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Anaerobic treatment of source-separated domestic bio-wastes with an improved upflow solid reactor at a short HRT

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ABSTRACT

Anaerobic treatment is the core technology for resource and energy recovery from source-separated domestic bio-wastes. The higher efficiency of an improved upflow solid reactor (IUSR) designed in this study was demonstrated in the treatment of concentrated black water and kitchen waste. The highest methane production of 48 L/person/day was achieved at the hydraulic retention time (HRT) of 7 days, while the other measures of performance at the HRT of 8.3 days were better than at the HRT of 7 or 10 days, achieving a methane production of 43 L/person/day, removal of total chemical oxygen demand (TCOD) of 89%, removal of soluble chemical oxygen demand (SCOD) of 92%, and conversion of chemical oxygen demand (COD) to methane of 71%. It is not recommended to decrease HRT lower than 7 days due to the instability of the initial period. The concentrations of volatile fatty acids (VFAs) in the IUSR were less than 10 mg/L, indicating that the anaerobic process was stable. Sludge bed development showed that sludge bed with high microbial activity was formed in the bottom and that the precipitation zone of effluents formed should preferably occupy 30% of the height of the IUSR. The effluents of the IUSR could be used for irrigation in agriculture in combination with a settling tank accompanied by disinfection to remove solids and pathogens.

Introduction

Anaerobic treatment is one of the most promising treatment technologies for building more sustainable sanitation and is considered to be the core technology for resource and energy recovery from domestic source-separated bio-wastes (Bernstad and la Cour Jansen, 2012; Larsen et al., 2013), including concentrated black water (CBW), concentrated brown water (BRW) from vacuum toilets, and kitchen waste (KW). However, there are only a few publications reporting the anaerobic treatment of source-separated domestic bio-wastes in various anaerobic reactors, such as the continuous stirring tank reactor (CSTR) (Wendland et al., 2006; Rajagopal et al., 2013), accumulation reactor (AC) (Kujawa-Roeleveld et al., 2003; Elmitwalli et al., 2006), upflow anaerobic sludge blanket (UASB) (de Graaff et al., 2010a, 2010b; de Graaff et al., 2011a, 2011b, 2011c) and UASB-septic tank (UASB-ST) (Kujawa-Roeleveld et al., 2005, 2006; Luostarinen et al., 2007). The CSTR reactor is a simpler reactor with a mixer rather than a high-rate reactor, because there is no retention of high-activity biomass. The simplest and largest reactor is the AC reactor, which is continuously fed and discharged at once when it reaches the required longer retention

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time. The AC reactor is recommended for more concentrated wastes, like livestock manure, brown water and kitchen waste. The UASB is suitable for treating bio-substrates with lower solid concentrations, and thus is only applied to treat concentrated black water, requiring a shorter hydraulic retention time (HRT) and smaller reactor volume. A gas/solid/liquid separator and influent distributor are indispensable for the UASB, resulting in its complicated configuration. The UASB-ST reactor, combining the features of a UASB and ST, can be applied to treat bio-substrates with higher solid concentrations (Fan et al., 2017), like CBW, BRW and KW. Above all, it can be concluded that development of a more efficient and simple reactor should be a priority.

The upflow solid reactor (USR), derived from the UASB, is a simple configuration reactor without a gas/solid/liquid separator and an influent distributor. The USR was first introduced to treat sea kelp (Srivastava et al., 1988), and had a longer solids and microorganism retention time than the UASB, leading to better performance. The USR is known for treating waste with higher total solid (TS) content, *e.g.*, livestock manure (Zhou and Yang, 1996), maize silage (Mumme et al., 2010) and wheat straw (Pohl et al., 2012). It has been reported that the biogas engineering applications of anaerobic digestion reactors operating in the surrounding counties of Beijing were generally dominated by USR technology by 2010 (Chen et al., 2012; Zhou and Zhou, 2013). However, the weaknesses of USR technology cannot be ignored, such as its low biomass transfer efficiency and the problem of encrustation (Wang et al., 2009). USR technology has not been investigated for the practicability of treating source-separated domestic bio-wastes, so it needs further study.

Considering the characteristics of mixtures of CBW and KW, and also the applicability of the USR, the project of this paper is to demonstrate the practicability of an improved upflow solid reactor (IUSR) to treat CBW and KW from vacuum toilets and to identify the optimal operation conditions, such as HRT and chemical oxygen demand (COD) loadings. In particular, the development of the sludge bed in the reactor was evaluated, and the potential utilization of the effluent and sludge was discussed.

