Anaerobic digestion of the organic fraction of municipal solid waste: Influence of co-digestion with manure

Hartmann, Hinrich; Ahring, Birgitte Kiær

Anaerobic digestion of the organic fraction of municipal solid waste: Influence of co-digestion with manure

Hinrich Hartmann, Birgitte K. Ahring*

The Environmental Microbiology/Biotechnology Research Group, Technical University of Denmark, BioCentrum-DTU, Building 227, Soltofts Plads, DK-2800 Lyngby, Denmark

Abstract

Anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) was investigated in two thermophilic (55 °C) wet digestion treatment systems R1 and R2. Initially OFMSW was co-digested with manure with a successively higher concentration of OFMSW, at a hydraulic retention time (HRT) of 14–18 d and an organic loading rate (OLR) of 3.3–4.0 g-VS/l/d. Adaptation of the co-digestion process to a OFMSW:manure ratio of 50% (VS/VS) was established over a period of 6 weeks. This co-digestion ratio was maintained in reactor R2 while the ratio of OFMSW to manure was slowly increased to 100% in reactor R1 over a period of 8 weeks. Use of recirculated process liquid to adjust the organic loading to R1 was found to have a beneficial stabilization effect. The pH rose to a value of 8 and the reactor showed stable performance with high biogas yield and low VFA levels. The biogas yield from source-sorted OFMSW was 0.63–0.71 l/g-VS both in the co-digestion configuration and in the treatment of 100% OFMSW with process liquid recirculation. This yield is corresponding to 180–220 m^3 biogas per ton OFMSW. VS reduction of 69–74% was achieved when treating 100% OFMSW. None of the processes showed signs of inhibition at the free ammonia concentration of 0.45–0.62 g-N/l.
© 2005 Elsevier Ltd. All rights reserved.

Keywords: Anaerobic; Co-digestion; Manure; Organic fraction of municipal solid waste; Process liquid; Recirculation

1. Introduction

Waste management has become of major concern around the world during the recent 30 years. Sustainable waste treatment concepts that favor waste recycling and the recirculation of nutrients back to soil will have the highest benefit for the environment (Lema and Omil, 2001; Sakai et al., 1996; Braber, 1995). Anaerobic digestion (AD) of the organic fraction of municipal solid waste (OFMSW) offers the advantage of both a net energy gain by producing methane as well as the production of a fertilizer from the residuals (Edelmann et al., 2000; Sonesson et al., 2000; Hamzawi et al., 1999).

In Denmark, the aim is to use AD as the main waste treatment process in the future with a capacity of 100,000 t of OFMSW by the year 2004 (Hartmann and Ahring, 2004). The existing 20 centralized biogas plants are the first option for the AD treatment of OFMSW in co-digestion with manure. In 2002, only 50,000 t of OFMSW were treated per year in nine biogas plants, where up to 10% (vol.) of OFMSW was added in co-digestion with manure (Hartmann and Ahring, 2004). For the realization of the goal to treat 100,000 t by AD in 2004, the ratio of OFMSW added has to be increased

*Corresponding author. Tel.: +45 45 25 61 83;
fax: +45 45 88 32 76.

E-mail address: bka@biocentrum.dtu.dk (B.K. Ahring).

in the existing plants and the installation of additional biogas plants for the treatment of OFMSW alone may be another option. Generally, OFMSW is a very attractive waste for the biogas plants as they are dependent on the addition of organic waste with a high biogas potential. The biogas yield from raw manure alone is only 20–30 m^3/t and the operation of the plant is only economically feasible when biogas yields higher than 30 m^3/t of treated material can be achieved (Danish Energy Agency, 1995). As the amount of industrial organic waste is limited in Denmark, there will be a high demand for OFMSW with a biogas potential of more than 100 m^3/t, especially with an expansion of the existing net of biogas plants. Adding OFMSW will, however, change the process characteristics due to the different characteristics of OFMSW compared to manure: it has a low water content, a low pH and it can have low concentrations of nutrients, when it consists of high ratio of, e.g. garden waste (Rivard et al., 1989, 1990). For high ratios of food waste, OFMSW can, however, also contain high concentrations of proteins, which can lead to inhibition by ammonia especially when process liquid is recirculated (Gallert and Winter, 1997). Furthermore, OFMSW can contain considerable amounts of heavy metals and xenobiotic compounds (Hartmann and Ahring, 2003; Braber, 1995).

The goal of the present work was to investigate how a thermophilic wet digestion system will react when adding OFMSW in a ratio of 50% (VS/VS) to the manure in the co-digestion process. Finally, the adaptation of the system to 100% of OFMSW using recirculated process liquid was investigated. Results of the reduction of xenobiotics have been previously studied (Hartmann and Ahring, 2003). The wet digestion system was preferred in order to achieve a well-mixed process in a conventional continuously stirred tank reactor (CSTR) and to make the results directly applicable in the Danish large-scale biogas reactors.

