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Biogas production from hemp – evaluation of the effect of harvest time on methane yield

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Abstract In the present study the biomass yield and specific methane yield for industrial hemp (*Cannabis sativa* L.) was determined at four different harvest times in the south of Sweden. After 34 days of thermophilic digestion there was no significant difference in the specific methane yield: 0.25, 0.27, 0.26, 0.23 Nm^3 methane per kg volatile solids for samples from 10th of July, 30th of July, 4th of September and 19th of October respectively. For the 10th of July an initial inhibition of the methane production was observed but the production recovered within time. The biomass yield for the four different harvest times was: 3.6, 6.9, 14.2 and 14.3 tons total solids per hectare. The energy yield in the form of methane per hectare was highest at harvest in September and October; 122 and 111 GJ per hectare respectively. Compared to production of vehicle fuels from other crops this is one of the highest energy yields achieved per hectare under Swedish conditions. Determinations of biomass yield and methane yield for hemp will be continued during year 2007.
Keywords Energy crops; resource efficiency; vehicle fuel; anaerobic digestion; energy

INTRODUCTION

In January 2007, the European Commission adopted an ambitious energy policy for Europe with a binding target of increasing the level of renewable energy from less than 7% today to 20% by the year 2020. Within the proposal there is a binding minimum target for 10% renewable vehicle fuels by year 2020. Energy crops are considered an important means to reaching the targets (COM, 2007). Sweden has an advantageous situation with the potential for both forestry and more extensive energy crop cultivation. While our share of renewable energy in the domestic and industrial sector is high (18% biomass, 11% hydropower), our domestic goal of 3%, or 9.7 PJ, renewable vehicle fuels in 2005 was not reached (Swedish energy agency, 2006). Thus, the challenge for Sweden is to exchange fossil vehicle fuels. The energy crop based vehicle fuels presently produced in Sweden are 1.5 PJ ethanol from wheat and 0.4 PJ biodiesel from rapeseed oil (RME). Straw from 30 000 hectares, Salix from 13 000 ha and minor amounts of hemp and reed canary grass (300 hectares) are used for combustion. In total, 2% of the arable land in Sweden is used for energy purposes (The Swedish Board of Agriculture, 2006). In an optimistic scenario, up to approximately 20%, or 600 000 hectares, could be made available for cultivation of energy crops (Herland, 2005). A resource efficient use of the available land will be necessary, and to optimize the output, plenty of work remains to identify and breed the best crops or crop combinations for vehicle fuel production. Also, an energy efficient conversion of plant biomass to vehicle fuels must be ensured. In the present study, hemp (*Cannabis sativa* L.) was evaluated for biogas production. The hemp presently cultivated in Sweden for energy purposes is used for combustion, and is harvested in spring (February to April) the year after sowing. In Germany, the use of energy crops for biogas production is widespread and maize is the most commonly grown biogas crop (Weiland, 2005). Hemp is a high-yielding crop, but for a long period, cultivation of hemp has been forbidden in Sweden. Since January 2007 it is allowed to cultivate hemp in Sweden for energy purposes according to the EU council regulation EG No 1782/2003. Since industrial hemp traditionally primarily has been grown for harvest of the fibers, and the preferred characteristics for fiber production and biogas production are different, the present study included an investigation on the effect of harvest time on the suitability of hemp as a biogas crop. The biomass yield and methane yield were determined at four different harvest times ranging from July to October in year 2006.

MATERIALS AND METHODS

Substrate and inoculum

Hemp (*Cannabis sativa* L.) of the variety Futura 75, was sown the 9th of May with 20 kg seeds and 120 kg N per hectare in Nöbbelöv (Lund, Sweden) in year 2006. Distance between rows was 12.5 cm. At four occasions; 10th of July, 30th of July, 4th of September and 19th of October, one square meter parcels, 3–4 meters from the field border, was harvested for determination of biomass yield and for collection of samples for laboratory tests. Parts of the fresh samples were frozen until pretreatment commenced, and parts were dried for chemical analysis. The proportion of leaves and stems based on wet weight was determined. Leaves and stems were chopped separately, frozen and then ground separately at 6000 rpm in a Grindomix GM200 (Retsch, Haan, Germany). Sample characteristics are given in Table 1. Sugars and lignin in the dried samples were determined according to Sluiter *et al.* (2004), by the Department of Chemical Engineering, Lund University (Table 2). In this method, the content of cellulose and hemicellulose is determined by measurement of sugars in dry biomass. The remaining part of total solids that was not identified as sugars, lignin or lignin ash was denoted with "other".

