Treatment of fatty solid waste from the meat industry in an anaerobic sequencing batch reactor: start-up period and establishment of the design criteria

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ABSTRACT

An anaerobic sequencing batch reactor (AnSBR) was used to treat the dissolved air flotation skimmings from a cooked pork meat plant. During the start-up period, the reactor was operated in fed-batch mode for 25 days and 7 batches were treated. The SBR was inoculated with sludge taken from a reactor treating distillery vinasse. The results showed that this kind of sludge is a very good source of inoculum for digesters treating residues with a high content in fats and long-chain fatty acids because it was able to adapt very rapidly to the new substrate and, from the second batch on, the sludge was already able to metabolize the fatty residue at quite high rates. The AnSBR was then operated with 5 batches per week for 110 days and the quantity of VS added per batch was regularly increased until the maximum treatment capacity of the reactor (i.e. maximum loading rate) was reached. The maximum organic loading rates were found to be 0.16 g VS/g VSS d, or 0.224 g VS/g VSS.batch when the reactor is fed 5 times a week. The biodegradability of the skimmings was very high, with more than 97% of TS removal, and the methane production was 880 ± 90 mL of methane/g of VS_{added}.

Key words | anaerobic digestion, AnSBR, dissolved air flotation skimmings, fatty solid wastes

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INTRODUCTION

Meat industries produce large amounts of organic solid wastes including wastes with a high quantity of lipids, such as the skimmings produced by the grease removal step in the pretreatment of effluents prior to aerobic treatment. Several solutions can be used for the treatment of these wastes: recycling as animal feed, incineration, composting, aerobic biological treatment or anaerobic digestion (Salminen & Rintala 2002).

Fatty residues are substrates well-suited to anaerobic digestion as high biogas or methane yields can be expected from lipids with, for example, between 870 and 1,320 L of biogas/kg of fat reported by Cammarota & Freire (2006); or methane production of 600 to 900 L/kg VS_{added} for poultry slaughterhouse wastes (Salminen & Rintala 2002). Furthermore, Grant *et al.* (2001) showed that the anaerobic digestion of dissolved air flottation skimmings from poultry processing wastewater was feasible at quite high loading rates.

The anaerobic SBR (sequencing batch reactor) is an attractive solution for the anaerobic treatment of fatty solid wastes because this process offers several advantages over a continuous process (Wilderer *et al.* 2001). For example, at the beginning of the reaction phase the substrate to microorganism ratio S_0/X_0 is high and the degradation reactions will occur at correspondingly high rates in accordance with Monod's kinetic equations. In addition, at the end of the reaction phase, the S/X ratio and the production of biogas are at a minimum, which permits the settling of the biomass and its separation from the supernatant. Furthermore, in an AnSBR process, reaction

doi: 10.2166/wst.2009.658

and settling occur in a single tank, following a time sequence, whereas in a continuous process several tanks are required.

The aim of this work was to assess the efficiency of the anaerobic SBR process (AnSBR) in the treatment of skimmings of the dissolved air flotation of the effluents and to collect technical data on the design and operation of this process focusing, first, on the start-up period; and second, on the establishment of the design criteria such as methane production, maximum loading of the reactor and solids removal.

METHODS

Fatty solid waste

The fatty solid waste was the residue (skimmings) collected from the dissolved air flotation treatment of the effluents at the on-site activated sludge treatment plant of a cooked pork meat plant. The average composition of the waste was 760 g of total solids (TS)/kg and 560 g of fat/kg. The organic fraction was very high, with volatile solids (VS) representing more than 99% of the TS. The fat fraction was mainly made up of triglycerides (80%) and diglycerides (15.5%), indicating a low level of hydrolysis. Five long-chain fatty acids (LCFA) were dominant (myristic acid (14:0), palmitic acid (16:0), stearic acid (18:0), oleic acid (18:1) and linoleic acid (18:2)) and represented 88% of the total fatty acids.

Reactor

A double-walled reactor of 5 L effective volume maintained at 35°C by a regulated water bath was used. Mixing was done by a system of magnetic stirring. The biogas production rate (BPR) was measured on-line by an Aalborg mass flow meter (0–20 mL/min or 0–50 mL/min) fitted with a 4–20 mA output.

Inoculum

The reactor was seeded with anaerobic sludge, taken from the outlet of an anaerobic reactor treating distillery vinasse, at a volatile suspended solids (VSS) concentration of 15.6 g/L.

Operation of the reactor

The start-up period lasted 25 days. During the first 18 days, 2 g of residue-VS/L were added 4 times, on days 1, 7, 12 and 15 (Table 1). Then the reactor was fed 3 times (days 19, 21 and 23) with 0.96 g of residue-VS/L.