2. Methods

2.1. Waste characterization

OFMSW used in this investigation came from the municipality of Grindsted (Denmark) where OFMSW is source-sorted in the households in paper bags and co-digested together with sewage sludge at the municipal wastewater plant. Samples were taken after the on-site shredder device, further homogenized in an industrial meat mincer and stored at $-18\,°C$ until used as feeding substrate. Two different batches of homogenized OFMSW were fed into the reactors R1 and R2, batch 1 before day 217 and batch 2 after day 217. Characterization of the waste was performed by analysis of TS,

VS, and COD according to standard methods (APHA et al., 1992). The composition of the OFMSW with regard to hemicellulose, cellulose and lignin was determined in triplicates in batch 1 by sequential fiber analysis according to the method of Goehring and van Soest (1970). The biogas potential of OFMSW collected in batch 1 and cow manure in different co-digestion ratios were measured in triplicate batch experiments with inoculum from reactor R1, treating OFMSW in co-digestion with manure. OFMSW and cow manure, diluted to a concentration of 5% VS, was filled into 100 ml batch vials in different ratios equivalent to a total amount of 1 g-VS. After adding 15 ml inoculum and 10 ml of tap water the vials were flushed with a gas mixture of 80% N_2 and 20% CO_2 before closing the vials. The vials were incubated at 55 °C for 60 d. Methane production was monitored every 3–4 d by analysis of CH_4 concentration in the headspace using gas chromatography with flame ionization detection. The CH_4 production was standardized by sampling the same volume (0.2 ml) from the batch vials under pressure as from a 30% CH_4 standard under standard conditions (1 bar, 20 °C). At a pressure higher than 2 bar in the vials, the pressure was released and the amount of CH_4 released was determined by the difference of the amount of CH_4 in the vials before and after release. The biogas potential was determined after 44 d of incubation, after which no significant increase in methane production was observed.

2.2. Reactor set-up

The treatment process was investigated in two 4.5 l lab-scale reactors R1 and R2 with an active volume of 3.0 l operated under thermophilic conditions (55 °C). Each reactor was fed three times a day with a total feeding volume of 170–210 ml/d, resulting in a hydraulic retention time (HRT) of 14–18 d. OFMSW and manure were diluted in a ratio of 1:5 and 1:1.43, respectively, to reach an influent VS concentration of 6% for both substrates, resulting in an organic loading rate (OLR) of 3.3–4.0 g-VS/l/d. New influent was prepared every 3–4 d and stored in 1 l glass vessels, which were stirred for 2 min before feeding. The reactors were stirred for 15 min in intervals of 15 min. Effluent from the reactors was collected in 1 l Erlenmeyer vessels. For recirculation of process liquid in reactor R1 the effluent was collected during a period of 3–4 d, centrifuged at 4000 rpm for 30 min and the supernatant was decanted and used for dilution of OFMSW for the influent (Fig. 1). After centrifugation 92±1% of the total effluent mass was recovered in the liquid phase, containing 34±3% and 25±4% of the total effluent TS and VS, respectively. Depending on volume loss by sampling and fluctuations in feeding volume, the ratio of the supernatant of the effluent, which was used as process liquid, to the whole
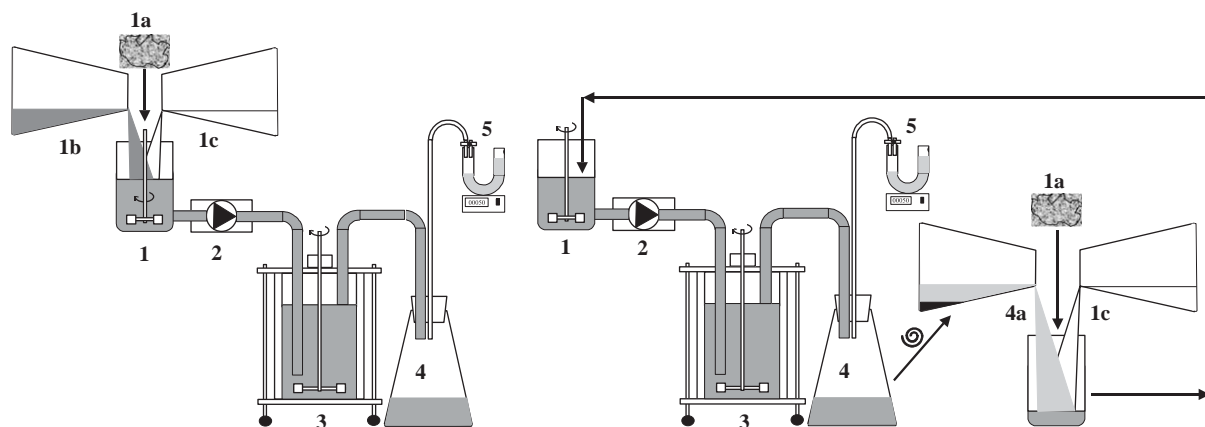
Fig. 1. Reactor set-up for co-digestion (left) and treatment of 100% OFMSW with recirculation of process water (right): (1) influent storage vessel; (1a) OFMSW; (1b) manure; (1c) water; (2) influent pump for reactor; (3) thermophilic reactor with heating jacket and mechanical stirrer; (4) storage vessel for effluent; (4a) supernatant of effluent after centrifugation and (5) gas meter.