Table 1. Properties of the substrates. The first three columns give the percentage (in terms of wet weight) of the pretreated substrates with the particle size (x millimeter). Total solids (TS) and volatile solids (VS) and the proportion of stems/leaves are based on wet weight.

Sample	$x < 0.85$	$0.85 < x < 4$	$4 < x$	TS (%)	VS (%)	Stems:Leaves
10th July	2.5	74.7	22.8	23.8	21.1	7:5
30th July	6.6	74.3	19.2	33.9	31.2	12:5
4th September	3.3	69	27.4	32.1	29.7	15:5
19th October	3.2	67.6	29.2	40.5	37.9	23:5

Table 2. Composition of dried hemp. Percentage of total solids.

Sample	Cellulose	Hemicellulose	Lignin	Other
10th July	46.1	18.3	17.7	17.4
30th July	50.8	20.4	18.6	10.4
4th September	51.1	22.1	21.4	4.9
19th of October	53.7	21.8	22.2	1.3

The inoculum was collected from the anaerobic digester at Källby wastewater treatment plant, Lund, where the digestion is run at thermophilic conditions (55ºC) from April to December. The inoculum had the following properties: pH 7.69; 4.97% TS; 2.89% VS; 8971 mg/L total bicarbonate alkalinity; 1.75 g/L NH_4^+; 3.70 g/L K^+ and 1.27 g/L PO_4^{3-}.

Experimental set up

Methane potential batch experiments were carried out in reactors (500 mL Erlenmeyer flasks) incubated in shaking water baths at a speed of 70 rpm at 50°C. The four hemp samples from the different harvest times (10th of July, 30th of July, 4th of September and 19th of October) were digested in 5 replicates. The ratio inoculum to substrate based on volatile solids (VS) was 2:1; 7.22

g VS of inoculum and 3.61 g VS of substrate was added in each flask. Two sets of controls were included; one set with only inoculum and one set of positive controls where 3.61 g of cellulose per flask was added. A mixture of celluloses (50% Avicel PH-101 Fluka, Biochemika, and 50% Cellulose powder microcrystalline, MP Biomedicals) was used as recommended by Hansen (2004). Two flasks for each set of samples and controls were used for liquid phase sampling on day 2, while the remaining triplicates were used for methane potential estimations. The gas produced was collected in gas-tight bags. To each flask 250 g of inoculum and 50 mL of nutrient solution was added. Macronutrients (N, P and K excluded), micronutrients and vitamins were added according to Zehnder (1980) to ensure that the degradation was not nutrient limited. For N, P and K, the concentrations already present in substrate and inoculum was sufficient. As sulfate source cysteine was added instead of the Na_2S suggested by Zehnder (1980). The experiment was terminated after 34 days, when the methane production was below 2 $mL_{CH4}/(g_{VS}*day)$.

Analytical methods

Total solids (TS), volatile solids (VS) and pH were measured using standard methods. Total bicarbonate alkalinity was measured as described by Jenkins (1991). Nutrient composition of the inoculum was analyzed using Dr Lange test kits (ammonium LCK303, potassium LCK328 and phosphate LCK348, Dr Bruno Lange GmbH, Germany) after filtrating the samples through 0.45 µm filters (Minisart, Sartorius). Sampling and analysis of volatile fatty acids (VFAs) was carried out as described by Björnsson *et al*. (2000). Gas volume was measured with a 100 mL glass syringe (Fortuna, Germany). Gas composition was analyzed by gas chromatography (Parawira *et al.,* 2007). Daily measurement of gas volume and gas composition was performed during the first 20 days, and thereafter every second day. Methane of the headspace in the reactors was added to the final yield at the last day of experiment. Methane produced from the inoculum was subtracted from the samples. The gas volume is expressed at standard temperature and pressure (273°K and 1 atm), denoted with Nm^3 (normal cubic meter). The average specific methane yields (Nm^3_{CH4}/kg_{VS}) of hemp from three harvest times (30th of July excluded from the analysis, see results) were analyzed with t-test using pooled variances. H_0: The average methane yields of the hemp from the different harvest times are the same. 5% significance level was used.

