Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22906

126 (2018) 60–66
September

Performance of a UASB reactor for low-strength wastewater treatment under different hydraulic loading rates

Xin Chao Ma[a], Tae Woo Yi[b], Bong Su Lim[a,*]

[a]*Department of Environmental Engineering, Daejeon University, Daejeon 34520, Korea; emails: bslim@dju.kr (B.S. Lim), xinchao-ma@outlook.com (X.C. Ma)*
[b]*National Institute of Ecology, 1210 Geumgang-ro Maseo-Myeon Seocheon-gun, Chungnam 33657, Korea; email: ytw117@nie.re.kr*

Received 5 January 2018; Accepted 3 August 2018

ABSTRACT

Upflow anaerobic sludge blanket (UASB) reactors have been used widely to treat high-strength wastewater. In this study, UASB reactor was operated in order to determine organic matter removal and methane production from low-strength synthetic and real wastewater. Also the optimum value of several parameters, specifically organic loading rates (OLRs) and hydraulic retention time (HRT), were investigated. While feeding synthetic wastewater, removal efficiencies of soluble chemical oxygen demand (SCOD) were around 97%, and methane production was around 0.2 L CH_4/g SCOD removed. Its methane content was 73% at HRT of 6.1 h (OLR of 1.8 kg chemical oxygen demand [COD]/m^3 d). With real domestic wastewater, removal efficiencies of SCOD were found to be 62%. Biogas production was 0.5 L/d, of which the methane content was 55%. At HRT of 5.7 h, methane gas yield was 0.19 L CH_4/g SCOD removed, indicating that optimum HRT is around 6 h in synthetic and real wastewater condition. In both conditions, biogas and methane production decreased with the decrease of HRT. At all HRT conditions, the decrease of pH was not observed; however, washout of volatile fatty acid increased with decrease of HRT. Compared with UASB fed with high-strength wastewater, it was found that HRT was most important parameter for the operation of UASB fed with low-strength wastewater. In addition, utilization of COD for biogas production and for cell production accounted for 68% and 14% at HRT of 6.1 h for synthetic wastewater, respectively.

Keywords: Hydraulic retention time; Low-strength wastewater; Methane gas yield; Upflow anaerobic sludge blanket; Organic loading rate

1. Introduction

The upflow anaerobic sludge blanket (UASB) process is simple in operation, low in energy consumption, and low in operating cost [1,2]. Because of low-sludge yield, good stability, easy to dehydration, and other advantages, the use of UASB in urban sewage treatment field should be vigorously promoted [3]. Recently, UASB has been investigated and tried to apply for the removal of domestic wastewater which has generally low concentration of chemical oxygen demand (COD) at ambient temperature [4] and relatively high concentration of suspended solids with low-specific methane yield [5]. In general, methanogenesis is considered as a rate-limiting step, especially at low-temperature conditions [6]. In high-strength wastewater condition, an important controlling factor is to control pH and to increase the rate of methanogenic process. It is clear that buffering is needed initially for maintaining the pH. However, in low-strength wastewater condition, UASB operation parameters are different at operational point of view. For example, in low-strength wastewater condition, pH drop and accumulation of volatile fatty acid (VFA) are negligible. Most important factor is to make methanogenic

---

[*] Corresponding author.

1944-3994/1944-3986

microbes effectively utilize VFA. Previous study also showed that the methanogenic activity was low at lower organic loading rate (OLR) conditions [6], indicating that low level of VFA production caused lower methanogenic activity and change of methanogenic community structure [7]. Due to the reason, major controlling factor in low-strength wastewater could be quite different with UASB fed with high strength wastewater. Up to date, most of anaerobic studies have focused on optimization of anaerobic process in high-strength wastewater condition [8,9,10]. In this study, lab-scale UASB was used to study the treatment of low-strength wastewater such as domestic sewage. Through this study, the process of treating domestic sewage could be proposed, which can provide the operating parameters and control conditions that is necessary for the application of UASB treatment technology. In this study, the feasibility of UASB treatment for the low-strength wastewater was verified.

The objective of this research was carried out to determine the optimum operating conditions of a UASB during low-strength wastewater treatment. The optimum parameters such as hydraulic retention time (HRT), OLR, biogas production, etc., will be suggested to design UASB.

