A comparative study of anaerobic digestion of food waste in a single pass, a leachate recycle and coupled solid/liquid reactors

H.L. Xu, J.Y. Wang, H. Zhang and J.H. Tay
Environmental Engineering Research Centre, School of Civil and Structural Engineering
Nanyang Technological University, Blk. N1, 50 Nanyang Avenue, Singapore 639798

Abstract A single pass reactor (R1), a leachate recycle reactor (R2) and a coupled solid/liquid bioreactor (R3-Rm) for anaerobic digestion of food waste were comparatively investigated in terms of digestion process and treatment efficiency. The coupled solid/liquid bioreactor is an enhanced two-phase system and distinctive from a traditional two-phase process with an upflow anaerobic sludge blanket (UASB) reactor as the methanogenic phase and a circulation of treated leachate between the acidification and methanogenic phases. In comparison with R1 and R2, R3-Rm enhanced the digestion process and increased the methane content of biogas. 100% of the R3-Rm methane yield was from the methanogenic phase with average methane content of 71%. The significant enhancement was also confirmed by the removal of 79% of total organic carbon (TOC), 60% of volatile solids (VS) and 80% of total COD in 12 days running of R3-Rm. However, no active methane fermentation was detected in R1 and R2 during 60 days operation. The results in this laboratory-scale study show that the rapid accumulation of volatile fatty acids (VFAs) due to the rapid acidification of food waste inhibits the development of effective methane fermentation in single pass and leachate recycle reactors. The coupled solid/liquid bioreactor is more efficient in converting food waste into methane and carbon dioxide.

Keywords Anaerobic digestion; coupled solid/liquid bioreactor; food waste; leachate recycle; single pass

Introduction
Food waste contributes about 40% (or 1.1 million tonnes) of the total municipal solid waste (MSW) collected for treatment and disposal per year in Singapore (ENV, 1999). Although food waste is a highly biodegradable component of MSW, its recycling rate is as low as 2.3% in 1999 in this country. With land scarcity and the rising cost of refuse disposal, the government has been encouraging all sectors of the community to set up materials recovery facilities (MRFs). Of all the different methods for elimination or treatment of MSW, anaerobic digestion of organic MSW has been drawing lots of attention over the last several years (Barlaz et al., 1992; Cecchi et al., 1992). Due to its economic advantages, anaerobic digestion is considered to be an alternative of MSW management to reduce the volume of waste and generate salable biogas, mainly methane, for energy recovery. The 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).

The conventional single pass digester demonstrated the advantages of mixing MSW with sewage sludge, including inoculation of the active bacteria to the digester and improvement of the pH buffering capacity of the digestion system (Diaz and Trezek, 1977). A technology to increase the digestion rate is the use of leachate recycling, which can increase moisture moving through the digester/landfill and accelerate the stabilization of waste (Pohland, 1980; Reinhart, 1996). However, the accelerated acidification in the leachate recycle reactor may cause the accumulation of volatile fermentation intermediates, especially the VFAs, in...
an anaerobic system. High concentrations of VFAs in a digestion system can inhibit the methanogenesis process since the growth requirements for non-methanogenic and methanogenic bacteria are rather different (Barlaz et al., 1992). In order to create optimal growth conditions for the two groups of bacteria, Pohland and Ghosh (1971) first proposed separating the process into two phases. A two-phase process involves a first reactor for acidification and a second reactor for methanogenesis. Although, to some extent, the two-phase system overcomes the problems encountered in the previous anaerobic digesters, the biogas production is still quite slow and the methane content is not as high as that in high-rate anaerobic wastewater reactors. In anaerobic filter (AF) and upflow anaerobic sludge blanket (UASB) reactors treating organic wastewaters, the methane content is usually over 70% (Verstraete et al., 1996).

Based on these considerations, in this study, a coupled solid/liquid bioreactor was designed and operated with acidification of food waste in a solid waste reactor and methanogenesis in an UASB reactor. The objectives of this study were (i) to use an UASB reactor as the methanogenic phase in a coupled solid/liquid bioreactor to enhance the two-phase process; (ii) to compare the coupled solid/liquid bioreactor with the single pass and leachate recycle reactors in terms of digestion process and treatment efficiency; and (iii) to investigate the food waste digestion process.

