Foodwaste as a co-substrate in a fed-batch anaerobic biowaste digester for constant biogas supply
Satoto E. Nayono, Claudia Gallert and Josef Winter

ABSTRACT

The use of foodwaste as a supplementary substrate for an anaerobic municipal biowaste digester during night times and as the sole substrate during weeks ends, when no biowaste suspension was available was studied in order to equilibrate biogas production. Assays were performed in semi-continuously fed laboratory reactors with real substrates, simulating practical feed conditions. Biogas production of biowaste or foodwaste reached 0.39 or 0.52 m³·kg⁻¹ CODadded, with an average methane content of 62–66%, respectively. By foodwaste co-digestion during the night in a semi-continuously fed bioreactor, the total biogas production of the reactor increased by 21–37% compared to biogas production during biowaste-only-fed periods during the day and no feeding during the night. After three weeks of supplementary foodwaste digestion during the nights and during week ends, the COD elimination efficiency of the reactor reached the same level as in biowaste-only-fed periods (51–65%). During co-digestion of foodwaste with biowaste, the volatile solids elimination efficiency was between 62–65%, which was insignificantly less compared to the volatile solids elimination during biowaste-only-fed periods (63–68%).

Key words | anaerobic digestion, biogas production, biowaste, co-digestion, foodwaste

INTRODUCTION

As a consequence of an increasing population and increasing activities in urban areas, the solid waste volume from human activities is drastically increasing. In Europe, it is estimated that more than 3,000 million tons of waste are generated annually (European Environment Agency 2003). Out of this number, 60 million tons of recyclable organic waste are collected separately from households and food industries (Barth et al. 1998). According to The European Landfill Directive, the Member States are required to step-wise reduce the quantities of biodegradable municipal solid wastes going to landfills from 75 to 50 and to 35% of the total amount of biodegradable waste produced in 1995 (by weight), in periods of 5, 8 and 15 years after 2001, respectively (Luning et al. 2003). As other methods to reduce biodegradable waste, such as incineration, pyrolysis and gasification had only limited success, biological treatment (anaerobic digestion and aerobic composting) boosted considerably by the introduction of source-sorted collection of a non-toxic biodegradable fraction. Among the newly installed biological treatment systems in countries such as Spain and Germany, anaerobic treatment plants accounted approximately for 30–50% (de Baere 2006).

For treatment of source-sorted biowaste from cities such as Karlsruhe/Germany, anaerobic digestion with biogas production for steam and electricity supply has been installed in full-scale (Gallert & Winter 1997; Gallert et al. 2003). To maintain a permanent energy supply for the customers, biogas must be available at constant amounts 24 h a day. This can be reached by supplementary biogas sources, for instance from a sanitary landfill or by steam generation from incineration of waste wood, as realized in Karlsruhe. The combination of biogas from biowaste and biogas from sanitary landfills even works at closed
landfills, when the gas production has passed its peak amounts. Whereas gas storage is limited and costly, waste wood incineration is flexible and could serve for steam and electricity supply during shortage of biowaste or revision periods of bioreactors. The treatment of biowaste and the incineration of waste wood at the site of a (closed) sanitary landfill has the advantage, that traffic infrastructure exists already and occasional odor problems can be minimized, since the distance towards neighbouring settlements is far enough. The use of landfill gas and biogas from the biowaste digestion plant as well as the use of heat from wood waste incineration for electricity and steam supply (Figure 1) is expected to contribute to the reduction of carbon dioxide emission and reduce dependency on fossil fuel.

Since landfill gas reaches its peak production approximately 10 years after closure and later on the amount of landfill gas (and its quality) will decrease significantly (Lee & Jones-Lee 1999), generator sets or high temperature furnaces for biogas must be supplied with other gas sources to maintain a constant energy supply. The biogas production in fed-batch anaerobic biowaste digestion plants varies during a day due to work hours from e.g. 7.00 a.m. to 21.00 p.m., during a week due to a deficiency of biowaste suspension at week ends and throughout the year, due to seasonal variation of organic matter in biowaste. In the early morning or from Saturday to Monday morning biogas production is very little (even near zero) because of a deficiency of digestible fresh biowaste. At a fed-batch feeding regime during regular work hours and insufficient storage capacities for biowaste suspensions and biogas as well, neither electricity nor heat can be supplied constantly.