1. Materials and methods

1.1. Feedstock and inoculum sludge

The CBW was prepared with feces–urine by collecting the wastes from a dry toilet and adding some urea to make it identical with the BW collected from vacuum toilets in Changshu, Jiangsu Province, China the first demonstration project applying source separation technologies in rural areas. According to the eating habits of residents in China (Zhang and Fu, 2010), KW was made from a mixture of 20% cooked kitchen waste (CKW) and 80% raw kitchen waste (RKW). The CKW was collected from a restaurant, and RKW was made up of 50% pre-prandial waste and 30% fruit waste. The mixed KW was shredded to a size less than 2 mm. Based on the average of 5 L of CBW and 500 g KW per person per day in China, the feedstock used in this study was prepared with KW:CBW = 100 g:1 L, and then was stored at −20°C. Characterization of the CBW, KW and feedstock mixture is given in Tables 1 and 2. Because of the much greater amount of KW generated per person per day (500 g/person/day, China; 200 g/person/day, Germany (Wendland et al., 2006); 150 g/person/day, Singapore (Rajagopal et al., 2013)), the feedstock in our study had a higher concentration of total chemical oxygen demand (TCOD), TS and volatile solids (VS) compared with other research. The NH_3-N content in the feedstock mainly originated from urine. According to Speece (Speece, 1983), most elements were at the optimal concentrations, while it is notable that concentrations of Fe and Co were less than the optimal concentrations (10 mg/L Fe and 0.02 mg/L Co).

Table 1 – Characteristics of concentrated black water (CBW), kitchen waste (KW), raw kitchen waste (RKW), cooked kitchen waste (CKW) and the feedstock.

Parameter	RKW	CKW	KW	CBW	Feedstock (5 L CBW + 500 g KW)
TS (%)	13.85	22.40	9.55	0.92	2.1
VS (%)	12.82	20.61	8.67	0.80	1.8
TCOD ($^{a/b}$)	103.2^a	304.5^a	175.6^a	13,960^b	28,554^b
SCOD ($^{a/b}$)	45.4^a	70^a	54.4^a	5134^b	13,043^b
SCOD/TCOD (%)	43.99	22.99	30.98	36.78	45.68
Total nitrogen ($^{a/b}$)	1.73^a	4.43^a	2.62^a	597.2^b	1353.1^b
NH_3-N ($^{a/b}$)	0.37^a	0.07^a	0.92^a	196.7^b	749.5^{b*}
TP (mg/L)	–	–	–	–	202.3
Soluble TP (mg/L)	–	–	–	–	163.1
TVFA (g COD/L)	–	–	–	–	1.07
Acetic-acid (g COD/L)	–	–	–	–	0.64
Propionic-acid (g COD/L)	–	–	–	–	0.26
Isobutyric-acid (g COD/L)	–	–	–	–	0.005
Butyric-acid (g COD/L)	–	–	–	–	0.15
Isovaleric-acid (g COD/L)	–	–	–	–	0.009
Valeric-acid (g COD/L)	–	–	–	–	0.007

TS—total solid, VS—volatile solid, TCOD—total chemical oxygen demand, SCOD—soluble chemical oxygen demand, TN—total nitrogen, TP—total phosphorus, TVFA—total volatile fatty acid.
^{a} and ^{b} are different units, ^{a} mg/g, ^{b} mg/L, * adding urea, – not measured.

Table 2 – Characteristics of feedstock in terms of trace elements.

Parameter	Feedstock	Parameter	Feedstock
Mn (μg/L)	1056	Ti (μg/L)	738.9
Fe (μg/L)	1058	Cr (μg/L)	13.59
Co (μg/L)	3.76	As (μg/L)	4.65
Ni (μg/L)	57.33	Rb (μg/L)	506.2
Cu (μg/L)	55.38	Sr (μg/L)	1654
Zn (μg/L)	619.7	Cd (μg/L)	0.32
Se (μg/L)	5.09	Pb (μg/L)	4.29

1.2. Reactor and experimental design

Anaerobic co-digestion of CBW and KW was performed in IUSR with a working volume of 5 L and an operating temperature of 33°C, which was equipped with a biogas recirculation mixer, aiming to increase biomass transfer efficiency and solve the problem of encrustation (Fig. 1). In the IUSR, complete mixing and forming of the sludge bed could be realized by using intermittent mixing to obtain higher efficiency. The reactor was fed once a day and the mixer was turned on for 3 min every 2 hr. The reactor was inoculated with 500 mL inoculum sludge, and filled with diluent feedstock of a 2 g/L COD concentration, then started with a relatively low organic loading (0.7 kg COD/m^3/day). The different operating conditions of daily loadings and HRT are shown in Fig. 2, and each operating condition was steady for at least two HRT durations. The periods were divided into five phases: phase I was the start-up phase with lower COD loading; phase II was operated at an HRT of 10 days and COD loading of 2.86 g/day/L; phase III was operated at an HRT of 8.3 days and COD loading of 3.45 g/day/L; phase IV was operated at an HRT of 8.3 days and COD loading of 3.86 g/day/L; phase V was operated at an HRT of 7 days and COD loading of 4.5 g/day/L.

The inoculum sludge was taken from an anaerobic digester in a municipal wastewater treatment plant, Beijing. The average TS and VS concentrations were in the range of 30.72 g/L and 15.08 g/L, respectively.

