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Digestion of thermally hydrolyzed sewage sludge by anaerobic sequencing batch reactor

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ABSTRACT

Laboratory experiments were conducted to investigate the performance of an anaerobic sequencing batch reactor (ASBR) for the digestion of thermally hydrolyzed sewage sludge. Both mesophilic ASBR and continuous-flow stirred tank reactors (CSTR) were evaluated with an equivalent loading rate of 2.71 kg COD/m^3 day at 20-day hydraulic retention time (HRT) and 5.42 kg COD/m^3 day at 10-day HRT. The average total chemical oxygen demand (TCOD) removals of the ASBR at the 20-day and 10-day HRT were 67.71% and 61.66%, respectively. These were 12.38% and 27.92% higher than those obtained by CSTR. As a result, the average daily gas production of ASBR was 15% higher than that of the CSTR at 20-day HRT, and 31% higher than that of the CSTR at 10-day HRT. Solids in thermally hydrolyzed sludge accumulated within ASBR were able to reach a high steady state with solid content of 65–80 g/L. This resulted in a relatively high solid retention time (SRT) of 34–40 days in the ASBR at 10-day HRT. However, too much solid accumulation resulted in the unsteadiness of the ASBR, making regular discharge of digested sludge from the bottom of the ASBR necessary to keep the reactor stable. The evolution of the gas production, soluble chemical oxygen demand (SCOD) and volatile fatty acids (VFAs) in an operation cycle of ASBR also showed that the ASBR was steady and feasible for the treatment of thermally hydrolyzed sludge.

1. Introduction

The treatment and disposal of sewage sludge are both an expensive and environmentally sensitive problem. Anaerobic digestion is a conventional biotreatment method for treating sewage sludge as this method can stabilize sludge, kill pathogens, and reduce solids. However, conventional anaerobic digestion is inefficient due to low volatile solid (VS) removal rate (30–40%) and long hydraulic retention time (HRT) of 20 days. The anaerobic digestion process is composed of four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Of the four stages, the hydrolysis rate of sewage sludge is considered to be the rate-limiting step in the overall anaerobic digestion process [1]. Several pretreatments of sludge to increase the hydrolysis in order to enhance the VS removal rates and biogas productivity have been conducted. These include chemical treatment (using ozone, acids or alkali), thermal hydrolysis, mechanical disintegration, and ultrasonic treatment [2].

Thermal hydrolysis pretreatment first ruptures the cell wall and cell membranes of bacteria in the sewage sludge. This allows the complex organic molecules such as carbohydrates, lipids, proteins, and nucleic acids to be released from the cells and be broken down. These hydrolysates can then be utilized by extracellular enzymes produced by anaerobic microorganisms, leading to improved anaerobic digestion [3]. The efficiency of the thermal hydrolysis process prior to anaerobic digestion has prompted many to develop technology [4–9]. For instance, the Norwegian Company, Cambi, established the first full-scale plant in Hammer, Norway in 1995 [10].

Conventional digesters employed to process thermally hydrolyzed sewage sludge in previous studies were continuous-flow stirred tank reactors (CSTR). These reactors were designed and operated in a way that solids and liquids traveled through the reactor together with the same retention time, i.e. the solid retention time (SRT) equaled the HRT. This resulted in a normal HRT period to be as long as 20 days. During the past 30 years, high-rate anaerobic treatment systems (characterized by a high ratio of SRT over HRT) have become popular because of shorter HRT, smaller reactor volume, and hence, lower construction costs. However, high-rate systems have been operated mostly for the treatment of wastes with low-solid content, for example, suspended solids (SS) below 8000 mg/L for upflow anaerobic sludge blanket (UASB) [11]. Recent developments such as anaerobic sequencing batch reactor

