

Anaerobic digestion of blackwater from vacuum toilets and kitchen refuse in a continuous stirred tank reactor (CSTR)

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Abstract The objective of this research was mesophilic anaerobic digestion of blackwater from vacuum toilets (BW) and kitchen refuse (KR) in a CSTR in an ecological sanitation system. A detailed investigation of the BW characteristics was carried out. The research on anaerobic digestion was performed with three CSTR of each 10 l volume at HRT of 10, 15 and 20 days. The digestion of BW at 20 days HRT showed stable performance, without inhibition effects due to relatively high ammonium concentrations. The removal of total and particulate COD was 61% and 53%, respectively, and the methane yield 10 ICH₄/cap/day. The addition of kitchen refuse (KR) improved the performance of the CSTR in terms of COD removal efficiency and methane yield. At 20 days HRT the removal of total and particulate COD increased up to 71% and 67%, respectively, and the methane yield to 27 ICH₄/cap/day. The results at 15 days HRT showed similar performance. At HRT of 10 days, the anaerobic treatment was limited but reached steady state conditions at higher VFA concentrations in the effluent, with a decrease of COD removal of 30-33% and of methane yield of 19-21%. Assumed that 65% of the COD load from BW is collected in the housing estate, the expected methane yields for 100% BW collection are accordingly higher.

Keywords anaerobic digestion; kitchen refuse; blackwater; ecological sanitation; vacuum toilets; CSTR

INTRODUCTION

In recent years, a new approach to wastewater management has been developed and implemented in many projects world wide, this approach is referred to as ecological sanitation (ecosan) or decentralised sanitation and reuse (desar) (Otterpohl & Lange 2000, Lens et al. 2001). As an answer to huge sanitation problems world wide as well as realised problems of centralised conventional wastewater treatment, ecological sanitation focuses on source separation of organic waste and wastewater on a household level, followed by an appropriate treatment of each stream in decentralised or semi-centralised systems and consequent reuse of water and nutrients. Anaerobic digestion plays a key role as an adequate technology for concentrated wastewater such as BW, as it requires less energy as aerobic treatment predominantly for technical aeration. But anaerobic digestion produces energy as biogas, and generates no sewage sludge but an organic fertiliser highly concentrated in nutrients like nitrogen and phosphorus.

In the pilot project Flintenbreite in Lübeck, Germany, the source separation was realised in the year 2000 in a housing estate for 350-400 inhabitants (Otterpohl et al. 1997; Wendland & Oldenburg 2003). The concept is characterised by vacuum toilets, followed by pasteurisation and anaerobic digestion of the blackwater (BW) in a semi-centralised biogas plant (CSTR) and finally recycling of digested anaerobic effluent in agriculture (figure 1). The vacuum toilets need 0.7 – 1.0 l water per flush and hence, produce a volumetrically small but high strength flow of about 5 l/cap/day BW. The second highly concentrated stream from households, the kitchen refuse (KR) is milled in a grinder and added to the BW before the pasteurisation step. The pasteurisation of 24 hours at 55⁰C or 1 hour at 75⁰C is required by German legislation for organic waste (BioAbfV 1998). The biogas resulting from this process is to be utilised in the combined power and heat generator (heating for houses/digester and production of electricity).