RESULTS AND DISCUSSION

The lignocellulose portion (cellulose, hemicellulose and lignin) of the hemp increased from July to September as shown in Table 2. Lignocellulose has been found to be slowly and often incompletely degraded under anaerobic conditions (Lynd *et al*., 2002), therefore a slower degradation of the later harvested samples was expected. In contrast, the initial degradation rate was lowest for the sample

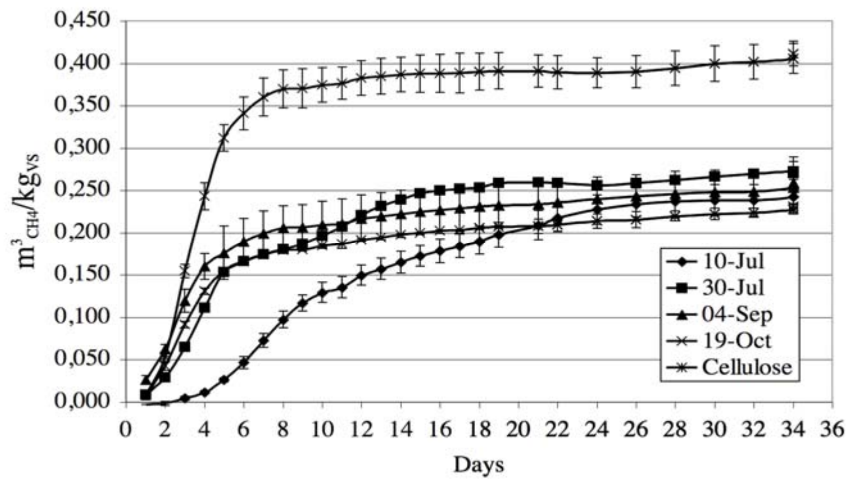

Figure 1. Accumulated methane production during 34 days of batch digestion for four hemp samples and the cellulose control. Standard deviation for triplicates (or duplicates in the case of 19th of October) denoted with bars. No standard deviation for the 30th of July since data are based on only one sample.

from the earliest harvest (Figure 1). The lag-phase in the methane production for the sample from the 10th of July indicates that an inhibition occurs in one or several of the degradation steps.

Table 3 shows the accumulated methane yield per kg volatile solids after 34 days of digestion. At this stage there was no significant difference in methane yield for the hemp from the different harvest times according to analysis with t-test (30th of July excluded from analysis). One sample with hemp from the 19th of October and two from the 30th of July were excluded from the experiment due to gas leakage. Since only one sample was left from the 30th of July, the average specific methane yield and standard deviation could not be determined and thus could not be compared with the average yield of the other samples.

Table 3. Specific methane yield after 34 days of digestion (standard deviation is given in parenthesis, for details see Figure 1), biomass yield and methane energy yield per hectare. The energy yield per hectare is based on the methane yield per hectare and the higher heating value of methane: 35.9 MJ per Nm^3.

	10th of July	30th of July	4th of September	19th of October
Nm^3_{CH4}/kg_{VS}	0.25 (0.02)	0.27	0.26 (0.03)	0.23 (0.00)
Ton_{TS}/ha	3.6	6.9	14.2	14.3
GJ_{CH4}/ha	29	62	122	111

The liquid phase sampling at day 2 showed that the pH did not decrease below 7 at the time of inhibition (Table 4). Therefore it is unlikely that the inhibition is due to accumulation of protonated volatile fatty acids. Korteekas (1995) noticed methanogenic inhibition when treating hemp black liquor and showed decreased inhibition after removal of apolar extractives. Kortekaas (1995) suggested with reference to Sierra-Alvarez and Lettinga (1990) that apolar phenols, monoterpenes and terpenols are the extractives that cause the main inhibition. Kamat *et al.* (2002) report that the amounts of extractives was higher at early hemp plant development, which is in line with the present study where the lignocellulosic portion increases and other components decrease with plant development (Table 2). Higher concentrations of inhibiting extractive compounds could be the reason of inhibition in the earliest harvested sample, but the concentration and composition of extractives have not been determined.

Table 4. Volatile fatty acids and pH after 2 days of digestion.

	pH	Acetic	Propionic	i-butyric	n-butyric	i-valeric	n-valeric
10-Jul	7.22	2374	403	58	216	1169	0
30-Jul	7.32	1921	458	36	144	87	0
4-Sep	7.54	419	279	25	0	52	0
19-Oct	7.58	290	290	0	0	0	0
Cellulose	7.33	1200	257	0	0	0	0
Control	7.75	514	350	0	0	0	0

The biomass yields of the four different harvest times are shown in Table 3. The highest biomass yield achieved, 14 tons TS per hectare, is a high compared to other crops grown under Swedish conditions (SOU, 2007). In Table 3 the energy yield per hectare in form of methane is also shown. The highest energy yield per hectare was achieved at harvest in September through October.

