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Anaerobic Treatment of Animal Byproducts from Slaughterhouses at Laboratory and Pilot Scale

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Abstract

Different mixtures of animal byproducts, other slaughterhouse waste (i.e., rumen, stomach and intestinal content), food waste, and liquid manure were codigested at mesophilic conditions (37°C) at laboratory and pilot scale. Animal byproducts, including blood, represent 70–80% of the total biogas potential from waste generated during slaughter of animals. The total biogas potential from waste generated during slaughter is about 1300 MJ/cattle and about 140 MJ/pig. Fed-batch digestion of pasteurized (70°C, 1 h) animal byproducts resulted in a fourfold increase in biogas yield (1.14 L/g of volatile solids [VS]) compared with nonpasteurized animal byproducts (0.31 L/g of VS). Mixtures with animal byproducts representing 19–38% of the total dry matter were digested in continuous-flow stirred tank reactors at laboratory and pilot scale. Stable processes at organic loading rates (OLRs) exceeding 2.5 g of VS/(L·d) and hydraulic retention times (HRTs) less than 40 d could be obtained with total ammonia nitrogen concentrations (NH_4-N + NH_3-N) in the range of 4.0–5.0 g/L. After operating one process for more than 1.5 yr at total ammonia nitrogen concentrations >4 g/L, an increase in OLR to 5 g of VS/(L·d) and a decrease in HRT to 22 d was possible without accumulation of volatile fatty acids.

Index Entries: Animal byproducts; anaerobic treatment; animal waste; biogas; slaughterhouse waste; codigestion.

Introduction

The outbreak of bovine spongiform encephalopathy (BSE) in Europe has made the traditional use of animal byproducts as animal feed impossible,

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and it is therefore important to find alternative solutions for treatment. In Sweden and Denmark, utilization of rumen, stomach and intestinal content, blood waste fractions, and sludge from slaughterhouse wastewater treatment in biogas plants is rather common *(1,2)*. Sweden is still (February 2002) free from BSE-infected cattle (S. Liljenström, personal communication), and the interest in using animal byproducts as a substrate for biogas production has increased lately.

Because of the high content of protein and lipids, animal byproducts are an energy-rich feedstock, which makes them interesting as a substrate for anaerobic digestion. However, the high content of protein and lipids may cause inhibition of the digestion process owing to high ammonia and long chain fatty acids (LCFA) concentration. Therefore, codigestion with other feedstock is an option to achieve satisfying stability and efficiency in the digestion process.

The objectives of the present study were to obtain results and experience that could be used for developing full-scale codigestion processes with animal byproducts from slaughterhouses during mesophilic conditions. In this article, we present the biologic performance such as process stability and biogas yield in relation to the organic loading rate (OLR) of the laboratory- and pilot-scale processes investigated.

Definitions

According to SJVFS 2000:166 *(3)*, *animal byproducts* are defined as carcasses or parts of animals, or products of animal origin, not intended for direct human consumption. Animal byproducts are classified either as (1) high-risk material, if it presents a serious risk of spreading communicable diseases to animals or humans; or as (2) low-risk material, if the animal byproducts are derived from healthy animals slaughtered in a slaughterhouse, which have passed health inspection. After the outbreak of BSE, the animal byproducts presenting a risk for transmissible spongiform encephalopathy have to be sorted out. This fraction is classified as specified risk material (SRM) and must be completely disposed of as waste by incineration, coincineration, or landfill. Rumen, stomach and intestinal content, and manure from stables and trucks are not characterized as animal byproducts.

Potential Biogas Substrates from Slaughtered Animals

The calculated quantity and composition of byproducts from slaughter of cattle and pigs is given in Tables 1 and 2, respectively. The calculation is based on the quantity of animal low risk material *(4)*, SRM and animal high-risk material (J. Hellström, personal communication). The composition of stomach and intestinal content is calculated from *(5–8)*, the animal byproducts from *(6,9)*, and blood from *(6,8,9)*.