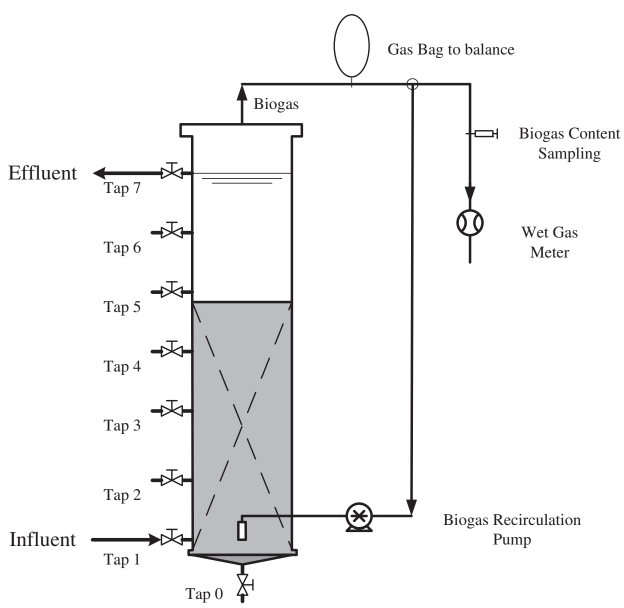

Fig. 1 – Schematic diagram of an improved upflow solid reactor (IUSR).

1.3. Analytical methods

Total solid (TS) and volatile solid (VS) were analyzed according to the Standard Methods (APHA, 1998). TCOD and soluble chemical oxygen demand (SCOD) concentrations were measured using the fast airtight catalytic digestion method with titration of ferrous ammonium sulfate according to the Standard Methods (MEP, 2002). SCOD concentrations were analyzed by measuring the samples filtered through a 0.45 μm membrane. Volatile fatty acids (VFAs) (acetic, propionic, iso-butyric, butyric, iso-valeric, and valeric acid) were determined using a gas chromatograph (Agilent Technologies 7890B, USA) equipped with a flame ionization detector (FID) and a DB-FFAP column (Agilent Technologies, USA). Total biogas production was monitored daily using a wet gas flow meter (Changchun Automobile Filter Co., Ltd., LMF-1, China). Biogas composition was analyzed by a gas chromatograph (Agilent Technologies 7890B, USA) equipped with a thermal conductivity detector (TCD) and an HP-PLOT column (Agilent Technologies, USA). The concentrations of total nitrogen (TN), NH_3-N, total phosphorus (TP), soluble phosphorus were measured according to the Standard Methods (MEP, 2002).

1.4. Calculations

COD removal was calculated with the following formula:

$$\text{COD removal} = \frac{\text{COD}_{\text{influent}} - \text{COD}_{\text{effluent}}}{\text{COD}_{\text{influent}}} \times 100\% \quad (1)$$

COD conversion was referenced to the fate of COD and was divided into three parts: COD conversion to methane, COD remaining in sludge and COD remaining in effluent. COD conversion was calculated based on the average daily COD loading, biogas production and methane content. COD conversion to methane was calculated from a conversion factor of 0.385 L CH_4/g COD at 25°C. COD remaining in sludge contained the fraction in discharged sludge. COD conversion was calculated as follows:

$$\text{COD}_{\text{influent}} = \text{COD}_{\text{methane}} + \text{COD}_{\text{effluent}} + \text{COD}_{\text{sludge}} \quad (2)$$

Stabilization of sludge was represented by the hydrolysis of suspended solids (de Graaff et al., 2010a, 2010b). The rate of hydrolysis was estimated using first order kinetics:

$$\frac{dF_{degr}}{dt} = -K_h \bullet F_{degr} \quad (3)$$

Assuming the sludge bed functions as a CSTR, it could be derived:

$$\frac{F_{degr}}{F_{degr,0}} = \frac{1}{1 + K_h \cdot \text{SRT}} \quad (4)$$

where, F_{degr} (mg/L) is the amount of biodegradable solids in the sludge bed, $F_{degr,0}$ (mg/L) is the amount of biodegradable solids in the influent and K_h (0.1/day) is the hydrolysis constant. Therefore, the stabilization of sludge was represented by $\left(1 - \frac{F_{degr}}{F_{degr,0}}\right)$.

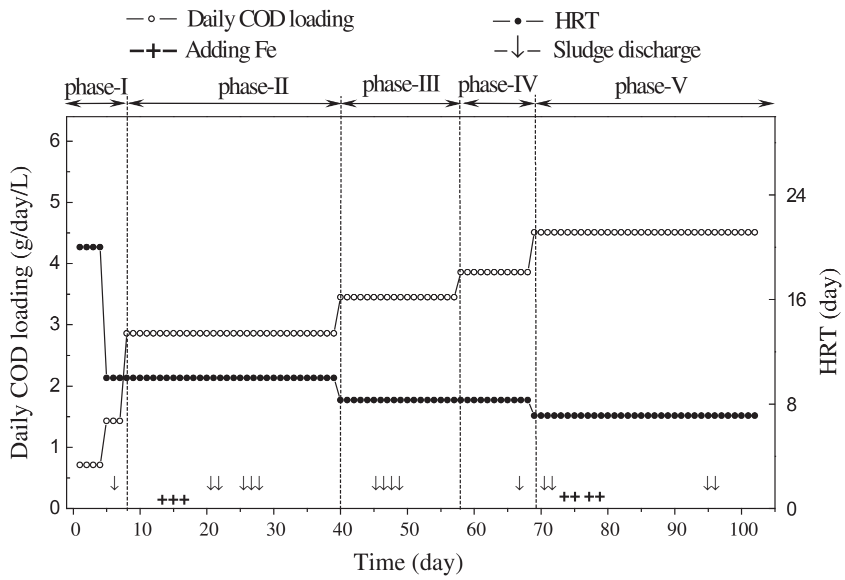

Fig. 2 – Different operating conditions of IUSR.

