

Anaerobic Co-digestion of Brown Water and Food Waste for Energy Recovery

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Abstract

The anaerobic digestion of brown water (BW), food waste (FW) and their mixture (MW) in batch digesters was evaluated under mesophilic conditions. BW collected from separating toilets and FW are high strength organic substrates that can be treated in a decentralized reactor via anaerobic digestion. The bio-methane potential of these substrates at different feed/inoculum ratios (F/Is) was studied using 100-mL serum bottles and biogas and methane production, pH and VS reductions were measured periodically to determine the extent of substrate degradation. The feasibility of co-digestion was also investigated to determine if further improvement of biogas yield could be achieved. Preliminary results suggested that BWs and FWs are potential substrates for biogas production. Brown water appeared to be the most biodegradable substrate in this study and its biogas yield was inhibited by the addition of food waste.

Keywords

Anaerobic digestion; food waste; brown water; biogas; co-digestion

INTRODUCTION

Anaerobic digestion (AD) has been widely applied in the treatment of organic wastewaters due to its high degree of waste stabilization and methane generation. Methane is a potentially valuable by-product that can be used as a fuel in producing heat and electricity, and the significance of this advantage is increasingly being emphasized in our energy conscious society. Having a fuel value of approximately 5,850 kg-cal/m³, biogas has been widely used in heating digesters and gas engines (Wang et al., 2007). The anaerobic digestion of food waste and animal manure (El-Mashad and Zhang, 2010; Neves et al., 2008; Ahn et al., 2010) has been extensively studied on while that on human faeces is not as common and extensive. Human faeces collected from toilet systems are known as brown water (without urine) and black water (mixed with urine), and their COD concentrations are dependent on the toilet flushing system. The concentration of black water collected from vacuum toilets ranged between 8.7 – 12.3 gCOD/L (Wendland et al., 2007; Marthe S. de Graaff et al., 2010), while that of brown water was around 38.8 gCOD/L (Elmitwalli et al., 2006). Wastewaters in Singapore are currently being transported long distances to centralized plants for treatment, which consumes too much unnecessary energy and water. An alternative approach would be to treat concentrated wastewaters in a decentralised plant. Source-separated domestic wastewaters tend to be more concentrated and this would improve the potential of energy recovery via anaerobic digestion. There have been some research activities on the AD of black water in rural areas and findings indicated the feasibility of treating human waste in decentralised sanitation systems (Wendland et al., 2007; Kujawa-Roeleveld et al., 2005; Zeeman et al., 2008). However, such research in the urban context has been scarce. With increasing population and concerns over water and fuel shortage, an onsite decentralised and anaerobic treatment of domestic wastewaters in urban cities might provide the sustainable solution. This paper aims to discuss the feasibility of anaerobic co-digestion of high strength domestic wastewaters – namely brown water and kitchen food waste in urban decentralised units



for energy recovery. This paper will describe the anaerobic digestion batch study of brown water and food waste alone, and then the co-digestion of the mixture of these two wastes.

MATERIAL & METHODS

Collection and preparation of inoculum and substrates

Sludge collected from an anaerobic digester at the Ulu Pandan Water Reclamation Plant (designed for domestic wastewater treatment) was used as inoculum in this study. As shown in Table 1, the total solids (TS) and volatile solids (VS) concentrations of sludge were 17.83 ± 0.04 g/kg and 12.52 ± 0.05 g/kg, respectively. Freshly collected sludge was stored at 35°C for one week to remove any remaining biodegradable fraction before using it as inoculum for the batch test. Two different types of organic waste - brown water and food waste were used as substrates in this study. Brown water (fecal waste without urine) mixed with 2 L of flush water was collected from a urine separation toilet located near the university's laboratory and then stored in a refrigerator at 4°C. Food waste used in this study was collected from the university's campus canteen, where the majority of the waste came from Chinese, Indian, Indonesian and Malay food stalls. After removing bones and non-food materials, the food waste was blended into slurry form with an average size of 2.0 mm using a kitchen blender. The blended food waste was then mixed well, and stored in a refrigerator at 4°C. As shown in Table 1, the TS and VS concentrations of brown water were 4.44 ± 0.06 g/kg and 3.77 ± 0.08 g/kg, respectively, and those for food waste were 295.16 ± 1.50 g/kg and 283.45 ± 1.53 g/kg, respectively. All these substrates were stored in a refrigerator at 4°C after collection and used within 7 days.