In order to fill the gap of biogas deficiency during night times and week ends, a biogas reactor might be fed with easily and automatically handlable biodigestible co-substrates. Reports on co-digestion of the organic fraction of municipal solid waste with any other waste streams, such as energy crops (Nordberg & Edström 2005), market residues (Gallert et al. 2003) or manure (Hartmann & Ahring 2005) are existing. A good co-substrate should fulfill several requirements, such as: i) its concentration of organic substances should be comparable with biowaste, so that addition will not change significantly loading and hydraulic retention time, ii) it should consist of easily degradable organics with a high biogas production potential, iii) it may not contain any dangerous or poisonous substances, which hinder anaerobic digestion or composting, vi) it must be available in sufficient quantities at a reasonable price and should be storable and vii) it should be pumpable without danger of clogging, thus allowing safe automatic feeding.

This study aimed to examine in laboratory experiments process equilibration of a 1,300 m³ fed-batch full-scale biowaste digester by supplying a food waste suspension during night time and during the week ends in order to maximize and equilibrate biogas production.

MATERIALS AND METHODS

This study was based on laboratory experiments. The general principle of the experiments follows the description by Gallert et al. (2003).

Source of substrates

The biowaste suspension used in this study was the same that was prepared from source-sorted domestic biowaste and that was treated in the biowaste treatment plant of Karlsruhe. The suspension was collected after the hydro-pulper and light and heavy material removal, before entering the full-scale digester. The different steps involved in biowaste processing at the treatment plant of the City of Karlsruhe are depicted in Figure 2. The separately collected biowaste fraction is squeezed in a mill to tear apart plastic bags and then defibered in the hydro-pulper after addition of...
two parts of process water (supernatant of centrifuged digester effluent + rain water). The addition of process water for hydropulping results in a moisture content of more than 90%. Heavy materials (stones, ceramics, knives, forks and spoons, etc.) are withdrawn from the bottom, light materials (plastics) from top of the hydropulper during and after hydropulping, but before fine sand separation during interim storage. For the laboratory experiments, the biowaste was collected monthly from the interim storage tank and stored in a refrigerator until it was used.

Food waste as a co-substrate can be obtained in sufficient quantity as a sanitized and homogeneous suspension from several private or municipal companies, which collect food residues from restaurants, hospitals, university canteens, supermarkets and catering companies. The food wastes are grinded, homogenized and must be autoclaved according to legal requirements. Homogeneous portions of 1 L were frozen until use. Food waste as a co-substrate in a biowaste digester for equilibration of biogas production was selected due to its steady availability, similar biodegradability and high methane potential. By feeding a food waste suspension in the night and at weekends the biogas production over 24 h could be equilibrated and thus a permanent energy supply was possible.

**Laboratory reactors**

Biogas productivity from biowaste and foodwaste was examined in Schott glass reactors (Mainz, Germany) in batch mode. The reactors (Figure 3a) had a working volume of 3.5 L, the temperature was maintained at 37°C by a warm water jacket and the mixing was performed with a large magnetic bar stirrer. Digester effluent from the full-scale biowaste reactor of Karlsruhe served as an inoculum. Biogas production was examined by addition of 400 ml of biowaste or 200 ml of foodwaste to 2,800 ml or 3,000 ml of starved inoculum sludge, respectively. Gas production was corrected against the same amount of inoculum in a control reactor without fresh biowaste addition. Cumulative biogas production was measured with a wet gas meter (Ritter, Germany) and corrected for background biogas production from the control reactor. The methane content of the biogas was measured daily by gas chromatography according to Gallert et al. (2003).
A Schott glass reactor (designated as BR1) with a working volume of 3.5 litres was run in a fed-batch, draw-and-fill mode to assess the stability of the biogas process at increasing supply of food waste and the specific biogas production from food waste during long term feeding. The reactor was started with filtered digestate of biowaste from the full-scale biowaste reactor of the city of Karlsruhe as an inoculum.

