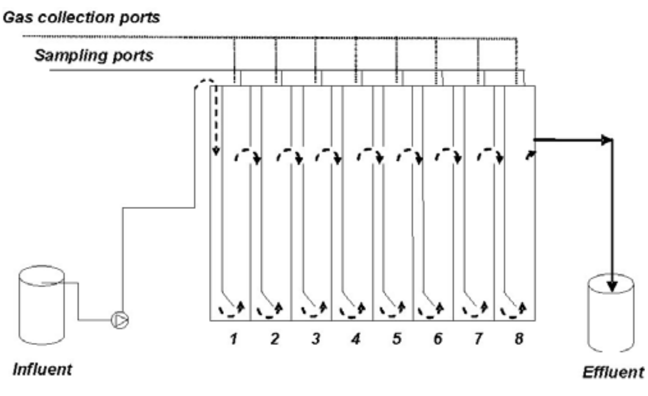


Fig. 1. Schematic diagram of experimental set-up (eight-compartment ABR).

2.2. Seeding and acclimatization

The systems were inoculated with anaerobic sludge taken from the ABRs, which were previously used for treating synthetic swine wastewater for approximately 3 months [9]. The seed sludge was fed into each reactor with an initial MLSS concentration of 28 g TSS/l; then, this sludge was left for 2 days settling. For acclimatization, the systems with seed sludge were fed with synthetic carbohydrate–protein wastewater containing a COD concentration of 4000 mg/l as designed strength. Each reactor was initially operated with HRT of 80 h, which was suggested to obtain high stability and effective COD removal [10]. Then, the operating HRT was gradually decreased to the designated HRT of 24 h.

2.3. Experimental set-up

The organic loading rate (OLR) of 4 g COD/l-d was applied to all three reactors to compare the effect of compartment number on treatment efficiency. Those experimental runs were named as 3C-OLR4, 6C-OLR4, and 8C-OLR4, respectively. Subsequently, the eight-compartment ABR was further investigated with OLRs increased to 8, 12 and 16 g COD/l-d (8C-OLR8, 8C-OLR12 and 8C-OLR16) experiments, respectively. The operating HRT was controlled at 24 h for the whole study. The performance of the ABR was conclusively determined at least for 1 week after they reached the steady state. This was defined as the occurrence, when the variations of COD removal efficiencies and effluent solid concentrations less than 5% were achieved continuously.

2.4. Synthetic wastewater

Wastewater used in this study was synthesized with carbohydrate and protein substances, sucrose and nutrient broth (Himedia®), respectively. This synthetic wastewater was daily prepared with tap water and some other nutrients ($CaCl_2$ 100 mg/l as Ca, KCl 200 mg/l as K and $MgSO_4{\cdot}7H_2O$ 75 mg/l as Mg). $NaHCO_3$ was also added as alkalinity capacity of about 2000 mg/l as $CaCO_3$. The feed contained constant COD concentration of 4000 mg/l for the OLR of 4 g COD/l-d, while COD concentrations of 8,000, 12,000 and 16,000 mg/l were prepared for the OLRs of 8, 12 and 16 g COD/l-d, respectively.

2.5. Analytical methods

Influent and effluent samples and supernatant of each compartment were collected and analyzed for COD, pH, ORP, alkalinity, volatile fatty acid (VFA) and solids in accordance with Standard Methods [11]. Biogas was collected and counted by gas meters using the water displacement principle.