Table 1
Calculated Quantity and Composition
of Waste and Byproducts from Slaughter of Cattle

	Weight (% of total)	DM (% of total)	Nitrogen (% of total)	Phosphorus (% of total)	References
Rumen, stomach and intestinal content	34	14	4	9	*5–8*
Animal low risk excluding blood	43	56	63	65	*6,9*
SRM[a]	14	22	21	22	Hellström, J., personal communication
Blood	7	5	9	1	*6,8,10*
Animal high risk (average)	2	2	3	3	Hellström, J., personal communication
Total[b]	270	68	5.3	0.8	*4*

[a]SRM shall go to an incineration plant, or after a preprocessing to burial in an approved landfill site *(11)*. Today, digestion is not an allowed treating method for SRM.
[b](kg/cattle)

Table 2
Calculated Quantity and Composition
of Waste and Byproducts from Slaughter of Pigs

	Weight (% of total)	DM (% of total)	Nitrogen (% of total)	Phosphorus (% of total)	References
Stomach and intestinal content	25	10	3	15	*5–8*
Animal low risk excluding blood	61	77	78	79	*6,9*
Blood	11	9	14	1	*6,8,10*
Animal high risk (average)	4	5	5	5	Hellström, J., personal communication
Total[a]	28	6.9	0.6	0.1	*4*

[a](kg/pig)

Materials and Methods

Waste Mixtures

A representative mixture of minced animal byproducts based on the amount produced at a slaughterhouse was used in fed-batch experiments. The potential gas yield was determined for a pasteurized (at 70°C, 1 h) and an unpasteurized mixture.

Table 3
Average Waste Mixtures Wet Weight Composition, DM, and Nitrogen Content Used

Process	Animal byproducts (% of WM)[a]	Stomach content and sludge (% of WM)[b]	Food waste (% of WM)	Dilution (% of WM)	Liquid manure (% of WM)	DM in WM (% of weight)	Nitrogen in WM (% of DM)
Lab. 1a	12	46	36	7	—	20	3.3
Lab. 1b	8	31	20	40	—	11.5	4.5
Lab. 1c	8	32	21	38	—	12.5	4.5
Lab. 2	13	21	14	51	—	11	5.9
Pilot 1a	10	39	26	25	—	14	4.7
Pilot 1b	8	31	20	40	—	12.5	4.5
Pilot 2	15	28	—	15	42	12	6.0

[a]Animal byproducts and blood. Animal byproducts used for the continuous digestion experiments came from a rendering plant, where they were crushed, minced, and heat treated (at a minimum of 133°C and 3 bar for a minimum of 20 min). WM, waste mixtures.
[b]Includes rumen and stomach and intestinal content from slaughtered animals and sludge from slaughterhouse wastewater treatment.

During the continuous experiments at laboratory and pilot scale, seven different mixtures were tested (four in laboratory scale and three in pilot scale). The composition of the mixture was mainly based on the amounts of substrates available in the planning of two separate full-scale biogas plants. The animal byproducts were codigested with other solid substrates such as food waste from restaurants and food distributors as well as sludge from a slaughterhouse wastewater treatment plant (Table 3). Liquid substrates such as fat from restaurant grease traps, glucose from a pharmaceutical manufacturer, and liquid manure from cattle were used to dilute the substrate and thus reduce the total ammonia nitrogen levels in the digester. Pure water was also used for dilution in some cases. All the mixtures were pasteurized for 1 h at 70°C before digestion.

The substrate mixtures differed mainly regarding the quantity of animal byproducts and the degree of dilution. The dry matter (DM) concentration of the animal byproducts was approx 30%, with a fat content of 35–40% of the DM and a protein content of approx 50% of the DM. The slaughterhouse waste (animal byproducts, blood, rumen, stomach and intestinal content, and sludge from slaughterhouse wastewater treatment) contributed to waste mixtures with 50–60% of the DM content. The nitrogen content in the waste mixtures varied between 3.3 and 6.0% of DM, and the nitrogen contribution from animal byproducts in the mixtures was 40–63%.

Process Descriptions and Analytical Methods

The fed-batch experiments were performed at 37°C in digesters with a 3-L active volume and a 5-L total volume. The continuous laboratory processes were operated in mesophilic (37°C), semicontinuously fed (once a day) continuous-flow stirred tank reactors (CSTRs) with a 30-L active volume and a 50-L total volume. The pilot-scale processes were in operation mainly to investigate technical parameters. The digesters were mesophilic (37°C), semicontinuously fed (once a day), and mixed CSTR with an active volume of 26 m^3 and a total volume of 30 m^3. The inocula used for batch experiments, laboratory digester 1, and pilot digester 1 were anaerobically treated sewage sludge.

Gas chromatography was used to determine concentrations of methane *(11)*. Carbon dioxide concentration and pH were determined according to ref. *12*. The standard methods, according to ref. *13*, were used to determine total ammonia nitrogen (phenate method), total Kjeldahl nitrogen (TKN), DM, and volatile solids (VS) content. Volatile fatty acids (VFA) were determined according to Örlygsson et al. *(11)*.