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Nomenclature

ASBR	anaerobic sequencing batch reactor
COD	chemical oxygen demand (g/L)
CSTR	continuous-flow stirred tank reactor
HRT	hydraulic retention time (days)
SCOD	soluble chemical oxygen demand (g/L)
SRT	solid retention time (days)
SS	suspended solid (g/L)
TCOD	total chemical oxygen demand (g/L)
TKN	total Kjeldahl nitrogen (mg/L)
TS	total solid (g/L)
UASB	upflow anaerobic sludge blanket
VFAs	volatile fatty acids (mg/L)
VS	volatile solid (g/L)
VSS	volatile suspended solid (g/L)

(ASBR) have made it possible to treat high-solids waste streams with high-rate system [12,13]. The ASBR operates in a cyclic batch mode with four distinct phases per cycle. The four phases are: feeding, reacting, thickening and drawing. The thickening and drawing phases are the key steps in the ASBR operation. The thickening phase brings about an accumulation of sludge as the solids are kept within the reactor.

According to Chang et al. [14], when sewage sludge was digested in an ASBR without thermal hydrolysis pretreatment, sludge settling was difficult even after one day of thickening. Clearly, the low settleability and poor solid–liquid separation of original sewage sludge have limited the potential of the ASBR to maintain a longer SRT. In fact, thermal hydrolysis pretreatment in the temperature range between 130 and 180 °C not only improved the digestibility but has also enhanced the settleability of sewage sludge since the floc structure was irreversibly changed. In addition, the thermal process also caused the rupture of bacteria cells which allowed the cell contents to be released [15]. Hence, thermal hydrolysis would provide effective preconditioning for the ASBR.

The objective of this research is to investigate the performance of the ASBR for the digestion of thermally hydrolyzed sewage sludge.

2. Materials and methods

2.1. Anaerobic reactors

Two identical laboratory-scale anaerobic digestion systems (I and II) were used (Fig. 1). Both digestion reactors consisted of a 15 cm diameter Plexiglas cylinder which carries a volume of 3-L and a headspace of 1-L. The shaft of the mixer was covered with a tube from the top of the reactor to two thirds of the liquid depth. Six sampling ports were installed. Both reactors were attached an external heating film with a thermostatic controller. The mixing of the sludge was carried out by a mechanical agitator. The agitating frequency and intensity were controlled with a timer and a agitation controller, respectively. The biogas from the reactor was collected in a biogas collector.

2.2. Pretreatment of sludge

Raw sludge was collected from the gravity thickener of a municipal wastewater treatment plant located in Beijing, China every 3 months. Large particles were removed from the raw sludge by filtering with a no. 6 mesh sieve (sieve pore is 3.2 mm × 3.2 mm) to prevent clogging. As a batch, 9-L sludge was hydrolyzed thermally in a 10-L autoclave at 170 °C for 30 min. The hydrolyzed sewage sludge was then stored at 3 °C until use. Table 1 shows the characteristics of the raw sludge and the feed sludge (thermally hydrolyzed sewage sludge).

Table 1
Characteristics of raw sludge and feed sludge (average ± S.D.)

Parameters	Raw sludge	Thermally hydrolyzed sludge
pH	6.62 ± 0.12	6.07 ± 0.22
TS (g/L)	43.42 ± 3.47	40.42 ± 3.44
VS (g/L)	27.34 ± 2.03	24.20 ± 2.37
SS (g/L)	42.02 ± 4.56	34.36 ± 3.50
VSS (g/L)	23.25 ± 2.31	19.17 ± 2.02
TCOD (g/L)	56.41 ± 4.22	54.20 ± 3.95
SCOD (g/L)	1.82 ± 0.32	13.77 ± 0.98
Alkalinity (mg/L)	780 ± 130	1580 ± 180
TKN (mg/L)	1513 ± 124	1445 ± 110
VFA (mg/L as COD)	376 ± 57	2581 ± 120