2. Materials and methods

2.1. Experimental equipment

The layout of the UASB reactor, which had a working volume of 4.2 L, is shown in Fig. 1. The reactor was constructed from acrylic plastic with 8 cm internal diameter and 138 cm height. A gas–solid–liquid three-phase separator was installed on the top portion of the column.

The influent to feed the reactor was synthetic wastewater with a total chemical oxygen demand (TCOD) of 500 mg/L, total nitrogen (TN) of 40 mg/L, total phosphorus (TP) of 4 mg/L. A total of 1 mm/L of trace element solution was added to the above wastewater. Compositions of the buffer and trace elements used were shown in Table 1. At the last, the raw sewage was used as the influent and compared with the synthetic wastewater during the experiment process. The comparison of synthetic wastewater and raw sewage used as the influent as shown in Table 2.

2.2. Reactor operation and experiment method

The reactor was operated at HRT of 13.4, 6.1, 2.6, and 1.7 h in the incubator. The reactor was kept at 35°C during

Table 1
Compositions of the buffer and trace elements

Name	Concentration (g/L)	Name	Concentration (g/L)
$NaHCO_3$	0.5	$CoCl_2{\cdot}6H_2O$	0.3
$ZnCl_2$	0.2	$NiCl_2{\cdot}6H_2O$	0.19
$MgCl_2{\cdot}2H_2O$	0.2	$FeCl_3{\cdot}6H_2O$	5.95
$CaCl_2{\cdot}2H_2O$	0.1	$MnCl_2{\cdot}4H_2O$	0.99

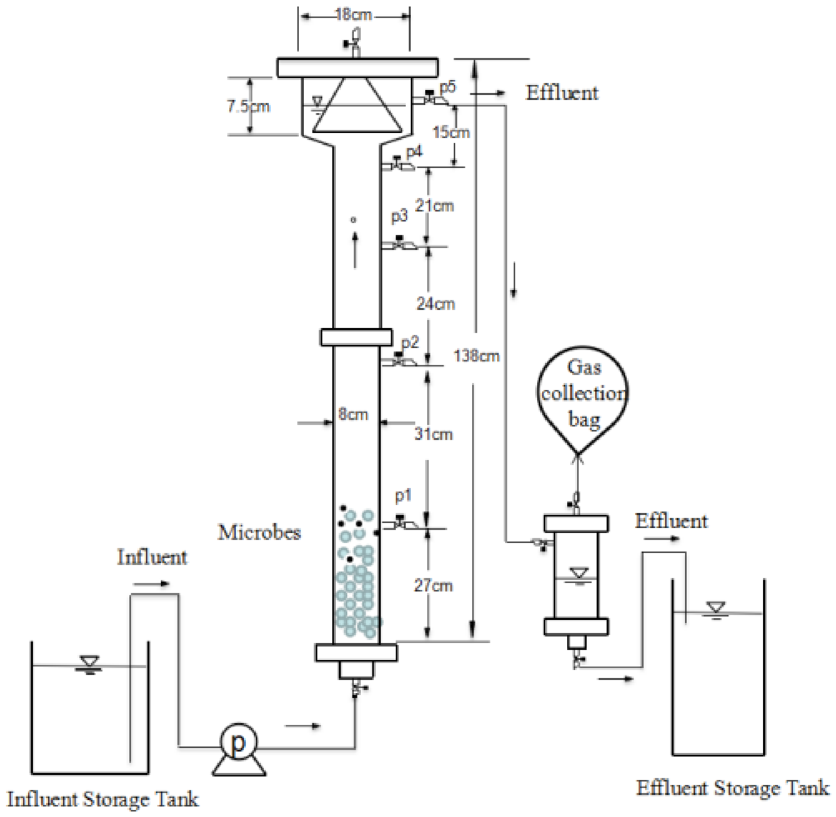

Fig. 1. Schematic diagram of the UASB reactor.

the study period. In order to keep the reactor at 35°C, incubator was made at the size of 185 cm height, 168 cm length, 30 cm width, and there are four heating equipment in its interior, by adjusting the external controller to regulate the temperature of the incubator.

