Co-digestion of energy crops and the source-sorted organic fraction of municipal solid waste

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Abstract The biological and technical performance during co-digestion of energy crops and the source-sorted organic fraction of municipal solid waste has been investigated at laboratory and pilot scale. A 50:50 (TS-based) mixture of energy crops and organic waste reached a loading rate of 6.0 gVS $L^{-1}d^{-1}$ with a methane yield of 0.33–0.38 L gVS^{-1}, while a 80:20 mixture showed elevated levels of volatile fatty acids at 5.5 gVS $L^{-1}d^{-1}$ The better performance of the 50:50 mixture can partly be explained by a better nutritional composition. Mincing the ley crop reduced viscosity and reduced problems with fibre floating and scum-blanket formation. The electricity consumed for mincing and stirring at a full-scale plant corresponds to ca 3% of the energy produced. Calculations of the costs for full-scale plants indicate that the price of the up-graded biogas has to be at least 0.078 Euro/kWh in order to balance the costs.

Keywords Biogas; co-digestion; energy crops; source-sorted organic fraction of municipal solid waste

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Introduction

During recent years considerable interest has been focused on the anaerobic digestion of various types of solid organic wastes. The biogas produced is mostly used for generation of electricity and heat, but the interest in upgrading biogas to vehicle fuel quality is increasing due to the environmental benefits associated with the use of biogas as a biofuel (Dalemo *et al.*, 2001). According to the biofuel directive (2003/30/EC), 5.75% of petrol and diesel should be replaced with biofuels by 2010. In the efforts to reach this target, biogas could play an important role. In Sweden, biogas corresponding to more than 100 GWh is currently used for vehicles and the number of biogas plants and up-grading facilities are steadily increasing. The theoretical biogas potential in Sweden has been estimated to ca 17 TWh, where the largest part (14 TWh) originates from agricultural feed-stock (Nordberg and Lindberg, 2001). Thus, if the correct measures were taken specifically grown energy crops could be an important substrate for increasing the production of biogas.

Co-digestion of energy crops and municipal solid waste is an option that would lead to several benefits. From the farmer's point of view, the set aside land could be used for producing energy crops, such as nitrogen fixing ley crop, thus improving the physical properties and nutritional status of the soil. The use of digestate would reduce the need for costly fertilisers and decrease problems with plant pathogens owing to the more varied crop rotation. From the society and municipality point of view it would reduce CO_2-emissions and facilitate the recirculation of organic waste, thus reaching goals of sustainability.

The objective of this study was to investigate biological and technical parameters important for process stability and production-scale dimension in order to obtain results and experiences that could be used for developing co-digestion plants with ensiled ley-crop and the source-sorted organic fraction of municipal solid waste (SS-OFMSW). The results obtained have been used together with information from existing production-scale plants digesting organic wastes for calculating the costs associated with producing biogas in a full-scale plant.

Methodology

The energy crop consisted of a mixture of grass and clover, which was harvested and ensiled according to conventional agricultural practices. The organic waste (mainly kitchen waste) was source sorted in paper bags and came from apartments (50%) and single houses (50%). The substrate composition is presented in Table 1. Before digestion both the ley crop and the organic waste was minced in a meat-mincer (Palmia, Ø 200 mm) containing knives and different perforated steel plates in order to achieve good mixing characteristics. The organic waste was pasteurised at 70 °C for 1 hour in order to ensure a hygienic safe application on farm land.

Two different substrate mixtures were tested. The 80:20 mixture (TS-basis) consisted of 80% energy crop and 20% SS-OFMSW, representing a smaller community where a larger part of ley crop is needed to obtain a 1 MW-biogas plant. The 50:50 mixture (TS-basis) consisted of 50% energy crop and 50% SS-OFMSW, thus representing a larger community.

The experiments were performed with conventional stirred tank reactors both in laboratory scale (35 L active volume) and pilot scale (16 m^3 active volume) at mesophilic (37 °C) conditions. The pilot reactor was equipped with a top-mounted stirrer, rotating at 44 rpm with two separate propellers having three blades each. In order to minimize the addition of water, digestate was dewatered and the liquid phase was recycled to the process. At the pilot plant, a screw press with screen cylinder and slot opening of 0.25 mm was used for phase separation.