In order to simulate digestion conditions in the full-scale anaerobic digester, a laboratory-scale reactor (designated as BR2) made from a vertical glass tube (inner diameter 0.1 m, total height 1.50 m, working volume of 8.0 litres, top and bottom sealed with rubber stoppers) was employed as a completely mixed reactor. The reactor was equipped with a warm water jacket to maintain the temperature at 37°C. The mixing was obtained by recirculation of the suspension from the head to the bottom of the reactor using a peristaltic pump (Figure 3b). The reactor was initially inoculated with effluent from the full-scale biowaste reactor of the City of Karlsruhe and fed biowaste at an initial HRT of 8 days. Later on the feeding was changed as indicated in the text. The biogas production was measured using a Ritter gas meter equipped with a built-in pulse generator. The biogas flow rates were measured using Rigamo V1.15 software.

### Analytical procedures

As performance parameters the chemical oxygen demand (COD), volatile solids (VS), volatile fatty acids residue and biogas production were measured. Furthermore, total solids (TS), volatile solids (VS), total Kjeldahl nitrogen (TKN) and ammonia were determined following standard procedures (DEV 1985).

COD was determined according to Wolf & Nordmann (1977). Organic matter was oxidized with potassium dichromate (K₂Cr₂O₇) in a mixture of sulphuric acid and phosphoric acid (H₂SO₄ + H₃PO₄). Silver sulphate (Ag₂SO₄) was used as a catalyst.

The volatile fatty acid concentrations in samples were determined as described by Gallert & Winter (1997), using a PACKARD model 437 A gas chromatograph, equipped with...
a flame ionisation detector (FID). Sample preparation was as follows: Effluent samples were centrifuged and the clear supernatant was acidified 1:1 with 4% H3PO4. One μl of acidified sample was injected into the liner in front of the column.

Biogas composition (methane and carbon dioxide) was analysed with a gas chromatograph CP 9001 (Chrompack, Frankfurt, Germany), equipped with a thermo conductivity detector (carrier and reference gas flow, 25 ml N2 min⁻¹).

RESULTS AND DISCUSSIONS

Main characteristics and biogas production potential of substrates

Table 1 shows the main characteristics of the two substrates used in this study. Concerning the total and soluble COD, the food waste was about three-fold more concentrated than the different batches of biowaste. On average, the total nitrogen content of food waste was also about threefold higher, so that after dilution to the COD of biowaste the same COD:N-ratio was resulting. In biowaste, varying amounts of propionate were present, whereas in food waste almost no propionate was found.

Due to mechanical pre-treatment of biowaste in a hydropulper the proportion of soluble or very fine particulate COD tended to be a little higher than in food waste (40% versus 35%, respectively). During pre-treatment of biowaste in a hydropulper part of the particulate organic matter apparently was disrupted or hydrolysed to soluble or colloidal compounds that could not or not rapidly be sedimented by centrifugation. In food waste approximately one third of the COD was soluble.

A wet anaerobic digestion system should be fed with organic slurries containing less than 15% total solids to maintain a gradient-free suspension (Vandevivere et al. 2002). Thus, i) to facilitate hydropulping of biowaste and ii) to operate a completely mixed methane reactor, one portion of fresh biowaste was suspended with 2 portions of process water for hydropulping and methane fermentation. The TS values of the biowaste slurries after hydropulping ranged from 5–9%. Food waste contained 25.5% total solids and, if fed undiluted as the sole substrate, would be suitable for dry digestion systems (Vandevivere et al. 2002). Since food waste consisted mainly of left-over food and undigested food residues, it had a much higher fat content than biowaste.