TABLE 1: Characterization of substrates

Parameter	Units	Brown Water	Food Waste	Sludge
TS	g/kg, wet basis	4.44 ± 0.06	295.16 ± 1.50	17.83 ± 0.04
VS	g/kg, wet basis	3.77 ± 0.08	283.45 ± 1.53	12.52 ± 0.05
pH		6.70	4.40	6.90
COD-total	g/L	8.16 ± 0.56	394.10 ± 13.80	14.71 ± 0.07
TOC	g/kg	471.40 ± 10.58	323.92 ± 16.59	377.75 ± 13.51
TN	g/kg	9.75 ± 0.35	1.12 ± 0.18	7.64 ± 0.71

Experimental design and set-up

The batch digestion tests were carried out using 100mL reactors (with 70mL working volume) at mesophilic temperature (35°C) for a period of 21 and 30 days. In each reactor, 14mL of inoculum (20% v/v) was added to 56mL of substrate diluted with tap water to achieve the desired VS load. The head space of all the reactors was purged with nitrogen gas for thirty seconds to create anaerobic conditions before the reactors were tightly closed with rubber septa and screw caps. Three blank reactors that contained only inoculum and tap water were also set up to monitor the biogas produced from the inoculum for the correction of biogas produced from the substrates under study. A total of ten reactors were set up for each condition and the contents were analysed periodically for pH, VS reductions and VFA by sacrificing two reactors each time. To ensure even mixing between substrate and inoculum, the reactors were placed on a shaker with speed 120 rpm throughout the study period. Four different conditions as shown in Table 2, (VS loading from 0.3g VS/L to 2.5g VS/L) were carried out for the batch study of brown water and food waste. For the co-digestion experiment, four different conditions were

designed, with brown water and food waste mixed in different proportions. Mixtures A, B and C had VS loading of 1g VS/L while mixture D had VS loading of 2g VS/L. The brown water to food waste ratio for mixtures A, B, C and D were 1:1, 3:7, 7:3 and 1:1 respectively.

Analytical methods

TS, VS, total chemical oxygen demand (TCOD) and soluble chemical oxygen demand (SCOD) were measured in the well-mixed samples in triplicates by standard methods (APHA, 1998). The pH value was measured using a pH meter (CORNING 145, England). The organic carbon and nitrogen content of substrates and sludge was determined using a Total Organic Carbon/Nitrogen Analyzer multi N/C 2100/ 2100s (Analytikjena). Samples were oven dried at 105°C for 2 hours before the addition of concentrated HCl to remove the inorganics. Approximately 20mg of the sample was analyzed and each sample was tested in triplicates. The determination of VFA was carried out using gas chromatography and the samples were filtered through Whatman 0.2µm nitrocellulose membrane filters. Biogas production was monitored daily using a syringe, while the biogas composition (methane and carbon dioxide contents) was analyzed by gas chromatography (GC) (HP5890A, HACH, Avondale, PA, USA) which was equipped with a thermal conductivity detector (TCD). Helium was used as carrier gas at a flow rate of 40 mL min⁻¹. The measurements were done at least once a week for each reactor. Biogas samples injected into the GC were extracted from the reactors head space after releasing the gas, using a 100-µL gas tight syringe (Fisher Scientific, Pittsburgh, PA, USA).