The processes were operated during 150 days of gradual increase in organic loading rate (OLR), while regularly analysing traditional parameters and variables. The processes were operated as a direct continuation of an earlier trial with ley crop silage, straw and manure (Nordberg and Edström, 1997a). Total gas production and concentrations of methane and carbon dioxide as well as pH were determined according to Jarvis *et al.* (1995). TS, VS, total ammonia nitrogen (NH_3-N + NH_4-N; the phenate method) and total Kjeldahl nitrogen were determined according to APHA's *Standard Methods* (1985). VFAs were analysed using a gas chromatograph (Chrompack 9000) with a flame ionization detector (Örlygsson *et al.*, 1993). Plant nutrients, trace elements and heavy metals were analysed according to ISO/IEC Guide 25 (1990:E). Electricity requirement was measured with a power clamp meter and viscosity was measured at 35 °C using a Brookfield viscometer.

Results and discussion

Process performance at laboratory and pilot scale

Stable operation was obtained at an OLR of 6.0 gVS $L^{-1} d^{-1}$ when the 50:50 mixture of ley crop silage and organic waste was digested, whereas the 80:20 mixture showed elevated levels of VFAs at an OLR of 5.5 gVS $L^{-1} d^{-1}$. The methane yield varied between 0.33 and 0.38 L gVS^{-1} for the 50:50 mixture, and between 0.30 and 0.33 L gVS^{-1} for the 80:20 mixture. The differences in methane yields are mainly due to a higher degree of

Table 1 Composition of ensiled ley crop and the source-sorted organic fraction of municipal solid waste

	TS (%)	VS (% of TS)	TKN	P	C/N	Fe	Ni	Co	Mo
			(g $kgTS^{-1}$)				(mg $kgTS^{-1}$)		
Silage	33	90	18	3.8	27	476	2.9	0.3	2.6
SS-OFMSW	31	87	21	5.2	19	2,310	2.3	0.8	1.1

degradation of the organic waste and a variation in the composition of the silage. The better performance of the 50:50 mixture compared with the 80:20 mixture can partly be explained by a higher concentration of cobalt (cf. Jarvis *et al.*, 1997), mainly coming from the organic waste (Table 1). Co-digestion of plant material with organic waste and sludge (Gosh and Klass, 1981) has previously been shown to give better stability than anaerobic digestion of plant material only (Klass and Gosh, 1981; Nordberg and Edström, 1997a). The OLR obtained (5.5–6.0 gVS $L^{-1} d^{-1}$) is generally higher than reported for digesting ley crop only, e.g. Stewart *et al.* (1984) and Mathisen and Thyselius (1984) achieved 2.5 gTS $L^{-1} d^{-1}$. The concentration of ammonia-N was maintained at a non-toxic level (1.0–2.5 g L^{-1}) by adding limited amounts of water. The specific results from the laboratory experiments are shown in Table 2 and the results from the pilot plant in Table 3. During the pilot test the composition of both energy crops and organic waste varied in comparison with the laboratory tests. The nitrogen content was on average higher in the silage used in the pilot experiments, thus explaining a higher level of ammonia-nitrogen. The OLR was not increased over 4 kgVS $m^{-3} d^{-1}$ during the pilot tests, since it was not necessary for the technical evaluation.

Rheological properties and electricity requirements

Fibrous substrate, such as ley crop, has a large impact on the rheological properties of the digester slurry. The shear force shown in Figure 1, was considerable lower for the 50:50 mixtures compared to digestion of only ley crop (minced with a 9.5 mm hollow perforated steel plate; data from Nordberg and Edström, 1997a). A "small" particle size (mix 2, small) corresponding to mincing with a 9.5 mm, hollow perforated steel plate, results in a lower shear force then mincing with a 18 mm, hollow perforated steel plate (mix 2, large). The TS-concentration was ca 9% in all cases. SS-OFMSW was minced with a 12 mm hollow perforated steel plate. Earlier experiences from anaerobic digestion of precision-chopped silage on a pilot-scale showed that fibres floated in the digester when the TS-concentration was ca 4–5% (Nordberg and Edström, 1997b). However, in the present study, fibre floating and scum-blanket formation could be avoided at a TS-concentration of ca 9% by operating the process with minced feedstock and continuous stirring.