Results

Fed-Batch Digestion

During the experiment, the digesters were fed for 3 wk with an average OLR of 2 g of VS/(L·d) (Fig. 1). The fed-batch experiment showed that the pasteurization at 70°C of the waste mixture considerably increased the

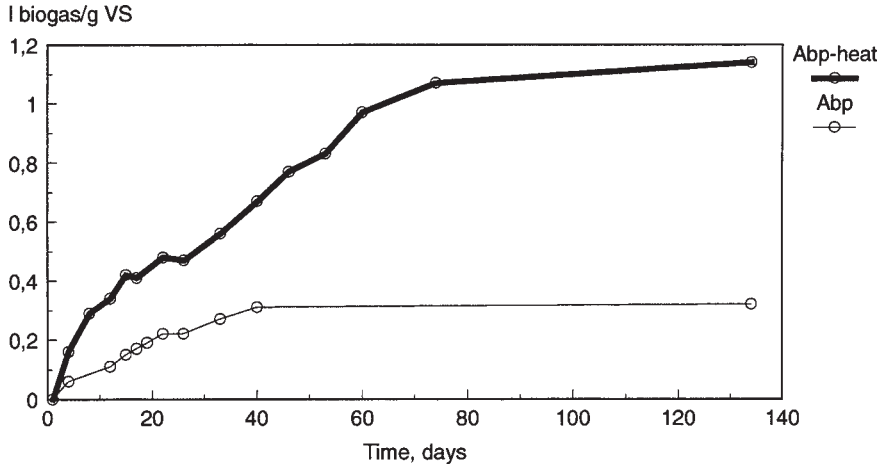

Fig. 1. Mesophilic fed-batch experiments with pasteurized animal byproducts (Abp-heat) and nonpasteurized animal byproducts (Abp).

biogas yield. The specific production of biogas and methane was 1.14 and 0.76 L/g of VS, respectively. Fed-batch digestion of non-heat-treated animal byproducts gave a biogas yield of 0.31 L/g of VS, only 25% of the biogas potential reached for the heat-treated waste.

Continuous Digestion

Laboratory Experiments

After the inoculation of laboratory digester 1, the OLR was gradually increased to 4 g of VS/(L·d) (Fig. 2, Lab. 1a) after 10 wk. During this period, the total ammonia nitrogen level increased rapidly from 0.8 to 4.1 g/L. Owing to low specific biogas production and accumulation of VFA, the OLR was reduced to about 1 g of VS/(L·d). After 30 wk, the total ammonia nitrogen level had reached 6.5 g/L, and it was very difficult to operate a stable digestion process at an OLR above 1 g of VS/(L·d) (Table 4). The VFA levels mostly exceeded 10 g/L (consisting of 25% acetate, 60% propionate, and 15% other VFAs). To improve the digestion process, the substrate mixture to Lab. 1b was changed (Table 3). After a gradual increase in the OLR, the laboratory digester could then be operated with satisfying stability at 3 g of VS/(L·d) (Fig. 2, Lab. 1b) with a concentration of total ammonia nitrogen at 4.5 g/L (Table 4). The biogas yield was 0.80 L/g of VS with a methane concentration of 70%. After operating the digester for 70 wk, the OLR could gradually be increased without any significant change in substrate mixture. At wk 100, the OLR reached 5 g of VS/(L·d) (Fig. 2, Lab. 1c), and the process was operated for another 11 wk (which corresponds to 3.5 HRTs) without any major increase in VFA. The improvement probably depended on the adaptation of the bacterial consortia to the ammonia-rich environment.