Table 1
Average process parameters in the different experimental phases

Parameter	Phase 1 (days 0–83)	Phase 2 (days 84–139)	Phase 3 (days 140–216)	Phase 4 (days 217–330)
	50% OFMSW R1, R2	100% OFMSW R1	Recirculation R1	Batch 2 OFMSW
HRT (d)				
R1	15.5 (2.2)	13.5 (2.8)	17.0 (5.5)	17.7 (7.7)
R2	15.3 (1.2)	17.5 (3.7)	17.9 (4.4)	16.0 (2.9)
OLR (g-VS/l/d)				
R1	3.5 (0.4)	4.0 (1.0)	3.3 (1.1)	3.4 (1.2)
R2	3.6 (0.3)	3.4 (0.7)	3.3 (0.8)	3.3 (0.6)
%Rec.				
R1	—	—	50	59

%Rec.: ratio of effluent supernatant to total liquid volume used for dilution of influent OFMSW; standard deviation in brackets.

liquid added for dilution of influent OFMSW varied between 23% and 100% and was in average 50% and 59% in the experimental phases, when recirculation was applied (Table 1).

The reactor experiment was divided in four phases (Table 1). In phase 1 (days 0–83) both reactors R1 and R2 were initially loaded with cow manure for 10 d and then adapted to a higher load of OFMSW by an increase of the OFMSW ratio in 5% steps (on VS basis) every 3–4 d. After one month both reactors were running with 50% (VS/VS) OFMSW for a period of 42 d (2.7 HRT). R2 was further used in phases 2–4 as control reactor maintaining a co-digestion ratio of 50% (VS/VS) OFMSW until the end of the experiment. From day 84 to 139 (phase 2) the OFMSW ratio in reactor R1 was increased to 100% and from day 116 to 139 OFMSW was added after dilution with water. Use of the liquid fraction of the effluent for dilution of OFMSW before feeding of R1 was started on day 140. Since a new batch

of OFMSW was used from day 217, the last experimental period was divided into phase 3 (days 140–216) and phase 4 (days 217–330). HRT and OLR were in average 13.5–17.9 d and 3.3–4.0 g-VS/l/d, respectively. The variations were due to variations of the pumping volume caused by the inhomogeneity of the substrate. Process parameters are displayed in Table 1 as averages of the whole period of phases 3 and 4 and of the periods of phases 1 and 2, when the reactors were fed with a constant mixture of 50% OFMSW:(VS/VS) and 100% OFMSW, respectively.

2.3. Monitoring parameters

Biogas production was measured by liquid displacement gas measurement systems connected to the headspace of the effluent vessels, logging the gas production automatically in 10 ml intervals. The methane content of the biogas was analyzed by gas chromatography as previously

described by Sørensen et al. (1991). The methane yield in the reactors was calculated as average over a period of 3–4 d as $Y_{CH_4} = \text{sum(ml CH}_4)_{prod}/\text{sum(g-VS)}_{feed}$. The process performance was monitored by volatile solids (VS) reduction, volatile fatty acids (VFA) concentration, pH, and ammonia formation. VS reduction was determined as difference in VS concentration in the influent times influent volume and VS concentration in the effluent times effluent volume. TS, VS, pH and ammonia in the influent and effluent of the reactor system were determined according to standard methods (APHA et al., 1992). The ratio of free ammonia to total ammonia was calculated according to Anthonisen et al. (1976):

$$\frac{\text{Free-NH}_3}{\text{Total-NH}_3} = \frac{10^{pH}}{10^{pH} + 1/K_a} = \frac{10^{pH}}{10^{pH} + e^{6344/(273+T)}}$$

where T is the temperature in °C.

The single VFA's acetate, propionate, isobutyrate and butyrate were analyzed by gas chromatography as described by Sørensen et al. (1991).

3. Results and discussion

3.1. Waste characteristics

VS concentration in the two batches of OFMSW used for the experiment was 31% with a VS/TS ratio of 86–91% and a COD/VS ratio of 1.4 (Table 2). The collected waste was, furthermore, characterized by only 1% (w/w) of impurities (plastic, metal, glass). This high purity of the waste shows the high efficiency of the waste collection concept in the municipality of Grindsted. The total nitrogen content of OFMSW was higher than that of the manure used, but lower per kg dry matter, meaning that manure contributed to more nitrogen during co-digestion of equal amounts of manure and OFMSW. The free ammonia concentration was three times lower for OFMSW than for manure.

In the batch experiment, a methane yield of 0.40 l/g-VS of OFMSW was found (Fig. 2), which was 82% of the maximal theoretical yield of 0.49 l/g-VS, calculated from the COD content of OFMSW. The methane yield in the co-mixture of OFMSW and manure increased linearly with higher ratios of OFMSW, showing no signs of inhibition or nutrient deficiency at high OFMSW ratios (Fig. 2). With a methane content of 60% in the biogas, the maximal biogas yield was 0.82 l/g-VS. This was close to the theoretical biogas yield of 0.81 l/g-VS, which was calculated by Scherer et al. (2000), based on a composition of 3% fat (1.42 l/g-TS), 13% protein (0.89 l/g-TS), 17% cellulose (0.96 l/g-TS), 8.5% lignin (0.01 l/g-TS) and 58.5% carbohydrates (0.84 l/g-TS).

