Faeces and food waste co-digestion for development of decentralised urban resource recovery in Singapore

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Abstract
As the core technology of decentralised urban resource recovery system, the objective of this study was to evaluate the feasibility of anaerobic co-digestion of faeces (brown-water, BW) and food-waste (FW). Batch assay indicated that anaerobic co-digestion (BW+FW) showed higher methane yield (0.54–0.59 LCH_4/gVS_{added}) than BW and FW alone. Anaerobic co-digestion was subsequently performed in a mesophilic (33°C) semi-continuously fed laboratory-scale two-phase CSTR reactors. No obvious lag phase was observed in the start-up period. During the 120-days of operation, CODs, CODt, VS removals were ranged of 75.9–93.4%, 51.9–69.6% and 63.4–69.4%, respectively, with methane yield of approximate 0.4 LCH_4/gVS under 16–20 days HRT conditions. Microbial analyses suggested that *Lactobacillus* and *Acetobacter* were important for initial degradation of BW+FW in the acidogenic reactor, while a complex bacterial populations and methanogens (*Methanosaeta* and *Methanosarcina*) were found in the methanogenic reactor. The overall positive findings show the great potential of applying anaerobic co-digestion of BW+FW for energy production and waste management. Decentralized, source-separation, and anaerobic co-digestion of BW+FW is expected to provide a practical solution for those countries experiencing rapid urbanization and water shortage issues, such as Singapore.

Keywords
Anaerobic co-digestion; faeces; brown water; food waste; decentralised

INTRODUCTION

Municipal solid waste management is critical for highly urbanized country lacking primary natural resources such as Singapore. The decentralised treatment of separating different type of wastewaters represents a sustainable and future solution (Elmitwalli et al., 2006). In Singapore, a decentralized urban resource recovery system has been developing to provide an alternate solution to current centralized urban waste management for sustainable urban living. An innovative No-Mix Vacuum Toilet (a low-flush, no-mix toilet) has been designed primarily to separate faeces (brown water, BW) and urine (yellow water) in order to facilitate resource recovery. This system will reduce 90% of "black water" generated, and provide concentrated substrates for subsequent processes. The collected urine can be properly treated for nutrients (nitrogen and phosphorus) recovery for fertilizer or soil amendments. Due to the high organic contents, the collected BW would be used for energy (biogas) recovery. Additionally, food waste (FW) is another remarkable urban organic waste as according to the waste statistics from Singapore's National Environment Agency (NEA), the annual generation of FW was 605,800 tonnes in 2011 and only 10% of FW was recycled.

The aim of this paper was to evaluate the technical feasibility of anaerobic co-digestion of BW and the FW, including (1) biomethane potential of co-digestion of BW and FW; (2) performance of laboratory-scale two-phase bioreactors; and (3) microbial populations in the reactors.

MATERIALS & METHODS

Feedstock and sludge source

FW (i.e., meat, rice, noodles, vegetables and salad) was collected from one of the University's canteens. After removing bones, fruit peels, egg shell and non-food materials, FW was blended to promote homogeneity of the substrate (within ≤ 0.2 cm) as well as disintegration of particulate organics, with water content around 70–80%; subsequently stored at 4°C. For BW, it was collected from a designed source-separation toilet located in our laboratory, where urine and BW was collected in separate tanks. BW used in this study was faecal mixed with 2 L of flush water per times. Collected BW was stored at 4°C. The characteristics of BW, FW and their mixture were shown in Table 1. Inoculated sludge was obtained from an anaerobic digester at UluPandan Wastewater Treatment Plant (Singapore), which contained TS (1.77 g/kg), VS (1.25 g/kg) and pH 6.9, respectively.

Table 1. Characteristics of brown water and food waste.

	Brown water (BW)	**Food waste (FW)**	**Feed mixture (2 L BW + 150 g FW)**
TS (g/L)	4.44 ± 0.06	295.78 ± 1.16	15.54± 1.58
VS (g/L)	3.77 ± 0.08	283.45 ± 1.53	14.13± 1.26
VS/TS (%)	84.90	95.80	90.90
pH	6.50±0.20	4.4 ±1.50	6.21± 0.42
CODt (g/L)	8.22±0.61	394 ±14.00	28.15± 6.81
CODs (g/L)	8.55±0.64	78.67±7.34	6.45 ± 1.62
TOCs (g/L)	2.490±0.13	34.40±5.12	2.74 ± 1.00

Biochemical methane potential (BMP)

Bench-scale experiments for determining the anaerobic biodegradability and ultimate methane (CH_4) potential of BW, FW and BW+FW mixture were carried out by using Automatic Methane Potential Test System (AMPTS) (Bioprocess Control, Sweden). Each reactor was mechanically stirred (mixing time: 1 min ON/1 min OFF) at 80 rpm (rotation per minute) and incubated at 35 ± 1^{o}C.

Laboratory-scale reactors

A semi-continuously fed laboratory-scale reactors two-phase CSTR system was set up and operated at 33 ± 1^{o}C. It consists of acidogenic reactor of 1.2 L (working volume) followed by methanogenic reactor of 4.1 L (working volume). A ratio of 150 g KW + 2 L BW (in accordance with the amount of waste generated per person per day in Singapore) was used to feed the reactor once daily. It contents were mixed continuously (mixing time: 5 min ON/5 min OFF) at 80 rpm using an overhead mechanical stirrer. Methanogenic reactor was fed with the effluent from the acidogenic reactor. The reactors were inoculated with anaerobic sludge (50% by v/v). Total solids (TS), volatile solids (VS), total chemical oxygen demand (CODt), soluble chemical oxygen demand (CODs) and, soluble total organic solids (TOCs) were measured during operation.