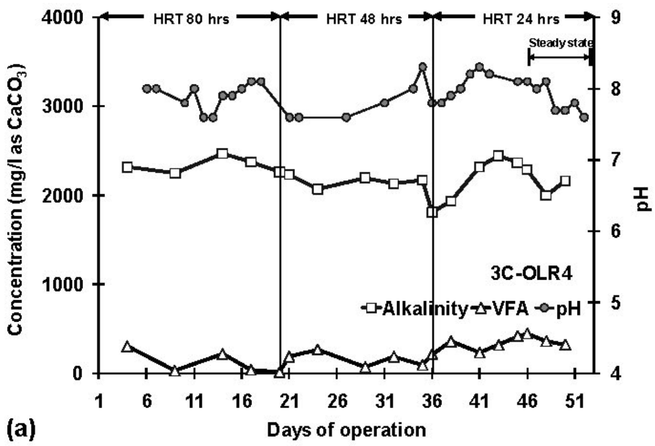
3. Results and discussion

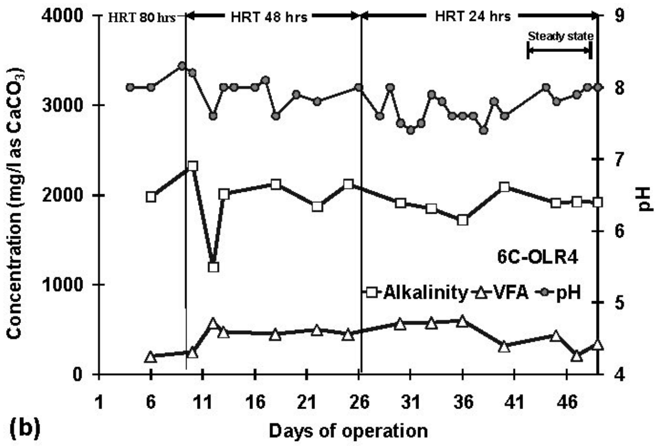
3.1. Effect of compartment numbers

Generally, pH, alkalinity and VFA are usually used as operating control parameters to indicate the stability of anaerobic wastewater treatment. Measuring effluent pH is a simple control parameter for an anaerobic system. When pH monitoring was combined with VFA concentration, these two parameters help indicate the imbalance of the anaerobic system more accurately. If the VFA production rate exceeds the maximum consumption capacity of methanogens, the accumulation of excess VFA will begin and consequently lowers the pH value in the system.

Fig. 2 illustrates profiles of the effluent pH, alkalinity, and VFA of the 3C-OLR4, 6C-OLR4, and 8C-OLR4 experiments. The effluent pH values were around 7.9 while effluent VFA and alkalinity concentrations were about 360 and 2000 mg/l as $CaCO_3$, respectively (values in detail are summarized in Table 1). The fluctuation of the three parameters was mostly insignificant overall for the experimental period (including acclimatization) in all ABRs. However, during adjusting HRT, especially lowering HRT, did affect pH and alkalinity concentration, but only a small drop that could be recovered within a few days. This should be noted that when OLR increased (decreasing HRT), the system obtained more substrate, consequently, more VFA production.

The effluent VFA concentrations overall during the experimental period were monitored and mostly were less than 500 mg/l as $CaCO_3$, which indicated good stability of the systems in substrate consumption. The observation from Fig. 2 illustrates that every increase in OLRs (or decreasing HRT) induced a slightly increasing VFA. Those were because higher OLR resulted in greater production of VFA [12–14]. However, the VFA:alkalinity ratios at steady-state of the 3C-OLR4, 6C-OLR4, and 8C-OLR4