The biodegradability of the OFMSW used, determined by the batch experiment, was much higher than

Table 2
Characteristics of OFMSW and manure used in the reactor experiment

	TS (%)	VS (%)	COD (g/kg)	Total-N (g/kg)	Total-N (g/kg-TS)	NH$_3$-N (g/kg)	NDF (non-soluble) (% of VS)	NDF–ADF (hemicellulose) (% of VS)	ADF–ADL (cellulose) (% of VS)	ADL (lignin) (% of VS)
OFMSW										
Batch 1	35.6 (0.10)	30.7 (0.17)	431 (9.3)	6.3 (0.46)	17.7	1.0 (0.10)	36.6 (2.1)	13.1 (3.5)	5.0 (0.4)	18.5 (0.9)
Batch 2	33.6 (0.49)	30.7 (0.16)	—	—	—	—	—	—	—	—
Manure	11.5 (0.45)	8.5 (0.03)	—	4.6 (0.06)	40.0	3.0 (0.02)	—	—	—	—

NDF: neutral detergent fiber fraction, ADF: acid detergent fiber fraction, ADL: acid detergent lignin fraction, standard deviation in brackets.
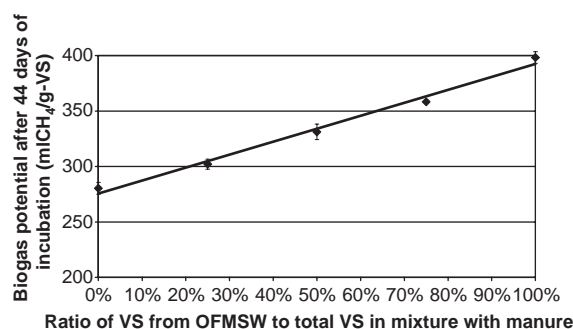
Fig. 2. Methane yield of OFMSW and manure in different mixtures in batch experiment after 44 d of incubation (55 °C).

the one, which can be calculated from the relationship between lignin content and biodegradable fraction found by Chandler et al. (1980) giving a biodegradable fraction of 38% of VS. This indicated that the lignin content was generally lower than the 19%, which was determined in the fiber analysis.

3.2. Reactor experiment

3.2.1. Phase 1: Start-up to a ratio of OFMSW:manure of 50%

The methane yield increased with higher ratios of OFMSW from 0.20 l/g-VS when feeding only manure, to 0.34 l/g-VS in the 50% co-digestion ratio (Fig. 3A1 and A2). The methane yield was equivalent to the methane yield found in the batch test. Due to the acidity of OFMSW the pH of the influent dropped from 7.3 of pure manure to 6.3 in the 50% (VS/VS) co-digestion mixture (Fig. 3D1 and D2). The pH in both reactors, however, dropped only from 8.5 to 8.0, showing that the co-digestion system was well buffered. Accordingly, the pH in the effluent stabilized at values of 7.6–7.8 at the end of phase 1. The VFA profile showed for both reactors a stable performance with total VFA concentrations below 8 mM after an initial transitory increase in VFA (Fig. 3C1 and C2) which is typical for start-up of an anaerobic process when the balance of the hydrolytic bacteria, fermentative bacteria and methanogens has not stabilized yet (Ahring, 1994). The further increase of the ratio of OFMSW did not show signs of process instability. The fluctuation of the methane yield was due to fluctuation in the feed volume and the waste composition of the single waste loads.

3.2.2. Phase 2: Increasing the OFMSW ratio to 100% in reactor R1

Loading R1 with a higher ratio of OFMSW showed an increase in methane yield and VS reduction up to an average value of 0.46 l/g-VS and 73%, respectively, on average in the last period of phase 2 (1.8 HRT) when 100% OFMSW diluted by addition of water, was fed to the reactor (Fig. 3A1 and B1, Table 3). These high values for the methane yield and the VS reduction were signs for a high content of biodegradable organic matter in the substrate. Parallel to the drop of the influent pH of R1 down to 4.0–4.5, the effluent pH declined to 7.0 (Fig. 3D1). Reactor R2 showed generally stable performance with low VFA concentration (Fig. 3C2), and about the same methane yield and VS reduction as in phase 1 (Fig. 3A2 and B2). The biogas yield and the VS reduction in R1, operating on 100% OFMSW, were 28% and 23%, respectively, higher than during co-digestion with manure in R2 (Table 3).

3.2.3. Phase 3: Recirculation of process liquid in reactor R1

When starting the recirculation of process liquid in R1 on day 140, using exclusively the supernatant of the effluent for dilution of OFMSW, a slight increase of VFA concentration and a drop of methane yield below 0.40 l/g-VS was detected (Fig. 3C1 and A1). The same process disturbance was, however, also seen in reactor R2 (Fig. 3A2 and C2), indicating that the process disturbance was related to the feeding of both reactors rather than the start of recirculation in R1. In general, low VFA concentrations in R1 showed stable reactor performance. The methane yield and VS reduction showed some variations and were, in average, lower than at the end of phase 2. The average biogas yield was, however, still higher than in the batch experiment and biogas yield and VS reduction in R1 were 14% and 25%, respectively, higher than found in R2 (Table 3).

Dilution of OFMSW with a high ratio of supernatant showed an instant buffering effect with an increase in the influent pH above 6.0 (Fig. 3D1). The effluent pH stabilized at a higher level of 7.2, showing beneficial effect of recirculation of the effluent for the pH stabilization of the process.

The ammonia load of R1 increased successively with recirculation of the effluent (Fig. 4) and the concentration in the effluent increased from 0.6 to 1.0 g/l, which corresponded to a level of 0.28 g/l of free ammonia in the reactor (55 °C, pH 8.0).