Stirring was the unit operation consuming the largest part of total electricity requirement. Full-scale calculations showed that the electricity needed for stirring the digester and storage tanks corresponded to ca 2% of the methane produced by a 1.6 MW biogas plant. The corresponding electricity needed for mincing was estimated to be ca 1.5%.

Table 2 Results from laboratory experiments at mesophilic conditions

Substrate mixtures	OLR (gVS $L^{-1}d^{-1}$)	HRT (d)	Recycled liquid/ water-ratio*	pH	NH_4-N (g L^{-1})	VFA (g L^{-1})	CH_4-conc (%)	CH_4-yield (LCH_4 gVS^{-1})	Vol gas prod. (L $L^{-1}d^{-1}$)
80:20	5.5	53	95/5	7.3	1.0	3.0	57	0.30	2.9
50:50	6.0	40	85/15	7.4	0.7	0.5	59	0.34	3.5

*Used for dilution of the feed

Table 3 Results from pilot experiments at mesophilic conditions

Substrate mixtures	OLR (gVS $L^{-1}d^{-1}$)	HRT (d)	Recycled liquid/ water-ratio*	pH	NH_4-N (g L^{-1})	VFA (g L^{-1})	CH_4-conc (%)	CH_4-yield (LCH_4 gVS^{-1})	Vol gas prod. (L $L^{-1}d^{-1}$)
80:20	4.0	50	78/22	7.8	2.4	3.0	60	0.33	2.2
50:50	4.0	50	81/19	7.9	2.1	0.5	63	0.38	2.4

*Used for dilution of the feed

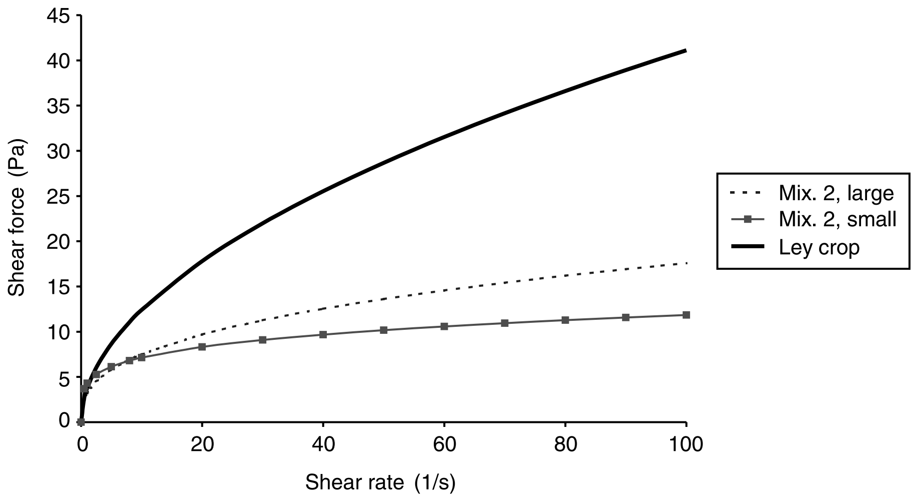

Figure 1 Calculated relations between shear rate and shear force for digester slurry with 50:50 mixture at different particle sizes. The figure also includes the rheological properties for digestion of only ley crop (from Nordberg and Edström, 1997a)

Digestate quality

The digester effluent (ca 9% TS) was dewatered, resulting in a solid phase (30–40% TS) containing ca 5% of the digester effluent wet weight, and a liquid phase (ca 7% TS) containing ca 95% of the wet weight. The solid phase can be used as a soil conditioner and the liquid phase can be used as an organic fertiliser. In the 50:50 mixture, the liquid phase contained 89% of the N and 69% of the P present in the total digestate. The plant nutrient and heavy metal content in the digester effluent (before dewatering) is presented in Table 4.

The heavy metals in the digester effluent were considerable lower than the criteria for the Eco-Label. Compared with liquid manure from cattle, the nitrogen concentration in the digester effluent was 75% higher and the heavy metals were in the range of equal to 4 times higher. In general, the waste does not seem to have increased the level of heavy metals compared to the contribution of energy crops. However, the level of lead is higher in the 50:50 mixture.