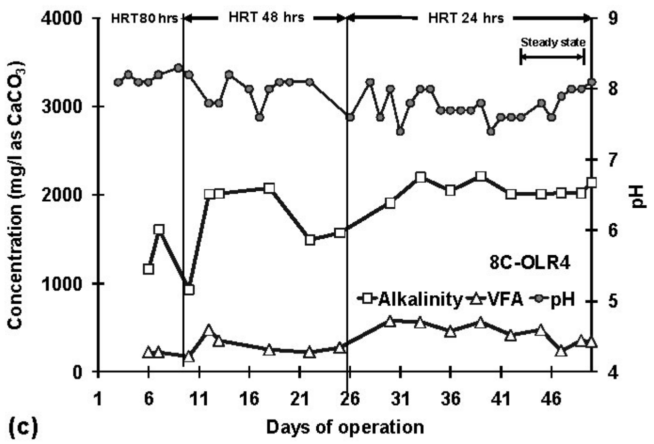
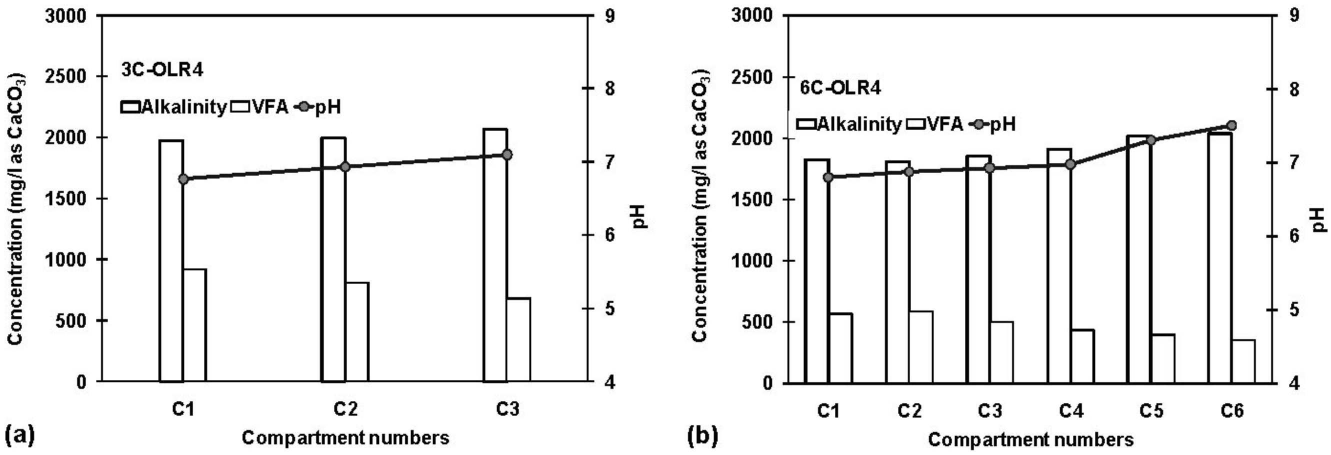


Fig. 2. Profiles of effluent pH, alkalinity and VFA in the experiments. (a) 3C-OLR4; (b) 6C-OLR4; (c) 8C-OLR4.

Table 1
Performance of the ABRs during the steady states

Parameters	Experiments					
	3C-OLR4	6C-OLR4	8C-OLR4	8C-OLR8	8C-OLR12	8C-OLR16
OLR (g COD/l-d)	4	4	4	8	12	16
COD removal efficiency (%)	74 + 0.9	78 + 0.4	83 + 0.8	96 + 0.6	88 + 1.7	System failed
Influent pH	8.2 + 0.04	8.1 + 0.25	8.1 + 0.25	8.3 + 0.2	8.3 + 0.1	8.5 + 0.14
Effluent pH	7.9 + 0.2	7.9 + 0.1	7.9 + 0.2	8.4 + 0.1	8.1 + 0.1	7.2 + 0.26
Influent alkalinity (mg/l as $CaCO_3$)	2220 + 51	2040 + 105	2040 + 105	2148 + 210	1963 + 128	2606 + 101
Effluent alkalinity (mg/l as $CaCO_3$)	2206 + 161	1948 + 61	2048 + 61	2407 + 67	2472 + 107	2590 + 61
Effluent VFA (mg/l as $CaCO_3$)	390 + 56	333 + 93	353 + 96	57 + 5.8	552 + 84	1683 + 230
VFA:alkalinity	0.2	0.17	0.2	0.2	0.02	0.2