3.2.4. Phase 4: Using a second batch of OFMSW

The feed of a new batch of OFMSW in phase 4 (6.4 HRT for R1 and 7.1 HRT for R2) showed a lower average of 0.38 l/g-VS than in phase 3 (Fig. 3A1 and Table 3). The VS reduction, however, increased by 5% compared to phase 3 (Fig. 3B1 and Table 3). The same can be seen for the co-digestion in R2 (Fig. 3A2 and B2), indicating that batch 2 of OFMSW had a lower content of high yielding organic matter (fat, protein, cellulose). VFA concentration fluctuated more during phase 4 than
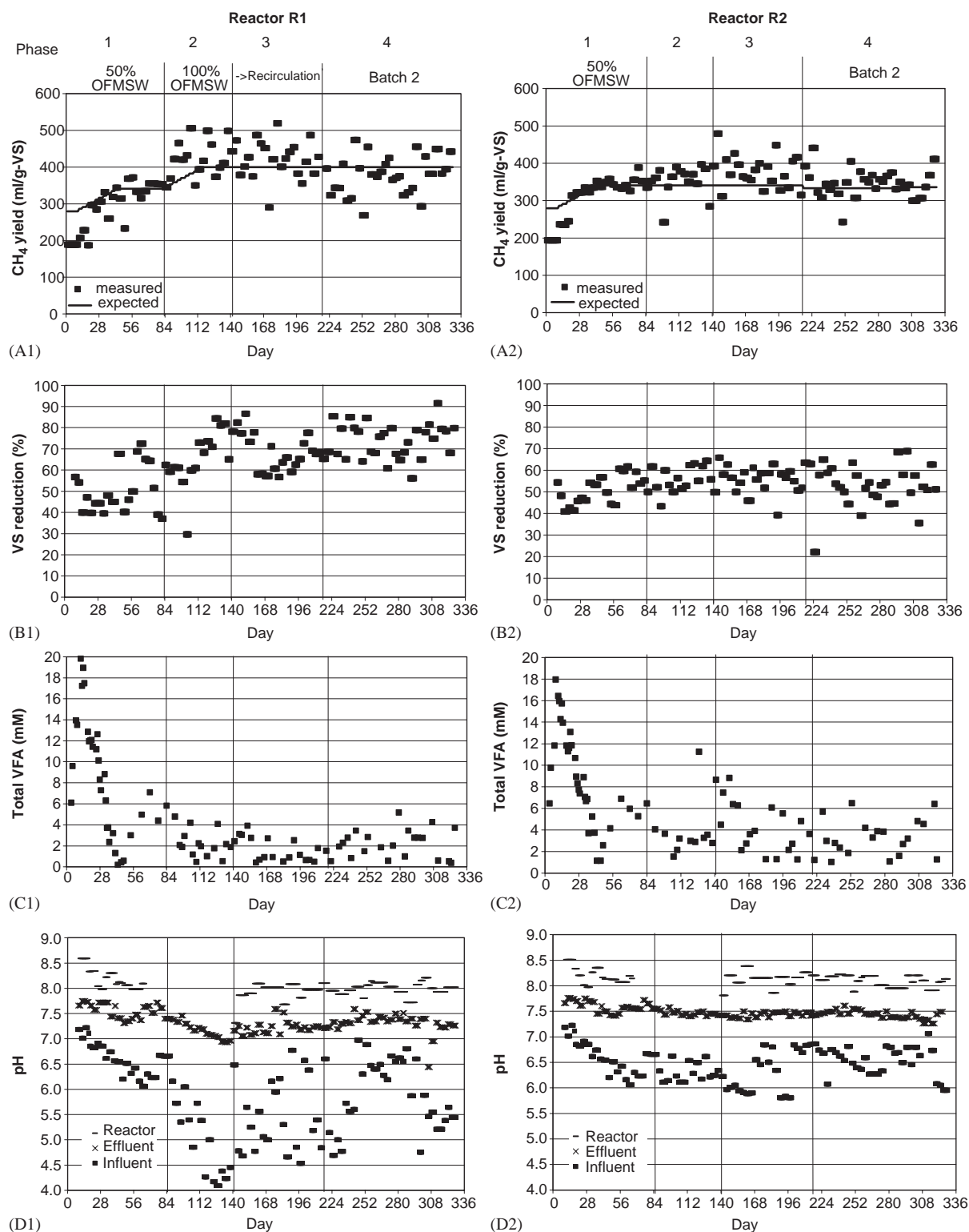
Fig. 3. Biogas yield (A1, A2), VS reduction (B1, B2), VFA concentration (C1, C2) and pH (D1, D2) in reactor R1 (left) and R2 (right); expected biogas yield in A1 and A2 is according to the methane yield found in the batch experiment (Fig. 2).

