Sustainable crop rotations and their potential for biogas production

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Abstract

Biogas production from agricultural raw materials is a key technology for an environmentally friendly production of renewable energy. Energy crops are used as the main substrate. To ensure a sustainable production of these energy crops, they need to be grown in ecologically balanced and diversified crop rotation systems. The central aim of the present research project was to determine optimal mixtures of energy crops as raw material for fermentation, to increase the specific methane yield and subsequently the methane yield per hectare, when a diverse crop rotation system is used. To detect a possible co-fermentation effect the specific methane yield per kg VS of maize silage, maize cob-corn-mix, sugar beet, sunflower, clover and rye has been investigated in mono-fermentation, as well as from 13 different mixtures, which differed in their protein-energy-proportion. With mono-fermentation the cob-corn-mix showed the highest specific methane yield with 344 l_N kg VS^{-1}. Due to a positive co-fermentation effect four mixtures had a specific methane yield above 380 l_N kg VS^{-1}. Considering a higher output when mixtures are used, energy crop rotations can achieve methane yields per hectare of 8,957 m^3_N CH_4 ha^{-1}.

Keywords: Anaerobic digestion, biogas, co-fermentation effect, methane yield, sustainable crop rotation

Introduction

According to the biomass action plans of Austria and the European Commission future demand for agricultural biomass for renewable energy production, such as anaerobic digestion, will increase. Suitable substrates for biogas production are: organic wastes, animal manures, and to a large extent, energy crops like maize, sorghum, sugar beet, wheat, rye, triticale, as well as forage grass and legumes. To avoid environmental problems in the form of pests and diseases or soil degradation, energy crops need to be grown in sustainable and site-adapted crop rotation systems.

Concerning the anaerobic digestion of organic raw materials it is known that the rate and velocity of the degradation and subsequently the specific methane yield is controlled by the biochemical composition of substrates (Amon et al., 2004). A maximum methane yield of the fermentation substrate can be achieved when the concentration of crude protein, crude lipids, crude fibre, and N-free extracts, as well as the nutrient supply for micro-organisms in the digester is optimal. Synergies can be achieved when mixtures from different energy crop silages are used (co-fermentation effect). In other words, higher gas yields can be expected from mixtures as compared to the mono-fermentation of single energy crops (Mukengele et al., 2006). The present paper will investigate the co-fermentation effect of substrate mixtures obtained from different energy crop silages as well as from cob-corn-mix (CCM), pig slurry and crude glycerine. The optimum substrate mixture in terms of a high specific methane yield and consequently high yielding crop rotation systems for Styrian (province in Austria) conditions are defined.

Material and Methods

The research has been conducted with the energy crops: sugar beet, maize, sunflower, clover/grass and green rye that have been grown within variety testing programmes of the Styrian chamber of agriculture. After biomass determination, the fresh plant material was used to prepare whole plant silages (WPS). The silage process was conducted in 2 litre plastic bottles over a period of 5 to 8 weeks. Additional substrates including cob-corn-mix (CCM), pig slurry and crude glycerine (by-product of ethanol production) have been used. Before analysis, the silages were chopped to a particle size of 0.1 to 0.3 cm.

Thirteen different mixtures of energy crops and co-substrates (Table 1) were prepared and their specific methane yield investigated. According to the mixing ratio and bio-chemical composition, the mixtures can be classified as energy-rich (mixtures 2 – 5), protein-rich (mixtures 6 – 9), and balanced (mixtures 10 – 13).