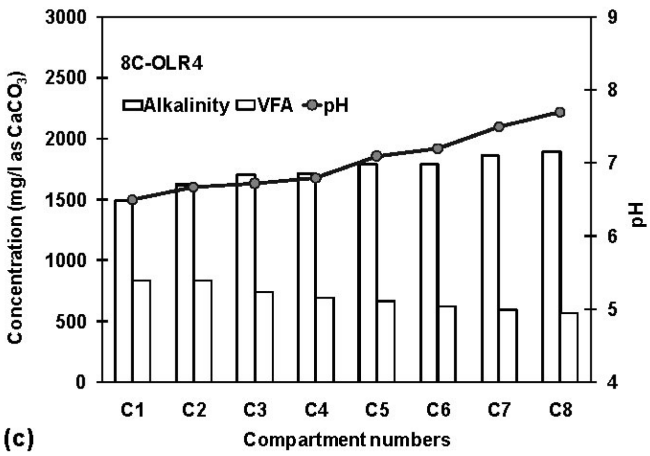


Fig. 3. pH, alkalinity and VFA in supernatant of each compartment during steady-states of the experiments. (a) 3C-OLR4; (b) 6C-OLR4; (c) 8C-OLR4.

experiments were 0.2, 0.17, and 0.2, respectively (Table 1). Obviously, those VFA:alkalinity ratios were maintained below the recommended value of 0.4, which showed that system had abundant buffering capacity [15].

Fig. 3 shows the supernatant pH, alkalinity and VFA in each compartment during steady state. The observed pH increased lengthwise through the reactor in contrast with VFA concentration that decreased longitudinally throughout the reactor. This verified the assumptions of microbial phase separation that occurred in the ABR [12] where the front of the reactor acts like an acidogenesis phase and the rear performs as the methanogenesis phase. Seemingly, in the front compartment, acidogenic bacteria utilized substrate and converted into intermediate products, such as VFA, resulting in higher VFA accumulation. Subsequently, methanogenic bacteria (the predomainnant organism group in the rear compartments) converted these VFA to methane gas, resulting in lengthwise decreasing VFA through the reactor [16].

However, the acidogenesis phase in the front compartments of reactors used in this study could not be clearly proclaimed because pH values in those front compartments were not lower than 6.5, the upper range of favourable pH for acidogenesis (5.5–6.5). Moreover, pH values in the rear compartments of all reactors were in the range of 7.1–7.7, which was adequate for a methanogenesis environment. However, phase separation was not obvious in the 3C-OLR4 experiment: pH values in the first to third compartment were 6.8, 6.9 and 7.1, respectively. In contrast with the experiments of 6C-OLR4 and 8C-OLR4, pH values in each compartment were in the range of 6.8–7.5 and 6.5–7.7, respectively. It appears that more compartments in a reactor could induce the proper environment for two phases (acidogenic and methanogenic) anaerobic operation. Interestingly, in the eight-compartment ABR, phase separation was more evident and pH in the last compartment was as high as 7.7, whereas the pH value in the last compartment of the three-compartment ABR was only 7.1, despite the fact that all ABRs were fed with the same OLR and their COD removal efficiencies were 74%, 78% and 83% for the three-, six- and eight-compartment ABRs, respectively. It was noticed that the buffering requirement for the ABR with more compartments could possibly be reduced.

3.2. *Effect of organic loading rates*

In this part, the eight-compartment ABRs are mainly considered; therefore, some results of the experiment 8C-OLR4 discussed above are included for comparison. High COD removal efficiencies of 96% and 88% (Table 1) were achieved though the organic loading rate increased to 8 and 12 g COD/l-d. For the experiment 8C-OLR16, a low COD removal efficiency (40%) was related to high biomass loss from the system; therefore, it could not maintain stability and eventually failed.