Table 3
Average performance parameters in the different experimental phases

Parameter	Phase 1 (days 0–83)	Phase 2 (days 84–139)	Phase 3 (days 140–216)	Phase 4 (days 217–330)
CH_4 yield (l/g-VS)				
R1	0.34 (0.03)	0.46 (0.05)	0.42 (0.05)	0.38 (0.08)
R2	0.35 (0.01)	0.36 (0.03)	0.37 (0.04)	0.34 (0.04)
%CH_4				
R1	64.2 (1.1)	59.7 (0.2)	59.4 (1.4)	60.6 (2.0)
R2	64.6 (0.6)	62.8 (1.6)	63.0 (1.3)	62.8 (1.9)
VS reduction (%)				
R1	56.0 (12.8)	73.1 (7.0)	69.0 (8.6)	74.3 (8.2)
R2	54.2 (5.7)	59.5 (4.4)	55.3 (6.0)	56.4 (9.9)
PH effluent				
R1	7.5 (0.1)	7.0 (0.1)	7.2 (0.1)	7.3 (0.2)
R2	7.5 (0.1)	7.4 (0.0)	7.4 (0.1)	7.2 (0.1)

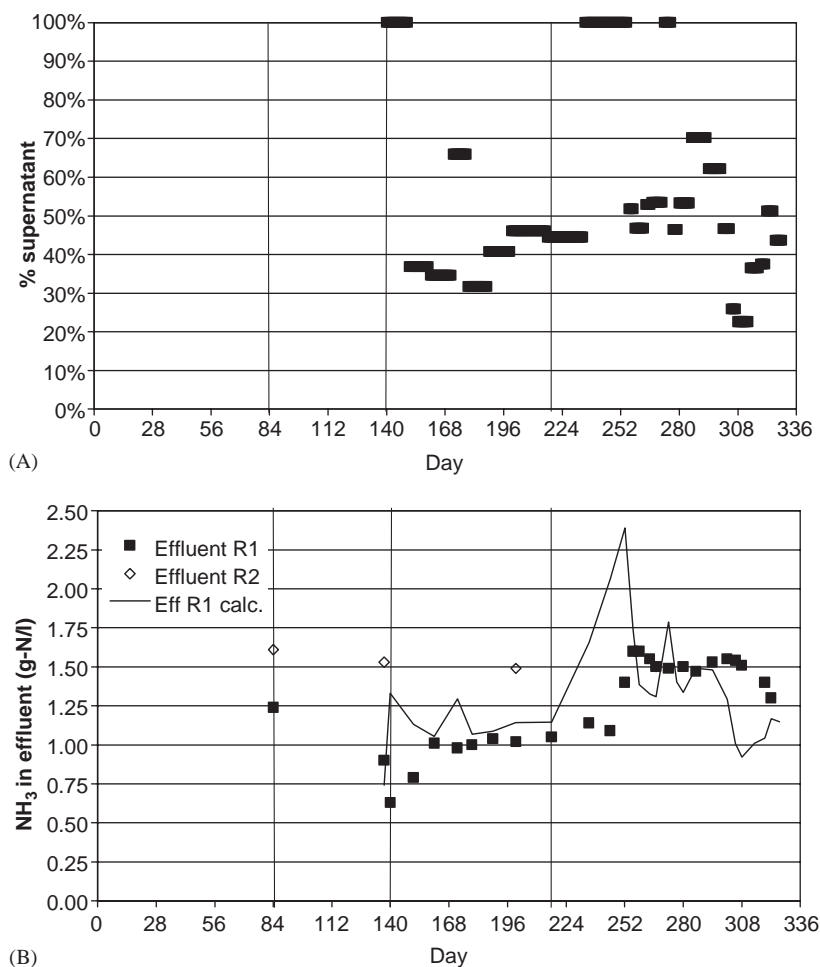%CH_4: methane content in biogas; standard deviation in brackets.

Fig. 4. Ratio of supernatant to total liquid volume used for dilution of influent OFMSW of R1 (A) and ammonia concentration in the effluent of R1 and R2 (B); Eff R1 calc. is the calculated NH_3 concentration in the effluent.

in the previous phases and showed a higher level than in phase 3 (Fig. 3D1). However, the concentration was always below 5 mM, indicating that the process was in balance. When using exclusively the supernatant of the effluent for dilution of OFMSW between day 235 and 255 (Fig. 4A), the influent pH was higher than 6.2 and the effluent pH rose to 7.5. During the whole period the pH in reactor R1 was stable around 8.0. Due to higher ratios of supernatant used for dilution of OFMSW in phase 4 (59%) compared to phase 3 (50%), the ammonia concentration in the effluent increased to values of 1.5–1.6 g-N/l, which was about the same level as for the co-digestion reactor R2 (Fig. 4B). Due to a lower pH in R1 compared to R2 (8.0 compared to 8.2), the free ammonia concentration can be calculated to be 0.42–0.45 g-N/l in R1 and 0.58–0.62 g-N/l in R2.

Assuming that the ammonia loss is as much as the volume loss in the process, the effluent ammonia concentration was calculated according to the mass balance:

$$C_{NH_3,e_{j+1}} = C_{NH_3,OFMSW}r_{OFMSW} + C_{NH_3,e_j}(1 - r_{OFMSW})r_{sn} + t_{org-N}(C_{TKN,OFMSW} - C_{NH_3,OFMSW})r_{OFMSW},$$

where C is the concentration (g-N/l), index i = influent, index e = effluent, index j = recirculation count, index NH_3 is the total ammonia-N, index TKN is the total Kjeldahl-N, r_{OFMSW} is ratio of OFMSW in influent, r_{sn} is ratio of supernatant:water used for dilution of OFMSW, t_{org-N} is ratio for release of NH_3-N from organic bound nitrogen (TKN)

with $t_{org-N} = \dfrac{C_{NH_3,e} - C_{NH_3,i}}{C_{TKN,i} - C_{NH_3,i}}$.