2.3. Operation condition of digestion

Before feeding, the thermally hydrolyzed sludge was preheated to 35 °C in an automated heating vessel. Both digestion reactors were maintained at 35 °C throughout the research. The seed sludge was obtained from the second-stage sludge digester of a municipal wastewater treatment plant located in Beijing, China. The solid concentrations of the seed sludge were as follows: total solid (TS) 30.12 g/L, VS 14.75 g/L, SS 26.49 g/L, and volatile suspended solid (VSS) 13.14 g/L. After being inoculated with the same amount of seed sludge, both reactors were operated at 20-day HRT with a loading rate of 2.71 kg COD/m^3 day (based on the mixed liquor volume, 3 L) for the first 150 days, then at 10-day HRT with 5.42 kg COD/m^3 day loading rate for the next 90 days. The daily influent and effluent for both reactors were 150 mL at 20-day HRT and 300 mL at 10-day HRT, respectively. Throughout the study, reactor I was operated in the CSTR mode, while reactor II was operated in the CSTR mode at the initial 80 days and then switching to ASBR mode for 160 days. Each cycle of the ASBR process comprised of filling, reacting, thickening, and drawing. For each cycle (24 h), the filling phase was carried out for 15 min, reacting phase for 20 h, thickening phase for 3.5 h, and the drawing phase for 15 min. Continuous mechanical mixing and intermittent mechanical mixing (10 min every hour) were provided during the filling and reacting phases.

2.4. Sampling and analysis

The total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD) removal, VS removal, biogas production, and biogas composition (methane and carbon dioxide contents) were used as the parameters for evaluating the performance of each system.

The biogas production was recorded daily while the methane and carbon dioxide content in biogas were measured twice a week. The reactor operation was considered to reach steady state when the daily biogas production variance was less than 5% during a 2-week period under identical test condition. When the reactor failed to reach steady state, the influent, effluent, and mixed liquor of each reactor were sampled 100 mL each time and analyzed once a week for pH, volatile fatty acids (VFAs), alkalinity, ammonia nitrogen, TCOD, and SCOD. The TS, SS, VS, and VSS samples (100 mL each) were collected and measured every 10 days. Once the reactor has regained steady state, samples (100 mL every time) were taken daily from the influent, effluent, and mixed liquor of each reactor for ten consecutive days and measured for all the above parameters. The average of the ten sets of data was then used as the performance data of the reactor for that test.

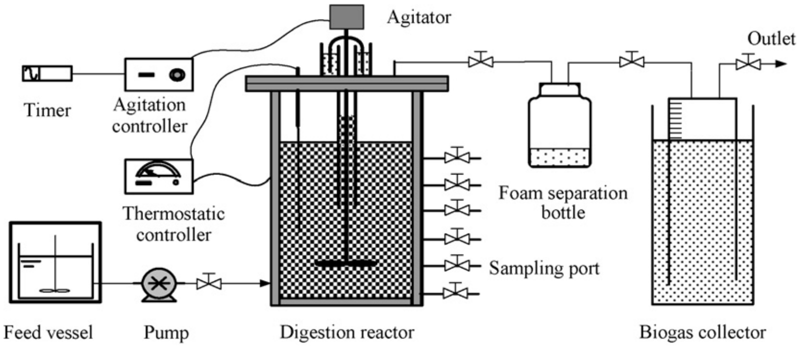

Fig. 1. Schematic diagram of anaerobic digestion systems (CSTR and ASBR).

To investigate the distributions of TS, SS, VS, and VSS in sludge along the reactor height at the end of the settling phase, samples (30 mL every time) from six sampling ports were periodically collected. Meanwhile, to investigate the evolution of biogas production, SCOD, and VFAs in ASBR during each cycle, the biogas production was recorded hourly and the sample (15 mL every time) collected from the mixed liquor in the ASBR every 2–4 h.

