

# Semi-continuous anaerobic digestion of food waste using a hybrid anaerobic solid–liquid bioreactor

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**Abstract** A hybrid anaerobic solid-liquid (HASL) bioreactor was developed to enhance food waste conversion. The HASL bioreactor is a modified two-phase anaerobic digestion system with a solid waste reactor and a high-rate anaerobic wastewater reactor, which was a UASB reactor. In this study, the methanogenesis in the UASB reactor was investigated under a semi-continuous operation of the food waste digestion system. The HASL process, including 7 days of start-up and 23 days of semi-continuous operation followed by 6 days of batch operation, was commenced by loading 2.8 kg of shredded food waste. During the semi-continuous operation, 0.2 kg of the same waste was loaded daily. The leachate from acidification phase, i.e., solid waste reactor, remained acidic (pH 4.9–5.5) and high in total VFA (TVFA), 9,500–11,500 mg/L, and COD (8,000–11,800 mg/L) levels. In the methanogenesis phase, i.e., UASB reactor, effective TVFA and COD removals ( $88 \pm 5\%$  and  $85 \pm 7\%$ , respectively) were obtained, while the methane content was 71%. At the end of operation, about 78% of VS added in the HASL bioreactor was removed, while TOC and total COD reductions were 78% and 79%, respectively. The results showed that the use of UASB reactor in the semi-continuous HASL system can enhance the methanogenesis process and increase the methane content in biogas production.

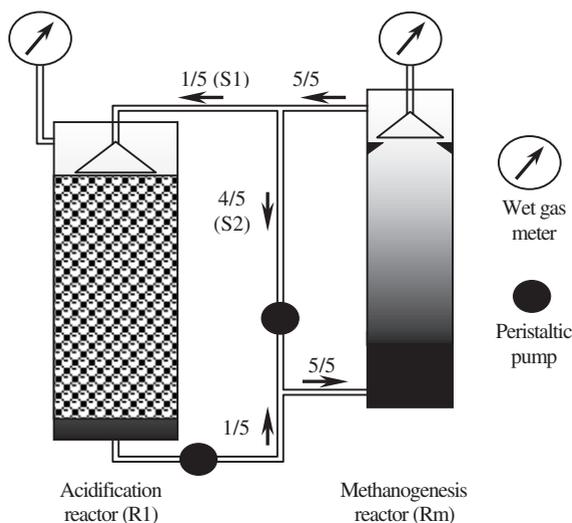
**Keywords** Anaerobic digestion; food waste; hybrid anaerobic solid–liquid bioreactor; methanogenesis; UASB

## Introduction

Food waste is a highly biodegradable component of municipal solid waste (MSW). In Singapore, food waste contributes about 40% (or 1.1 million tonnes per year) of the total MSW collected for treatment and disposal, but its recycling rate is as low as 1.0% (ENV, 2000). With land scarcity, rising cost of refuse disposal and low efficiency of food waste incineration, an alternative food waste treatment and disposal is hence needed. As the regulations for disposing of MSW in incineration plants and landfills are getting more stringent, anaerobic digestion provides a new way of thinking for waste management.

Anaerobic digestion is an attractive technology for the treatment of the organic fraction of MSW due to its economic advantages (Barlaz *et al.*, 1992; Cecchi *et al.*, 1992). It reduces the volume of solid waste, generates saleable biogas (mainly methane) for energy recovery, and produces organic residue that can be used as soil conditioner/fertilizer. Anaerobic digestion consists of a series of biological processes. Complex organic substrates are first metabolized by non-methanogenic bacteria to produce fermentation intermediates, mainly volatile fatty acids (VFAs). These intermediates are then degraded by the methanogenic bacteria to methane and carbon dioxide (Thiele and Zeikus, 1988).

Previous studies demonstrated that: (i) mixing MSW with sewage sludge has the advantages of inoculation of the active bacteria and improvement of pH buffering capacity of the digestion system (Diaz and Trezek, 1977); (ii) leachate recycling increases the digestion rate by means of increasing moisture moving through the digestion system and accelerating the stabilization of waste (Pohland, 1980; Reinhart, 1996); and (iii) separating anaerobic process into two phases, i.e., acidification and methanogenesis phases, facilitates the optimal growth for non-methanogenic and methanogenic bacteria (Pohland and Ghosh, 1971).



**Figure 1** Schematic of the batch HASL bioreactor

Based on these considerations, a hybrid anaerobic solid–liquid (HASL) bioreactor for solid waste digestion was developed recently (Xu *et al.*, 2001). The HASL bioreactor, which is schematically shown in Figure 1, is an enhanced two-phase system with a leachate recycle reactor as the acidification phase and an upflow anaerobic sludge blanket (UASB) reactor as the methanogenesis phase. The preliminary results on batch operation showed the feasibility of the HASL bioreactor system for solid waste digestion (Xu *et al.*, 2001).