From day 25 (end of the start-up period) and for 110 days, the reactor was fed 5 times a week with increasing quantities of VS (Table 1). The reactor was operated with 5 batches per week to simulate the operating conditions at industrial scale as the production plants will be generally closed on Saturdays and Sundays. The loading rate was 0.94 g VS/L.batch for 22 days (days 26–48), 1.18 g VS/L.batch for 25 days (days 49–74), 1.58 g VS/L.batch for 13 days (days 75–88), 2.12 g VS/L.batch for 13 days (days 89–102) and 2.60 g VS/L.batch for the last 33 days (days 103–136). The S_0/X_0 ratio increased from 0.075 to a maximum of 0.208 g of VS_{added}/g $VSS_{reactor}$. For the four 24-h batches, there was a manual feeding at the beginning of the batch followed by a reaction phase lasting 24 hours without withdrawal. For the 3-day batch, the sequence was: manual feeding, reaction phase for 70 hours, 2 hours of settling and then withdrawal of the excess liquid.

The quantity of VS added was increased until the maximum treatment capacity of the reactor was reached, that is to say until the added organic matter was not fully eliminated at the end of the 3-day batch, showing an over-loading of the reactor. In our operating conditions, the limit chosen was a biogas production rate (BPR) of more than 2 mL/min at the end of the 3-day batch. A BPR greater than 2 mL/min showed that the endogenous respiration was not reached at the end of the 3-day batch, indicating that the metabolization of the added organic matter was not finished and that the maximum treatment capacity of the rector had been reached.

NH_4Cl (1.72 g) was added to the reactor on days 100 and 112, when N-NTK concentration in the reactor was below 60 mg/L. No trace elements were added.

Analysis

Volatile fatty acid (VFA) concentration was measured using a gas chromatograph (GC-8000, Fisons instruments) with a flame ionization detector and an automatic sampler

Table 1 | Feed conditions and main results

		Quantity of residue added (g VS/L.batch)	Duration of the batch (h)	Maximum biogas production rate (mL/min)	Maximum biogas production rate (mL/min)	Volumetric loading rate (g VS_{added}/L d)	Mass loading rate (g VS_{added}/g VSS d)
Start-up Period							
Day of feed	1st	2	95	4.50	–	0.51	0.032
	7th	2	77	6.70	–	0.62	0.040
	12th	2	56	7.30	–	0.86	0.057
	15th	2	50	7.90	–	0.96	0.064
	19th, 21st, 23rd	0.96	18	7.10	–	1.7	0.090
Increasing loading rates							
Time interval	Days 26 to 48	0.94	–	8	1.80	1.53	0.12
	Days 49 to 74	1.18	–	13	1.50	1.78	0.174
	Days 75 to 88	1.58	–	16.50	3.50	1.43	0.142
	Days 89 to 102	2.12	–	>20	3.70	1.67	0.162
	Days 103 to 136	2.60	–	22	5	1.86	0.142

(AS 800, Fisons instruments). The column was a semi-capillar Econocap FFAP (Alltech) column with 15 m length, 0.53 cm diameter and Phase EC^{TM} 1,000 film 1.2 μm. The temperature of the spitless injector was 250°C, the temperature of the detector was 275°C. The temperature increased from 80°C to 120°C in 3 min. The carrier gas was nitrogen (25 kPa). The internal standard method (1 g of ethyl-2-butyric acid in 1 L of water acidified with 50 mL of H_3PO_4) was used to measure total VFA concentration by mixing 1/1 volume of the internal standard solution and the sample or the standard solution. The margin for error of this measurement was between 2% and 5% with a quantification threshold of 0.1 g/L.

Biogas composition (CO_2, H_2, O_2, N_2 and CH_4) was determined using a gas chromatograph (Shimadzu GC-8A) connected to a C-R8A integrator and equipped with a CTRI Alltech column made up of 2 concentric columns (3.175 mm-diameter inner column filled with Sillicagel and a 6.350 mm-diameter outer column filled with a molecular sieve). The carrier gas was argon at 2.8 bars. The temperatures were 30°C for the oven and 100°C for the injector and the detector. The margin for error of this measurement was 5%.

Soluble COD was measured by a colorimetric method using Hach 0–1,500 mg/L vials. Other parameters (TS, VS, SS and VSS) were measured following Standard Methods, APHA (1992).