The analyses of TS, VS, SS, VSS were based on the Standard Analytic Methods promulgated by the National Environmental Protection Agency of China (1989). The TCOD and SCOD were measured using the Hach closed reflux method [16]. The SCOD, pH, and alkalinity were measured with samples centrifuged at $6000 \times g$ for 10 min. Total Kjeldahl nitrogen (TKN) and ammonia nitrogen (NH_3-N) were determined using a Benchtop pH/ISE meter (Model 720A, ATI Orion) and an ammonia probe (Orion 95-12). The samples were filtered through 0.45 μm filters before measurement of VFA with a gas chromatograph (Model SQ206, Beijing Analyzer Company) that was equipped with a FID detector (column: 3 m × 3 mm stainless steel GDX-103) was conducted. The various VFAs included acetic, propionic, *iso*-butyric, butyric, *iso*-valeric, and valeric acids. The biogas composition was also determined by a gas chromatograph (Model SQ206, Beijing Analyzer Company) equipped with a TCD detector (column: 3 m × 3 mm stainless steel Porapack Q 80/100 mesh).

SRT has been calculated as a ratio of the mass of VSS within reactor to the mass of VSS in effluent removed from the reactor. In this study, when SRT was calculated at 10-day HRT, both the VSS of mixed liquor and the VSS of the effluent was based on the average value for consecutive 10 days (one HRT).

2.5. Statistical analysis of data

The procedures for analysis of variance and Duncan's multiple range test ($P < 0.05$) implemented in the software package MATLAB [17] were used to determine statistical differences between the two systems in organic removals, biogas production rates, and characteristics of digested sludge. Each analysis was run at least in triplicates.

3. Results and discussion

3.1. Performances of the ASBR

The daily gas production was one of the predominant estimators for the performance of anaerobic reactors. Fig. 2 below shows the daily gas production for both reactors.

The biogas production was different between the two reactors during the initial 24 days following inoculation. However, no statistical difference in daily gas production and TCOD removal rate was observed between the two reactors in CSTR mode at day 40.

After reactor II was switched to ASBR mode after 80 days of operation, significant differences in daily gas production was observed between the two systems (Table 2). The daily gas production of ASBR was 15% ($P < 0.05$) higher than that of CSTR at 20-day HRT. On the other hand, the daily gas production of ASBR was 31% ($P < 0.05$) higher than that of CSTR at 10-day HRT.

There were no statistically significant differences between the effluent SCOD concentrations of the two reactors. The SCOD removal exceeded 90% at both 20-day and 10-day HRT, indicating that the thermally hydrolyzed sludge were highly degraded. The average TCOD removal of the CSTR at 20-day and 10-day HRT were 60.25% and 48.20%, respectively. The average TCOD removal ratios of the ASBR at 20-day and 10-day HRT were 67.71% and 61.66%, respectively. Therefore, the ASBR experienced a significant ($P < 0.05$) increase of 12.38% and 27.92% in TCOD removal with respect to the CSTR at 20-day and 10-day HRT, respectively. Thus, in comparison to the CSTR, the ASBR was able to achieve the same TCOD removal ratio at shorter HRT. Hence, this has illustrated the potential of the ASBR to shorten HRT and reduce reactor volume for the treatment of thermally hydrolyzed sewage sludge.

Compared to the 40% TCOD removal rate in conventional digestion [10], the TCOD removal rate (over 60%) at 20-day HRT was much higher for both systems studied here. It could be attributed to the fact that the characteristics of the sludge had changed during thermal hydrolysis pretreatment. The concentration of SS and VSS in thermally hydrolyzed sludge had decreased significantly as part of the solids had dissolved during the thermal hydrolysis pretreatment. On the other hand, the SCOD, VFA, and alkalinity had increased significantly with respect to the raw sludge (Table 1). Moreover, the digestibility of the sludge was improved as part of the large organic molecules (carbohydrate, protein, and fat) in raw sludge was broken down during pretreatment phase.