Data processing

Since the biogas production rates and methane content of the substrates vary considerably over the digestion period, the weighted average methane content (WA) and standard deviation (STDV) over the digestion period was calculated using the method as described by (El-Mashad and Zhang, 2010) as follows:

$$WA (\%) = \frac{\sum_{i=1}^n DBP_i \times MP_i}{\sum_{i=1}^n DBP_i}$$

$$STDV = \sqrt{\frac{\sum (MP_i - WA)^2}{n-1}}$$

where:

DBP_i = biogas production on day i,

MP_i = methane content on day i,

n = number of observations.

RESULTS AND DISCUSSION

Anaerobic digestion of brown water

A summary of the weighted average methane content, biogas and methane yields and VS reduction of brown water at different F/I after 21 and 30 days of digestion are shown in Table 2. The average biogas yields and rates during the 30-day anaerobic digestion of brown water are also shown in Figs. 1a and 1b. As shown in Fig. 1a, BW3 with F/I of 0.40 produced the highest biogas yield, as compared to brown water with other F/Is. The biogas yield after 30 days was calculated to be 762, 736, 916, and 754 L/kg VS_{added} and approximately 88%, 93%, 96%, and 98% of the final biogas yield for BW1, BW2, BW3 and BW4 respectively, could be obtained after 21 days of digestion. With weighted average methane contents of 70%, 73%, 73% and 78%, the average methane yield after 30 days of digestion was 537, 535, 672 and 587 L/kg

VS_{added} and 88%, 92%, 96% and 98% of the final methane yield for BW1, BW2, BW3 and BW4 respectively, could be obtained after 21 days of digestion. Although BW4 had the highest methane content at 78% (Table 2), the methane yield of BW3 was still higher than the others.