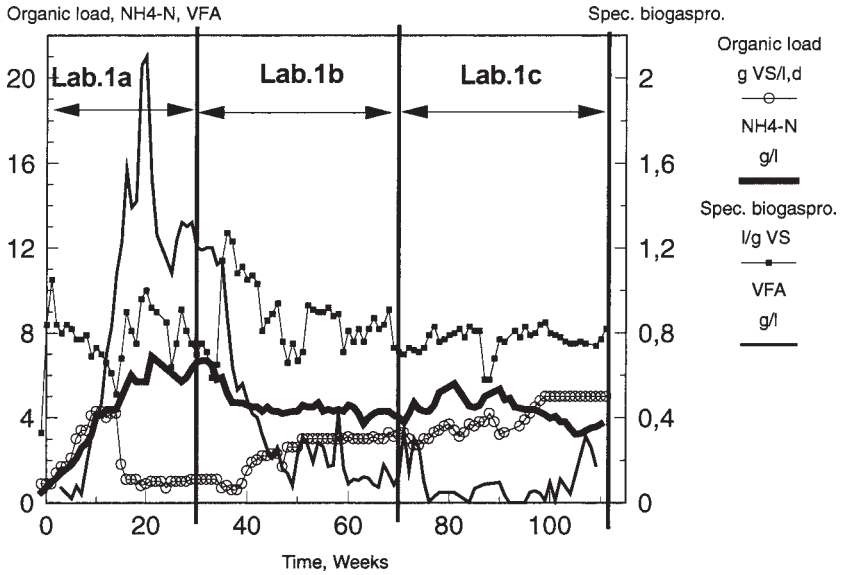

Fig. 2. Specific biogas production, organic load, total ammonia nitrogen, and VFA levels during experiment with laboratory digester 1.

Laboratory digester 2 (Lab. 2) was started with an inoculum from Lab. 1c, and the amount of animal byproducts in the waste mixture was increased to 13%. The addition of animal byproducts was about the same as for the Lab. 1a period, but in this case the dilution was considerably larger. This digestion process was operated for 12 wk, and the OLR was 2.5 g of VS/(L·d) (Table 4). The VFA levels in the digester during the last 9 wk in operation were <1.2 g/L.

Pilot Experiments

The OLR for pilot digester 1 was gradually increased up to 3 g of VS/(L·d) (Fig. 3, Pilot 1a) during the first 10 wk. This led to an increase in total ammonia nitrogen. After 10 more weeks with a total ammonia nitrogen concentration of 5 g/L and VFA levels about 5 g/L (Fig. 3), the substrate mixture to Pilot 1b was changed (Table 3) in the same way as for Lab. 1b. After that, the digester could be operated with satisfactory stability at an OLR of 2.5 g of VS/(L·d) (Fig. 3, Pilot 1b) and a concentration of total ammonia nitrogen of 4.1 g/L (Table 4) for 16 wk (which corresponds to 2.5 HRTs).

The pilot 2 digestion process started with an inoculum from Pilot 1b and the amount of animal byproducts in the waste mixture was 15% (Table 3). The OLR was 3.2 g of VS/(L·d), and the concentration of total ammonia nitrogen was 4.5 g/L (Table 4). The VFA level never exceeded 2 g/L, and the specific yield of biogas was 0.70 L/g of VS.

Table 4
Some Characteristic Data from Laboratory and Pilot Digestion Experiments

Process	Time (wk)	HRT (d)	OLR (g VS/[L·d])	pH	NH_4-N (g/L)	NH_4-N/TKN (%)	CO_2 (% of biogas)	Specific gas (L biogas/g VS)
Lab. 1a	30	200	1	7.8	6.5	75	36	0.75
Lab. 1b	70	39	3	7.8	4.3	65	29	0.80
Lab. 1c	110	22	5	8.0	4.0	55	28	0.80
Lab. 2	12	40	2.5	8.0	5.0	75	28	0.86
Pilot 1a	20	75	2	7.9	5.0	75	30	0.80
Pilot 1b	65	45	2.5	7.8	4.0	60	28	0.81
Pilot 2	26	35	3.2	8,0	4.5	65	30	0.70

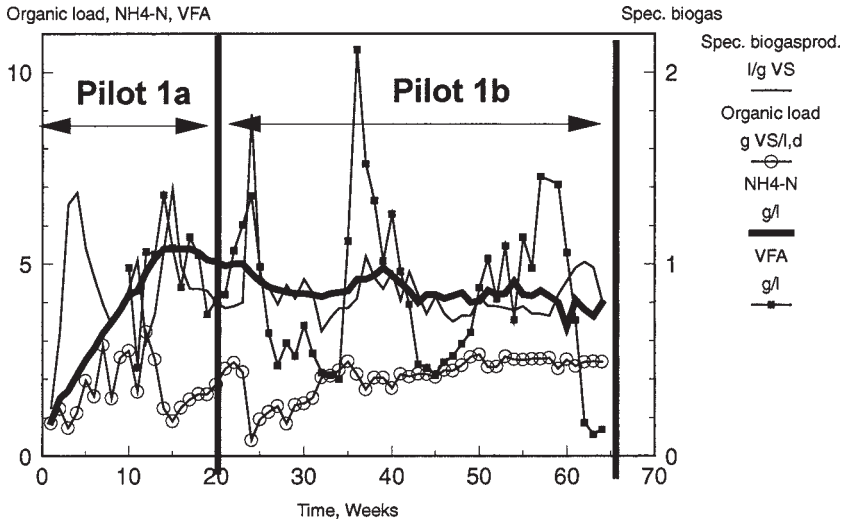

Fig. 3. Specific biogas production, organic load, total ammonia nitrogen, and VFA levels during experiment pilot 1.