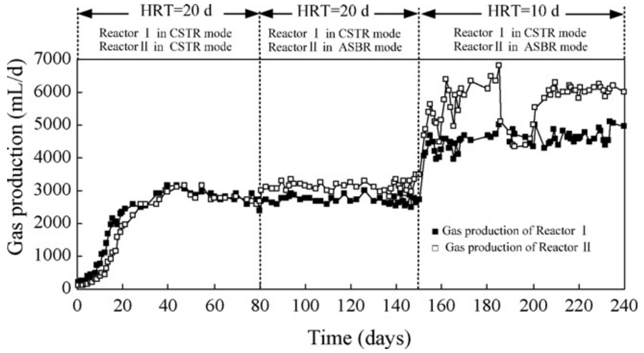

Fig. 2. Daily gas production for CSTR and ASBR systems.

Table 2
Steady state performances (average ± S.D.)

Parameters	HRT = 20 days		HRT = 10 days	
	CSTR	ASBR	CSTR	ASBR
Digested sludge characteristics				
pH	7.49 ± 0.12	7.58 ± 0.10	7.77 ± 0.08	7.74 ± 0.11
Alkalinity (mg/L as $CaCO_3$)	3843 ± 134	3893 ± 145	3546 ± 110	3714 ± 100
SCOD (mg/L)	1120 ± 45	1008 ± 32	1151 ± 70	1055 ± 40
VFA (mg/L as COD)	109.50 ± 10.41	92.33 ± 12.02	121.55 ± 13.11	101.14 ± 16.24
Acetate (mg/L as COD)	51.02 ± 5.22	48.29 ± 4.57	50.42 ± 8.33	49.40 ± 7.00
NH_3-N (mg/L)	671 ± 32	699 ± 24	530 ± 40	657 ± 55
Solids and COD removals				
VS removal (%)	54.32 ± 2.11	63.77 ± 1.45	45.21 ± 3.20	55.60 ± 2.44
TCOD removal (%)	60.25 ± 2.05	67.71 ± 1.55	48.20 ± 2.89	61.66 ± 2.13
SCOD removal (%)	91.86 ± 0.51	92.67 ± 0.89	91.64 ± 0.65	92.33 ± 0.75
Gas production				
Gas production rate (L/day)	2.75 ± 0.25	3.15 ± 0.15	4.59 ± 0.25	6.02 ± 0.3
Methane content (vol.%)	63.21 ± 0.18	62.74 ± 0.88	62.20 ± 0.78	63.10 ± 0.90
Gas yield (mL CH_4/g COD_{input})	213 ± 22	243 ± 30	175 ± 32	233 ± 23

The pH, SCOD, VFAs, and acetate in digested sludge from the two reactors at 20-day and 10-day HRT were not significantly different ($P = 0.38$). However, the average alkalinity and NH_3-N in the ASBR at 10-day HRT was significantly ($P < 0.05$) higher than that in the CSTR. The low VFAs concentration (less than 100 mg/L) in effluents indicated that both reactors achieved desirable operation.

3.2. Solids evolution and SRT

The TS profiles in the ASBR and the effluent during the whole study were shown in Fig. 3. When the reactors were operated in the CSTR mode during the initial 80 days, the TS concentration of effluents was the same as the mixed liquor within the reactors. However, after reactor II was switched to ASBR mode, the TS concentration of effluent decreased significantly from 20.34 g/L to 2.46 g/L ($P < 0.05$). This was because most of the solids had settled during the thickening phase and only supernate was discharged from the upper drawing port during the drawing phase. As time elapsed, sludge had continuously accumulated within the ASBR and this resulted in the TS of mixed liquor to increase gradually. Along with the enhancement of TS within the ASBR, the TS of effluent had also increased. The TS of mixed liquor in the ASBR was 65–80 g/L while the TS in the CSTR was about 20 g/L measured at 10-day HRT. This clearly showed that the ASBR system was able to maintain a higher sludge content which was inevitably beneficial to the biodegradation of organic solids.