Materials and methods

Reactor description
The experimental set-up of a single pass reactor (R1), a recycle reactor (R2) and a coupled solid/liquid reactor (R3-Rm) used in this study are schematically shown in Figure 1. R1, R2 and R3 were cylindrical reactors with identical physical features and configurations. The inner diameter (ID) was 140 mm with a height of 500 mm and a total effective volume of 5.4 litres. The coupled solid/liquid reactor R3-Rm consisted of one reactor treating solid waste (R3) as the acidification phase and another reactor treating wastewater (Rm) as the methanogenic phase. Rm was an UASB reactor with 600 mm height, 90 mm ID and a working volume of 3.0 litres (Teo et al., 2000). The reactors were operated in a temperature-controlled room at 35 ± 1°C.

Feedstock, seed sludge and UASB granule description
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 88%, and the volatile solids (VS) content was 62% of total solids (TS). The seed sludge was collected from an anaerobic digester of the Ulu Pandan Sewage
Treatment Plant in Singapore. Its suspended solid (SS) and volatile suspended solid (VSS) concentrations were 4.6 g/L and 3.1 g/L, respectively. Mature sludge granules adapted to VFA wastewater were from a 5-L UASB reactor, which had been operated for more than 6 months with a synthetic wastewater (pH 5.5–6.0) as reported by Teo et al. (2000).

Experimental design and protocol
The shredded food waste was loaded to R1, R2 and R3 with 3.0 kg per reactor. The experiments were initiated by inoculating food waste-filled R1/R2/R3 with 1.5 litres of seed sludge. R1 was operated for 60 days and its leachate was collected and analyzed daily in the first 12 days. R2 was operated by immediately recycling the leachate with a recirculation rate of 1.0 ml/min on day 0. The leachate sample was analyzed daily during day 0–12, and the reactor was operated for 60 days. Prior to operation of the coupled solid/liquid bioreactor R3-Rm, Rm with addition of 1.0 litre of the UASB 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 OLR as the influent. An effluent of less than 500 mg COD/L (COD removal efficiency was more than 90%) and an average CH₄ content of biogas of 75% indicated that Rm had been active in methanogenesis. The R3-Rm operation was commenced when Rm was coupled to R3. Daily sampling of R3 leachate and Rm effluent was conducted during day 0–12. In R3-Rm bioreactor, R3 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 R3, while S2 was used to dilute R3 leachate and then pumped back into Rm (Figure 1). The flow rates of S1 and S2 changed according to the COD concentrations in R3 leachate and Rm effluent in order to keep an optimal Rm influent concentration of less than 5,000 mg COD/L and an organic loading rate (OLR) of less than 10.0 g COD/L/day.

Results and discussion
The single pass reactor R1 and leachate recycle reactor R2 were operated for 60 days. No methane was generated either in R1 or R2. The coupled solid/liquid bioreactor R3-Rm was operated for 12 days because of the low COD and TVFA levels in R3 leachate at the end of operation. The results are presented below, and the operating parameters in R1, R2 and R3-Rm during day 0–12 are comparatively discussed.

Food waste is a highly biodegradable component of MSW. The rapid hydrolysis/acidification in anaerobic digestion of food waste was observed. R1 leachate pH value dropped from 6.7 on day 0 to about 4.0 on day 2, and after that, remained acidic (pH < 5.0) (Figure 2). R2 leachate pH reached its lowest value (about 4.0) in only one day, and remained acidic (pH < 5.0) from then on (Figure 2). This demonstrated that the leachate recycling accelerated the acidification process.

The rapid acidification of food waste was also confirmed by COD and TVFA levels of R1 and R2 leachate (Figure 3 and Figure 4). Both R1 and R2 leachate COD reached their highest levels on day 2. R1 leachate TVFA concentration increased slowly to about 17,000 mg/L on day 9, while in R2, the leachate TVFA concentration increased to the same level on day 4. This showed the beneficial effect of leachate recycling on the acidification process.

In the coupled solid/liquid bioreactor R3-Rm, VFAs produced in the acidification reactor (R3) were removed in the methanogenic reactor (i.e. UASB reactor Rm). The UASB technology has been widely applied in treating high-strength organic wastewater. It retains high biomass concentrations, despite the upflow velocity of the wastewater and the production of biogas, by means of sludge granulation (Teo et al., 2000). The sludge granules, where anaerobic consortia grow in a dense and eco-physiological way, can powerfully
biocatalyze and convert organic compounds into biogas (Schmidt and Ahring, 1996; Verstraete et al., 1996).