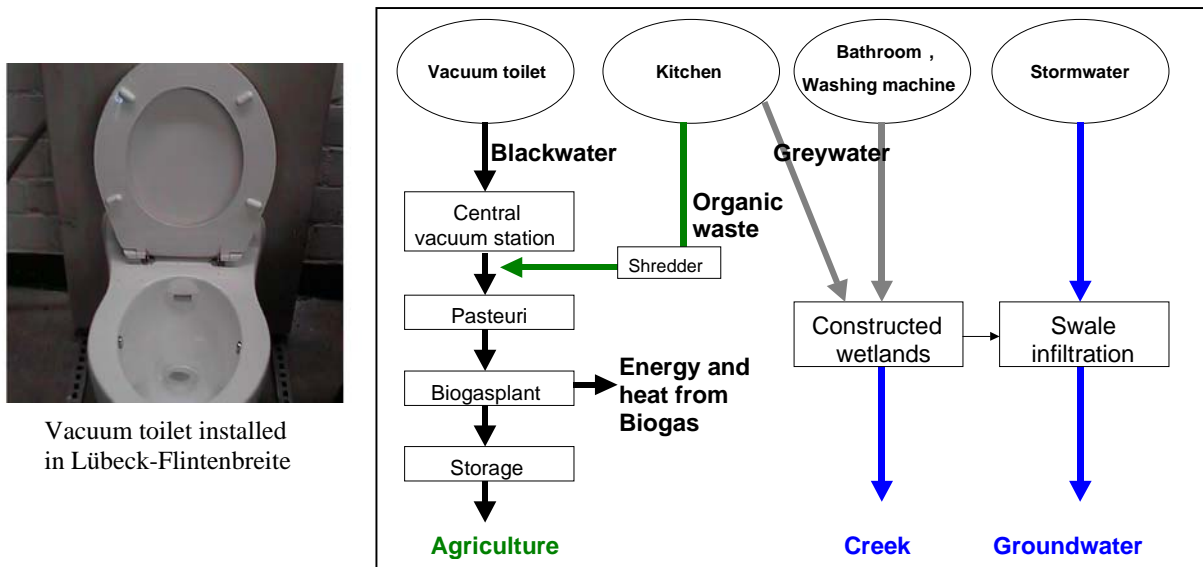


Figure 1 Scheme of the pilot project Flintenbreite, Lübeck, Germany

The third wastewater stream in households, the greywater is a volumetrically big flow but low in nutrient loads. There is already much experience for greywater treatment world wide (Li et al. 2001). In Flintenbreite, greywater with a quantity about 60 l/cap/day is collected and treated separately in vertical flow constructed wetlands.

The presented preliminary studies for the biogas plant in Lübeck-Flintenbreite aimed at finding out the performance of anaerobic digestion of blackwater from vacuum toilets and kitchen refuse (KR) in a CSTR, in particular:

- characterisation of blackwater from vacuum toilets (BW)
- COD removal efficiency and methane yield of BW digestion at 20 days HRT
- COD removal efficiency and methane yield of BW + KR digestion at 10, 15 and 20 days HRT

METHODS AND MATERIALS

Experimental set-up and analysis

At the Institute of Wastewater Management, the bench scale pilot plant was installed, see figure 2. It consisted of three parallel CSTR (10 l each) kept at mesophilic temperature in a heated water tub. The reactors were continuously stirred by an electric engine. The headspace of the reactors (about 1.5 l) was connected to a gas meter that registers continuously the quantity of biogas produced by displacement. By means of online measurements of air temperature and barometric pressure, the biogas norm volume was calculated continuously on a base of standard conditions. Gas samples are taken from time to time and analysed in a gas chromatograph. The pH is measured three times a week using a sample of influent and effluent.

Weekly, total COD (chemical oxygen demand) and dissolved COD (<0.45µm), VFA (volatile fatty acids), VSS (volatile suspended solids), TOC (total organic carbon), NH₄-N (Nitrogen as Ammonium) and TN (total Nitrogen) were analysed weekly in influent and effluent. Total P and SO₄-S were analysed only in 2-4 spot samples in the influent. All parameters were analysed according to APHA (1995), only COD and NH₄-N were analysed by cuvette tests.