Table 1: Proportion of the different raw materials in the mixtures (% of fresh material)

Block	Mix	Sunflower	Clover	Rye	Maize	CCM	Slurry	Sugar beet
-	1*	0	0	0	31	15	54	0
A (energy rich)	2	20	0	0	30	10	20	20
	3	15	0	0	25	20	10	30
	4	30	0	0	20	0	20	30
	5	20	0	0	40	0	30	10
B (protein rich)	6	5	30	10	10	5	40	0
	7	5	40	20	0	0	35	0
	8	5	30	30	5	0	20	10
	9	0	40	20	5	0	30	5
C (balanced)	10	20	10	10	20	0	20	20
	11	30	5	5	10	10	20	20
	12	35	7,5	7,5	35	5	0	10
	13	15	0	10	45	0	15	15

[*] Mixture 1 contains 4 % of crude glycerine; CCM … cob-corn-mix

Anaerobic digestion experiments to measure the bio-chemical methane potential (BMP) were carried out in accordance with VDI 4630 and DIN 38414. The specific methane yield of each single component and of the mixtures was measured in 3-4 replicates. The amount of biogas production was monitored every day, whereas the biogas quality (CH_4, H_2S, NH_3) was analysed 10 times during the 6-week digestion period. Methane concentrations in the biogas were analysed with a Gas Data LMS NDIR analyser (accuracy: ±1–3% of the measurement reading). Prior to anaerobic digestion, the pH of the substrates was measured and the nutrient composition (dry matter, crude ash, crude protein, crude lipid, crude fibre, cellulose, hemi-cellulose, lignin, starch, and sugar) was analysed according to standard procedures. Gross energy was measured with a calorimeter.

Results and discussion

Biomass

The highest biomass yield was obtained from silo maize with 29.7 t DM ha^{-1}. Sugar beet (body without leaves) and cob-corn-mix (CCM) had similar yields with an average of 15.3 t DM ha^{-1}. The whole plant silage (WPS) of green rye and sunflower had biomass yields of 14.3 and 12.7 t DM ha^{-1}, respectively. A clover/grass cropping system, which was harvested 4 times, attained a biomass yield of 10.2 t DM ha^{-1}.

Specific methane yield

From the observed fermentation raw materials the cob-corn-mix had the highest specific methane yield with 343.5 l_N kg VS^{-1}. A similar methane yield (338.2 l_N kg VS^{-1}) was achieved from maize WPS. No significant differences were found between the methane production from the silages of green rye, sunflower and clover/grass with 290.7, 293.5 and 290.7 l_N kg VS^{-1}, respectively. The lowest specific methane yield was measured with the raw materials: sugar beet (260.8 l_N kg VS^{-1}), pig slurry (205.7 l_N kg VS^{-1}), and glycerine (42.4 l_N kg VS^{-1}).

Comparing the mixtures, the highest specific biogas yield was obtained from mixture 1. Due to a low methane concentration in the biogas, the specific methane production of this mixture was average. The highest specific methane yield, with 426.5 l_N kg VS^{-1}, was achieved from mixture 13, which had a high proportion of maize silage. Significantly lower levels of methane yield were observed with mixtures 4 and 12, in comparison to mixture 13. Mixture 12, which achieved a methane yield of 303 l_N kg VS^{-1}, had a high percentage of sunflower silage and therefore high crude lipid content (15.6 % in DM). It is known that high crude lipid content results in high fatty acid concentrations in the fermentation substrate, which limits anaerobic digestion and methane production (Machmüller et al., 1998). Concerning the different composition of the mixtures it is evident that protein rich mixtures (Block B) had significantly higher biogas yields in contrast to the energy rich and balanced mixtures (Block A and C). The mean methane yield of Block B with 378.4 l_N kg VS^{-1} was significantly higher compared to Block A with 341.0 378.4 l_N kg VS^{-1}.

Co-fermentation effect

Table 2: Co-fermentation effect of fermentation substrate mixtures

Block	Specific methane yield (l_N kg VS^{-1})		Difference between measured and expected		
	Mix	Measured	Expected	Absolute (l_N kg VS^{-1})	Relative (% of expected)
-	1*	383^{ab}	258	+ 125^{a}	+ 49
A (energy rich)	2	367^{ab}	287	+ 79^{ab}	+ 28
	3	349^{ab}	295	+ 54^{abc}	+ 18
	4	302^{b}	274	+ 28^{bc}	+ 10
	5	347^{ab}	281	+ 66^{abc}	+ 23
B (protein rich)	6	371^{ab}	267	+ 104^{ab}	+ 39
	7	363^{ab}	267	+ 96^{ab}	+ 36
	8	395^{a}	283	+ 111^{ab}	+ 39
	9	386^{ab}	271	+ 115^{a}	+ 42
C (balanced)	10	369^{ab}	281	+ 89^{ab}	+ 32
	11	378^{ab}	279	+ 99^{ab}	+ 36
	12	303^{b}	311	- 7^{c}	- 2
	13	427^{a}	298	+ 129^{a}	+ 43