RESULTS AND DISCUSSION

The operation of the anaerobic SBR (Sequencing Batch Reactor) can be divided into 2 periods: first, a period of 25 days corresponding to the start-up of the reactor, followed by a second period of 110 days during which the quantity of VS added to the reactor was regularly increased.

Start-up period

There was no adaptation phase prior to the seeding of the reactor. A high concentration of sludge was used (15.6 g VS/L) for seeding to study the acclimatization of the microorganisms to the new fatty substrate, without consideration for biomass growth. During this period, the reactor was operated in fed-batch mode and 7 batches were processed with neither a settling nor withdrawal phase. During the first 18 days, 2 g of residue-VS/L.batch were added on days 1, 7, 12 and 15 (Table 1). As the length of the last 2 batches was around 2 days, it was decided to feed the reactor after the 18th day with around 1 g VS/L.batch so as to reduce the treatment batch to less than 24 h. Three feedings were then made, on days 19, 21 and 23, with 0.96 g of residue-VS/L.batch.

The biogas production rate (BPR) was monitored online for each batch (Figure 1) thus making it possible to follow the progress of the reaction phase and ascertain exactly when a batch ended. In the start-up period, the reaction phase was considered as over when the biogas production rate reached a low value (<1.5 mL/min), indicating that most of the biodegradable material added had been eliminated. However, the duration of batch was extended after the BPR had reached 1.5 mL/min in order to get further information on the evolution of the BPR towards the end of the batch.

The first batch was the longest (4 days). The shape of its BPR curve (Figure 1) was completely different from that of the following batches: (i) during the first 2 days following the feed, the BPR remained very low (<1.3 mL/min), indicating very weak metabolic activity; (ii) then a peak was observed during the third day, indicating an increase in the organic matter degradation rates; and (iii) the BPR decreased during the 4th day, stabilizing between 1 and 1.3 mL/min, which indicated the end of the reaction.

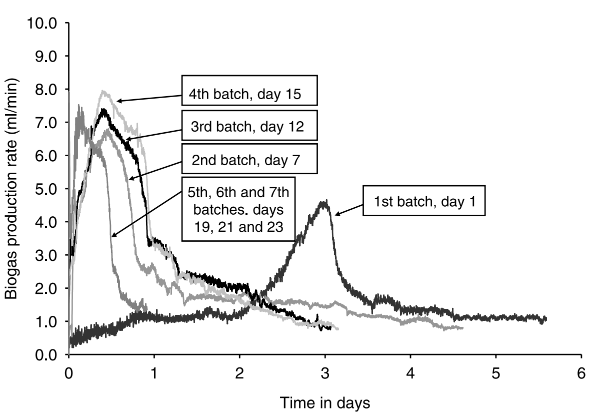

Figure 1 | Evolution of the biogas production rate for batches during the start-up period.

The shape of the BPR curve obtained during the second batch (7th day) differed greatly from the first one and proved to be already quite close to the curves obtained during the rest of the experiment: (i) the maximum BPR was recorded at the beginning of the batch and lasted for a few hours; (ii) it was followed by a quick decrease of the BPR, indicating the exhaustion of the rapidly biodegradable material; (iii) thereafter, the BPR was low and decreased slowly, indicating the metabolization of slowly biodegradable organic matter. For the 2nd, 3rd and 4th batches with 2 g of VS/L.batch (days 7, 12 and 15), the shape of the BPR curves was quite similar though some acclimatization was still occurring with: (i) a shortening of the duration of the batches (Table 1, column 3); (ii) an increase in the maximum BPR (around +9% each time); (iii) an increase in the volumetric loading (VLR) and the mass loading (MLR) rates.

The 3 curves representing the evolution of the BPR over time for the last 3 batches, with 0.96 g VS/L.batch, were very close; thus, only the third one is presented in Figure 1 (23rd day). This curve had the shape of the final curves observed during the continuation of the experiment, with a maximum BPR reached after 2 hours and lasting for 11 hours.

The main conclusion on the the start-up of the reactor is that the acclimatization of the sludge to the new fatty substrate occurred very rapidly and as early as the second batch, the sludge was already able to metabolize the fatty substrate at fairly high rates. The mass loading rate (MLR) was low for the first batch with 0.032 g of VS/g VSS d (Table 1 and Figure 2) but it increased rapidly and linearly during the first 25 days and was multiplied almost three-fold between the first and the seventh batches.