The biogas potential of biowastes depends on the content of digestible carbohydrates, lipids and proteins, as well as on the content of more resistant cellulose, hemicellulose and lignin (Gallert & Winter 1999; Hartmann & Ahring 2006). Figure 4a depicts the biogas production with time from the biowaste suspension of the biowaste treatment plant of Karlsruhe in a batch assay. After 2–3 days more than 90% of the biogas was released. In the following 2–3 days gas production ceased and even upon prolonged incubation no biogas was evolved any more. This gas productivity was in accordance with that of the full-scale biogas plant of Karlsruhe during week ends, when no substrate was added (Gallert et al. 2003; Gallert & Winter 2008). The maximum biogas production was 0.39 m³ kg⁻¹ COD or 0.59 m³ kg⁻¹ VS added. The highest biogas production rate was obtained within the first 24 hours with rates of around 15.9 l l⁻¹ d⁻¹ for biowaste suspensions with 9% COD, respectively, as calculated from data of Figure 4a. The average methane content of the biogas produced by digestion of biowaste was 62%.

The biogas production of food waste with an inoculum from the biowaste digester was little less during the first

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Biowaste</th>
<th>Foodwaste</th>
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<tbody>
<tr>
<td>COD total</td>
<td>77–111 g l⁻¹</td>
<td>350 g l⁻¹</td>
</tr>
<tr>
<td>COD soluble</td>
<td>30–45.5 g l⁻¹</td>
<td>120 g l⁻¹</td>
</tr>
<tr>
<td>Total solids</td>
<td>50–90 g l⁻¹</td>
<td>255 g l⁻¹</td>
</tr>
<tr>
<td>Volatile solids</td>
<td>40–70 g l⁻¹</td>
<td>225 g l⁻¹</td>
</tr>
<tr>
<td>NH₄-Nitrogen</td>
<td>0.32 g l⁻¹</td>
<td>0.22 g l⁻¹</td>
</tr>
<tr>
<td>Total Kjedahl Nitrogen</td>
<td>2.3 g l⁻¹</td>
<td>7.8 g l⁻¹</td>
</tr>
<tr>
<td>Fat</td>
<td>0.031–0.047 g g⁻¹ TS</td>
<td>0.2–0.25 g g⁻¹ TS</td>
</tr>
<tr>
<td>pH</td>
<td>4.2</td>
<td>5.1</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>30–68.5 mM</td>
<td>43 mM</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>3–21.5 mM</td>
<td>0.75 mM</td>
</tr>
<tr>
<td>Butyric acid</td>
<td>0–4.0 mM</td>
<td>0 mM</td>
</tr>
<tr>
<td>Valeric acid</td>
<td>0–0.8 mM</td>
<td>0.5 mM</td>
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</tbody>
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*After hydropulping, the low and high values of different analyses correspond with each other, respectively.
†After thermal hygienization.
48 hours of digestion (0.32 m³·kg⁻¹ COD added), but the maximal gas production rate within the first 24 h was around 14 l·l⁻¹·d⁻¹. With feeding of only food waste, about 50% of the biodegradable compounds were digested within 48 h (Figure 4b) and biogas production continued at decreasing rates for about 5 days, before it leveled off to almost zero. After 10 days, foodwaste yielded more biogas than biowaste (0.59 versus 0.39 m³·kg⁻¹ COD added). The average methane content of the biogas from food waste was 66%, and thus was a little bit higher than that of biowaste. This might, at an identical pH, indicate a higher fat content of the food waste.

The degradability of foodwaste was approximately 20–30% higher than that of biowaste. This might have been due to the higher concentration of digestible fat in foodwaste. To achieve the higher biogas amount or conversion efficiency of organics with food waste a relatively long digestion time of around 6 days was required, as compared to about 3 days with biowaste (Figure 4a, b).