Water quality analysis was performed according to Standard Methods [11]. During the period of operation, the pH level of the reactor, true bicarbonate alkalinity, total alkalinity (TA), TCOD, and soluble chemical oxygen demand (SCOD) was a daily survey to symbolize the stability evaluation of reactor [12]. In order to measure volatile acids (VAs), 500 mL samples were taken from the effluent. Total VFAs were measured using a distillation method [12]. The sample was centrifuged for 5 min. And then, 100 mL of supernatant was placed in a 500 mL distillation flask. Next, 100 mL of distilled water was added to the solution along with 0.3 g of boiling stones and 5 mL of sulfuric acid (95.9%), and then 150 mL of solution was placed in a 250 mL graduated cylinder. The solution was titrated with 0.1N NaOH.

2.3. MGY and substrate removal rate

The methane gas yield (MGY) was calculated from the values of methane production rates and COD removed, and the volumetric rate of substrate uptake (TCOD) or substrate removal rate can be obtained from Eq. (1):

$$-(\gamma_{\mathrm{COD}}) = (\mathrm{COD}_0 - \mathrm{COD})/\mathrm{HRT} \tag{1}$$

where COD_0 is TCOD concentration in influent; COD is TCOD concentration in effluent; and HRT is the hydraulic retention time. The minus sign in $-\gamma_{\mathrm{COD}}$ has physical meaning, and it indicates that COD concentration reduced when increasing the HRT.

2.4. COD mass balance

When the $\mathrm{COD}_{\mathrm{influent}}$ equals the COD output such as effluent and biogas, it shows that the reactor is functioning properly as an indicator, Thus, COD mass balance can be used to evaluate the performance of UASB reactor. COD mass balance was calculated using Eq. (2). $\mathrm{COD}_{\mathrm{biogas}}$ is referred to as $\mathrm{COD}_{\mathrm{methane}}$ since a system of CO_2 absorption was incorporated in the experimental set up since methane was assumed to be the major gas produced. $\mathrm{COD}_{\mathrm{influent}}$ and $\mathrm{COD}_{\mathrm{effluent}}$ were directly measured, and sludge concentration was periodically monitored by directly measuring sludge from UASB reactor. Others were considered as solid settled in sedimentation zone.

Table 2
Comparisons of synthetic wastewater and raw sewage used as the influent

Synthetic wastewater		Raw sewage	
Parameter	Influent (mg/L)	Parameter	Influent (mg/L)
TCODcr	500	TCODcr	366
SCODcr	450	SCODcr	136
TN	40	TN	34
TP	4	TP	2.4

$$\mathrm{COD}_{\mathrm{influent}} = \mathrm{COD}_{\mathrm{effluent}} + \mathrm{COD}_{\mathrm{biogas}} + \mathrm{COD}_{\mathrm{sludge}} \text{ (as growth of microbes)} + \text{others} \tag{2}$$

3. Results and discussion

3.1. Organic matter removal

The concentration of the influent was kept constant at 500 mg COD/L (as TCOD) during the operation of UASB fed with synthetic wastewater and decrease of HRT resulted in an increase in OLR. At the end of operating time, the HRT was 1.7 h, which resulted in OLR of 6.4 kg/m^3·d. The operating length of each different HRT was chosen based on TCOD and SCOD removal performance. When the synthetic wastewater was fed as influent at HRT of 6.1 h, the SCOD removal efficiency achieved was 97%; and when the raw sewage was used as influent, the SCOD removal efficiency was about 62%. At HRT of 1.7 h, SCOD removal efficiency was sharply reduced to 75% and caused poor water quality of effluent. Compared with the UASB fed with synthetic wastewater, TCOD removal efficiency was reduced to 80% at HRT of 5.7 h in UASB fed with real domestic wastewater (RDW) due to non-biodegradable organic matters which could not be biodegraded by microbes. Fig. 2 shows the average concentration of RDW was 336 mg/L, and the concentration of non-biodegradable chemical oxygen demand was about 50 mg/L which accounts for about 15% in TCOD.

