Co-digestion of energy crops and industrial confectionery by-products with cow manure: batch-scale and farm-scale evaluation

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Abstract The possible co-digestion of energy crops and industrial confectionery by-products with cow manure was evaluated firstly, through long-term batch experiments and secondly, in a farm-scale digester. In batch assays, digestion with mesophilically digested cow manure as inoculum resulted in specific methane yields ($m^3\ kg^{-1}\ VS_{\text{added waste}}$) of 0.35 for grass hay (particle size <1.0 cm); 0.26 for oats (0.5 cm) and 0.21 for clover (2.0 cm) harvested at vegetative stage and 0.14 (2.0 cm) for clover harvested at flowering stage. Specific methane yields ($m^3\ kg^{-1}\ VS_{\text{added waste}}$) for confectionery by-products were 0.37 for chocolate, 0.39 for black candy and 0.32 for confectionery raw material. Out the three particle sizes (2.0, 1.0 and 0.5 cm) tested, particle size of 1.0 cm was found ideal for digestion of grass hay and clover while, particle size reduction did not influence methane production from oats. Stage of the crop influenced the methane yields, with clover harvested at vegetative stage yielding 33% higher methane than when harvested at flowering stage. An approximate 60% enhancement in methane yield was noticed with the co-digestion of industrial confectionery wastes with cow manure in a full-scale farm digester.

Keywords Anaerobic digestion; biogas; co-digestion; confectionery by-products; cow manure; energy crops; farm-scale

Introduction

Agricultural biogas plants offer several environmental benefits including production of renewable energy (methane) and a nutrient-rich stabilized liquor, which when applied to soil, improves soil physico-chemical properties. Further, farm digesters may also assist to reduce the greenhouse gas emissions from manure management. However, to make farm-scale digestion more cost effective, co-digestion of cow manure with supplementary materials is of interest to increase methane yields. Such potential materials include the non-risk industrial organic by-products, which often have a higher biogas potential than manure, varying from 30 to 500 $m^3\ ton^{-1}$ (Ahring *et al.*, 1992; Angelidaki and Ahring, 1997). These materials could also give additional income through gate fees. Another possibility is the inclusion of energy crop species e.g., grass or clover in cropping systems, specifically grown as feed stock for energy production (Borjesson, 1998). Biomass thus obtained can be converted directly to energy on-site, in the farm digesters and thereby, diversify agricultural activity (Nordberg, 1996). One of the major problems encountered while digesting energy crops is low digestibility due to their ligno-cellulosic composition. In order to increase the methane yields of energy crops, physical pre-treatment by reducing the particle size to enhance hydrolysis (Sharma *et al.*, 1988) and maturity stage to examine the influence of biochemical plant composition on digestion (Pouech *et al.*, 1998) have been studied.

The concept of co-digestion (Ahring and Johansen, 1992; Converti *et al.*, 1997), its advantages (Mata-Alvarez *et al.*, 2000) and its application for centralised co-digestion of organic wastes are not new (Callaghan *et al.*, 1999; Lafitte-Trouque and Forster, 2000).

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However, industrial application of co-digestion is still scarce (Mata-Alvarez *et al*., 2000) and co-digestion of cow manure with energy crops and/or industrial wastes in on-farm biogas plants is seldom reported. Recently one report on a study of co-digestion of pure fat with cattle slurry (20/80% on dry matter basis) in a biogas plant showed a 75% increase in methane yield compared to slurry alone (Amon *et al*., 1998).

The objective of the present study was to select proper materials and to establish successful initiation of the use of supplementary materials in a full-scale cow manure digesting farm digester. For that purpose, the methane yields of various energy crops and industrial confectionery by-products were studied in batch assays with digested cow manure as inoculum. In addition, the effects of particle size reduction and crop maturity for energy crops on methane yields were investigated in batch experiments. The performance of semi-continuous co-digestion was evaluated in a full-scale farm biogas plant.

Materials and methods

Substrates and inoculum

Energy crops (EC) and digested cow manure (DCM) originated from the farm (Kalmari Farm, Leppävesi village, Jyväskylä, Finland). Cow manure was produced from 80 cows (40 adults). EC: clover, grass hay, oats were grown on the farm. Confectionery by-products (CBP): chocolate, black candy and confectionery raw material (CRM) were obtained from a nearby confectionery factory (Panda Oy, Jyväskylä, Finland). Field crops were harvested at a maturity stage corresponding to usual harvest for animal feed. For batch experiment, representative samples of ECs were drawn from the farm and stored at 4°C. For clover, methane production was performed at different stages of maturity (vegetative and flowering). All plant samples were chopped to ca. 0.5, 1.0 to 2.0 cm size particles with stainless steel knife. Mesophilically DCM from the farm digester was used as inoculum. Characteristics of the substrates and inoculum are presented in Table 1. In the farm-scale studies, ECs were harvested and stored in the field under plastic sheet. The stock was mechanically ground with meat grinder to particle size of 2.0 cm before feeding.