Discussion

The results obtained in our study show that feedstock mixtures with 8–15% of animal byproducts (corresponding to 19–38% of the DM in the mixture) can be codigested during stable conditions at OLRs exceeding 2.5 g of VS/(L·d) and HRTs less than 40 d, reaching total ammonia-nitrogen concentrations of 4.5–5.0 g/L. The feedstock mixtures tested corresponded to the relative amount of different wastes generated in Uppsala and Linköping municipality. Kirchmayr et al. *(14)* managed to operate a mesophilic, continuous process with only animal byproducts diluted with water at an OLR of 2.5 g of chemical oxygen demand/(L·d) (corresponding to about 1.2 g of VS/[L·d]) and a total ammonia nitrogen concentration of 2.0 g/L. Thus, codigestions of animal byproducts with other organic wastes or liquid manure clearly improve the process performance.

After operating laboratory digester 1 for more than 1.5 yr at total ammonia nitrogen concentrations >4 g/L, an increase in the OLR to 5 g of VS/(L·d) and a decrease in HRT to 22 d was possible without accumulation of VFA. This is likely a result of adaptation of the microorganisms to higher total ammonia concentration *(15)*. The level of total ammonia concentration reported as inhibitory varies in the literature, depending on different conditions, such as inoculum, substrate, operation period, pH, and temperature *(16)*. Typical levels reported range from 1.7 *(17)* up to 5 g/L *(15)*. The inhibiting effect increases with increasing pH owing to the release of free ammonia, which is considered the active component causing inhibition. Levels of free ammonia inhibition have been found at 80 mg/L *(17)*, 150 mg/L *(18)*, and 0.7 g/L *(19)*. Wellinger and Fruteau *(20)* found upper limits of 3.5 g/L of total ammonia corresponding to approx 0.15 g of

NH_3/L when digesting solid slaughterhouse waste with blood. The pH of the continuous mesophilic digestion experiments in the present study were between 7.8 and 8.0, and the total ammonia nitrogen levels varied from 4.0 to 6.5 g/L. Calculating according to Wikberg *(21)*, the concentration of free ammonia (NH_3-N) during the experiments is in the range of 0.45–0.56 g/L. This is above the levels reported by Braun et al. *(18)* and Wellinger and Fruteau *(20)*, but below the level reported by Angeledaki and Ahring *(19)*. Another explanation for the poor degradation of VFA could be an accumulation of LCFAs, which can inhibit anaerobic digestion *(22,23)*. In the present study, LCFAs were not analyzed, but the high content of fat in the substrate could likely result in high LCFA levels.

Pasteurization of animal byproducts at 70°C for 1 h led to a fourfold increase in the potential methane yield compared to nonpasteurized animal byproducts. This shows that pasteurization before digestion can be motivated not only from a sanitation point of view, but also for increasing degradability and energy recovery. The reason for the increased degradability owing to pasteurization was not investigated in detail. However, the increased degradability is likely a result of an increased accessibility of lipids for the microorganisms, resulting from the heat treatment.

Conclusion

The biogas plants that digest slaughterhouse waste usually use rumen, stomach and intestinal content, as well as blood waste fractions and sludge from slaughterhouse wastewater treatment. However, the use of animal byproducts for anaerobic digestion is not very common in Europe. The animal byproducts, including blood, represent 70–80% of the total biogas potential from waste generated during slaughter of animals. The total biogas potential from waste generated during slaughter is about 1300 MJ/cattle and about 140 MJ/pig (Table 5). In addition, the animal byproducts contain 60–80% of the nitrogen and phosphorus, which is important to consider from a sustainable point of view. Hence, since the animal byproducts cannot be used in the feed industry, anaerobic digestion offers a sustainable treatment method to facilitate energy recovery in combination with the use of the residue as a fertilizer on farmland.

The results of the present study have been used to design the first full-scale biogas plant using animal byproducts in Sweden (Linköping Biogas AB). The plant has a capacity to treat 16,000 t of grinded and sterilized animal byproducts. Today, seven Swedish plants digest animal byproducts (S. Liljenström, personal communication) generated from slaughter. Hence, anaerobic digestion has been proven to be a competitive treatment method for the huge amount of animal byproducts currently generated in Europe.