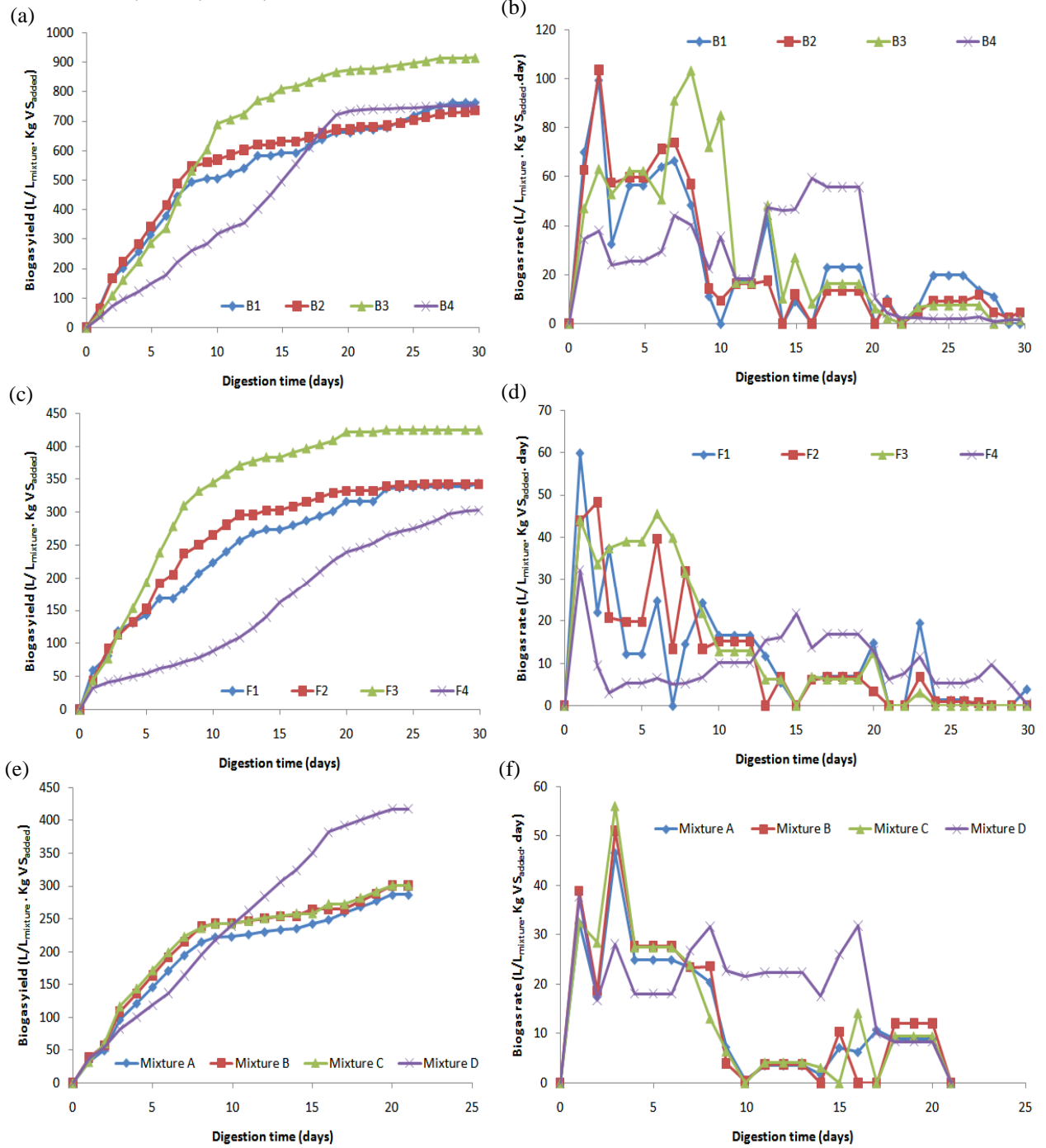
Throughout the 30 days of anaerobic digestion, the pH value of reactor content was determined periodically, as shown in Fig. 2a. The pH of brown water at all F/Is showed a similar trend. After 6 days of digestion, the pH value of BW1, BW2, BW3 and BW4 dropped from 7.21, 7.06, 6.94 and 6.76 to 6.51, 6.56, 6.48 and 6.29 respectively. After that, the pH recovered slightly and was raised to the range of 6.53 to 6.63 for all four sets after 12 days of digestion. The pH remained constant for the next 7 days but increased further to 6.78, 6.83, 6.77 and 6.95 respectively after 23 days of digestion. The final pH measured after 30 days of digestion dropped slightly to 6.69, 6.67, 6.67 and 6.86 respectively.

The average VS reductions after 30 days of digestion were calculated to be 49%, 55%, 55% and 60% and after 21 days of digestion, approximately 96%, 96%, 95% and 90% of the final VS reductions for BW1, BW2, BW3 and BW4, respectively could be obtained.