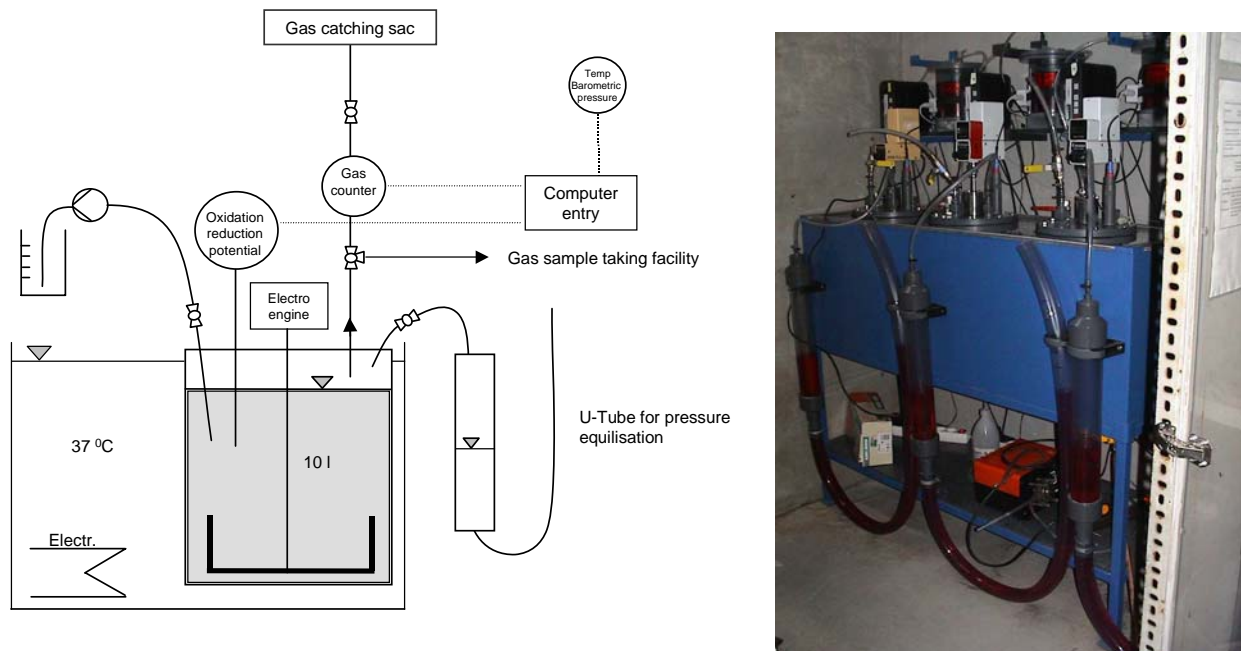


Figure 2 Experimental set-up

Reactor feeding

BW was taken from the housing estate Lübeck-Flintenbreite. It was collected from the storage tank behind the vacuum pumps. KR was collected from the student restaurant at TUHH once in a sufficient quantity. It represented typical fresh KR with about 30% raw and 70% cooked material. It was a mixture of potatoes, pasta, bread, vegetables, salad and meat. The KR was milled at less than 2mm diameter and stored in the refrigerator at 6°C.

Weekly the feeding mixture of BW and KR was prepared and subsequently fed to the reactors or stored in the refrigerator at 6°C until the feeding time. The reactors were fed discontinuously three times per week in case of HRT of 20 and 15 days and six times a week in case of 10 days HRT.

The addition of KR to the BW was done according to statistical German values of 0.2 kg/cap/day. Related to BW, this amounts to 40 g KR per liter BW. The CSTR were started with adapted sludge and the feeding was as shown in table 1.

Table 1 Investigation program divided into 4 phases

Phase	Feeding	HRT	Duration
Phase 1	Raw BW	20 days	413 days
Phase 2	Raw BW + KR	20 days	70 days
Phase 3	Raw BW + KR	15 days	36 days
Phase 4	Raw BW + KR	10 days	54 days

RESULTS AND DISCUSSION

Characteristics of BW, KR and the mixture

Most of samples were analysed of pure BW, table 1 shows the measured concentrations of BW, KR and the mixture, the number of analysed samples and the calculated load per capita and day for each parameter. Compared to typical raw domestic wastewater, BW from vacuum toilets is very homogeneous due to the vacuum system with a pressure of 0.8 bar. Also the KR is well homogenised by the grinder. However, their concentrations are varying highly, especially for the organic parameters like COD, VSS and TOC. These high standard deviations result from the high fraction of solids in the BW and even higher in the KR. The particulate COD in BW represents 72% of the total COD which is in the typical range for domestic and municipal wastewater from 65% -

80% as reported by Wendland et al (2006), Elmitwalli et al (2002) and (Wang 1994).