Table 5
Calculated Methane Potential from Slaughter of Cattle and Pigs Divided into Different Waste Fractions (% of total methane potential) and Total Amount (MJ/animal)

	Rumen, stomach and intestinal content (% of total)	Animal low risk (meat and bone) (% of total)	SRM[a] (% of total)	Blood (% of total)	Animal high risk (average) (% of total)	Total (MJ/animal)
Cattle	9	62	21	5	3	1300
Pig	6	82	—	8	5	140

[a]SRM shall go to an incineration plant, or after a preprocessing to burial in an approved landfill site *(12)*.

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References

1. Mathisen, B. (1997), in *Proceedings of the 5th FAO/SREN Workshop*, Verstrate, W., ed., REUR Technical Series 52, Rome, pp. 257–261.
2. Hjort-Gregersen, K. (1999), Report, Centralised Biogas Plant—Integrated Energy Production, Waste Treatment and Nutrient Redistribution Facilities, Danish Institute of Agricultural and Fisheries Economics, Esbjerg, Denmark.
3. Council Directive 90/667/EEC, Official Journal of the European Communities, Brussel, Belgium.
4. Danell, L. (1979), Report, Biproduktsmätningar storboskap 1977–78, Rapport från avräkningskommittén, Slakteriförbundet.
5. Thyselius, L. and Edström, M. (1994), in *Proceedings of the 4th FAO/SREN Workshop*, Marchaim, U. and Ney, G., eds., REUR Technical Series 33, Rome, pp. 254–261.
6. Wikberg, A., Blomberg, M., and Mathisen, B. (1998), AFR-report 234, Naturvårdsverket, Stockholm.
7. Oeschner, H. and Gosch, A. (1998), in *Kofermentation*, Arbeitspapier 249, Biskupek, B., ed., KTBL, Darmstadt, pp. 17–28.
8. Braun, R. and Kirchmayr, R. (2000), in *Proceedings of Biogas Event 2000*, Nordberg, A., ed., Swedish National Energy Administration, Eskilstuna, Sweden, pp. 14.1–14.7.
9. Lindberg, A. (1995), JTI Report Kretslopp & Avfall no. 1, Institutet för jordbruksmiljöteknik, Uppsala, Sweden.
10. Tritt, W. P. and Schuchardt, F. (1992), *Bioresour. Technol.* **41,** 235–245.
11. Örlygsson, J., Houwen, F. P., and Svensson, H. B. (1993), *Swed. J. Agric. Res.* **24,** 45–54.
12. Jarvis, Å., Nordberg, Å., Mathisen, B., and Svensson, B. H. (1995), *Antonie Leeuwenhoek* **68,** 317–327.
13. APHA. (1985), *Standard Methods for the Examination of Water and Wastewater*, 16th ed., American Public Health Association, Washington, DC.
14. Kirchmayr, R., Steffen, R., Grasmug, M., et al. (2001), in *Proceedings of the 9th World Congress Anaerobic Digestion 2001-Anaerobic Conversion for Sustainability, part 1*, van Velsen, A. F. M. and Verstraete, W. H., ed., Technologisch Instituut vzw, Antwerpen, Belgium, pp. 469–472.
15. van Velsen, A.F.M. (1979), *Water Res.* **13,** 995–999.
16. Angeledaki, I. and Ahring, B. K. (1993), *Appl. Microbiol. Biotechnol.* **38,** 560–563.
17. Koster, I. W. and Lettinga, G. (1984), *Agric. Wastes* **9,** 205–216.
18. Braun, R., Huber, P., and Meyrath, J. (1981), *Biotechnol. Lett.* **3,** 159–164.
19. Angeledaki, I. and Ahring, B. K. (1994), *Water Res.* **28(3),** 727–731.
20. Wellinger, A. (2000), in *Anaerobic Digestion: Making Energy and Solving Modern Waste Problems*, Ørtenblad, H., ed., AD-NETT, Herning, Denmark, pp. 8–21.
21. Wikberg, A. (1996), Licentiate of Engineering Thesis at the Royal Institute of Technology, Department of Chemical Engineering and Technology, TRITA-KET R 57, Stockholm, Sweden.
22. Angeledaki, I. and Ahring, B. K. (1992), *Appl. Microbiol. Biotechnol.* **37,** 808–812.
23. Salminen, E., Rintala, J., Lokshina, L. Y., and Vavilin, V. A. (2000), *Water Sci. Technol.* **41(3),** 33–42.