

Batch- and Semi-continuous Biogas Production from Different Grass Species

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ABSTRACT

The importance of forage as a feed supply for dairy and beef cattle stocks is decreasing. Therefore, interest is rising in alternative use of grasslands. An ecologically sound option is the anaerobic digestion of the biomass as co-substrates in biogas plants.

Three fresh and ensiled grass species were investigated in lab-scale batch experiments at 35° C to determine their maximum biogas production potential. The volatile solid-based biogas and methane yield were observed to be in the range of 0.65-0.86 and 0.31-0.36 m³/(kg VS), respectively.

Semi-continuous experiments were conducted to examine biomethanation of grass and cattle slurry at two organic loading rates (OLR) of 0.7 and 1.4 kg VS/(m³ d). The anaerobic digestion was carried out in completely stirred tank reactors at 35° C with a mixture of three fresh grass species as mono-substrate, cattle slurry and a mixture of both as co-digestion. The biogas yield observed from the grass as mono-substrate at OLR of 0.7 and 1.4 kg VS/(m³ d) was 0.61 and 0.56 m³/(kg VS), respectively. However, for both, co-digestion and cattle slurry digestion, the impact of OLR in the range of 0.7 and 1.4 kg VS/(m³ d) on biogas yield was small. At this range of OLR, the averaged biogas yield obtained to 0.5 and 0.38 m³/(kg VS), respectively. The biogas yield in case of co-digestion was proportional to the amount of VS from grass in a mixture with cattle slurry. Moreover, the methane content decreased from 59-63% to 53-59% with the increasing proportion of grass.

Keywords: Biomethanation, biogas, cattle slurry, co-digestion, forage grass

1. INTRODUCTION

In Germany, crop biomass is increasingly used as a co-substrate in agricultural biogas plants. This trend is due to the Renewable Energy Sources Act (Anonymous 2000; 2004) that guarantees determined fees for electricity produced from biomass for a period of up to twenty years per plant. The widespread introduction of anaerobic digestion in Germany has shown that biogenic organic wastes are a valuable source for energy and nutrients (Weiland, 2000). Studies on biogas production on the basis of sewage sludge (Edelmann et al., 2000) or animal wastes (Moller, 2004) in co-digestion with both organic wastes (Delborghi et al., 1999) and energy crops (Gunaseelan and Nallathambi, 1997; Lemmer and Oechsner, 2002) were of special interest in recent years. The aim of other studies, using batch experiments (Kang et al., 1993), was to optimise anaerobic digestion of agro-industrial residues.

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Approximately one third of German farmland is grassland. The current reduction in dairy and beef cattle stocks and the continuous increase in forage quality standards required have brought a decrease in the utilisation of grassland as a feed source for ruminants (Hochberg, 2001). This offers opportunities for an alternative use of grass as a co-substrate in biogas production. Depending on the substrate, co-substrates can be digested in agricultural biogas plants to increase biogas production and to improve the financial viability of the plant (Grundmann et al., 2002). The value of a substrate in the biogas process depends on its potential as a high yield plant species and on the quality of the biogas produced, such as the achievable methane content. The most suitable plant species for the production of biogas are those which are rich in degradable carbohydrates, such as sugars, lipids and proteins, and poor in hemicelluloses and lignin, which have a low biodegradability (El Bassam, 1998). Hence, to find the optimal crop species for anaerobic digestion is of particular interest. The conservation and storage of biomass is also a necessary factor for the quality, using the substrate continuously as feedstock for biogas production.

This paper presents the results of lab-scale experiments conducted in a batch mode to determine biogas yield and the specific methane content of fresh and ensiled perennial ryegrass, cocksfoot and meadow foxtail. Further semi-continuous experiments in daily fill and draw mode were conducted to compare biomethanation of the same grass species as single substrate and as a mixture with slurry to anaerobic digestion of single cattle slurry. The objective of this paper is to determine the maximum biogas yield by means of batch experiments in order to verify the effect of the OLR on the biogas yield in continuous experiments.

2. MATERIALS AND METHODS

2.1 Substrates

First cut of perennial ryegrass (*Lolium perenne*), cocksfoot (*Dactylis glomerata*) and meadow foxtail (*Alopecurus pratensis*) were harvested mid-May 2001 at the State Institute for Consumer Protection and Agriculture Brandenburg, Department of Grassland and Forage Management, near Potsdam. The perennial ryegrass and cocksfoot were growing on humous sand with a fertilisation of 600 kg N/ha and the meadow foxtail on fen turf with 1200 kg N/ha. Plant protection measures have not been applied. The average annual temperature was 9.0° C and the average rainfall 519 mm. After one day of wilting at around 25° C, a portion of each grass variety was frozen at -18° C to be used later as fresh material in the anaerobic digestion studies. The other portion was packed and sealed in 1.0 litre glass vessels for a period of eleven months to undergo natural ensiling. The second cut of the grass varieties was used to prepare the mixture for the semi-continuous anaerobic digestion experiment. The mixture consisted of the same quantity of each grass species. The slurry used as a substrate was delivered from a dairy cattle farm. Before starting the anaerobic digestion experiments, samples of the assigned substrates were analysed according to standard methods as follows: total solids at 105° C (TS), volatile solids at 550° C (VS); volatile fatty acids (VFA), pH, C:N, crude protein (XP), crude fibre (XF), crude fat (XL) and saccharide.