As a result, the calculated SRT was 34, 36, 40 days in three consecutive ASBR cycles with an average of 37 days at 10-day HRT. Thus, this showed that ASBR could maintain longer SRT along with shorter HRT.

Studies have reported that settling of raw sludge during ASBR was difficult due to floatation of the sludge materials [14]. However, this was not observed with the thermally hydrolyzed sludge in our studies here, as rapid settling of solids was observed in the thickening stage within the ASBR. This could be attributed to the thermal hydrolysis pretreatment which had improved the settleability of the sludge [18]. Therefore, the improved settlement of the sludge ensured in a higher SRT. This indicated that thermal hydrolysis had provided an effective preconditioning for ASBR to maintain higher sludge content and hence a higher SRT/HRT ratio for the treatment of sewage sludge.

3.3. ASBR stability

The daily gas production was observed to decrease from 6.79 L/day to 5.10 L/day (Fig. 2) after 186th day. This decrease in gas production indicates a phase of ASBR instability. At day 186, the TS of mixed liquor in ASBR remained at a high level of 94.25 g/L. When the solids profile at the end of the thickening stage was examined (Fig. 4), it was found that the average TS concentration at the bottom of the ASBR was at a high concentration of 162 g/L. In contrast, the organic proportion (VS/TS) was at a low level of 31% for digested sludge. This may suggest that the bottom sludge had been almost completely biodegraded. Since the biodegraded (or mineralized) sludge took up 20% of the liquor volume in the ASBR, the actual effective volume of the ASBR had decreased. The decrease of effective volume might wash out the microorganisms. Furthermore, the

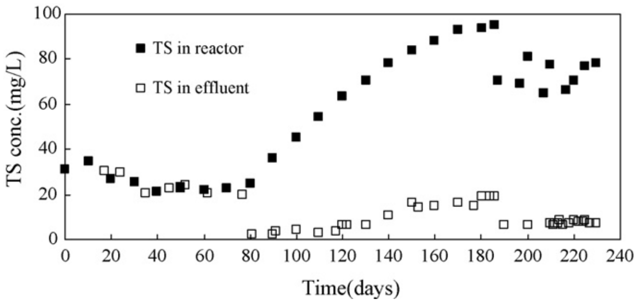

Fig. 3. TS of mixed liquor within ASBR and of effluent vs. time.

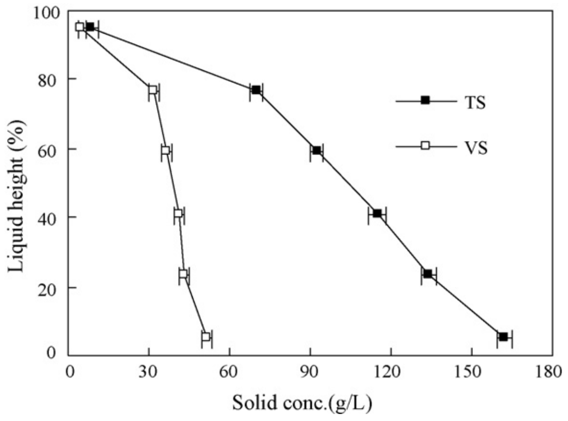

Fig. 4. Solids profiles in ASBR at the “threshold point”.

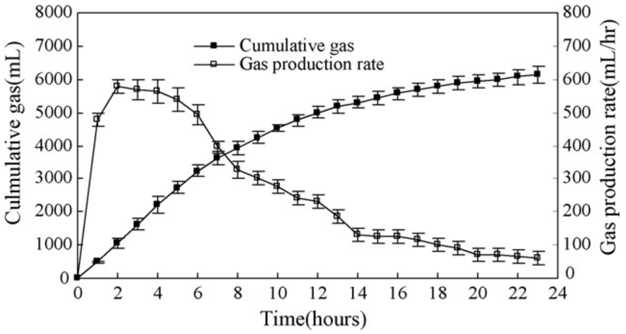

Fig. 5. Gas production during a 24-h cycle.