Figure 4 shows that the accumulation of VFAs in R3 leachate was reduced, resulting in a higher level of pH and lower levels of COD and TVFA than those in R1/R2 leachate (Figure 3). In the acidification phase, R3 leachate pH decreased from 6.6 to 5.0 in the first day, and then increased gradually to 6.0 on day 4 and to 7.1 at the end of operation (Figure 2). In the methanogenic phase, Rm effluent pH remained constant, in the range of 7.5–7.8, indicating that Rm adapted very well to the acidified feed influent from R3. This 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 COD and TVFA removal in R3-Rm were confirmed by the variations of COD and TVFA concentrations in R3 leachate and Rm effluent (Figure 3 and Figure 4). During 12 days operation, R3 leachate COD and TVFA levels were much less (95% and 95%, respectively) than those in R1/R2 leachate, i.e. 325 mg/L and 430 mg/L, respectively. Rm effluent COD and TVFA levels were 175 mg/L and 20 mg/L, respectively, on day 12. COD removal of 60–89% and TVFA removal of 80–98% in Rm were obtained.

Although the effective biodegradation in Rm was observed, the acidification products, mainly VFAs were still accumulated to some extent. The highest COD and TVFA concentrations in R3 leachate were about 20–25% lower than those in R1/R2 leachate. This was probably due to the rapid acidification of food waste in R3 and slow leachate-effluent
circulation (about 1.0 ml/min) between R3 and Rm (Figure 1). A circulation rate of 1.0 ml/min was corresponded to a hydraulic retention time of about 3.8 days. It was set to result in the OLR of Rm of less than 10.0 g COD/L/day (R3 leachate COD level was 16,600 mg/L in the first day, see Figure 3).

The rapid acidification of food waste, and consequentially the accumulation of acidification products inhibited the development of methanogenesis in R1 and R2. At the end of operation, on day 60, R1 and R2 pH values were 5.0 and 5.1, respectively. The COD and TVFA concentrations were also at the same levels as those on day 12. The high VFA production would decrease the pH level in anaerobic digestion systems, and subsequently inhibit the methane fermentation (Graven and Pohland, 1987; Barlaz et al., 1992). During 60 days operation, there was no methane generated in either R1 or R2 (Figure 5).

In comparison with R1 and R2, the methane production rate and cumulative methane yield in R3-Rm increased rapidly (Figure 5). The use of an UASB reactor as the methanogenic phase facilitated the rapid biogas production. Rm biogas and methane production rates were about 14–17 L/day and 10–12 L/day, respectively, in day 0–5. From day 9, methane production gradually leveled off. This coincided with the decreases in R3 leachate COD and TVFA concentrations. Methanogenesis in UASB reactor also facilitated the biogas production with high methane content. In the whole process of R3-Rm operation, the methane content of Rm biogas was in the range of 66–72% with an average of about 71%.

Interestingly, 100% of the methane yield was from the methanogenic phase (Rm). The
fact that no methane was detected in the head-space of R3 indicated that no active methane fermentation was developed in R3. This was probably due to the Rm effluent, which could not bring enough methanogenic bacteria to R3. 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. At the end of operation, about 60% of VS added in R3 was removed with a methane yield of about 0.25 L/g VS added. TOC and total COD reduction were 79% and 80%, respectively.

**Conclusions**

- The hydrolysis/acidification was a rapid process in anaerobic digestion of food waste.
- No methane production was detected in the single pass reactor and recycle reactor during 60 days operation. The acidification products, mainly VFAs, greatly inhibited the methane fermentation.
- The coupled solid/liquid bioreactor was an enhanced two-phase system, which was more efficient in conversion of food waste into methane and carbon dioxide. 100% of the total methane generated was from the methanogenic phase with average methane content of 71%.
- In the coupled solid/liquid bioreactor, the use of an UASB reactor enhanced the methanogenesis process and increased the methane content in biogas production. The treated leachate circulation washed out the fermentation intermediates from the acidification phase without fresh water addition, and hence prevented wastewater production.

**References**