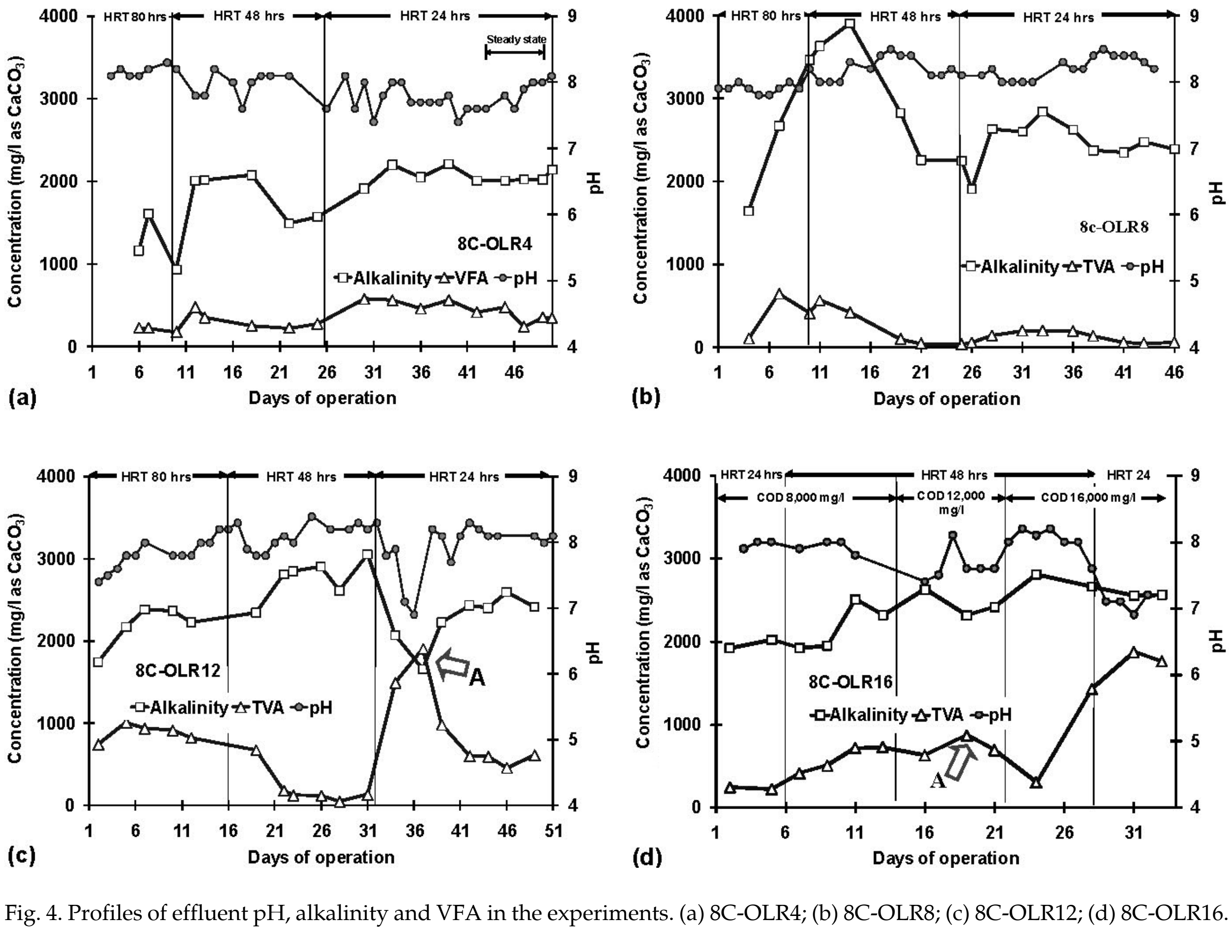
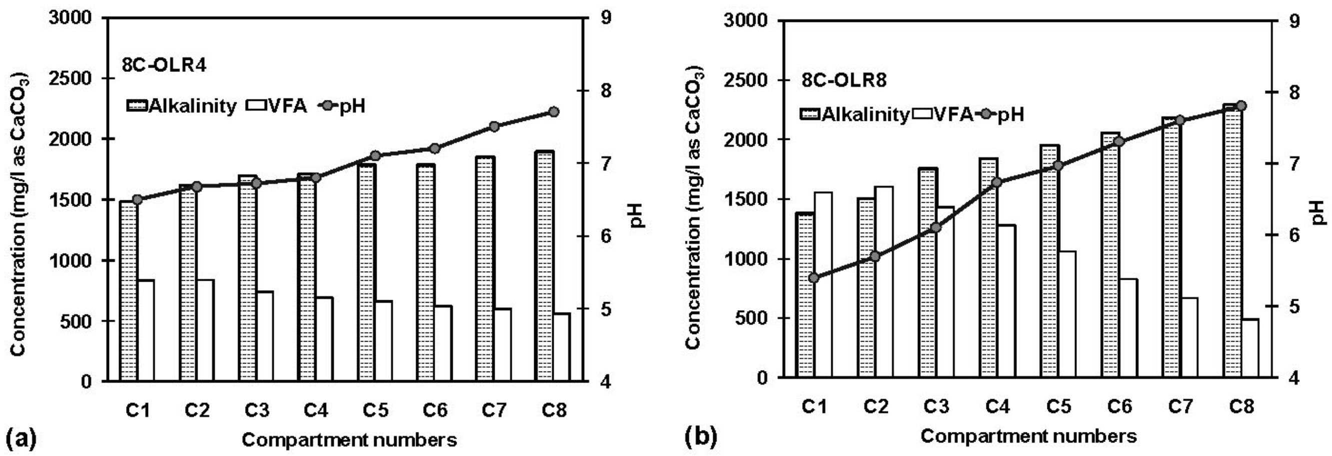