VS … volatile solids; Different letters in a column indicate significant differences (P<0.05; Scheffé-Test)

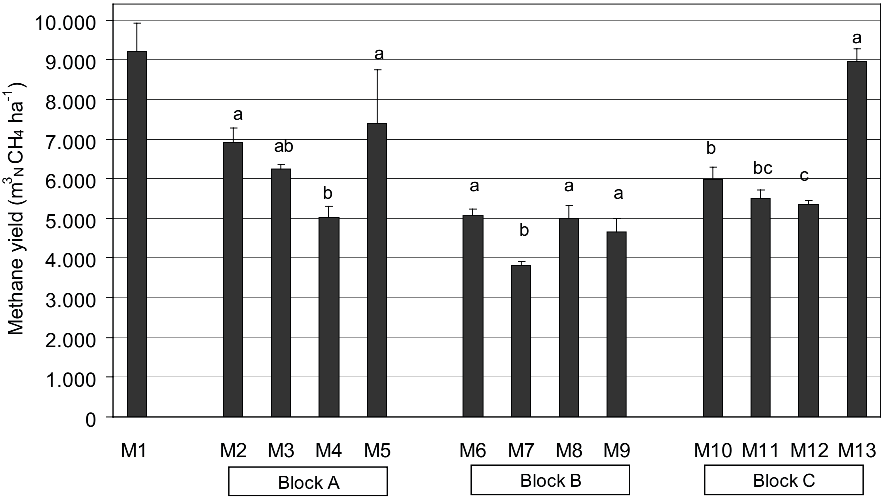
Table 2 shows the difference between measured and expected specific methane yield of the investigated mixtures. The expected methane yield was calculated by the specific methane yield of the single energy crops with respect to their mixing ratio. With the exception of mixture 12, all mixtures showed a positive co-fermentation effect. The highest co-fermentation effects were obtained from mixture 13, 1 and 9, which respectively produced 129, 125 and 115 l_N kg VS^{-1} more than expected. Mixture 4 offered only a slightly higher methane yield. No increase in methane yield was observed in mixture 12.

Generally the highest co-fermentation effects have been observed in the mixtures with a high proportion of protein (Block B). These mixtures yielded on average 107 l_N kg VS^{-1} more as compared to mono-fermentation, and were therefore significantly higher than the mixtures in Block A (57 l_N kg VS^{-1}) and C (77 l_N kg VS^{-1}).

Methane yield per hectare

The methane yield per hectare was calculated by the specific methane yield of the mixture and the biomass yield of the respective energy crops according to their ratio in the mixture (Figure 1). According to their composition the different mixtures/crop rotation systems achieved between 3,823 and 9,192 m^3_N CH_4 ha^{-1}. The highest methane yield per hectare was obtained from mixture 1, which was mainly based on maize (WPS and CCM). From the other crop rotation systems, mixture 13 received the highest methane yield per hectare with 8,957 m^3_N CH_4 ha^{-1}, and was significantly higher than the other mixtures. Generally it was observed, that within each block, mixtures that contained a higher maize percentage produced more methane per hectare. Mixtures in Block B, where maize covered only a small proportion of the crop rotation system, methane yields of about 5,000 m^3_N CH_4 ha^{-1} were still achieved.

Figure 1: Methane yield per hectare of various mixtures/crop rotation systems. Different letters within a block indicate significant differences (P > 0.05, Scheffé-test)



Conclusions

The present results indicate that the anaerobic digestion of energy crops in mixtures almost always gave higher methane yields as compared to mono-fermentation of the used substrates. This suggests that diverse crop rotation systems can achieve similar methane yields per hectare as compared to maize monocultures. Nevertheless, maize is an important component in energy crop production.

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