Microbial analyses

Genomic DNA from the acidogenic reactor was extracted using a chemical lysis and followed by phenol-chloroform-isoamyl alcohol purification, and it was used for PCR amplification with 16S rRNA gene universal primer set 530F and 1490R. A clone library was constructed with TOPO TA cloning kit (Invitrogen, CA) according to the manufacturer's instruction. Individual clones showing unique digested pattern of RFLP were subsequently selected for sequencing analysis.

RESULTS AND DISCUSSION

Biochemical methane potential (BMP)

The methane production during the 30 days batch incubation per batch reactor per gVS_{added} for BW, FW and BW+FW mixture was shown in Fig. 1. Methane production rate was significantly better for the BW+FW mixture (with a maximum methane yield of 0.56–0.59 L CH_4/gVS_{added}) than individual FW and BW in non-mixture conditions (an average value of 0.40–0.42 and 0.26–0.30 L CH_4/gVS_{added}, respectively). No lag phase or inhibition phenomena were observed in the experiments, and biogas production was nearly over within the first 10 days of incubation period. Anaerobic biodegradability was higher for the BW+FW mixture with 94% of CODs removal efficiency measured on day 30. From the results, it can be seen that co-digestion increased the biogas production rates and also improved the total biogas production. Nayono et al. (2010) reported that addition of FW had improved the biogas production, most probably due to its higher lipid content.

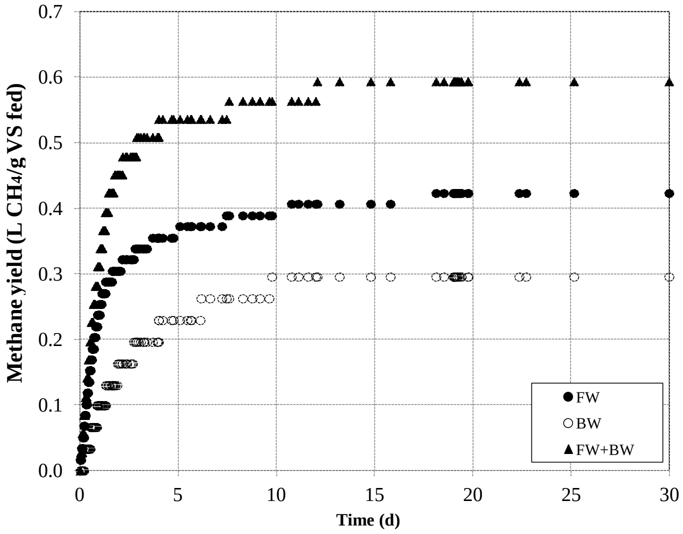

Figure 1. Biochemical methane potential for BW, FW and BW+FW mixture.

Reactor performance

Long HRT and an appropriate inoculum at the start-up of reactor operation allowed for a high-stabilization of organic matter removals (Table 2). In the first 40 days of operation (HRT was maintained at 19–20 days), which were acidogenic (4 days) and methanogenic (16 days). From day 41 onwards, the HRT was reduced to about 16 days, which corresponded to 2–3 and 13–14 days of HRT for the acidogenic and methanogenic reactors, respectively. However, a decrease in HRT resulted to a drop in the performance of methanogenic reactor in terms of pH drop and VFA accumulation (data not shown) probably due to the washout of active biomass. To recover the digester performance or to avoid further acidification, on day 96, HRT was increased back to 16–17 days for the methanogenic reactor, which corresponded to 20 days HRT for the entire two-phase CSTR system. Towards the end, the obtained effluent quality corresponded to a CODt removal efficiency of 68.4 ± 6.4, while the CODs removal in 75.9 ± 1.1. An average methane yield of about 0.4 LCH_4/gVS was recorded during this operation period. Methane content of 50–60% was observed in the total biogas.

Table 2. Reactor performance of two-phase CSTR system.

Time	HRT	Removal Efficiency (%)					Methane Yield (LCH_4/gVS_{fed})
		CODt	CODs	TS	VS	TOCs	
0–40	20–19	51.9 ± 11.7	93.4 ± 3.9	61.3 ± 5.6	69.4 ± 5.3	—	—
41–95	16	69.6 ± 11.0	84.2 ± 13.5	57.6 ± 8.1	63.4 ± 8.9	63.2 ± 9.0	0.40
96–120	20	68.4 ± 6.4	75.9 ± 1.1	62.7 ± 0.4	68.6 ± 2.0	65.5 ± 4.3	

Microbial analyses

16S rRNA gene clone-sequencing analysis suggested, the dominant bacteria in the acidogenic reactor were related to the members in *Firmicutes* (*Lactobacillus*) and *Proteobacteria* (*Acetobacter*). In the methanogenic reactor, more diverse bacterial populations were found including *Bacteroidetes*, *Firmicutes*, *Proteobacteria*, *Chloroflexi*, *Fusobacteria*, *Spirochaetates*, *Verrucomicrobia*, *Acidobacteria*, and *Thermotogae*. Additionally, both aceticlastic methanogens *Methanosaeta* and *Methanosarcinacea* populations were observed in methanogenic reactor.

CONCLUSION

This study shows the great potential of anaerobic co-digestion of BW+FW for energy production and waste management, and "decentralized and source-separation-based sanitation concepts" can eventually be introduced to other mega cities around the world.

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