Fig. 3 also shows the variation of COD removal along with OLR. In order to remove more than 90% of the SCOD of synthetic wastewater, OLR of UASB reactor should be less than 3.4 kg/m^3·d and in order to remove more than 80% of SCOD, OLR of UASB reactor should be less than 5.5 kg/m^3·d. Compared with the SCOD, TCOD removal efficiency was reduced by about 5%. When OLR was 0.5 kg/m^3·d, SCOD and TCOD removal efficiency of RDW was about 60% and 80%, respectively. As a result, the lower COD removal efficiencies were a result of an increase in the VFA concentration in effluent at short HRT. Methanogenic step is known as the rate-limiting in anaerobic process. When HRT decreased from 6.1 of 1.7 h, methane production and TCOD removal efficiencies decreased gradually. It indicates that HRT less than 6 h is not long enough to allow methanogenesis converting VFA to methane. In addition, the removal efficiencies of COD during the period being fed with RDW were lower than that of UASB fed with synthetic wastewater, indicating lower removal efficiencies was caused by non-biodegradable COD.

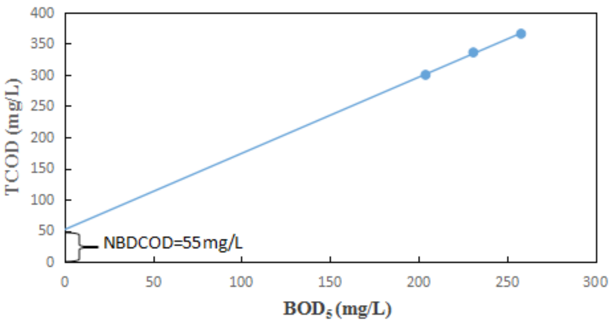

Fig. 2. Relationship of TCOD and BOD in raw sewage.

It means that washout of VFA increase with the increase of ORL, indicating optimum OLR is 2 kg COD/m^3·d.

3.2. Variations of alkalinity and VAs

Fig. 4 shows the variations of alkalinity and VAs in the influent and effluent during the operation period. The alkalinity of influent and effluent was very similar to each other at all HRT conditions. TA concentration in influent was 500–600 mg/L (as $CaCO_3$) and in effluent 34–38 mg/L. In general anaerobic digestion, TA is operated in the range of 1,000–5,000 mg/L for sewage; however, TA concentration is lower than general anaerobic digestion in this study. Possibly river water is mainly used as source of water supply in South Korea. Due to the reason, alkalinity level in domestic wastewater is lower compared with other countries. VA concentration increased with the decrease of HRT, there was no large change when the HRT was changed from 13.4 to 2.6 h. VA concentrations at HRT of 13.4 and 2.6 h were 38 and 35 mg/L, respectively. However, when the HRT was 1.7 h (OLR = 6.4 kg SCOD/m^3·d), the VA concentration was 122 mg/L, and it was 1.4 times than the VA of influent. This is because increase of OLR caused the increase of VFA production.

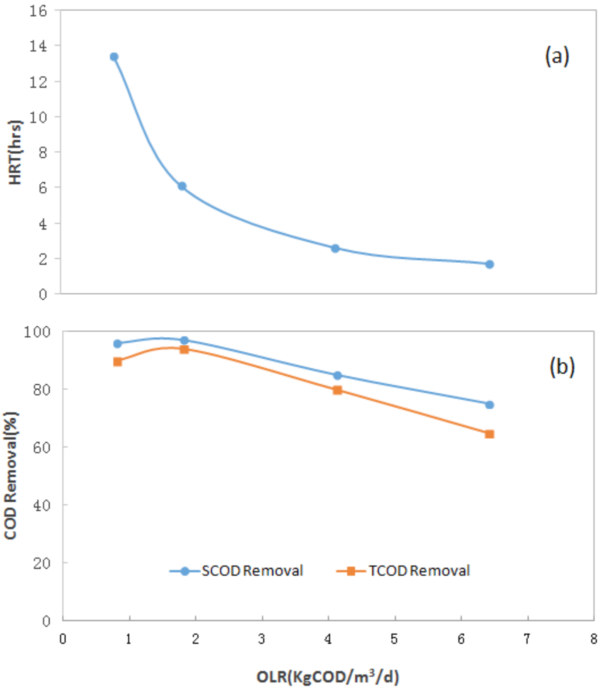

Fig. 3. Relationship of organic loading rate and COD removal efficiency in UASB reactor.

Fig. 5 shows the variation of pH by time and pH of the influent and effluent was about 7.0. The pH only varied from 6.9 to 7.2 during the operation period. However, pH was low at the beginning of the operation time. pH in the effluent was stable, and there was no acidification in the UASB reactor.