Economic consequences for production-scale operation

Based on the results obtained, a feasibility study was carried out for a Swedish municipality (OPTI-gas, 1999). The proposed biogas system would digest ley crop from ca 250 ha of set-aside land (ca 6,000 tonnes) and 6,000 tonnes of source-sorted municipal solid waste. In addition, liquid manure and waste from food industry would be co-digested resulting in total 26,000 tonnes/yr of diluted substrate mixture and 23,000 tonnes/yr of digestate. The plant would annually generate vehicle fuel equivalent to ca 14 GWh (1.6 MW size) with ley crops and source-sorted municipal solid waste representing ca 90% of total biogas production. The ley crop contributes 36% of the gas production.

The calculations made include management and treatment of ley crop and waste at the biogas plant as well as the up-grading facility (separation of CO_2, H_2S and H_2O, compressing to 250 bars, high pressure storage, pipes for gas transport and a filling station). In addition, costs associated with digestate management are included. The farmer is contracted and compensated for cultivating the energy crop, but harvest, transport and ensiling will be managed by the biogas company.

The total investment for the biogas system was calculated to be 8.2 MEuro with the biogas plant contributing with 6.3 MEuro and the up-grading plant with 1.8 MEuro. The

Table 4 The pilot plant digestate content of plant nutrients and heavy metal, including characteristics for liquid manure and criteria for European Eco-label

		80:20	50:50	Liquid manure*	Eco-label
N	% of TS	6.8	7.0	4.0	
P	% of TS	0.65	0.73	0.8	
K	% of TS	6.9	5.8	4.1	
Pb	Mg kg ts^{-1}	1.3	5.6	0.9	
Cd	mg kg ts^{-1}	0.31	0.32	0.12	1
Cu	mg kg ts^{-1}	50	53	30	100
Cr	mg kg ts^{-1}	8.5	10	2.4	100
Hg	mg kg ts^{-1}	0.03	0.04	n.a.	1
Ni	mg kg ts^{-1}	10	9.1	3.2	50
Zn	mg kg ts^{-1}	150	170	184	300

*Cattle manure: Steineck *et al.* (1999)

Table 5 Calculated capital, operating and maintenance costs for a production scale plant on a yearly basis and per kWh produced

	Cost MEuro/yr	Cost Euro/kWh
Biogas plant	1.04	0.075
Ley crop	0.14	0.011
Upgrading	0.40	0.029
Total	1.58	0.115

corresponding capital cost was annually 1.0, 0.74 and 0.28 MEuro, respectively. The total cost, i.e. capital, operating and maintenance costs, are presented in Table 5. Approximately 40% of the costs for ley crop relates to cultivation, while the rest represents the handling costs. The farmers' compensation for cultivation is 0.034 Euro/kg TS.

The calculated income (Table 6) is based on an average gate fee of 47 Euro/tonne of waste (manure not included). In addition, a calculated income from the digestate in relation to nutrient content (60% of total N, 100% of P and K) and based on the price of artificial fertilizers is accounted for. In order to balance the cost, the price of up-graded biogas at the filling station has to be at least 0.078 Euro/kWh. Biogas for vehicles is free from tax in Sweden and can be compared with the price of petrol (0.10 Euro/kWh) or diesel (0.075 Euro/kWh). Thus, the best economic outcome is to use biogas for replacing petrol. However, the best environmental effect is reached if diesel in inner city buses is replaced.

A production-scale plant is currently being built in the City of Västerås as a part of an EU-demonstration project (AGROPTIgas). The plant will digest 14,000 tonnes of kitchen waste, 4,000 tonnes grease trap removal sludge and 5,000 tonnes of ley crop. The plant will be evaluated for process performance, handling systems and socio-economic impact.

Table 6 Calculated income on a yearly basis and per kWh produced

	Income MEuro/yr	Income Euro/kWh
Gate fees	0.37	0.027
Vehicle fuel	1.08	0.078
Digestate*	0.13	0.010
Total	1.58	0.115

*price to balance the cost

Conclusions

A 50:50 (TS-based) mixture of energy crop and SS-OFMSW could reach a loading rate of 6.0 gVS $L^{-1} d^{-1}$ with a methane yield of 0.33 and 0.38 L gVS^{-1}.The better performance of the 50:50 mixture compared with the 80:20 mixture can partly be explained by a better nutrient composition.