The SRT of the reactor was calculated according to the following formula:

$$SRT_{reactor} = \frac{Solids_{reactor}}{Solids_{effluent} + Solids_{discharging}} \quad (5)$$

where, $Solids_{reactor}$ (g VS) is the amount of volatile solids in the reactor, $Solids_{effluent}$ (g VS/day) is the amount of solids in effluent, and $Solids_{discharging}$ (g VS/day) is the amount of solids discharged manually.

2. Results and discussion

2.1. *Digester performance of IUSR under different operating conditions*

2.1.1. *pH and VFA*

The growth of methane-producing microorganisms is maximized in the optimum pH range between 6.6 and 7.8, and VFA is an important intermediate production in the anaerobic process. Thus, monitoring the variation of pH and VFA could indicate the tendencies of the anaerobic process, so the pH and VFA concentrations were measured in the effluents, Fig. 3a–c. The pH exhibited a small variation of 7.11–7.65 under different conditions, which was in the suitable range for methanogens. Total volatile fatty acid (TVFA) concentrations increased with increasing COD loadings after the reactor started (phase I), then reached a maximum of 800 mg COD/L in phase II. Corresponding to VFAs, the concentrations of acetic, iso-butyric, butyric, iso-valeric, valeric acid decreased gradually, showing that acetogenesis and methanogenesis processes were relatively stable, while the concentrations of propionic acid increased with increasing COD loadings in phases I and II (1–15 days) and accumulated to 850 mg/L. Propionic acid is an important product of the anaerobic digestion process. It has been shown that propionic acid, as an intermediate in methane production, accounts for 35% of the total methane production in anaerobic digestion of excess sludge (Zhao et al., 2005), and the oxidation process of propionic acid to acetic acid is more difficult than for other VFAs (McMahon et al., 2004). Therefore, the accumulation of propionic acid would inevitably result in a lower methane production. It is also in dispute whether the accumulation of propionic acid has inhibitory effects on methanogenic bacteria. During the accumulation of propionic acid in our study, the pH value did not fluctuate greatly, which showed that the alkalinity was sufficient to maintain the pH at a suitable level for methanogenic bacteria.

Studies have shown that the lack of trace elements can easily lead to the accumulation of propionic acid (Ma et al., 2009; Zhang and Deokjin, 2012), especially Fe (Oechsner et al., 2008; Schmidt et al., 2014). As a result, we added a certain concentration (2 mg/L) of $FeCl_2$ to the reactor at the 14th day, after which the concentration of propionic acid decreased significantly within 4 days, as well as the TVFA concentrations. The concentrations of iso-butyric, butyric, iso-valeric, and valeric acid could not be detected (<0.5 mg/L) and acetic + propionic acid was less than 10 mg/L in phases III and IV, indicating the robustness of IUSR to bear the increasing COD loadings. However, concentrations of TVFA and propionic acid increased in phase V due to the decrease of HRT to 7 days. Adding Fe again caused a slow depletion of propionic acid, which lasted for 10 days, resulting from the rapid acidogenesis process at the higher COD loading. At the end, only a small amount of acetic acid (<10 mg/L) could be found in the reactor. It can be concluded from the above results that Fe is crucial to the oxidation process of propionic acid to acetic acid. Moreover, the HRT of 7 days may be the minimum HRT due to the instability of the initial period.

2.1.2. *Biogas production and methane yield*

The biogas production of the IUSR increased with increasing COD loading (Fig. 3d). In the accumulation stage for propionic