3.3. Biogas production

For the design and operation of anaerobic processes, determination of methanogenic activity is important and its activity in the biomass relies mostly on wastewater characteristics, environmental, and operational conditions. Using MGY, it would be possible to determine the potential loading capacity of the anaerobic treatment systems, allowing appropriate OLRs to be applied. The MGY depends on the feature of the granular sludge, type of the substrate, and environmental conditions such as temperature and HRT [13,14]. Also, a change in MGY indicates an inhibition or an accumulation of slow degradable or even non-biodegradable organic substrate from influent. Biogas yield according to the OLR was summarized in Table 3.

MGY, as shown in Fig. 6, was the amount of gas which was measured produced per gram of the removed COD; it was converted to standard state. In the UASB operation fed with synthetic wastewater, OLR was 0.8 kg COD/m^{3}d (HRT = 13.4 h), and the amount of methane gas was 0.78 L/d. MGY decreased as the OLR increased, and the amount of methane

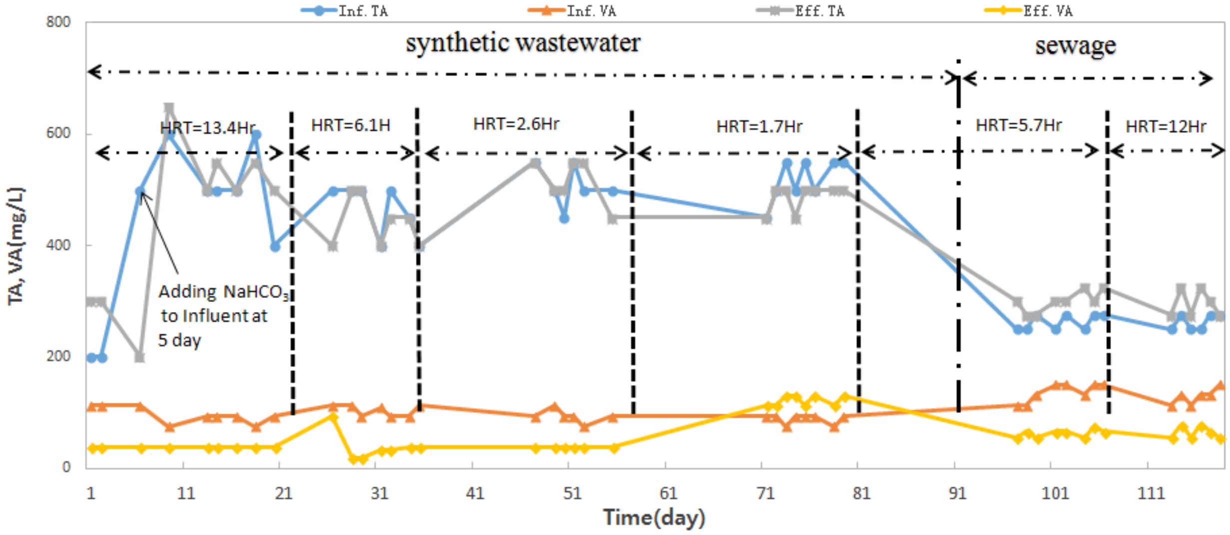

Fig. 4. Variation of TA and VA during the operation period.