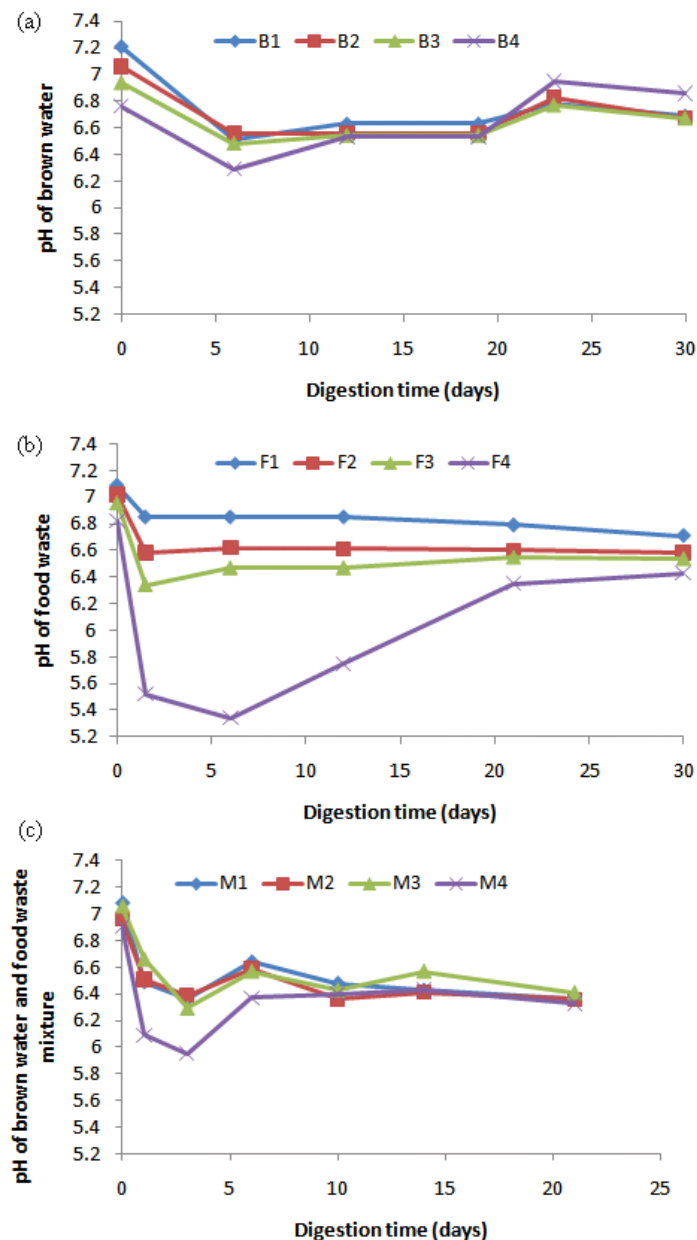
TABLE 2: Results of batch anaerobic digestion of brown water, food waste and their mixture

Initial VS Loading	F/I	CH ₄ content		Biogas yield		CH ₄ yield		VS reduction		
		(%)		(L/kg VS _{added})		(L/kg VS _{added})		(%)		
		21 days	30 days	21 days	30 days	21 days	30 days	21 days	30 days	
<u>Brown water (BW)</u>										
BW1 - 0.3gVS/L	0.12	69.91	70.38	672	762	470	537	47.27	49.10	
BW2 - 0.5gVS/L	0.20	72.60	72.66	681	736	494	535	52.97	55.32	
BW3 - 1.0gVS/L	0.40	73.36	73.35	876	916	642	672	52.62	55.35	
BW4 - 2.5gVS/L	1.0	77.95	77.82	738	754	575	587	53.30	59.53	
<u>Food waste (FW)</u>										
FW1 - 0.3gVS/L	0.12	72.77	72.85	316	343	230	250	44.16	45.44	
FW2 - 0.5gVS/L	0.20	66.58	66.74	333	343	221	229	27.60	28.91	
FW3 - 1.0gVS/L	0.40	67.74	67.77	421	425	286	288	59.17	59.72	
FW4 - 2.5gVS/L	1.0	54.78	57.30	246	303	135	173	41.32	43.33	
<u>Mixture</u>										
	<u>BW:FW</u>									
MW1 - 1.0gVS/L	1:1	0.40	74.08	*n.d.	287	*n.d.	212	*n.d.	16.94	*n.d.
MW2 - 1.0gVS/L	3:7	0.40	71.16	*n.d.	301	*n.d.	217	*n.d.	26.85	*n.d.
MW3 - 1.0gVS/L	7:3	0.40	72.45	*n.d.	301	*n.d.	220	*n.d.	28.35	*n.d.
MW4 - 2.0gVS/L	1:1	0.80	68.24	*n.d.	417	*n.d.	287	*n.d.	33.47	*n.d.

*n.d. = not determined



Figs. 1a-f: (a) and (b) biogas yield and rate of brown water, (c) and (d) biogas yield and rate of food waste, (e) and (f) biogas yield and rate of mixtures of brown water and food waste.