Fig. 4. Profiles of effluent pH, alkalinity and VFA in the experiments. (a) 8C-OLR4; (b) 8C-OLR8; (c) 8C-OLR12; (d) 8C-OLR16.

Fig. 4 exhibits profiles of effluent pH values, alkalinity, and VFA concentrations from the experiments 8C-OLR4, 8C-OLR8, 8C-OLR12 and 8C-OLR16. The same influent alkalinity of 2000 mg/l as $CaCO_3$ was applied to these experiments. It appeared that effluent pH values and alkalinity concentrations throughout the operating period were almost constant. The average effluent pH values of 8C-OLR4, 8C-OLR8, and 8C-OLR12 experiments at steady state were still around 8.0, while effluent VFA:alkalinity ratios were always lower than 0.4. Surprisingly, alkalinity concentrations gradually increased during the first 15 days of operation in the 8C-OLR8 experiment (almost reached 4,000 mg/l as $CaCO_3$) for an unknown reason. However, it gradually decreased and was almost constant around 2,400 mg/l as $CaCO_3$ until steady state (Fig. 4b).

In this experimental part, sodium bicarbonate ($NaHCO_3$) was added into the feed to supply about 2,000 mg/l as $CaCO_3$ of alkalinity for the system. Apparently, the effluent pH and alkalinity in all ABRs, except in the experiment of 8C-OLR16, were slightly higher than 8.0 and 2,000 mg/l as $CaCO_3$, respectively, while the VFA: alkalinity ratios were quite low (about 0.2). As previously, this signifies that less buffering could be required in an eight-compartment ABR though OLR increased up to 12 g COD/l-d. Therefore, a smaller amount of $NaHCO_3$ may be adequate for maintaining the ABR buffering capacity, resulting in chemical cost reduction.