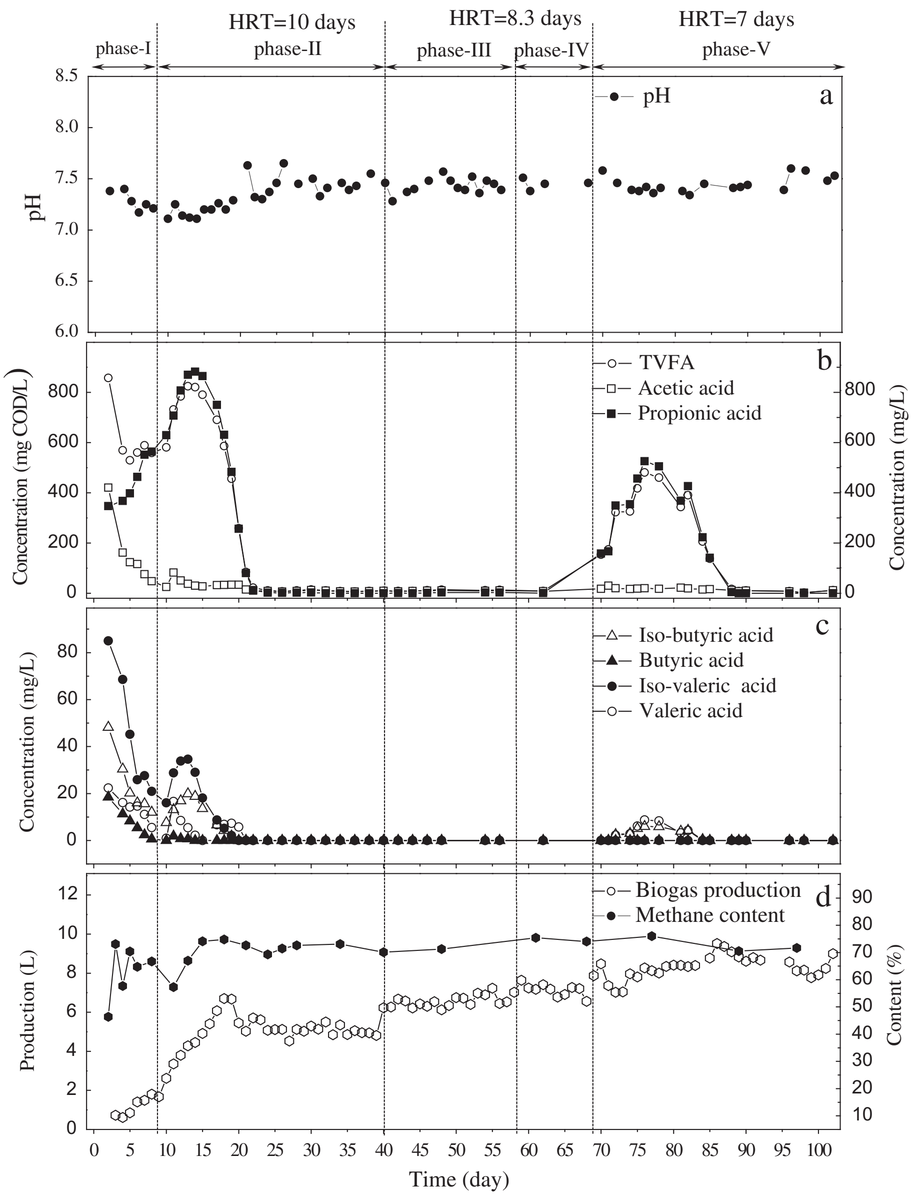

Fig. 3 – Performance of IUSR under different operating conditions. a: pH; b and c: TVFA and VFAs; d: biogas production and methane content.

acid (5–13 days), biogas production increased continuously (14–19 days), until propionic acid was completely oxidized after adding $FeCl_2$. Gradually, biogas production had little fluctuation except for the influence of sludge discharge. At HRT of 10 and 8.3 days, biogas production was on average 5.2 L/day (s.d. 0.26) and 6.5 L/day (s.d. 0.24) for COD loading of 2.9 and 3.5 kg COD/m^3/day, respectively. With increasing COD loadings from 3.5 to 3.9 kg COD/m^3/day at the same HRT of 8.3 days, biogas production increased to 7.2 L/day (s.d. 0.24), indicating that fluctuations in COD loadings had little influence on the anaerobic process. At an HRT of 7 days, biogas production decreased in the beginning, and then increased after adding Fe, and finally became stable at 8.6 L/day (s.d. 0.36) until propionic acid was completely depleted.

In the early startup phase, the methane content fluctuated in the range of 46%–73% (Fig. 3d). As the COD loadings became stable, methane content stabilized within a small variation range of 70%–75%, and an average of 72% (s.d. 2.1%) was achieved. Decreasing the HRT did not have a significant influence on the methane content.

Assuming that the daily production of CBW and KW is respectively 5 L and 0.5 kg per person, applying a mesophilic IUSR to treat CBW and KW at an HRT of 10, 8.3 and 7 days will respectively generate 41, 43 and 48 L methane per person per day (Table 3), and the methane yields amounted to 262, 271 and 271 L CH_4/kg COD and 404, 419 and 468 L CH_4/kg VS based on the daily input of COD and VS.

2.1.3. *COD removal and conversion*

The COD concentrations of effluents and COD removal under different operating conditions are shown in Fig. 4. In the early startup phase, TCOD and SCOD concentrations of effluents

Table 3 – Specific methane production based on COD, VS, mixture output and reactor volume.

Methane yield (unit)	CBW + KW HRT = 10 days	CBW + KW HRT = 8.3 days	CBW + KW HRT = 7 days
Based on COD added per day (L methane/kg COD $_{added}$/day)	262	271	271
Based on VS added per day (L methane/kg VS $_{added}$/day)	404	419	468
Based on mixture output per person per day (L methane/person/day)	41	43	48
Based on reactor volume (L methane/L reactor/day)	0.75	0.98	1.24

were much higher because of the excessive suspended sludge in the reactor with the increasing COD loading, indicating that sludge discharging might be needed. Therefore, sludge discharging measures were taken on the 18th to 20th days, after which COD concentrations decreased notably. With the growth of methanogens and adaptation to the COD loading, the COD concentrations of effluents became stable at an HRT of 10 days, where the TCOD and SCOD removals were calculated at 89% and 89%, respectively (Table 4). The TCOD concentrations of effluents increased at 41 days because of the fluctuations in the sludge bed due to increasing COD loading, but SCOD concentrations showed little change, and then TCOD concentrations gradually became stable after sludge discharge. At an HRT of 8.3 days, TCOD and SCOD removals were calculated at 89% and 92%, respectively. Again, on increasing the COD loading from 3.5 to 3.9 kg COD/m^3/day in phase IV, the COD concentrations of effluents showed little fluctuation, indicating the robustness of the IUSR. However, at an HRT of 7 days, the COD concentrations of effluents were unstable for 20 days due to the suspended sludge in the reactor. Finally, TCOD and SCOD removals were calculated at 88% and 91%, respectively.