Figs. 2a-c: (a) pH profile of brown water, (b) pH profile of food waste, (c) pH profile of mixtures of brown water and food waste.

Anaerobic digestion of food waste

Exactly the same conditions were designed for the anaerobic digestion of food waste. A summary of the weighted average methane content, biogas and methane yields and VS reduction of food waste at different F/Is after 21 and 30 days of digestion are shown in Table 2. The average biogas yields and rates during the 30-day anaerobic digestion of food waste are also shown in Figs. 1c and 1d. The biogas yield after 30 days was calculated to be 343, 343, 425 and 303 L/kg VS_{added} and approximately 92%, 97%, 99% and 81% of the final biogas yield for FW1, FW2, FW3 and FW4 respectively could be obtained after 21 days of digestion. With weighted average methane contents of 73%, 67%, 68% and 56%, the average methane yield after 30 days of digestion was 250, 229, 288 and 173 L/kg VS_{added} and approximately 92%, 97%, 99% and 78% of the final methane yield for FW1, FW2, FW3 and FW4 respectively could be obtained after 21 days of digestion. Similar to brown water, food waste with F/I of 0.40 produced the highest biogas and methane yield. As compared to brown water with F/I of 0.40, the biogas and

methane yield for food waste with F/I of 0.40 was 54% and 57% lesser respectively, suggesting that brown water is a more biodegradable substrate as compared to food waste. As shown in Table 2, biogas yield increased with increasing F/I in the range of 0.12 to 0.40 due to the greater availability of substrate. When F/I was raised to 1.0, biogas yield decreased, indicating the possibility of substrate overloading, resulting in some inhibition of methanogenic bacteria due to VFA accumulation.

The initial pH value of food waste with different F/Is ranged from 6.82 to 7.09. Other than food waste with F/I of 1.0 (FW4), the pH of FW1, FW2 and FW3 remained relatively constant at around 6.81, 6.60 and 6.47 respectively from day 2 until the end of the study. The pH of FW4 dropped sharply from 6.82 to 5.52 after 2 days and dropped further to 5.34 after 6 days of digestion. The measured pH on day 12 increased to 5.75 and it continued to increase until the end of the digestion period to 6.43. The significantly lower biogas and methane yield of FW4 (Fig. 1c and Table 2) could be accounted for by the large drop in pH, causing the inhibition of methanogenic bacteria. In comparison with brown water, the pH values of food waste mixtures did not recover as much after 21 days of digestion.

The average VS reductions after 30 days of digestion were calculated to be 45%, 29%, 60% and 43%, and after 21 days of digestion, approximately 97%, 95%, 99% and 95% of the final VS reductions for FW1, FW2, FW3 and FW4 respectively could be obtained. For food waste at all F/Is, the VS reduction percentages and biogas yields followed the same trend.

In general, the weighted average methane content, biogas yield and VS reductions of food waste mixtures were lower than that of brown water (Table 2). As majority of the food waste collected came from Chinese, Indonesian, Indian and Malay food stalls, the food waste contained large amounts of gravy, fats and salts. Hence, these complicated food components could have brought about some inhibitory effects on the methanogens (Cho et al., 1995), leading to lower biogas and methane yield as compared to brown water with similar F/I. Long chain fatty acids that are present in food with high fat content and in food preservatives have inhibitory effects on methanogenic bacteria. Further studies on the effect of the complicated composition of food waste on biogas yield and process stability are required.

In comparison with the batch anaerobic digestion of food waste under mesophilic conditions reported by other authors, the biogas yield in this study appeared to be much lower. El-Mashad et al. reported an average biogas yield of 657 L/kg VS_{added} from a 2gVS/L food waste with F/I of 0.19 (El-Mashad and Zhang, 2010). In this study, FW2 with a similar F/I of 0.20, produced only 343 L of biogas/kg VS_{added}. Even at a much higher loading (F/I of 3.1), (Liu et al., 2009) reported an average biogas yield of 430 L/kg VS_{added} from a 12.5gVS/L food waste mixture.