For the experiment of 8C-OLR8, the effluent VFA concentrations during the first 15 days were about 500–600 mg/l as $CaCO_3$, and then drastically decreased to approximately 50 mg/l as $CaCO_3$ during the operating HRT of 48 h. When operating with an OLR of 8 g COD/l-d (HRT reduced to 24 h), VFA concentration gradually increased to about 200 mg/l as $CaCO_3$ (Fig. 4b). Likewise, VFA concentrations in the 8C-OLR12 experiment during the early period of operation was quite high, about 1,000 mg/l as $CaCO_3$; then they decreased to about 100 mg/l as $CaCO_3$ during the operation with HRT of 48 h. However, at a steady state of 24 h HRT operation, the VFA concentrations of 8C-OLR12 were about 600 mg/l as $CaCO_3$. In this experiment, there was an abrupt change in VFA, pH and alkalinity as shown by "A" pointing in Fig. 4c due to an adverse effect on ABR performance caused by changing room temperatures. In the case of the 8C-OLR16 experiment, VFA concentrations increased from about 200 mg/l as $CaCO_3$ from start-up period to



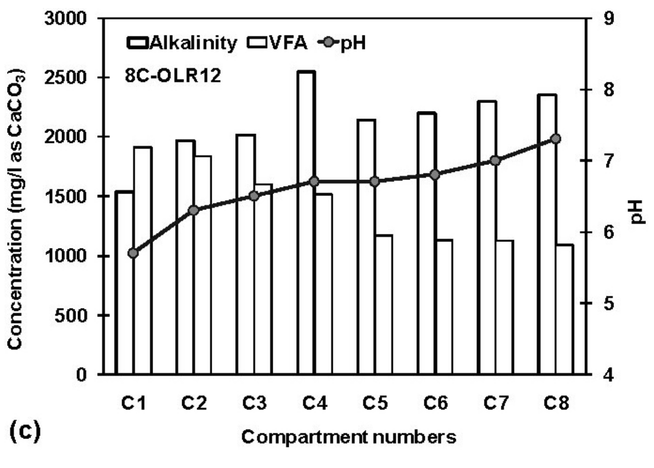


Fig. 5. pH, alkalinity and VFA in supernatant of each compartment during steady state of the experiments. (a) 8C-OLR4; (b) 8C-OLR8; (c) 8C-OLR12.

about 1800 mg/l as $CaCO_3$ during the operation at OLR of 16 g COD/l-d (HRT of 24 h). This increased VFA concentration affected a reduction of COD removal efficiencies, which indicated the system imbalance and failure.

During steady state, supernatant from each compartment was investigated and the results are shown in Fig. 5. Steady-state results of the 8C-OLR16 experiment are not shown in this figure because of overloading failure. As previously shown, pH and alkalinity monitored in all eight-compartment ABRs increased longitudinally from the inlet through the outlet, which was in contrast with VFA concentrations. The pH values in the front compartments presented more of the acidogenesis phase when the OLR increased. For instance, pH values of 6.5, 5.4 and 5.7 were found in the first compartment of the experiments 8C-OLR4, 8C-OLR8, and 8C-OLR12, respectively. In the same way, increase of the OLR affected the last compartment pH, i.e., those pH values were 7.7, 7.8 and 7.3 in the experiments of 8C-OLR4, 8C-OLR8, and 8C-OLR12, respectively.

4. Conclusions

The findings of this study show that the alkalinity requirement in an anaerobic operation could be reduced when ABR was applied, especially ABRs consisting of more compartments. In this study, with an OLR of 4 g COD/l-d, the eight-compartment ABR treating carbohydrate–protein wastewater required less than 2,000 mg/l as $CaCO_3$. Therefore, a smaller amount of chemicals supplying alkalinity may be adequate to maintain the stability of the ABR process and cost savings on the chemicals can be achieved.

Acknowledgement

This study was partly supported financially by a grant from the Post-Graduate Education, Training and Research Program in Environmental Science, Technology and Management under the Higher Education Development Project of the Commission on Higher Education, Ministry of Education. The authors would also like to thank the Department of Sanitary Engineering, Faculty of Public Health, Mahidol University, for remarkable assistance and support.

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