When adding KR to the BW, the concentration of particulate COD decreases to 65% although it should increase due to the high particulate COD-fraction in the KR of 77%. This difference is assumed to be caused by the fact that there is an immediate start of hydrolysis after mixing of BW and KR and there were up to 24 hours time difference between mixing, sample-taking and analysing.

Table 2 Characteristics of BW, KR and the feeding mixture; concentrations \pm standard deviation and their daily loads

Parameter	Unit	Blackwater (BW) Flintenbreite	Kitchen refuse (KR)	BW+KR
Volume	l/day or g/day	5.0 l/day	200 g/day	5.2 l/day
Total COD	mg/l	8,687 \pm 3,977	335,132	19,152 \pm 6,552
	No of samples	126	3	25
	g/cap/day	43	67	96
Dissolved COD	mg/l	2,440 \pm 653	78,632	6,784 \pm 1,051
	No of samples	22	3	25
	g/cap/day	12	16	34
VSS	mg/l	4,545 \pm 2,676	181,512	8,821 \pm 3,895
	No of samples	126	3	25
	g/cap/day	23	36	44
TOC	mg/l	2,541 \pm 945		5,898 \pm 2,332
	No of samples	126		13
	g/cap/day	13		29
NH₄-N	mg/l	1,115 \pm 143	283	1,148 \pm 109
	No of samples	116	2	25
	g/cap/day	5.6	0.06	5.8
Total N	mg/l	1,500 \pm 246	5,140	1,520 \pm 172
	No of samples	126	2	25
	g/cap/day	7.5	1.0	7.9
Total P	mg/l	202	577	171 \pm 51
	No of samples	3	2	4
	g/cap/day	1.0	0.1	0.9
SO₄-S	mg/l	43		
	No of samples	3		
	g/cap/day	0.22		

Considering the daily loads of BW, the values are 30-45% lower than the loads reported by Larsen & Gujer (1996), Fittschen & Hahn (1998), and Otterpohl et al. (2003) in human excreta. These differences are caused mainly by two facts: First, the housing estate Lübeck-Flintenbreite is a pure living space, the employed persons are not present most of the day. Second, about 40% of the inhabitants are children who produce less excreta and are half-time not at home either, but in kindergarten and at school. In extensive investigations in Swedish housing estates, Jönsson et al (1999) found that only 65% of the human excreta are produced on-site.

The daily loads of KR here are based on average German values but they might be different according to the people's motivation to collect kitchen refuse separately. As statistical data show, the variation of collected KR is naturally higher than the variation of BW.

Performance of CSTR at varying HRT

COD mass balance. Because of the varying concentrations of organic matter in BW and KR, it is important to calculate mass balances to find out the level of error of the experiments. The

calculated COD mass balances for the different conditions are given in figure 3. They are calculated based on the COD loads in each phase after at least one HRT. The COD masses of input and output show a relatively small differences with up to 8% for phase 1 (BW at 20 days HRT) which might be caused by sample-taking-errors and analysis-errors (COD and CH₄).