Stability of the biogas process with foodwaste as a substrate

To test process stability of the biowaste digester during change of the feed from biowaste to food waste, reactor BR1 was operated for the first two weeks with biowaste as the sole substrate at 8 days HRT, until a steady state was reached. Feeding of the reactor was then continued with appropriately diluted foodwaste to maintain the same space loading and HRT. The biowaste and foodwaste substrates were fed twice a day at 9.00 a.m. and 16.00 p.m. from Monday to Friday (working days of the biowaste digestion plant of Karlsruhe), respectively and feeding was interrupted during week ends as in the full-scale plant. COD values of diluted foodwaste ranged from 84 to 132 g·l⁻¹.

Figure 5 presents the range of organic loading rates (OLR) and related COD elimination during the experiment. The biowaste suspension for start-up had a COD of 110 g·l⁻¹, which corresponded to an initial OLR of 13.8 kg·m⁻³·d⁻¹. A steady state was obtained after one week with about 62% COD-removal. Twelve days after the start, the biowaste substrate was changed to diluted foodwaste (1:3.5) with a COD of 102 g·l⁻¹, corresponding to an OLR of 12.9 kg·m⁻³·d⁻¹.

COD elimination during foodwaste feeding varied over a broad range. Within the first 15–20 days of foodwaste feeding, the COD removal efficiency decreased from over 60% to around 50% (Figure 5). The OLR was then maintained at around 10.7 kg·m⁻³·d⁻¹ by dilution of the foodwaste to 85 g·l⁻¹. After an improving COD removal for
several days the OLR was stepwise increased. Finally, for an OLR of 16 kg·m⁻³·d⁻¹ (Figure 6, from 55 days onwards) the COD elimination averaged 70%.

As shown in Figure 6, the average biogas production was 4.6 m³·m⁻³·d⁻¹ for an OLR of 10.7 kg·m⁻³·d⁻¹. The gas production increased to 4.8 and 5.2 m³·m⁻³·d⁻¹, respectively when the OLR was increased to 12.2 and 14.9 kg·m⁻³·d⁻¹. The fluctuation of daily biogas amounts was not higher at high OLR compared to lower OLR.

Figure 7 presents volatile fatty acid concentrations for the different loading rates of biowaste and food waste during the experiment. During the initial start-up, no butyric and valeric acid was detectable. The initially present acetic acid was rapidly degraded, whereas the propionate concentration increased to 1,793 mg·l⁻¹. When propionate degradation began after 5 days, acetic acid was accumulating instead, presumably from propionate decarboxylation. Acetic acid reached a maximum concentration of 1,153 mg·l⁻¹. As has been reported by several authors (e.g. Inanc et al. 1999; Gallert et al. 2003), the accumulation of fatty acids is normally occurred during start-up periods or process instability following shock loading. The methanogenic population was reported to be inhibited at propionic acid concentrations in excess of 1,000 mg·l⁻¹. Although there was accumulation of acetic and propionic acid during start-up and every successive OLR increment (propionic acid reached 1,793 mg·l⁻¹ during start-up and 1,037 mg·l⁻¹ after OLR increment to 16.6 kg·m⁻³·d⁻¹), the reactor did not show any shock loading symptoms and the performance was not drastically deteriorated.

Figure 8 hourly biogas production rates of the reactor during 3 weeks of biowaste feeding, followed by three weeks of biowaste + food waste feeding were projected upon each other. The hourly biogas production of foodwaste varied