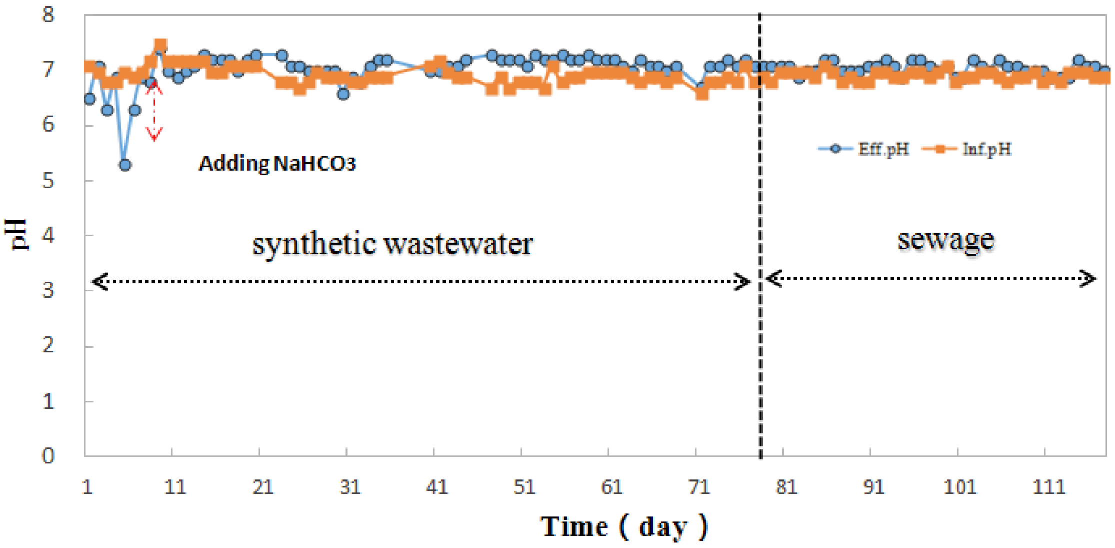

Fig. 5. Variation of pH in effluent during the UASB operation period.

Table 3
Biogas yield according to the organic loading rate

	HRT (h)	OLR (kg/m^3 d)	Biogas production (L/d)	Methane production (L/d)	Methane contents (%)	Methane production (LCH$_4$/gCOD removed)	COD removal efficiency (%)	Methane production (v/v d)	$-\gamma_{COD}$
Synthetic wastewater	13.4	0.8	0.78	0.48	62	0.132	37.7	0.18	14.1
	6.1	1.8	2.2	1.61	73	0.200	57.1	0.52	46.8
	2.6	4.1	3.8	2.76	73	0.165	47.1	0.90	90.6
	1.7	6.4	4.35	2.78	64	0.124	35.4	1.03	104.1
Real domestic sewage	12	0.3	0.23	0.10	45	0.128	36.5	0.05	11.1
	5.7	0.5	0.5	0.28	55	0.188	53.7	0.12	34.5

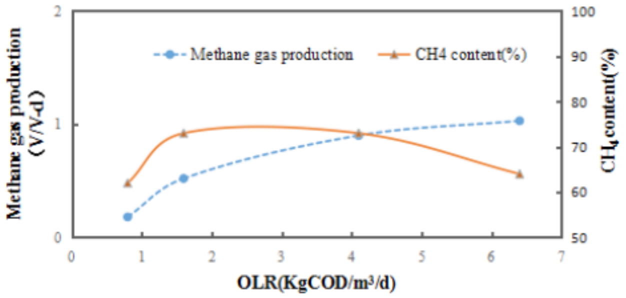

Fig. 6. Variation of methane gas production and methane content according to organic loading rate.

gas at HRT of 6.1 h increased to 0.20 L CH$_4$/g SCOD removed. It indicates that when HRT increased because washout of VFA methanogenic activity decreased. Previous study also reported that the methanogenic activity decreased with the decrease of organic loading, indicating that low level of VFA production caused lower methanogenic activity and reduced the stability and diversity in methanogens [7]. In UASB fed with RDW, the MGY at HRT of 5.7 h was 0.19 L CH$_4$/g COD removed. The lower methane production in UASB fed with RDW was possibly caused by two main reasons. One was that RDW contains nitrate even though its concentration is low. Nitrate as electron acceptor consumed COD. In general, the reduction of 1g nitrate consumes 3.74 g COD. In this experiment, nitrate concentrations in influent ranged from 2 to 3.5 mg/L (average 3 mg/L). 2–3.5 mg/L of NO_3^- is contained in domestic wastewater. A theoretical maximum of 12 mg/L COD removed could be attributed to this phenomenon.

It indicates that the lower methane production in UASB fed with RDW was explained by COD or VFA loss caused by nitrate reduction by denitrifying bacteria. The other reason was due to the different substrate characteristics or biodegradability between synthetic and real wastewaters. Shown in Table 3, substrate removal rate clearly shows that substrate removal rate during feeding RDW (HRT of 12 and 5.7 h) was lower than that during feeding synthetic wastewater, indicating substrate contained in RDW was not easily biodegradable. And different methane production between synthetic and real wastewater is possibly due to substrate characteristics. Also Moe and Tyrrell [15] showed methane production rate depends on the type of carbohydrates because carbohydrate is a main source of energy for bacteria. Due to the reason, carbohydrate composition affects dominant bacteria in UASB reactor and its removal efficiency.