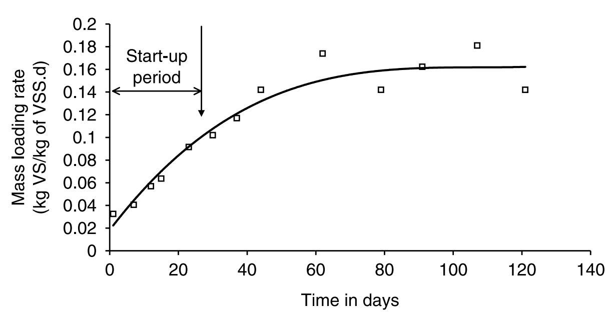

Figure 2 | Evolution of the specific activity of the anaerobic biomass during the whole experiment.

This speedy adaptation of the anaerobic sludge to the fatty substrate might well be explained by the following two facts:

(i) First, sludge treating distillery vinasse has a high microbial diversity, particularly in respect of the bacteria. Indeed, Godon *et al.* (1997) studied the microbial community structure of an anaerobic sludge treating distillery vinasse using molecular biological techniques which showed that the ecosystem was composed of more than 146 different organisms, out of 579 sequences analysed, belonging to the three domains, bacteria, eucarya and archaea. The representation of the bacteria domain was extremely diverse and contained more than 133 molecular phylotypes distributed among at least eight of the major groups;

(ii) Second, the sludge was fed with distillery vinasse, which contains a wide variety of organic compounds. Indeed, this substrate is the residue remaining after wine distillation and contains a wide variety of substrates present at several g/L (Flanzy 1998), such as polysaccharides, polyols, organic acids, polyphenols, nitrogenous compounds, etc.

The results obtained have shown that a sludge fed with a distillery vinasse is a very good source of inoculum for seeding anaerobic digesters treating residues with a high concentration of fats and long-chain fatty acids (LCFA).

Increase in the quantity of VS added

In the second part of the experiment, the reactor was fed with increasing quantities of fatty residue (Table 1) in order to establish the criteria to be used for the design of a full-scale anaerobic SBR treating such residue. The reactor was fed 5 times a week (four 24-hour batches and one 3-day batch). At the beginning, the reactor was fed with around 1 g of VS/L.batch for 3 weeks. Then, the quantity of VS added was regularly increased, according to the behavior of the reactor, until the reactor was overloaded, indicating that its maximum treatment capacity had been reached, that is to say when the biogas production rate was higher than 2 mL/min at the end of the 3-day batch.

Evolution of biogas production rate profiles

Figure 3 presents the changes in the biogas production rate (BPR) profiles as the quantity of VS added was increased.

The main remarks on the evolution of these curves are:

(i) The maximum BPR at the beginning of the batch increased considerably over time and was multiplied by almost 3 between the end of the start-up period (8 mL/min at day 30) and the maximum loading rate (22 mL/min at day 121). This reflects a high increase in the kinetics of degradation of the easily biodegradable fraction of the waste.

(ii) The volumes of biogas and methane produced during a batch increased proportionally to the increase of the loading rate, with 1,260 ± 130 mL of $\text{biogas}_{\text{produced}}$/g of VS_{added} which corresponded to 880 ± 90 mL of $\text{methane}_{\text{produced}}$/g of VS_{added} (average methane content of 70 ± 4%). It is important to underline that these data include the endogenous respiration and, thus, the volume of $\text{methane}_{\text{produced}}$/g of VS_{added} is not the actual methane potential of the waste.

(iii) For the higher loadings, the BPR at the end of the 24-hour batches tended to increase, indicating that the remaining bacterial activity at the end of the 24-hour batches increased with the rise of the quantity of VS added (Table 1, 5th column) and that the organic matter added at the beginning of the batches was not fully eliminated in 24 hours.

Though the maximum BPR increased significantly over time, the global specific activity of the biomass did not increase after day 60 (Figure 2) because of the

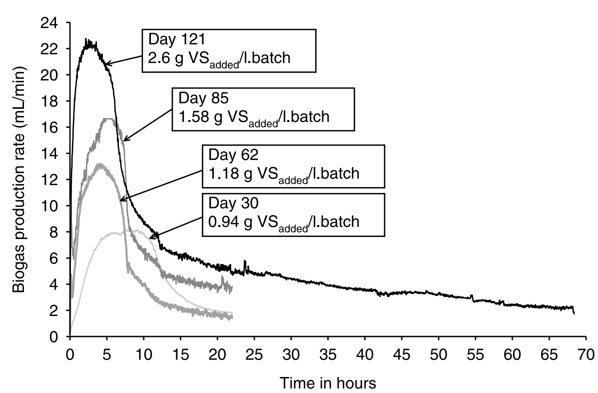

Figure 3 | Evolution of biogas production rates at different organic loading rates.

slowly-biodegradable compounds which prolonged the duration of the batches. However, the quantity of VS added could be further increased as the VSS concentration in the reactor increased from 10 g/L on day 60 to 14 g/L on day 140.