Co-digestion of biowaste and food waste: loading regime and biogas production

Loading regime of the reactor

A 81 laboratory-scale reactor was started in November 2006 with biowaste as a substrate. After reaching steady state conditions, co-digestion of foodwaste was started. During steady-state operation, the reactor was fed with biowaste at a hydraulic retention time of 8 days and organic loading rates of 11.7 – 13.6 kg·m⁻³·d⁻¹, caused by COD variation of the biowaste suspension from 93.4 g·l⁻¹ to 107.1 g·l⁻¹. According to previous results with the same source of biowaste, the reactor could be fed with an organic loading rate up to 18 kg·m⁻³·d⁻¹ without any instabilities (Gallert et al. 2003). For co-digestion of foodwaste with biowaste, the reactor was fed with 1 litre biowaste (corresponding to a HRT of 8 days) and 80 ml of foodwaste, resulting in an organic loading rate of 16.8 kg·m⁻³·d⁻¹. During the biowaste-only-fed period, the reactor was fed twice a day at 09.00 a.m and 16.00 p.m., while during the co-digestion period the reactor was fed three times per day: at 09.00 a.m and 16.00 p.m. with biowaste and at 17.00 p.m. with foodwaste. The co-digestion of foodwaste reduced the hydraulic retention time from 8 to 7.4 days.

Biogas production

In Figure 8 hourly biogas production rates of the reactor during 5 weeks of biowaste feeding, followed by three weeks of biowaste + food waste feeding were projected upon each other. The hourly biogas production of foodwaste varied.
from 0.027 m$^3$·m$^{-3}$·h$^{-1}$ to 0.456 m$^3$·m$^{-3}$·h$^{-1}$. Minimal gas production rates were observed on each Monday morning, when the reactor has been starving since Friday night. After resuming the biowaste feeding, maximal gas production rates were reached one hour after the 2nd daily feeding at around 16.00 p.m. and then the biogas production rate decreased slowly until the next morning. Since the last feeding during every working days was at 16.00 p.m., the biogas production decreased to a minimum rate of approximately 0.105 m$^3$·m$^{-3}$·h$^{-1}$ until the next morning, before feeding was continued at 9.00 a.m.

The hourly biogas production rates were slightly higher when a mixture of biowaste and foodwaste was fed into the reactor (Figure 8). The minimum gas production rate after the weekend was 0.042 m$^3$·m$^{-3}$·h$^{-1}$, whereas the minimum daily gas production rate after 10 h starvation was 0.135 m$^3$·m$^{-3}$·h$^{-1}$. The highest gas production rates were between 0.55 and 0.65 m$^3$·m$^{-3}$·h$^{-1}$. The highest biogas production rate at all was measured on the third day of co-fermentation of foodwaste. The shape of the biogas production curves of the reactor fed with biowaste or during co-digestion of foodwaste was similar.

Figure 9 shows daily biogas rates during biowaste-only-fed periods and co-digestion periods, projected upon each other. From the graph it can be concluded, that, although the hourly biogas production during the co-digestion period only slightly increased, on a daily basis the biogas production increased significantly. During a biowaste-only-fed period, the daily biogas production reached its minimum value of 1.09 m$^3$·m$^{-3}$·d$^{-1}$ on Sundays and the maximum values during the week (5.62–5.70 m$^3$·m$^{-3}$·d$^{-1}$). During the first week of foodwaste addition, the daily biogas production increased immediately to 7.82 m$^3$·m$^{-3}$·d$^{-1}$ but came down to the level of biowaste-only-feeding at the weekend (Figure 9). The decrease of gas production was accompanied by less COD elimination and higher fatty acid concentrations in the effluent due to the necessity of the population to adapt to the new substrate and to cope with the higher organic loading rate (Figures 10 and 11, day 20 onwards). In the second and third week of foodwaste co-digestion the performance of the reactor had stabilized and the daily biogas production of the reactor increased by 21–37% compared to the level of production during biowaste-only-fed periods (Figure 9).

Co-digestion: COD and volatile solids elimination

The success of solid waste digestion is mainly dependent on removal of soluble organics and of suspended solids.
If the effluent of a treatment plant has to be deposited in a landfill, high solid reduction will be beneficial in terms of handling, transportation and volume requirement in a sanitary landfill. Elimination of biodegradable organic matter is also important in order to fulfill the requirement of the European Landfill Directive.