Batch experiments

The batch experiments were performed in duplicate two litre (l) glass bottles at 35 ± 1°C. First 1 l (17 gl^{-1} volatile solids (VS)) of inoculum was added, then substrate (volumes adjusted to have 51 gl^{-1} VS for all ECs and 25.8 gl^{-1} VS for all CBPs resulting in $VS/VS_{inoculum}$ -ratios of 3.0 and 1.5 for ECs and CBPs, respectively), and finally distilled water was added to make total liquid volume of 1.5 l. Anaerobic conditions were induced by flushing the contents with nitrogen/carbon dioxide mixture (80/20%) and sealed

Table 1 Characteristics of the energy crops, confectionery by-products and inoculum used in the batch assays

Substrates	pH	TS (%)	VS (%)	VS/TS	N total (gl^{-1})
Energy crops					
Clover (vegetative)	7.8	18.7	16.9	0.90	3.1
Clover (flowering)	7.8	13.5	11.9	0.88	3.8
Grass hay	7.9	25.9	23.6	0.91	1.7
Oats	7.6	60.2	55.9	0.93	1.6
Confectionery by-products					
Chocolate	7.2	97.5	93.7	0.96	n.a
Black candy	8.2	84.6	78.3	0.93	n.a
CRM	6.1	89.1	89.0	1.00	n.a
Inoculum	8.1	2.7	1.7	0.63	2.8

n.a. not analysed

immediately with butyl rubber stoppers. The outlets provided on the stoppers were used for collecting biogas into aluminium foil bags. DCM alone was assayed to subtract its methane production from those of the samples.

Farm biogas plant

Biogas plant is a vertical steel digester (150 m^3 capacity, liquid volume 120 m^3), operated at 35–37°C with a central mechanical stirring system. The feed was prepared every week or on alternate weeks in the feed tank by feeding the well mixed cow manure from the pre-storage tank (760 m^3 capacity) to a feed tank where EC/CBP were mixed periodically. The feed was pumped to the digester from the feed tank 2–3 times per day with a total average amount of ca. 6 m^3d^{-1}. Hydraulic retention time was 22 d. Degassed or digested biomass leaves the digester, and enters the slurry storage tank. The specifically designed slurry storage tank has a dome shaped soft top membrane and functions as gas storage, able to hold biogas, amounting to one week's consumption and collect biogas (annually on average ca. 10% additional methane, methane production varies e.g. according to temperature) produced from the already degassed slurry in the slurry storage tank. The slurry is spread in spring and autumn resulting in retention times varying from 1 week to 9 months in the slurry tank. The biogas thus produced, is led to the biogas combined heat and power generator.

Analyses

Analyses were performed as described elsewhere (Kaparaju and Rintala, in preparation.).

Results and discussion

Batch experiments

The methane yields for various CBPs and ECs along with the effect of particle size and maturity stage (for clover alone) were studied on long-term (155 days) batch assays (Figure 1). Among the substrates tested, grass hay produced methane at a faster rate followed by clover, black candy, chocolate, CRM and oats. These substrates also exhibited 1–3 day lag phases.

The mean specific methane yields (m^3 $kgVS^{-1}$) from duplicate assays (variation standard error less than 13%) are presented in Table 2. With all materials methane production accounted for prolonged time; methane production by day 22 accounted from 70 to > 95% for ECs and between 83–95% for CBPs of the final methane yields (Table 2). Among the CBPs, highest specific methane yield (per $kgVS^{-1}$) was produced by black candy (0.39 m^3)