Fig. 6 shows the variations of methane content and the biogas production according to the OLR. Biogas increased as OLR increases. For synthetic wastewater, OLR was 6.4 kg COD/m^3·d. The methane content was 64% and MGY was decreased to 0.12 L CH_4/g COD removed. TCOD removal efficiency was decreased to 67%. Compared with the other study using high-strength wastewater at 35°C, the methane content had the increasing trend according to the increase of OLR [16]. For raw sewage, under the condition that OLR was 0.5 kg COD/m^3·d, the methane content was 55%, which was lower than the methane content of synthetic wastewater under the condition that OLR was 1.8 kg COD/m^3·d. The possible reason is that substrate in synthetic wastewater is almost biodegradable; whereas real wastewater contains some non-biodegradable organic matter. Methane gas production was the methane gas volume that produced per unit volume of UASB reactor in a day.

In addition, HRT is an important parameter for methane production because it determines the amount of organic substrate to be fed into anaerobic reactor and the production level of volatile solids in digester. Currently, most of anaerobic reactors in wastewater treatment plant are operated with HRT of 15–30 d to stabilize waste sludge. In case of high-strength wastewater condition, shorter HRT leads to the decline in pH because of high-rate VFA production. Thus, MGY decreased. In this experiment, biogas and methane production decreased with decrease of HRT. Although HRT decreased in low-strength wastewater condition, the level of pH was not changed due to low level of VFA production. However, VFA washout occurs at short HRT, and thus it caused the reduction of MGY. As a result, HRT needs to be long enough to convert VFA produced to methane because methanogenesis are usually the rate-limiting steps during digestion of organic substrate. The results in this study indicate that HRT of 6 h is needed to prevent VFA washout.

3.4. Mass balance in the UASB reactor

Fig. 7 shows that at the HRT of 6.1 h, there was about 68% of the COD entered the biogas gas, 6% of the COD entered effluent, and about 14% of the COD entered the microbes. The others COD was settled in sedimentation zone at upper in UASB reactor for 12%. In the other study, the removal of COD in the form of methane accounted for 30%, the growth of microbes accounted for 27%, the effluent COD accounted for 43% in similar operating conditions with this study [17,4]. Compared with the other study, in the form of methane removed was larger, and the growth of microbes was smaller at the almost same HRT, this is because the synthetic wastewater was used as the influent; however, the influent was raw sewage in the study, for there were many non-biodegradable organic matters in it.

4. Conclusions

In this study, performance of a UASB fed with synthetic and RDW was studied at the different operational OLRs. During feeding synthetic wastewater, it was found that TCOD removal efficiency was about 95% under the condition that OLR was 2 kg COD/m^3·d at HRT of 6 h. In RDW condition, TCOD removal efficiency was about 80% in which of the situations of OLR was 1.4 kg COD/m^3·d at HRT of 5.7 h. Increase in the biogas production was observed as the HRT was shortened, and showed methane production was about 0.2 L CH_4/g COD removed at HRT 6.1 h for the synthetic wastewater and for RDW, methane production was about 0.19 L CH_4/g COD removed at HRT of 5.7 h. The methane content of the biogas produced during the operation period was 62%–73% for the synthetic wastewater and was 45%–55% for the raw sewage. When HRT decreased, the level of pH was not changed but washout of VFA occurred. Compared with UASB studies fed with high-strength wastewater, in UASB fed with low-strength wastewater it was found that HRT is most important design parameter. Through the mass balance of UASB process, the removal of COD in the form of methane accounted for 68%, the growth of microbes accounted for 14%, and the effluent COD accounted for 6% at HRT of 6.1 h for the synthetic wastewater.