The objectives of this paper were: (i) to develop a semi-continuous HASL bioreactor; (ii) to study the anaerobic digestion of food waste with methanogenesis in a UASB reactor; and (iii) to investigate the acidification and methanogenesis processes in semi-continuous HASL operation.

## Materials and methods

### Feedstock, seed sludge and UASB granular sludge

The food waste was collected from a canteen of the university. It contained the food components associated with food preparation such as residual fruits, vegetables, eggshell, and spoiled noodles. The waste was shredded into particles with average size of 6.0 mm. The moisture content was 90%, and the volatile solids (VS) content was 90% of total solids (TS).

The seed sludge was collected from a sludge anaerobic digester of the Ulu Pandan Water Reclamation Plant in Singapore. Its suspended solid (SS) and volatile suspended solid (VSS) concentrations were 4.6 g/L and 3.1 g/L, respectively.

The mature sludge granules adapted to VFA wastewater were from a 5-L UASB reactor. Prior to the HASL operation, the methanogenesis reactor (Rm), which was inoculated with 1.0 litre of the granular sludge, had been run for one week with 5,000 mg COD/L of the synthetic wastewater and 10.0 g COD/L/day of organic loading rate (OLR) as the influent (Teo *et al.*, 2000). In this one-week UASB operation, an effluent of less than 500 mg COD/L (COD removal efficiency was more than 90%) and an average CH<sub>4</sub> content of biogas of 75% indicated that Rm had been active in methanogenesis.

### Reactor set-up

As an enhanced two-phase system, the HASL bioreactor is distinctive from a conventional two-phase process with a UASB reactor as the methanogenesis phase and a circulation of

treated leachate between the acidification and methanogenesis phases. The HASL system used in this study, which was operated in a temperature-controlled room at  $35 \pm 1^\circ\text{C}$ , consisted of a semi-liquid recycling reactor with an effective volume of 4.5 L as the acidification reactor (R1) and a UASB reactor with a working volume of 3.0 L as the methanogenesis reactor. R1 was filled with 2.8 kg of shredded food waste on day 0 and inoculated with 1.0 L of seed sludge. From day 8 to day 30, 0.2 kg of food waste was added to R1 daily.

### Experimental design

The HASL process was commenced when Rm was coupled to R1 on day 0, and operated for start-up in batch mode, as described previously (Xu *et al.*, 2001). From day 8 to day 30, the HASL process was in its semi-continuous mode, where R1 was rotated by  $180^\circ$  daily immediately after the addition of 0.2 kg of food waste per day. The daily rotation of R1 was to mix the fresh waste with R1 liquid phase (seed sludge/leachate). From day 31 to day 36, the HASL bioreactor was operated in batch mode, without daily feedstock addition, for further treatment of R1 leachate and digestion residue.

During the whole HASL process, R1 leachate was 5 times diluted with Rm effluent. The mixture, as a new influent, was fed into Rm. Rm effluent was divided into two streams, S1 and S2, and the flow rate ratio of S1 and S2 was 1:4. With the set-up, S1 was circulated to R1, while S2 was used to dilute R1 leachate and then pumped back into Rm, as illustrated in Figure 1. The flow rates of S1 and S2 changed according to the COD concentrations in R1 leachate and Rm effluent in order to keep an optimal Rm influent concentration of less than 5,000 mg COD/L and an OLR of less than 10.0 g COD/L/day.

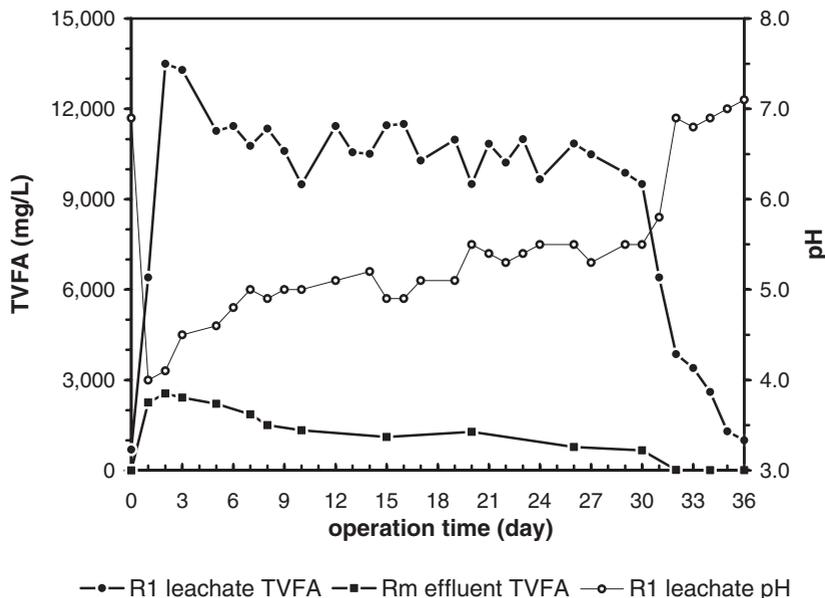
### Measurement methods

R1 leachate and Rm effluent samples were taken daily from their outflow ports from day 0 to day 36. The pH, COD and VFA levels of the samples were determined (Xu *et al.*, 2001). Biogas production and methane content were monitored daily by wet gas meter (Ritter TG 05, GmbH) and gas chromatography (Hewlett Packard 5890 series II), respectively (Tay *et al.*, 2000).