The COD elimination efficiency of the reactor ranged from 51%–65% (average 56%) during the biowaste-only-fed periods. Typically COD elimination decreased throughout weekdays and within a week (Figure 10). This phenomenon happened due to incomplete degradation of the substrate from the previous day(s). After the start of foodwaste addition, the COD elimination efficiency of the reactor decreased to its lowest value of 50%. However, in the 2nd week of co-digestion, the elimination efficiency increased throughout weekdays from 52 to 62%. This indicated that the reactor was able to cope with the additional OLR from foodwaste (should be compared also with biogas production and fatty acid concentration in the effluent: Figures 10 and 11). During the 3rd week of co-digestion, the COD elimination efficiency of the reactor reached the same level as in biowaste-only-fed periods.

Volatile solid elimination during biowaste-only-fed operation of the reactor, the dominant volatile fatty acids in the effluent were acetic and propionic acid. The concentrations of acetic and propionic acid reached their maximum values of 198 mg·l$^{-1}$ and 422 mg·l$^{-1}$ at the end of each day or week and disappeared completely during the weekend, when no substrates were added. The increasing concentrations for acetate and propionate during the week can still be considered as low, indicating that the acetogenic and methanogenic population in the reactor was intact. Other volatile fatty acids such as i- and n-butyric and valeric acid were not present in the reactor effluent.

When the reactor was fed a mixture of biowaste and foodwaste, in the first week of foodwaste co-digestion the concentration of acetic and propionic acid increased to 715 mg·l$^{-1}$ and 2,660 mg·l$^{-1}$, respectively (Figure 11). The increase of fatty acid concentrations was caused by the higher organic loading rate and the new type of substrate, which apparently differed from biowaste. Previous research (Gallert et al. 2003) demonstrated that there was accumulation of propionic acid for some time after reducing the HRT from 8 days to 7.1 days. However, after 3 days the concentration of acetic acid decreased to nearly the same level as the previous concentration without foodwaste addition. Propionic acid removal required about 1 week time to reach the low steady-state concentration levels and was completed about 2 weeks after foodwaste introduction.

As shown in Figure 11, the pH was almost constant throughout the experimental period, ranging from 7.3 to 7.5. Only during the first week of co-digestion, the pH decreased to 7.1 and came back again to 7.3–7.5 in the following week. The decrease of the pH value during the first week of co-digestion was caused by residual volatile fatty acids in the effluent, especially by high concentrations of propionic acid. According to Dinamarca et al. (2003) and the experience from this study, it is not necessary to control the pH throughout steady state operation, since the pH is kept stable by the buffer effect of biowaste and food waste.
CONCLUSIONS

From the results of this study it can be concluded that foodwaste can be used as co-substrate in anaerobic treatment of biowaste during night times and weekends, when no biowaste suspension is available in order to maximise or equilibrate biogas production. During relatively long feeding with foodwaste as the sole substrate, there was no indication of an inhibitory or poisonous effect on methanogenesis. The concentration of organic matter of food waste can be adjusted to that of biowaste and co-digestion of biowaste with foodwaste will not disturb the capacity of the biowaste plant to treat the regular biowaste volume from the city, whenever biowaste is available. Although there was slight decrease in solid reduction during food waste digestion, this can be regarded as insignificant and is compensated by the significant increase of biogas production. Since the autoclaved food waste is perfectly homogenous, continuous addition during night time or weekends at low pumping rates without control personnel is possible. Thus, the benefits for the operator of the biowaste digester are two-fold. Firstly, no third shift of workers is required for a constant gas supply during night and during weekends since a continuous addition of food waste by pumps is less susceptible to troubles than of a heterogeneous biowaste suspension. Secondly, there is a constant gas generation, which allows a permanent hot water supply for heating and warm water of an adjacent city neighbourhood. Overall, biogas production from organic waste material does exert less environmental impact than composting, since the energy of the organic matter is conserved and used before the carbon is remineralized and released into the atmosphere as carbon dioxide.

REFERENCES