Anaerobic co-digestion of brown water and food waste

Since approximately 90% of the VS reductions, biogas and methane yields could be obtained after 21 days of digestion, as seen from the results of brown water and food waste (Table 2), the digestion period for the mixture of brown water and food waste was reduced to 21 days. The anaerobic digestion of mixed waste (F/I of 0.40) with three mixing ratios based on VS was carried out to study the effect of brown water and food waste mixing ratio on the biogas and methane yield. The anaerobic digestion of MW4, which had the same mixing ratio as MW1 but two times its VS concentration, was carried out to study if biogas and methane yield will improve when VS loading increased to more than 1gVS/L (the organic loading for MW1, MW2 and MW3).

A summary of the weighted average methane content, biogas and methane yields and VS reduction of mixed waste at different mixing ratios after 21 days of digestion are shown in Table 2. The average biogas yields and rates during the 21 days of digestion are shown in Fig. 1e and 1f. After 21 days of digestion, the biogas yield was calculated to be 287, 301, 301 and 417 L/kg VS_{added} for MW1, MW2, MW3 and MW4 respectively. With an average methane content of 74%, 71%, 72% and 68%, the methane yield was calculated to be 212, 217, 220 and 287 L/kg VS_{added} respectively. As shown in Fig. 1e, the biogas yield of MW1, MW2 and MW3 showed no significant difference, indicating that the mixing ratio of brown water and food waste did not affect the biogas yield. On the other hand, increasing the F/I from 0.40 to 0.80 improved the biogas yield by approximately 70%, as shown by MW4 in Fig. 1e. This is in contrast to the results obtained from brown water or food waste alone whereby the biogas yield started to drop when F/I was increased beyond 0.40.

The addition of food waste did not improve the biogas yield of brown water. Instead, the biogas yield was affected negatively when food waste was introduced to the anaerobic digestion of brown water. Comparing FW2 with MW1, MW2 and MW3, where all had the same amount of food waste added (0.5gVS/L), showed that their biogas yield after 21 days of digestion were similar at 333, 287, 301 and 301 L/kg VS_{added} respectively.

The pH values of the brown water and food waste mixtures were in the range of 6.91 to 7.08 before the start of digestion and dropped to the range of 6.33 to 6.41 after 21 days of digestion (Fig. 2c).

In general, there were no lag phase and biogas production started after the first day of digestion for all substrates and conditions studied (Fig. 1b, 1d, 1f). Multiple peaks in biogas production rates were observed throughout the 30-day digestion period.

CONCLUSIONS

The biogas and methane yields of brown water, food waste and their mixture at different F/Is using an anaerobic batch digester at $35 \pm 2^\circ\text{C}$ were determined in this study. The batch digestion tests for brown water and food waste were performed for 30 days to achieve complete digestion. Since about 90% of the final biogas yield and VS reductions from brown water and food waste could be obtained after 21 days of digestion, the digestion period of the subsequent study on the mixture of brown water and food waste was reduced to 21 days. At a F/I of 0.40, the biogas yields obtained for brown water, food waste and their mixtures were 876, 421 and approximately 300 L/kgVS_{added} respectively after 21 days of digestion. As brown water produced the highest biogas yield, highest methane content in the biogas produced, and highest average VS reduction (Table 2), it appeared to be more biodegradable than food waste. The biogas yield of brown water was also inhibited by the addition of food waste, as shown by the biogas yields produced by mixtures of brown water and food waste (Fig 1e). The feasibility study of co-digesting brown water and food waste revealed that their biogas yields were lower than that obtained from brown water or food waste alone (with the same F/I), which could be due to some inhibition effects brought about by food waste. As it would be both economically and environmentally advantageous for such a co-digestion process to take place in decentralised anaerobic digesters, further studies should be carried out to investigate the effect of intermediates such as volatile fatty acids on biogas yield and digestion performance.

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