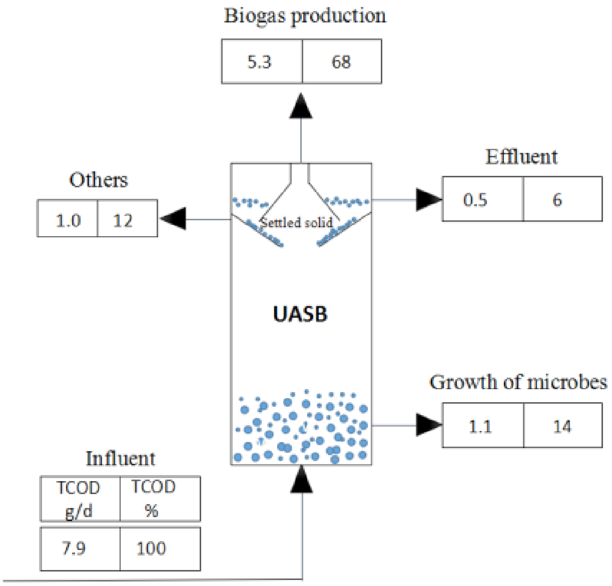

Fig. 7. COD mass balance in the UASB at HRT of 6.1 h.

References

[1] K.S. Min, Y.H. Ahn, S.M. Park, Dilute wastewater treatment using an upflow anaerobic sludge bed reactor, J. Korean Soc. Environ. Eng., 24 (2002) 1379–1389.

[2] K.S. Singh, H. Harada, T. Viraraghavan, Low-strength wastewater treatment by a UASB Reactor, Bioresour. Technol., 55 (1996) 187–194.

[3] R.Z. Gaur, A.A. Khan, B. Lew, V. Diamantis, A.A. Kazmi, Performance of full-scale UASB reactors treating low or medium strength municipal wastewater, Environ. Proc., 4 (2017) 137–146.

[4] D. Khanh, L. Quan, W. Zhang, D. Hira, K. Furukawa, Effect of temperature on low-strength wastewater treatment by UASB reactor using poly(vinylalcohol)-gel carrier, Bioresour. Technol., 102 (2011) 11147–11154.

[5] C. Ratanatamskul, T. Siritiewsri, A compact on-site UASB–EGSB system for organic and suspended solid digestion and biogas recovery from department store wastewater, Int. Biodeter. Biodegrad., 102 (2015) 24–30.

[6] B. Lew, I. Lustig, M. Beliaski, S. Tarre, M. Green, An integrated UASB-sludge digester for raw domestic wastewater treatment in temperate climates, Bioresour. Technol., 102 (2011) 4921–4924.
[7] A.A. Khan, I. Mehrotra, A.A. Kazmi, Sludge profiling at varied organic loading and performance evaluation of UASB reactor treating sewage, Biosyst. Eng., 131 (2015) 32–40.
[8] I.H. Franke-Whittle, A. Walter, C. Ebner, H. Insam, Investigation into the effect of high concentration of volatile fatty acids in anaerobic digestion on methanogenic communities, Waste Manage., 34 (2014) 2080–2089.
[9] K. Braber, B.V. Novem, Anaerobic digestion of municipal solid waste: a modern waste disposal option on the verge of breakthrough, Bioresour. Technol., 9 (1995) 365–376.
[10] L.G. Seluy, M.A. Isla, A process to treat high-strength brewery wastewater via ethanol recovery and vinasse fermentation, Ind. Eng. Chem. Res., 53 (2014) 17043−17050.
[11] APHA, AWWA, and WEF, Standard Methods for the Examination of Water and Wastewater, 21st ed., Washington D.C., USA, 2005.
[12] R. DiLallo, O.E. Albertson, Volatile acids by direct titration, J. Water Pollut. Control Fed., 33 (1961) 356–365.
[13] M. Jawed, V. Tare, Microbial composition assessment of anaerobic biomass through methanogenic activity tests, Water SA, 25 (1999) 345–350.
[14] M. Soto, R. Méndez, J.M. Lema, Methanogenic and non-methanogenic activity tests theoretical basis and experimental setup, Water Resour., 27 (1993) 1361–1376.
[15] P.W. Moe, H.F. Tyrrell, Methane production in dairy cows, J. Diary Sci., 62 (1979) 1583–1586.
[16] B.S. Lim, A Comparative Study on the Basic Design Parameters for Aerobic and Anaerobic Biofilm Processes, PhD Thesis, Korea University, 1987.
[17] X.L. Guo, Y.Y. Hu, UASB treatment of extremely low concentration domestic sewage, J. South China Univ. Technol., 30 (2002) 66–71.