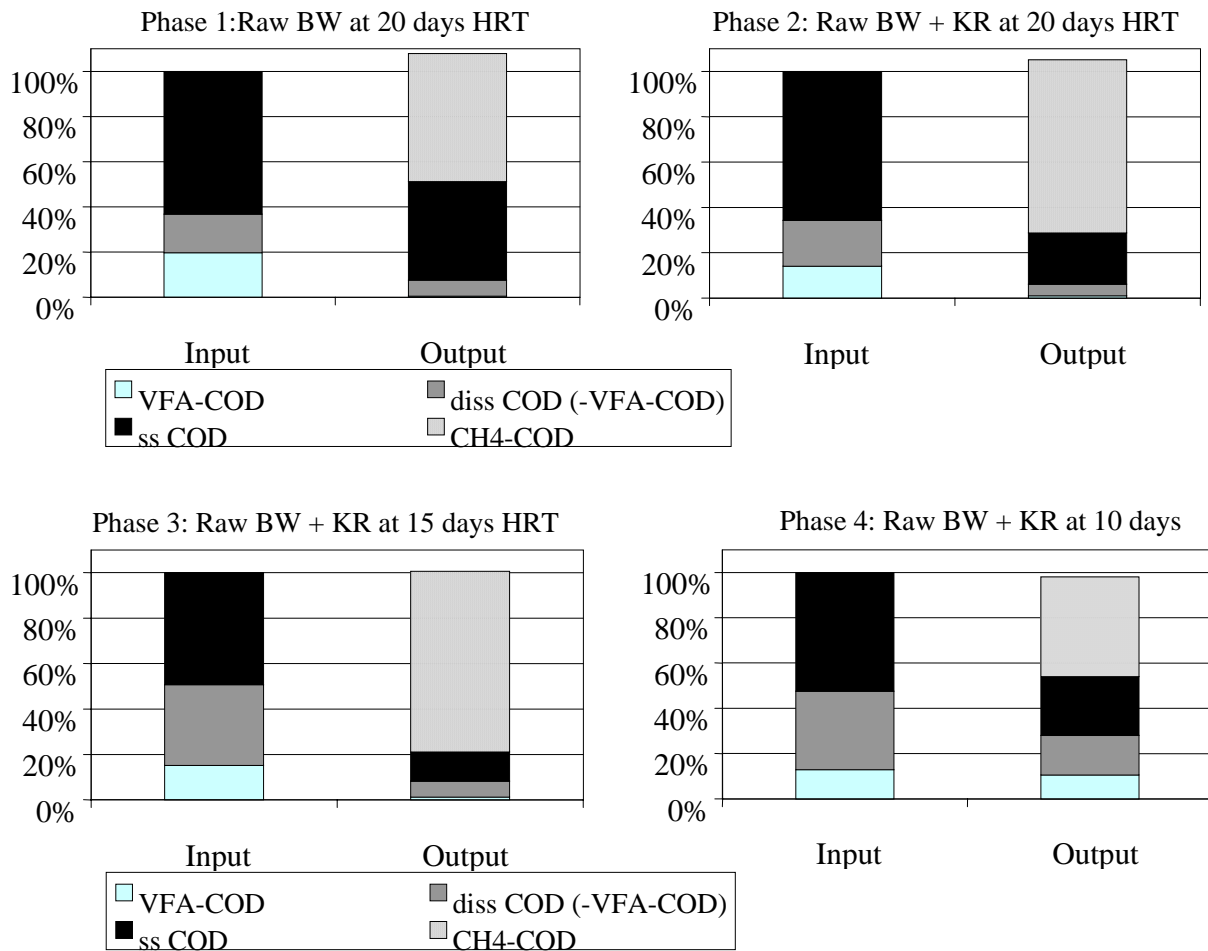


Figure 3 COD mass balances for all phases

Removal of COD fractions. The removal of total and particulate COD is shown in table 3. In BW digestion at 20 days HRT, the removal of total and particulate COD is 61% and 53% respectively. Low VFA concentrations in the effluent prove that, although high nitrogen concentration, the process was stable and uninhibited. When adding KR, the organic load rate increased from 0.5 to 1.0 kgCOD/m³ reactor/day both at 20 days HRT. The removal ratio rose to 71% and 67% for total and particulate COD because of the higher anaerobic biodegradability of KR.