Comparing the measured values with the calculated data, it can be seen that changes of the concentration followed the values predicted by the mass balance after about one retention time (Fig. 4B). The predicted increase on day 235, for example, is first apparent after 15 d and the fluctuations in the concentration as predicted are leveled out. This indicated that ammonia from organic bound nitrogen was not instantly released, but over the period of one retention time. With a constant ratio of the supernatant of 50% (phase 3) and 59% (phase 4), an effluent ammonia concentration of 1.2 and 1.4 g-N/l, respectively, can be calculated from the mass balance. An effluent ammonia concentration of 3.7 g-N/l and a respective free ammonia concentration of 1.0 g-N/l could be predicted when recirculating 100% of effluent supernatant. This is in agreement with results found by De Laclos et al. (1997) who measured an increase of the effluent ammonia concentration in the Valorga process from 1.3 to 3 g-N/l over an operation period of 2 years.

3.2.5. Overall performance

The overall process performance of reactor R1 and R2 in phases 3 and 4 can be summarized as follows: Anaerobic treatment of OFMSW showed stable performance in a thermophilic wet digestion treatment system both when co-digested with manure in a ratio of 50% (VS/VS) and as sole substrate with recirculation of the effluent. The biogas yield from OFMSW was in both treatment configurations 0.63–0.71 l/g-VS, corresponding to 180–220 m^3/t_{OFMSW}, which is more than 50% higher than in comparable thermophilic dry digestion systems using source-sorted OFMSW (Kayhanian and Tchobanoglous, 1993; Six and De Baere, 1992) and more than 25% higher than in comparable mesophilic systems (Krzystek et al., 2001; Mtz.-Viturtia et al., 1995). This gives evidence for both a high quality of the collected waste and for the advantage of the thermophilic wet digestion treatment of OFMSW. Similar biogas yields of OFMSW have, so far, only been found in a thermophilic wet digestion system by Scherer et al. (2000). Treating exclusively OFMSW with recirculation of process liquid in a ratio of 50–59% for dilution of influent OFMSW was beneficial and stabilized the process at a pH 8.0 in the reactor and with an ammonia level similar to the one found during co-digestion with manure. Stabilization of the process by recirculation of process liquid has been shown previously (Cecchi et al., 1990). Compared to other treatment processes with recirculation of process liquid, like the BTA and the Valorga process, the biogas yield in the present investigation was more than 50% higher (Kübler, 1994; De Laclos et al., 1997). The higher degradation efficiency is suspected to be due to a better contact of the microorganisms to the more homogenous substrate in the present process configuration. The results from the lab-scale system have to be verified in a large-scale process. The homogeneity of the substrate may be less in a large-scale process, the process fluctuations in the feed volume (i.e. the OLR) are, however, higher in the lab-scale system. Both the co-digestion and the recirculation process showed to be robust towards these fluctuations and no inhibition was detected at free ammonia levels as high as 0.62 g/l.

The co-digestion conditions with a ratio of 50% (VS/VS) of OFMSW could be achieved without addition of water in a mixture of 77.9% (v/v) manure together with 22.1% (v/v) of OFMSW. In this case, the resulting VS and TS concentration would be 13.2% and 16.6%, respectively. This would be at the limit of mechanical handling in a CSTR. Addition of higher ratios of OFMSW would make recirculation of the liquid effluent necessary. Large-scale separation of the liquid fraction from the effluent could be achieved in a continuous process using a decanter centrifuge as it is currently applied for manure (Møller et al., 2000).

4. Conclusions

Adaptation of the thermophilic AD process to OFMSW in co-digestion with manure was established at a ratio of 50% (VS/VS) over a period of 6 weeks. Addition of higher ratios of OFMSW and AD treatment solely of OFMSW was achieved after dilution with tap water and with recirculation of process liquid. Both the co-digestion process and the treatment of 100% OFMSW with recirculation of process liquid showed stable operation despite fluctuations in the feed volume. The biogas yield from the source-sorted OFMSW used was 0.63–0.71 l/g-VS in both configurations, corresponding to 180–220 m^3 biogas per ton waste. VS reduction of 69–74% was achieved when treating 100% OFMSW. Recirculation of process liquid showed a beneficial effect on the process performance with a stabilization of the pH. Using the liquid effluent of the process for dilution of the influent OFMSW in a ratio of 59% resulted in an ammonia level in the effluent of 1.5 g-N/l, which was similar to the values found during co-digestion with manure. Both reactor systems showed no signs of inhibition at the corresponding free ammonia concentration of 0.45–0.62 g-N/l.

Acknowledgements

References

Ahring, B.K., 1994. Status on science and application of thermophilic anaerobic digestion. Water Sci. Technol. 30 (12), 241–249.

American Public Health Association (APHA), American Water Works Association (AWWA), and Water Environment Federation (WAE), 1992. In: Greenberg, A.E., Clesceri, L.S., Trussel, R.R. (Eds.), Standard Methods for the Examination of Water and Waste Water (18th ed.).

Anthonisen, A.C., Loehr, R.C., Prakasam, T.B.S., Srinath, E.G., 1976. Inhibition of nitrification by ammonia and nitrous acid. J. Water Pollut. Control Fed. 48, 835–849.