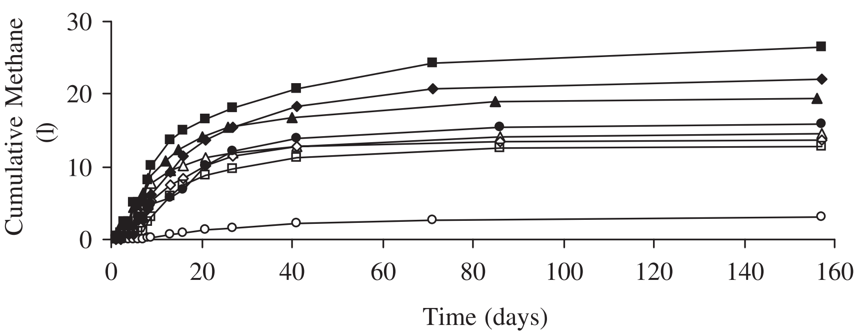

Figure 1 Mean cumulative methane production from energy crops: clover (vegetative, ▲), clover (flowering, ●), grass hay (■), oats (◆) and confectionery by-products: chocolate (◇), black candy (△) and confectionery raw material (CRM, □) co-digested with digested cow manure, control (○) under batch assays at 35°C

Table 2 Specific methane yields, pH, soluble chemical oxygen demand (SCOD) for various energy crops and confectionery by-products with digested cow manure as inoculum in batch assay at 35°C

Substrate	Particle size (cm)	pH (final) (final)	SCOD (gl^{-1})	Specific methane yield[1] ($m^3\ kgTS^{-1}$)	($m^3\ kgVS^{-1}$)	($m^3\ t^{-1}$)	Methane yield on day 22 to final yield[1] (%)
Energy crops							
Clover (vegetative)	2.0	7.61	5.9	0.19	0.21	35.5	98.6
	1.0	7.61	5.4	0.13	0.14	23.7	126.8
	0.5	7.62	5.6	0.18	0.20	33.8	97.4
Clover (flowering)	2.0	7.69	7.6	0.12	0.14	16.7	90.6
Grass hay	2.0	7.46	8.3	0.25	0.27	63.7	79.3
	1.0	7.48	8.4	0.32	0.35	82.6	73.3
	0.5	7.48	8.3	0.29	0.32	75.5	83.8
Oats	2.0	7.44	6.7	0.23	0.25	139	70.0
	1.0	7.43	7.2	0.23	0.25	139	72.4
	0.5	7.47	7.6	0.24	0.26	145	77.0
Confectionery by-products							
Chocolate	–	7.54	6.1	0.36	0.37	346	90.4
Black candy	–	7.44	6.6	0.36	0.39	305	94.6
CRM	–	7.42	4.6	0.32	0.32	284	83.5
Inoculum	–	7.41	6.3	0.11	0.18	175	41.7

[1] methane yield of inoculum subtracted

followed by chocolate (0.37 m^3) and CRM (0.32 m^3) corresponding to methane yields of 284–346 m^3 (ton of by-product)$^{-1}$. Of the various ECs tested, grass hay produced the highest specific methane yield per kgVS followed by oats and clover whereas, per ton of material oats had the highest yield. The effects of particle size were different for different ECs. For oats no effect was observed, whereas, 1.0 cm size was optimal for clover and least optimal for grass hay. The methane yields were ca. 10–30% higher at optimal particle sizes as compared to the least optimal ones. This response of particle size reduction on methane production in grass hay might be due to lower lignin content in grass hay than compared to clover and oats (Moore, 1958). On the other hand, Sharma *et al*. (1988) found that methane yields increased with decrease in particle size. Out of the five particle sizes (0.088, 0.40, 1.0, 6.0 and 30.0 mm) which the authors tested, maximum quantity of biogas (4–10% increase) was produced from particle size of 0.088 and 0.4 mm for raw materials like wheat straw, rice straw, and Bermuda grass. As the hydrolysis of ligno-celluloses is dependent on lignin to cellulosic ratio and the digestibility of grasses is highly correlated with the lignin content (Scharer and Moo-Young, 1979), the stage of crop also influences the methane yields as the composition of the plant changes over the growing season. For the same particle size (2.0 cm), higher methane yield (33%) was produced by clover harvested at vegetative stage than harvested at flowering stage. However, studies by Pouech *et al*. (1998) showed that crop maturity was weakly influential on methane yields for wheat, clover and rye-grass.

The batch results show that CBP and hay could produce at least 50% more methane per ton of VS than cow manure alone (methane yield of 0.21 $m^3\ kgVS^{-1}$ (10 m^3 (ton slurry)$^{-1}$ in a 108-day batch assay; Luostarinen and Rintala, (unpublished)) while, other studied ECs would have comparative methane production with cow manure. On the other hand, per ton of the material are more drastic; CBP would give up to about 30 fold and EC up to about 10 fold (oats) more methane per ton of material than the studied cow manure alone (Table 2). Thus suggesting that CBPs can also be thought of as an ideal co-digestates that would give an appreciable enhancement in methane production. This could be due to the positive synergism established in the digestion medium and the supply of missing nutrients by the co-substrates (Mata-Alvarez *et al*., 2000).