Figure 2 shows the data for hemp from the present study (based on harvest in September) in comparison with recently published data on total energy contained in various energy crops, as well as gross and net energy yields of different combinations of energy crops and energy carriers (SOU, 2007). The energy contained in the biomass of one hectare, based on total solids yield of the full plant and the higher heating value, is denoted with "total energy" in Figure 2. For hemp the higher heating value of spring harvested hemp according to SOU (2007) was used; 17.64 GJ/ton_{TS} . Biomass yields refer to good soils in southern Sweden (Götalands södra slättbygder). The energy amounts of different fuels that can be produced from the crops are denoted with "gross fuel" in Figure 2. The higher heating value of methane (35.9 MJ per Nm^3) was used to determine the gross energy yield for biogas from hemp. For "net fuel" (not determined for biogas from hemp) the direct energy input in cultivation and conversion to fuel is subtracted from the gross fuel yield. Data for hemp is based on the present study while all other data originates from SOU (2007). Hemp is mentioned by SOU (2007) but the data are based on spring harvest, with a hectare yield of 6.5 tons TS (for use of fibers or combustion). The present study shows that a much higher biomass yield, 14 tons TS, can be achieved at harvest in September through October.

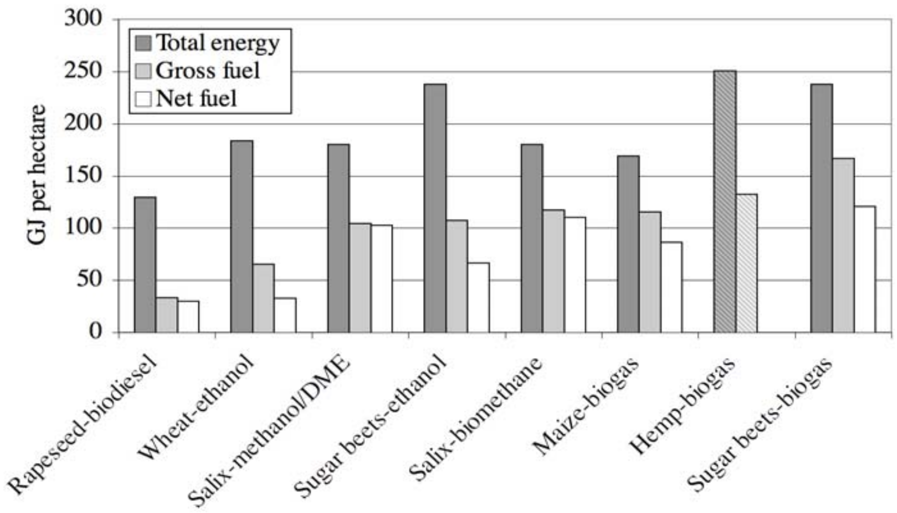

Figure 2. Comparison of the area efficiency of biogas production from hemp with other crop/energy carrier combinations. Data for hemp is based on this study while all other data originates from SOU (2007). See text for further details.

As shown in Figure 2 approximately twice the gross fuel yield per hectare can be achieved when producing biogas from hemp compared to the presently dominating energy crops/energy carriers in Sweden; ethanol from wheat and biodiesel from rapeseed. The gross fuel yield of methane from hemp is also higher or in the same range as for thermal gasification of Salix (Willow) for production of methanol, DME or methane, ethanol production from the cellulose of Salix and biogas from maize. Germany has the highest number of agricultural biogas plants in Europe. Weiland and Rieger (2005) estimated that maize was used in 80% of the agricultural biogas plants in Germany. Biogas production from beets gives the highest gross and net energy output per hectare in Sweden (SOU, 2007). Beets have also yielded good results in a study on hydrogen enriched biogas production in UK (Martínez-Pérez *et al.* 2007), together with maize and perennial ryegrass. The energy yield in biomass per hectare is in the same range for sugar beets and hemp. As shown by the big difference between the total energy content of the hemp and the gross energy output achieved in form of methane there is a great potential of improving the degradation and increasing the methane yield (Figure 2). The net energy yield of biogas production from hemp still needs to be determined to enable a full comparison with other alternatives. The biomass yields at different harvest times also need to be confirmed, and the cultivation experiments are continued during 2007.

CONCLUSIONS

The results of this study show that biogas production from hemp is a promising possibility for production of vehicle fuel from energy crops. The harvest of year 2006 showed a high biomass yield for hemp, more than 14 tons TS per hectare, and if other harvest determinations will confirm this, hemp will be one of the highest yielding crops in Sweden, if not the highest. Already with the simple batch digestion used in the present study, the biogas yield from hemp gave one of the highest gross yields of vehicle fuel per hectare achieved in Sweden. Still, there is a large potential to improve the methane yield. The harvest time showed to have little effect on the specific methane yield but a large effect on the biomass yield and thus the methane yield per hectare. The best methane yield per hectare was achieved when harvesting in September through October. Caution should be taken if digesting hemp harvested early (July), and possibly also for later harvested hemp, because of the risk of inhibition of the process.

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