The conversions of COD were calculated based on the daily loading of COD added and methane production per day (Fig. 5). Conversion of COD indicates the fate of COD and this fate has three paths in the reactor: conversion into CH_4, discharge with effluent or remaining in sludge. It can be calculated that on average 68% of total COD was converted into CH_4, 21% remained in the sludge and 11% was in the effluents at an HRT of 10 days, where TVFA concentrations were less than 10 mg COD/L. At an HRT of 8.3, an average of 71% of total COD was converted into CH_4, and 18% remained in the sludge. Moreover, at an HRT of 7 days, an average of 70% of total COD was converted into CH_4, 12% remained in the effluents and 18% was in the sludge.

In summary, the performance at the HRT of 7 days was better than at the HRT of 8.3 or 10 days in terms of biogas production due to the higher amounts of available substrates, while the longer accumulation of VFA that took place in the initial period at the HRT of 7 days should be prevented. Therefore, it is not recommended to decrease the HRT lower than 7 days. The greatest conversion of COD to methane and the highest removal of COD occurred at the HRT of 8.3 days, indicating that the anaerobic digestion process was more complete than that at the HRT of 7 or 10 days.

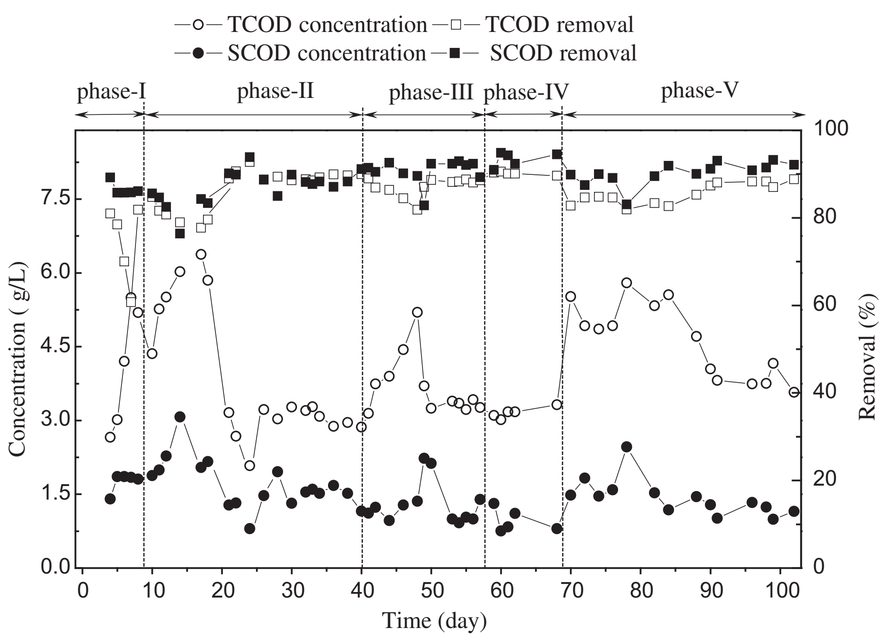

Fig. 4 – COD concentrations of effluents and COD removal under different operating conditions.

Table 4 – COD removal under different operating conditions.

Total removal	CBW + KW HRT = 10 days	CBW + KW HRT = 8.3 days	CBW + KW HRT = 7 days
TCOD	89%	89%	88%
SCOD	90%	92%	91%

2.1.4. Development of sludge bed

In the reactors with biomass retention, the formation and development of the sludge bed is crucial to the performance of reactors. However, the IUSR designed in this study is a hybrid reactor where complete mixing and formation of a sludge bed can be achieved by intermittent mixing to prevent the loss of biomass. Obviously, the sludge bed was formed quickly after mixing (Fig. 6). The concentrations of TS and VS decreased with increasing height in the reactor. In the lower parts of the IUSR (Tap0 to Tap5), the VS/TS ratio of sludge was between 72% and 80%, which showed that there was a more active sludge bed at the bottom of IUSR, while the ratios of VS/TS and concentrations of TS, VS were basically similar from Tap5 to Tap7, where a good precipitation zone was formed. During the operation of the reactor, the sludge accumulated in the bottom became more active.

For the sake of better effluent quality, it is necessary that the height of sludge bed not be higher than the height of Tap5, and sludge discharge measures should be taken if the bed becomes higher, especially when the COD loading changes. In this study, it is suggested that the amount of one-off sludge discharge should not be too much (<5% of reactor volume) to avoid a negative influence of sludge discharge on the anaerobic digestion process, and multiple discharging on consecutive days would be better than one larger discharge. For example, the daily biogas production at the 27th day decreased clearly because of the excessive sludge discharge (400 mL, 8% of reactor volume) on the 26th day.