At the end of all the assays, pH values were between 7.4–7.7 for ECs and 7.4–7.5 for CBPs whereas, SCOD values were only slightly higher than in inoculum, suggesting that no significant accumulation of soluble organics occurred.

Farm biogas plant

The digester has been in operation since 1998. Co-digestion with EC and/or CBP was taken up in spring 2000 (Figure 2). During this period, the digester showed reliable performance with both co-digestates CBPs and ECs. Approximately 40 to 50% of VS were degraded with <100–200 mgl^{-1} of volatile fatty acids and 0.6–1.7 gl^{-1} of ammonium nitrogen concentration in digestate. Digestion of cow manure alone produced an average specific methane yield of 0.22 m^3 $kgVS^{-1}$ $_{\text{added waste}}$. Addition of CBP increased the specific methane yield to about 0.28 m^3 $kgVS^{-1}$ $_{\text{added waste}}$ whereas, with EC methane yield was about similar to that obtained from cow manure alone (ca. 0.21 m^3 $kgVS^{-1}$ $_{\text{added waste}}$). The plant produced about 150 m^3 d^{-1} biogas (55–58% CH_4 content) per 6 m^3 biomass in co-digestion of CBP and cow manure. Without CBP, that amount of manure yielded about 85 m^3 biogas. These figures also include biogas from the post-storage tank.

Conclusions

Results from both batch- and farm-scale studies suggested that energy crops (EC) and confectionery by products (CBPs) are potential co-substrates to be digested with cow manure. Especially, CBPs showed potential for highly enhanced methane yields compared to digestion of cow manure alone. Pre-treatment of ECs by reducing particle size (2.0, 1.0 and 0.5 cm) did not influence methane yields in oats while, 1.0 cm particle size seems to be

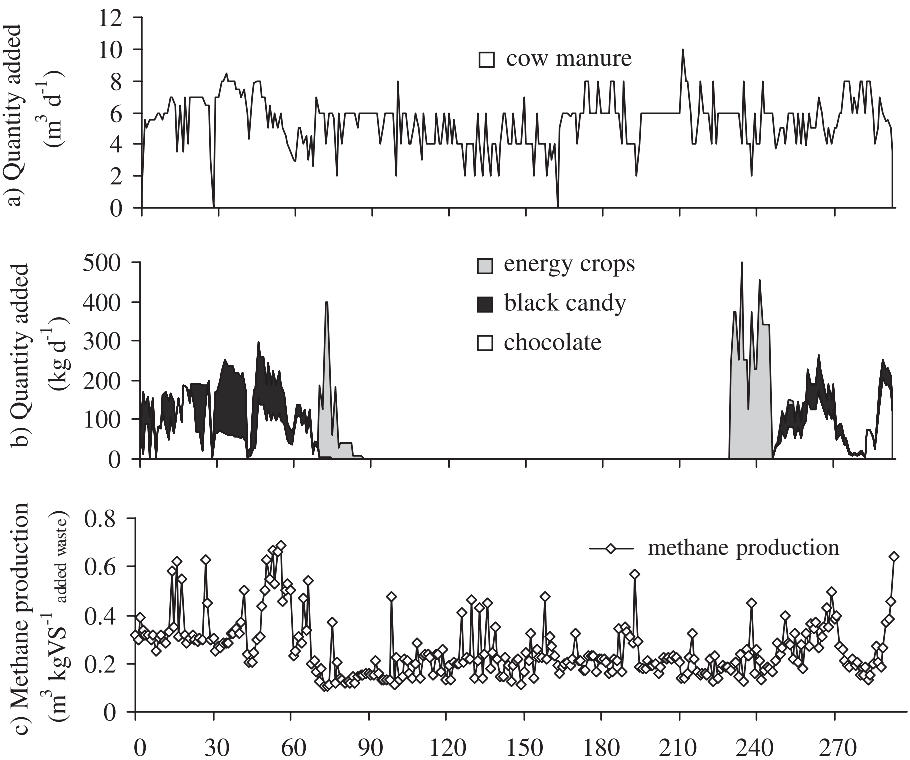

Figure 2 The added amounts of cow manure (a), energy crops and confectionery by-product (b) and the methane production (c) during the mesophilic digestion from farm-scale digester (day 0 = 6.2.2000)

optimal for clover and hay. Application of co-digestion technology of safe industrial by-products in the farm-scale biogas digesters will ensure new economic incentive for farmers and an utilisation of the by-products of industry. Energy crops would also give additional resources to be converted into energy.

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