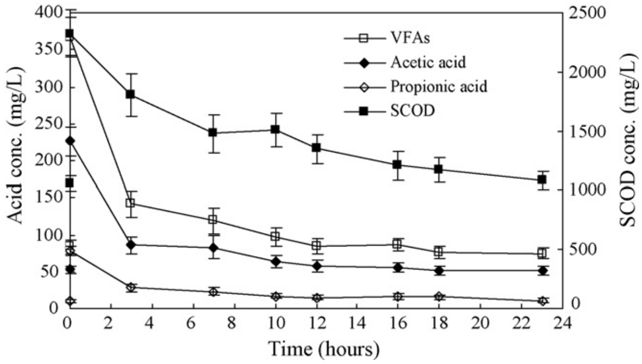

Fig. 6. SCOD and VFAs profiles during a 24-h cycle.

VS of effluent at day 186 was at a high concentration of 17.15 g/L, which indicated that some portion of highly biodegradable solids (or substrates) was also removed. These combination factors might result in the instability phase of the ASBR. This instability phase was also called the "threshold point" and it referred to the capability of the ASBR to accumulate solids without negative effect.

However, as observed in Fig. 2, the daily gas production of ASBR gradually increased over 10 days when 600 mL of digested sludge (20% of the total volume of liquor) was discharged from the bottom. This suggests that a periodic discharge of bottom-digested sludge, in addition to daily withdrawal of supernate, was necessary for an effective ASBR operation when it is close to the "threshold point". Based on the rate of solid accumulation, 300 mL of the bottom sludge was discharged from the ASBR at every tenth day in a HRT cycle since day 206. This regular removal of digested sludge was proved to be effective as no fluctuation of daily biogas production was observed in the subsequent study period.

To further investigate the stability of the ASBR under the above TS controlled condition, the evolution of biogas production, SCOD and VFAs during a 24-h cycle was studied. The results were presented in Figs. 5 and 6. Immediately after filling, SCOD had reached a maximum concentration, as was VFAs, since thermally hydrolyzed sewage sludge contained high concentrations of VFAs (around 2500 mg/L). During the first 4 h following filling, the rapid consumption of SCOD and VFAs resulted in a higher biogas production rate (around 600 mL/h). At the 15th hour of the cycle, the biogas production rate, SCOD, and VFAs concentrations decreased slowly. Acetic acid was found to be the major constituent of the VFAs (over 50%), while the butyric and valeric acids concentrations were very low (about 15 mg/L). After 15th hour, the VFA concentration remained relatively constant and the gas production rate was kept within 50–100 mL/h, suggesting that VFAs were consumed as soon as they were produced during the acidogenesis stage. This also inferred that acidogen and methanogen levels in the reactors were kept in equilibrium. Thus, this showed that ASBR was feasible for the treatment of thermally hydrolyzed sewage sludge.

4. Conclusion

The ASBR performed better than the CSTR with higher TCOD removal and higher biogas production rates for the treatment of thermally hydrolyzed sludge at 20-day and 10-day HRT.

The accumulation of solids affected the performance of the ASBR. Solids accumulation resulted in high solid content within the reactor which in turn resulted in a higher SRT, more than three times than HRT. High solid content sludge and high SRT were beneficial to the biodegradation of organic solids and ensured improved organic removal. On the other hand, solids accumulation over a certain "threshold point" caused instability of the ASBR.

To maintain the ASBR stability, excessive solids accumulation should be avoided. From our studies, it was shown that a regular discharge of bottom sludge was necessary and effective when the ASBR was close to the "threshold point". Finally, the ASBR was feasible for the treatment of thermally hydrolyzed sludge due to the high organic removal ratio and high stability.

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