### Results and discussion

With a total loading of 7.4 kg of food waste, the HASL bioreactor in this study was run for 7 days of start-up and 23 days of semi-continuous operation followed by an additional 6 days of batch operation. The HASL process was commenced immediately when acidification reactor R1 was coupled to methanogenesis reactor Rm. The leachate from R1, containing high concentration of VFAs, was carried over to the UASB reactor Rm after dilution, where the VFAs were converted into methane and carbon dioxide. A performance profile for 36 days of HASL process is shown in Figures 2–4. The results are presented and discussed below.

In the HASL start-up period, a rapid acidification was observed in terms of leachate pH value and TVFA level of the acidification reactor. Initially, the pH in R1 leachate was about 6.9 on day 0. It dropped rapidly to about 4.0 within 24 hours, and remained in the range of pH 4.1–5.0 during the start-up of HASL bioreactor (Figure 2). Meanwhile, TVFA concentration of R1 leachate increased from 690 mg/L on day 0 to 13,500 mg/L on day 2. This was consistent with the previous study on HASL batch operation that the acidification reactor went acidic quickly (Xu *et al.*, 2001). After the significant increase in TVFA level in R1 leachate, it decreased steadily during the rest of the start-up period. This was due to the UASB reactor Rm (methanogenesis phase) where VFAs from R1 were converted into methane and carbon dioxide by means of methanogenesis. This was also confirmed by the

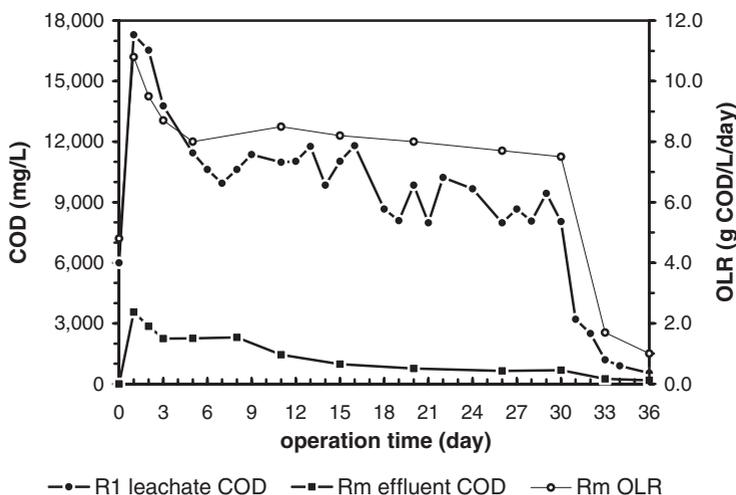


**Figure 2** TVFA and pH variations during 36-day HASL operation

variation of COD concentration in R1 leachate, which increased from 6,000 mg/L to 17,300 mg/L on the first day, but decreased to 10,000 mg/L in the following 6 days (Figure 3), indicating that the organic compounds were effectively degraded in the HASL bioreactor.

During the HASL start-up, the hydrolysis/acidification of food waste produced VFAs in R1, while the methanogenesis in Rm converted the VFAs into biogas. The methanogenesis in Rm prevented the accumulation of VFAs in R1 to some extent and maintained an appropriate pH condition for acidification in R1.

In the semi-continuous HASL operation (days 8–30), 0.2 kg of fresh food waste was loaded into R1 daily. R1 leachate pH slightly increased from pH 4.1–5.0 to pH 4.9–5.5 (Figure 2), while the Rm effluent pH remained constant, in the range of 7.1–7.6. The TVFA and COD levels in R1 leachate were relatively stable in 23 days of semi-continuous operation, in the ranges of 9,500–11,500 mg/L and 8,000–11,800 mg/L, respectively (Figures 2 and 3).