To achieve good mixing characteristics with a reasonable energy input at TS-concentrations at ca 9%, the particle sizes of silage had to be reduced with a meat-mincer. With continuous stirring fibre floating and scum-blanket formation could be avoided.

Calculations of the costs for full-scale plants indicate that the price of the raw biogas has to be at least 0.078 Euro/kWh in order to balance the costs. These calculations do not include any investment subsidies for the biogas plant.

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References

APHA. (1985). *Standard methods for the examination of water and wastewater*. 16th edn, American Public Health Association, Washington DC.

Dalemo, M., Baky, A. and Nordberg, Å. (2001). Environmental systems analysis of management systems for organic waste. In *Proceedings of the 9th World Congress Anaerobic Digestion 2001 – Anaerobic Conversion for Sustainability*, Proceedings Part 1. pp. 235–240.

Ghosh, S. and Klass, D.L. (1981). Advanced digestion process development for methane production from biomass-waste blends. In *Biomass as a nonfossil fuel source*, Klass, D.L. (ed.), American Chemical Society, Washington DC, pp. 251–278.

Jarvis, Å., Nordberg, Å., Jarlsvik, T., Mathisen, B. and Svensson, B.H. (1997). Improvement of a grass-clover silage-fed biogas process by the addition of cobalt. *Biomass and Bioenergy*, **12**(6), 453–460.

Jarvis, Å., Nordberg, Å., Mathisen, B. and Svensson, B.H. (1995). Stimulation of conversion rates and bacterial activity in a silage-fed two-phase biogas process by initiating liquid recirculation. *Antonie van Leeuwenhoek*, **68**, 317–327.

Klass, D.L. and Gosh, S. (1981). Methane production by anaerobic digestion of bermuda grass. In *Biomass as a nonfossil fuel source*, Klass, D.L. (ed.), American Chemical Society, Washington DC, pp. 229–249.

Mathisen, B. and Thyselius, L. (1984). Biogas production from fresh and ensiled plant material. In *Bioenergy 84*, Egnéus, H. and Ellegård, A. (eds), Vol. III. Elsevier, London, pp. 289–294.

Nordberg, Å. and Edström, M. (1997a). Co-digestion of ley crop silage, straw and manure. In *The Future of Biogas in Europe*, Bio Press, Herning, Denmark, pp. 74–81.

Nordberg, Å. and Edström, M. (1997b). Co-digestion of ley crop silage, source-sorted municipal solid waste and municipal sewage sludge. In *Anaerobic conversion for environmental protection, sanitation and re-use of residues*, Verstraete, W. (ed.), REUR technological series 52. FAO regional office for Europe, University Gent, Belgium, pp. 162–172.

Nordberg, Å. and Lindberg, A. (2001). Geographic assessment of potential sites for AD-plants in Sweden. In *Proceedings of the 9th World Congress Anaerobic Digestion 2001 – Anaerobic Conversion for Sustainability*, Proceedings Part 2. pp. 131–133.

OPTI-gas. (1999). Biogas for the future. Preparations of an infrastructure for biogas as vehicle fuel from crops, manure, and organic waste with optimal recirculation of nutrients in the municipality of Växjö, Sweden. Altener prestudy. AL/98/291.

Örlygsson, J., Houwen, F.P. and Svensson, B.H. (1993). Anaerobic degradation of protein and the role of methane formation in steady state thermophilic enrichment cultures. *Swedish Journal of Agricultural Research*, **23**, 45–54.

Steineck S., Gustafsson G., Andersson A., Tersmeden M. and Bergström, J. (1999). *Animal manure – content of nutrients and trace elements* (in Swedish). Rapport 4974. Naturvårsverket. Stockholm.

Stewart, D.J., Bouge, M.J. and Badger, D.M. (1984). Biogas production from crops and organic wastes 2. Results of continuous digestion tests. *New Zealand Journal of Science*, **27**, 285–294.