2.2. Further fate of effluent and sludge

The characteristics of effluents and sludge under different operating conditions are shown in Table 5. TCOD and SCOD concentrations of effluents were much lower than in the sludge bed due to the higher solid concentrations in the bed. The higher nitrogen concentration in the effluent was mainly

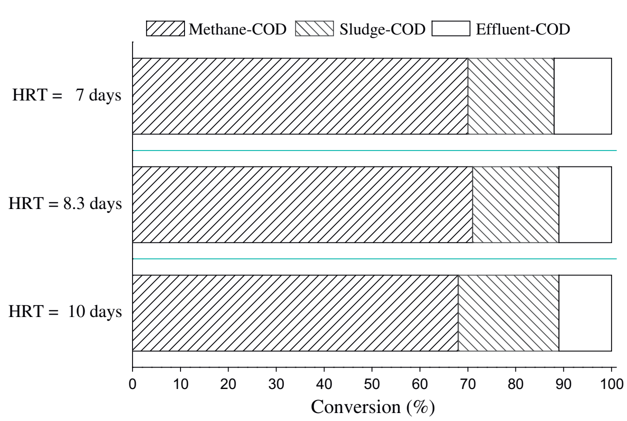

Fig. 5 – COD conversions under different operating conditions.

in ammonium form, and the ammonium concentration of the effluent increased by 50% resulting from the biological conversion of organic nitrogen. The fate of phosphorus was direct precipitation in solids (about 55%) and discharge with effluents (45%), and the sludge in the bottom of the IUSR would be a resource reservoir of phosphorus.

In anaerobic digestion of source-separated mixtures, there have been two patterns for treating the effluent and sludge. One is the direct reuse of digested flows (effluent and sludge) in agriculture, where disinfection of the digested flows is an indispensable step before agricultural reuse. In cases where direct reuse for agriculture is not feasible due to a long distance between cities and agriculture, and also in the case of strict standards where effluents are even not allowed for agriculture, the effluents require retreatment for removal of nitrogen (de Graaff et al., 2010a, 2010b, 2011a, 2011b, 2011c) and recovery of phosphorus (de Graaff et al., 2011a, 2011b, 2011c) before discharging to surface waters, which is the second pattern. Zeeman et al. (2008) have proposed the second pattern to treat effluents from the UASB or UASB-ST, resulting in recovery of 0.14 kg P/person/year and potential production of 90 L reusable water, as well as energy savings of 200 MJ/person/year.

In our study, the effluents were precipitated for 2.0 hr, as characterized in Table 5. The results showed that part of TS and VS were precipitated in the bottom, resulting in a significant decrease of TCOD, TP and SCOD concentrations, while TN and NH_3-N were almost invariant. Therefore, it is suggested that the effluents of the IUSR could be reused for drip irrigation in agriculture when combined with a settling tank accompanied by disinfection to remove solids and pathogens. A storage tank might also be needed for periods when irrigating with the effluents is forbidden in the non-growing season. The volume of storage tank needed is about 1 m^3 per person for 6 months. The stabilization of discharged sludge is related to the solid retention time (SRT), where a longer SRT will result in more stabilization of sludge (de Graaff et al., 2010a, 2010b). As calculated, 85% of sludge was stabilized at the SRT of 55 days in IUSR, and more stabilization will occur with the development of the sludge bed. Therefore, discharged stabilized sludge could be used as fertilizer directly or after further treatment. Nevertheless, some risks should be avoided as far as possible (Winker et al., 2009; Vazquez-Rowe et al., 2015), such as ammonia volatilization, nitrate leaching, contamination by heavy metals and organic pollutants (recalcitrant compounds and pharmaceutical compounds), and hygiene risks (pathogens).

2.3. Overall comparisons

Anaerobic treatment is the core technology for treating concentrated bio-wastes. Overall performance data for anaerobic reactors treating source-separated substrates are presented in Table 6. The performance of a reactor consists of two aspects: digestion efficiency represented by the methane production and COD removal, and cost efficiency related to the reactor temperature and reactor volume. For the AC, although the reactor operates at a lower temperature, a larger volume is required, indicating the need for greater land use and enormous construction cost. The volume of an AC to treat CBW and KW is about 40 times larger than the volume of an IUSR. With less