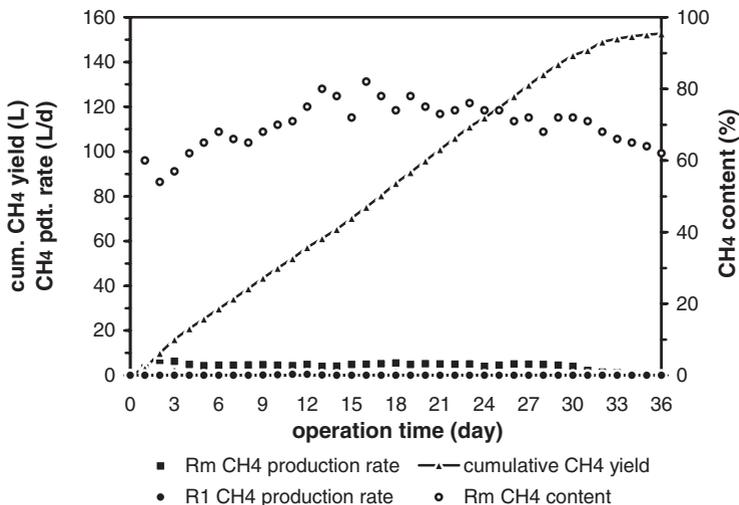
**Figure 3** COD and OLR variations during 36-day HASL operation

The TVFA and COD removals in methanogenesis reactor Rm remained efficient, which were  $88 \pm 5\%$  and  $85 \pm 7\%$ , respectively during days 8–30. This indicated that Rm adapted very well to the acidified feed influent from R1. It was probably due to the dilution of VFAs prior to their entering into the UASB reactor and/or the sludge granules, which had been operated with the synthetic wastewater of pH 5.5–6.0. The effective TVFA and COD removals in Rm were also demonstrated by the deviation of TVFA/COD concentration in R1 leachate and Rm effluent (Figures 2 and 3). In days 8–30, both TVFA and COD concentrations in Rm effluent (670–1,500 mg/L for TVFA and 670–2,300 mg/L for COD) were much lower than those in R1 leachate. On day 36, the Rm effluent contained 10 mg/L of TVFA and 180 mg/L of COD.

During the whole HASL process, the flow rates of the two streams (S1 and S2) of Rm effluent were adjusted according to R1 leachate and Rm effluent COD levels in order to supply Rm with an OLR of less than 10.0 g COD/L/day (Figure 3). The OLR of Rm was about 7.5–11.0 g COD/L/day during the start-up and semi-continuous operation, but decreased gradually to 1.0–1.7 g COD/L/day at the end of operation because there was no more food waste addition to the system from day 31 to day 36, and consequently R1 leachate COD level decreased.

The use of a UASB reactor for methanogenesis facilitated the rapid biogas production. The methane production rate during the semi-continuous operation was quite stable, and the cumulative methane yield increased steadily (Figure 4). Rm biogas and methane production rates were about 6.5–10.0 L/day and 3.2–6.7 L/day, respectively, during the start-up and semi-continuous operation (days 0–30). From day 31, methane production gradually leveled off due to the lack of food waste loading. This coincided with the decreases in R1 leachate COD and TVFA concentrations. Methanogenesis in UASB reactor also facilitated the biogas production with high methane content. In the whole HASL process, the methane content of Rm biogas was in the range of 54–82% with an average of about 71% (Figure 4).

Similar to the batch operation, 99% of the methane yield in this study was from the methanogenesis phase (Rm), indicating that no active methane fermentation was developed in R1 (Figure 4). This was probably due to the Rm effluent, which could not bring enough methanogenic bacteria to R1. As Rm retained its biomass in the form of sludge granules, biomass washout was scanty (Young and Dahab, 1983; Thaveesri *et al.*, 1994). The concentrated methane generation and high methane content will be beneficial to energy recovery.



**Figure 4** Methane production during 36-day HASL operation

At the end of operation, about 78% of VS added in R1 was removed with a methane yield of about 0.29 L/g VS added. In total 7.4 kg of food waste (containing 666 g of VS) was loaded in the whole HASL process and only 1.48 kg (containing 145 g of VS) was left in R1 after 36 days of operation. TOC and total COD reduction were 78% and 79%, respectively.

## Conclusions

1. A 36-day laboratory-scale semi-continuous HASL operation was conducted in this study, which included the effective acidification in a semi-liquid recycle reactor and the high-rate methanogenesis in a UASB reactor. The use of a UASB reactor enhanced the methanogenesis process and increased the methane content in biogas production. The results showed that the UASB system could be used as the methanogenesis phase of a two-phase anaerobic process.
2. During 23 days of semi-continuous operation, the leachate from the acidification reactor with 9,500–11,500 mg/L of TVFA and 8,000–11,800 mg/L of COD was efficiently treated in the UASB reactor, with about  $88 \pm 5\%$  of TVFA removal and  $85 \pm 7\%$  of COD removal.
3. 99% of the total methane generated was from the methanogenic phase with average methane content of 71%. This concentrated methane production with high methane content will be beneficial to energy recovery.
4. At the end of operation, 78% of VS removal and 0.29 L/g VS of methane production were obtained.

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