Braber, K., 1995. Anaerobic digestion of municipal solid waste: a modern waste disposal option on the verge of break-through. Biomass Bioenergy 9 (1–5), 365–376.

Cecchi, F., Marcomini, A., Pavan, P., Fazzini, G., Mata-Alvarez, J., 1990. Anaerobic digestion of municipal solid waste. Biocycle 31 (6), 42–43.

Chandler, A.J., Jewell, W.J., Gossett, J.M., van Soest, P.J., Robertson, J.B., 1980. Predicting methane fermentation biodegradability. In: Proceedings of the Biotechnology and Bioengineering Symposium no. 10, pp. 93–107

Danish Energy Agency, 1995. Progress Report on the Economy of Centralized Biogas Plants. The Biomass Section of the Danish Energy Agency.

De Laclos, H.F., Desbois, S., Saint-Joly, C., 1997. Anaerobic digestion of municipal solid organic waste: Valorga full-scale plant in Tilburg, the Netherlands. Water Sci. Technol. 36 (6–7), 457–462.

Edelmann, W., Schleiss, K., Joss, A., 2000. Ecological, energetic and economic comparison of anaerobic digestion with different competing technologies to treat biogenic wastes. Water Sci. Technol. 41 (3), 263–273.

Gallert, C., Winter, J., 1997. Mesophilic and thermophilic anaerobic digestion of source-sorted organic wastes: effect of ammonia on glucose degradation and methane production. Appl. Microbiol. Biotechnol. 48 (3), 405–410.

Goehring, H.K., van Soest, P.J., 1970. Forage fiber analysis (apparatus, reagents, procedures, and some applications). In: USDA US (Ed.), Agricultural Handbook No. 379, Agricultural Research Service. US Government Printing Service, Washington, DC.

Hamzawi, N., Kennedy, K.J., McLean, D.D., 1999. Review of applications of high-solids anaerobic digestion to solid waste management. J. Solid Waste Technol. Manage. 26 (3), 119–132.

Hartmann, H., Ahring, B.K., 2003. Phthalic acid esters found in municipal organic waste: enhanced anaerobic degradation under hyper-thermophilic conditions. Water Sci. Technol. 48 (4), 175–183.

Hartmann, H., Ahring, B.K., 2004. Efficiency of the anaerobic treatment of the organic fraction of municipal solid waste: collection and pretreatment. Waste Manage. Res. 22 (1), 35–41.

Kayhanian, M., Tchobanoglous, G., 1993. Innovative 2-stage process for the recovery of energy and compost from the organic fraction of municipal solid waste (MSW). Water Sci. Technol. 27 (2), 133–143.

Krzystek, L., Ledakowicz, S., Kahle, H.J., Kaczorek, K., 2001. Degradation of household biowaste in reactors. J. Biotechnol. 92 (2), 103–112.

Kübler, H., 1994. Experiments of thermophilic digestion of municipal organic waste. Müll Abfall 26 (8), 478–488 (in German).

Lema, J.M., Omil, F., 2001. Anaerobic treatment: a key technology for a sustainable management of wastes in Europe. Water Sci. Technol. 44 (8), 133–140.

Møller, H.B., Lund, I., Sommer, S.G., 2000. Solid–liquid separation of livestock slurry: Efficiency and cost. Bioresour. Technol. 74 (3), 223–229.

Mtz.-Viturtia, A., Mata-Alvarez, J., Cecchi, F., 1995. 2-phase continuous anaerobic digestion of fruit and vegetable wastes. Resour. Conserv. Recycling 13 (3–4), 257–267.

Rivard, C.J., Vinzant, T.B., Adney, W.S., Grohmann, K., 1989. Waste to energy—nutrient requirements for aerobic and anaerobic digestion. J. Environ. Health 52 (2), 96–100.

Rivard, C.J., Vinzant, T.B., Adney, W.S., Grohmann, K., Himmel, M.E., 1990. Anaerobic digestibility of 2 processes municipal solid waste materials. Biomass 23 (3), 201–214.

Sakai, S., Sawell, S.E., Chandler, A.J., Eighmy, T.T., Kosson, D.S., Vehlow, J., van der Sloot, H.A., Hartlen, J., Hjelmar,

O., 1996. World trends in municipal solid waste management. Waste Manage. 16 (5–6), 341–350.

Scherer, P.A., Vollmer, G.R., Fakhouri, T., Martensen, S., 2000. Development of a methanogenic process to degrade exhaustively the organic fraction of municipal "grey waste" under thermophilic and hyperthermophilic conditions. Water Sci. Technol. 41 (3), 83–91.

Six, W., De Baere, L., 1992. Dry anaerobic conversion of municipal solid waste by means of the Dranco process. Water Sci. Technol. 25 (7), 295–300.

Sonesson, U., Björklund, A., Carlsson, M., Dalemo, M., 2000. Environmental and economic analysis of management systems for biodegradable waste. Resour. Conserv. Recycling 28, 29–53.

Sørensen, A.H., Winther-Nielsen, M., Ahring, B.K., 1991. Kinetics of lactate, acetate and propionate in unadapted and lactate-adapted thermophilic, anaerobic sewage sludge—the influence of sludge adaptation for start-up of thermophilic UASB reactors. Appl. Microbiol. Biotechnol. 34 (6), 823–827.