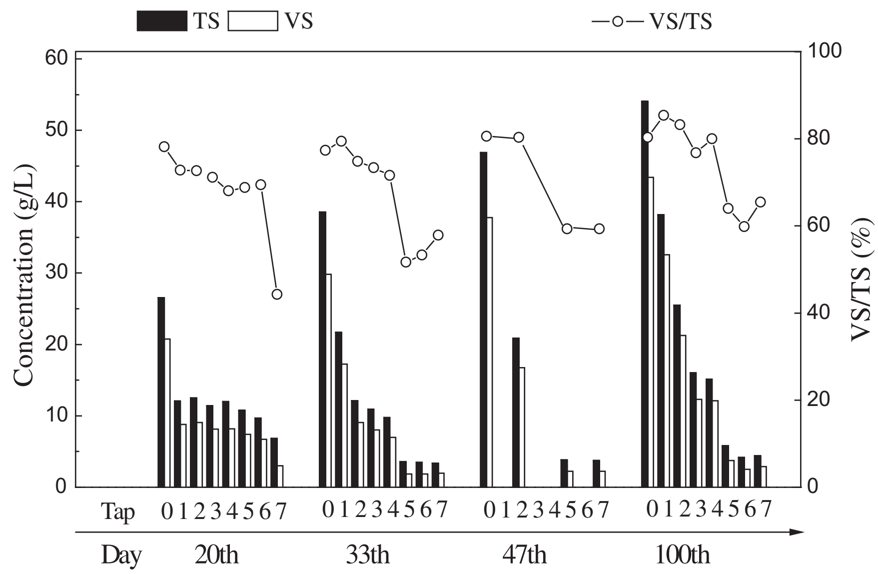

Fig. 6 – Characterization of sludge bed at different heights.

emphasis on methane production, the AC combines biological conversion and storage retention of treated substrates. Compared with the use of a CSTR to treat CBW and KW, the IUSR is superior in all aspects of methane production, reactor volume and removal efficiency owing to the massive biomass retention in the IUSR. Subsequent sedimentation and circulation of sludge might be needed to maintain the biomass in a CSTR. The digestion efficiency of CSTR treating CBW at 33°C can be achieved with a UASB at 25°C, thus the cost efficiency of the UASB is much higher than the CSTR. However, the UASB is suitable for treating bio-substrates with lower solid concentrations, and thus is only applied to treat CBW. At the same operational temperature of 25°C, the digestion efficiency of the UASB-ST is slightly better than that of the UASB, resulting from the 3 times longer HRT. So far, an efficient reactor to treat CBW and KW has not been available, thus it can be concluded that the IUSR is an efficient reactor with the highest TCOD removal of 88% as well as the maximum methane production of 48 L/person/day at a relatively high loading of 4.1 kg COD/m^3/day, and is also a low-cost reactor, having the smallest reactor volume of 0.04 m^3/person and shortest HRT of 7 days. Moreover, the IUSR has a simpler construction, without the need for a gas/solid/liquid separator and influent distributor, and the provision of a blender results in better transfer efficiency, higher biomass and non-encrustation in the reactor. Therefore, IUSR technology is a simple, efficient, robust system to treat source-separated domestic bio-wastes.

3. Conclusions

The higher efficiency of the IUSR in treating concentrated black water and kitchen waste based on the source-separated sanitation concept, compared to other anaerobic treatment technologies, was demonstrated in this study. A methane production of 43 L/person/day, TCOD removal of 89%, and COD conversion to methane of 71% were achieved at a relatively high loading of 3.45 kg COD/m^3/day and short HRT of 8.3 days, which was better than at the HRT of 7 or 10 days, except that the highest biogas production of 48 L was achieved at the HRT of 7 days. The sludge bed in the bottom of the IUSR had high activity for the removal of solids. The effluents of the IUSR could be used for irrigation in agriculture when combined with a settling tank accompanied by disinfection to remove solids and pathogens.

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Table 5 – Characterization of effluent and sludge.

Parameter		TCOD (g/L)	SCOD (g/L)	TS (g/L)	VS (g/L)	TN (mg/L)	NH_3-N (mg/L)	TP (mg/L)
Effluent	HRT = 10 days	3.1	1.5	3.5	1.9	1269	1098	89.9
	HRT = 8.3 days	3.3	1.0	3.7	2.2	1254	1144	91.2
	Precipitation	2.0	1.0	2.7	1.3	1174	1160	73.6
	HRT = 7 days	3.9	1.1	4.2	2.5	1319	1262	99.3
Sludge		51.4	2.1	42.1	29.4	3890	1212	856.2

Table 6 – Performance data of reactors treating source-separated bio-substrates.

Reactors	Substrates	Operating parameters			Performance			
		Temperature (°C)	HRT (days)	OLR (kg COD/m^3/day)	COD removal (%)	Methane production ($^{a/b}$)	Methane content (%)	Reactor volume (m^3/person)
CSTR	CBW	37	20	0.5	61	10^a	76	0.14
(Wendland et al., 2006)	CBW + KW	37	20	1.0	71	27^a	65	0.14
	CBW + KW	37	10	2.0	50	17^a	65	–
AC (Elmitwalli et al., 2006)	CBW + KW	20	150	0.1–0.3	58	–	–	1.4–1.6
UASB-ST (Kujawa-Roeleveld et al., 2005)	CBW	25	27	0.33–0.42	78	14^a	66	0.2
UASB (de Graaff et al., 2010a)	CBW	25	8.7	1.0	78	10^a	78	0.06
Two-phase CSTR (Rajagopal et al., 2013)	BRW + KW	33	20	1.5	68.4	0.21–0.40^b	–	–
CSTR (Rajagopal et al., 2013)	BRW + KW	33	16	2–3	76.7	0.37–0.46^b	–	–
IUSR	CBW + KW	33	8.3	3.4	89	43^a/0.42^b	72	0.04
(this study)	CBW + KW	33	7	4.1	88	48^a/0.47^b	72	0.04

^{a} and ^{b} are different units, ^{a} L methane/person/day, ^{b} L methane/g VS, – not provided.

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