For the highest loadings, the BPR at the end of the batches tended to increase from one batch to another, indicating that no degraded organic matter accumulated during the week. Nevertheless, the curve at day 121 in Figure 3, which gives an example of a 3-day batch, shows that at the end of the last batch of a week, it was possible to reach a very low BPR (2 mL/min in that example) which facilitates a good liquid/solid separation in the settling phase, prior to withdrawal of the supernatant from the reactor.

VFA concentration was measured 3 times a week at the end of the batches and was found always to be nil, indicating that there was no accumulation of VFA from one batch to another.

In the range of organic loadings used in this work, feeding the reactor 5 days a week with a long 3-day batch at the end of the week permitted the complete elimination of the organic matter fed into the reactor during a week and prevented any overloading. However, loads higher than 2,6 g VS/L.batch were not tried because at such a level, the activity at the end of the 3-day batches was rather high (BPR of 2 mL/min at the end of the 3-day batches), indicating that the maximum capacity of the reactor had been reached.

Design criteria

According to the results of this experiment, stable anaerobic digestion of the skimmings from the dissolved air flotation treatment of effluent from a cooked pork meat plant appears to be feasible when loading rates are less than about 0.16 g residue-VS/g VSS d (Table 1, 7th column), which corresponds to a load of 0.21 g of solid residue/g VSS d. If the reactor is fed 5 times a week with four 1-day batches and one 3-day batch, the maximum loading rates should be less than 0.224 g residue-VS/g VSS.batch and 0.30 g of solid residue/g VSS.batch. The maximum volumetric loading rate applied was 1.86 g VS/L d (Table 1, 6th column).

Solid removal was always very high (more than 97%) as the concentration of the feed was, on average, 760 g of TS/kg and the maximum solid concentration in the reactor was, on average, 18 g TSS/L.

The loading conditions used in this work (maximum volumetric loading rate of 1.86 g VS/L d) are lower than those used by Grant *et al.* (2001) for the treatment, at pilot scale, of the skimmings from poultry processing wastewater (volumetric loading rate of 2.54 g VS/L d). However, this author obtained a lower solid removal efficiency with 73% on average.

As a result of the high fat content of the residue and its excellent biodegradability, methane production was very high (880 ± 90 mL of methane/g of VS_{added}) and close to the results of Salminen & Rintala (2002) for a mixture of offal, feet and heads from poultry slaughterhouse (700–900 mL of methane/g VS_{added}) and for a mixture of trimmings and bones (600–700 mL of methane/g VS_{added}). Specific methane yields for a mixture of solid poultry slaughterhouse waste in the range 550–670 mL/gVS_{added} were found in batch by Salminen *et al.* (2000). Banks & Wang (1999) found much lower methane production (270 mL/g TS_{added}, i.e. around 300 mL/g VS_{added}) for the treatment of mixed abattoir wastes.

In this work, soluble COD at the end of the reaction phase was always less than 1 g/L and TSS and VSS stabilized respectively at 18 g/L and 13 g/L, indicating that there was no accumulation of the added organic matter, either in the solid or soluble form. These results and the high methane production show that the organic matter added was effectively eliminated. It should be also underlined that no fatty acid inhibition was observed in this work even at quite high loading rates.

CONCLUSIONS

Stable anaerobic digestion of the dissolved air flotation skimmings of a cooked pork meat plant was obtained in an anaerobic SBR operated at 5 batches/week. The main conclusion for the start-up period of the reactor is that sludge from a reactor treating a distillery vinasse is able to adapt very rapidly to a fatty residue. Indeed, as early as the second batch, the sludge was already able to metabolize the fatty substrate at quite high rates, demonstrating that this kind of sludge is a very good source of inoculum for seeding anaerobic digesters treating residues with a high concentration of fats and long-chain fatty acids (LCFA). The maximum design parameters recommended for use are: 0.16 g VS/g VSS d or 0.224 g VS/g VSS.batch if the reactor is fed 5 times a week with four 24-hour batches and one 3-day batch. In these operating conditions, both biodegradability and methane production were found to be very high, with more than 97% TS removal and methane production of 880 ± 90 mL of methane/g of VS_{added}. Neither soluble COD nor VSS accumulations were observed in the reactor, confirming that the skimmings were effectively eliminated.

ACKNOWLEDGEMENTS

This work was supported by ADEME (French environment and energy management agency) and ACTIA (Association for technical coordination in the food industries) and managed by ARITT Franche-Comté.

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