At 15 days HRT, the removal efficiency is with 75% total COD removal even higher whereas the removal of particulate COD stayed at the same level. The increase of total COD removal performance can be explained by a different input load in phase 2 and 3. As seen in figure 3, the particulate COD fraction in phase 3 was much higher (66%) than in phase 4 (49%). Accordingly, the performance of the CSTR at 15 days is equal at 20 days. The good and stable performance of the CSTR at 15 and 20 days HRT was further underlined by the low concentrations of volatile fatty acids (see figure 4). The VFA (as criteria for the stability of the anaerobic process) were varying, but were typically less than 150 mg/l as COD. In BW digestion the pH value was stable around 7.5, as well as in phase 2 with KR addition. In phase 3 the pH slightly decreased to 7.3 but went back to

7.5.

Table 3 Removal efficiency of organic matter and total N at different HRT in % per weight with standard deviation

Parameter	Phase 1 BW (20 days HRT)	Phase 2 BW+KR (20 days HRT)	Phase 3 BW+KR (15 days HRT)	Phase 4 BW+KR (10 days HRT)
Duration	413 days	70 days	36 days	54 days
No of samples	56	9	4	7
Total COD	61 ± 12	71 ± 13	75 ± 7	50 ± 15
Particulate COD	53 ± 24	67 ± 15	67 ± 13	53 ± 22
VSS	51 ± 19	65 ± 20	69 ± 12	51 ± 21
TOC	55 ± 12	72 ± 12	71 ± 29	52 ± 15
NH ₄ -N	-11 ± 14	-14 ± 8	-15 ± 6	-5 ± 10
Total N	Below 2			

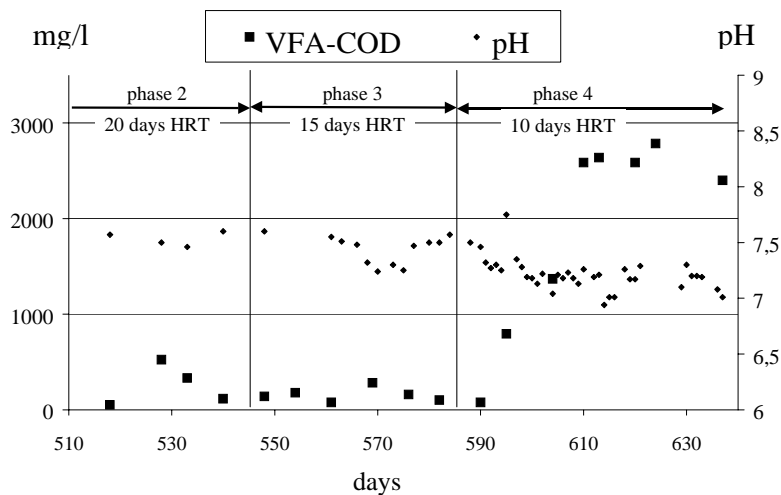


Figure 4 pH and VFA concentration in CSTR with raw BW and KR at different HRT

In the last phase, the HRT is further decreased to 10 days and the organic load rate rose to 2.0 kgCOD/m³_{reactor}/day. There is an increase of VFA up to 2,600 mg/l COD. During 20 days (2 HRTs), the VFA accumulated in the CSTR and kept then constantly at that high level for more than 30 days (3 HRTs). Due to good buffering capacity of BW, the pH did not fall below 7.0 and a steady state process was achieved. The methanogenic activity and thus the COD removal was limited by the low HRT. The COD removal was stable about 50% which is 30-33% less than the removal at uninhibited conditions of 15 to 20 days HRT. Particulate COD removal was about 53%, which is 20% lower than the removal at 15 and 20 days HRT. Thus, also the hydrolysis is partly inhibited at HRT of 10 days. However, these results show that a stable digestion with BW and KR can be realised with major COD removal even at HRT of 10 days.

Removal of VSS and TOC. The parameter VSS and TOC represent the organic matter similar to COD. The VSS is a value for organic SS like particulate COD and the TOC is similar to total COD. The removal efficiency given in table 3 shows that the VSS correlated mainly to the particulate

COD as well as the TOC to the total COD. These values are underlining the results discussed above.

Removal of total nitrogen and ammonium. The analysis of total nitrogen in influent and effluent show that there was no significant nitrogen removal, as it was expected. There was an increase of ammonium of 5-15% in the effluent caused by the conversion of organic nitrogen to ammonium due to protein hydrolysis.

Methane yield. In table 4, there are shown the methane yield related to total COD_{added} and capita and day for the different investigation phases. For BW digestion 240 l/kg COD_{added} which amounts to 10 l CH₄/cap/day based on the COD load found out in Lübeck-Flintenbreite (see table 2). If BW is treated together with KR, the methane yield is 270/280/205 lCH₄/kgCOD_{added} and 27/28/21 lCH₄/cap/day at 20/15/10 days HRT. If it is assumed that only 65% of the produced BW is collected in the housing estate, the expected methane yield for 100% BW collection and treatment can be calculated accordingly (16 l CH₄/cap/day). In case of BW+KR digestion at 15-20 days HRT the expected methane yield is 32-33 l CH₄/cap/day which corresponds well to the methane yield of 35.6 l CH₄/cap/day, respectively, reported by Kujawa-Roeveld et al (2003) for an accumulation digester at longer HRT. The chosen load for BW and KR were similar. The 10% higher methane yield might be due to the longer HRT or indicates that even less than 65% of COD load is collected in Lübeck-Flintenbreite.

Table 4 Methane yield based on the loads of each phase and fraction with standard deviation

	Phase 1 BW (20 days HRT)	Phase 2 BW+KR (20 days HRT)	Phase 3 BW+KR (15 days HRT)	Phase 4 BW+KR (10 days HRT)
Methane yield				
(l CH ₄ /kg COD _{added})	240	270	280	205
(l CH ₄ /cap/day)	10	27	28	21
Expected methane yield based on 100% BW collection and treatment*				
(l CH ₄ /cap/day)	16	32	33	26
Methane-fraction in the biogas (% by weight)	0.76 %	0.65 %	0.65 %	0.65 %

* It is assumed that only 65% of the COD load is produced in Lübeck-Flintenbreite.

CONCLUSIONS

It could be shown that mesophilic anaerobic digestion in CSTR is an appropriate technique to treat high strength BW and BW+KR. Although the composition of BW is not ideal for anaerobic digestion due to high ammonium concentrations, the process at 20 days HRT is very stable. The feeding of the CSTR can be discontinuous (3-6 times per week) but should be regular. By adding KR, the performance of anaerobic treatment is highly improved in terms of COD removal and methane yield. At HRT of 15 and 20 days, a stable and uninhibited process was achieved. Even at HRT of 10 days, a steady state process with a decrease of COD removal of 30-33% and of methane yield of 19-21% could be achieved, however at a higher level of VFA concentration in the effluent. Thus, for designing a CSTR for BW+KR, a HRT of 15 days is recommended, if the influent feeding is regular and the influent load in a common range. In case of higher fluctuating influent loads, e.g. caused by varying kitchen refuse quantity and quality, a HRT of 20 days is recommendable. As expected, nitrogen removal does not take place, but this is not required either. The effluent is

supposed to be used in agriculture, and the contained nutrients can partly replace chemical fertiliser. Fertilising experiments with the effluent of the CSTR showed very good results as quick acting fertiliser in field and greenhouse tests (Simons & Clemens 2004).

For further evaluation of the performance of the CSTR and deepen the knowledge under operation conditions with varying influent quantities and qualities the application of the ADM1 model has recently been started by Feng et al (2005).

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