2.2 Lab-scale experiments

Batch experiments were carried out in lab-scale vessels with a working volume of 2.0 litres and two replicates (except cocksfoot) as described by Linke and Schelle (2000) and according to the guideline VDI 4630 (2004). A constant temperature of 35° C was maintained through a water bath. Anaerobically digested material from a preceding batch experiment was used as inoculum for the current experiments. 1.5 kg of the stabilised inoculum was mixed with 0.05 kg fresh matter forage grass assigned for anaerobic digestion. The reactor vessels were connected to calibrated wet gas meters for measuring biogas production for up to 28 days. The biogas produced, at standard conditions (0° C, 1013 mbar), from fresh and ensiled matter was determined daily during the digestion period t and plotted as a cumulative curve $y(t)$ related to volatile solids. According to Mähnert et al. (2002), an exponential function of the *Chapman function with three parameters*-type $y(t) = y_{\max}(1 - e^{-a*t})^b$ has been used for calculating the possible maximum gas production y_{\max} . The content of methane in the biogas p_{CH_4} was analysed six to seven times by a gas analyser (*ANSYCO GA94*) and fitted by an empirical equation of the *Hill function with four parameters*-type as follows: $p_{CH_4}(t) = p_0 + a \frac{t^b}{c^b + t^b}$ with a minimum content of methane p_0 and the coefficients a , b and c . By means of this function the biogas daily produced was multiplied with the corresponding methane content. The summation of the methane yield daily produced gives the accumulated methane yield y_{CH_4} .

Semi-continuous experiments were carried out over a period of about 20 weeks in three mechanically stirred bioreactors with a digester volume of 2.0 l for the slurry digestion and 9.0 l in the case of the digestion of the mixture and the single grass, respectively. A constant temperature of 35° C was maintained by water circulation through the jacket of the bioreactors. All reactors were operated in a daily fill and draw mode and mixed slowly at a speed of about 100 revolutions per minute for 15 minutes in every hour. For the start up, all bioreactors were inoculated with anaerobically digested manure from previous experiments. This preliminary step was followed by a series of semi-continuous experiments with different substrates (mixture of three grass species, grass-slurry-mixture at a VS-ratio of 2:1, cattle slurry). Thereby, the daily input of substrates (VS-load) was increased three times once a week until an organic loading rate (OLR) of 1.42 kg VS/(m³ d) was reached. After a stabilisation period of four weeks a period of approximately six weeks was used to measure the gas production at the OLR of 1.42 kg VS/(m³ d). A transition period of three weeks induced a period of 13 weeks with an OLR of 0.71 kg VS/(m³ d). The biogas produced was measured daily using a multi-chamber rotor gas meter (*RITTER TG1/5*) and analysed with a gas analyser (*PRONOVA SSM6000*).

3. RESULTS AND DISCUSSION

3.1 Substrates

Data presented in Table 1 show that TS of first and second fresh cut grasses ranged from 16-19% and 23-26%, respectively, and VS ranged from 89-91%. Furthermore, forage quality parameters (XP, XF, XL) are in good accordance to the required feed values for ruminants summarised by Kirchgeßner (1997).

Table 1. Characterisation of applied substrates as fresh matter (FM): total solids (TS), volatile solids (VS), volatile fatty acids (VFA), pH, C:N, crude protein (XP), crude fibre (XF), saccharide and crude fat (XL)

	TS [% FM]	VS [% TS]	VFA [g/kg FM]	pH [-]	C:N [-]	XP [% TS]	XF [% TS]	saccharide [% TS]	XL [% TS]
Fresh grasses for batch-experiments									
Perennial ryegrass	17.6	90.1	0.5	6.5	16.4	14.7	24.8	10.8	2.1
Cocksfoot	18.6	89.1	0.5	6.7	13.7	18.5	24.8	9.8	2.3
Meadow foxtail	15.8	91.1	0.3	6.6	--	--	25.3	3.3	2.2
Silages for batch-experiments									
Perennial ryegrass	18.7	88.5	6.9	4.6	15.5	17.0	31.3	3.4	4.9
Cocksfoot	27.3	88.8	14.3	6.1	14.3	18.4	30.1	3.1	4.6
Fresh grasses for semi-continuous experiments									
Perennial ryegrass	25.6	90.6	0.7	6.5	19.8	11.8	29.1	19.3	2.4
Cocksfoot	22.9	88.8	0.5	7.1	12.0	21.4	28.0	9.8	2.6
Meadow foxtail	24.2	90.6	0.6	7.1	13.5	18.8	31.5	9.1	2.1
Mixture	24.2	90.0	0.6	6.9	15.1	17.4	29.5	12.7	2.4
Slurry for semi-continuous experiments									
Cattle Slurry	6.5	80.0	7.9	6.8	--	--	--	--	--

3.2 Batch-experiments

All tested samples of fresh and ensiled grass species showed monophasic curves of accumulated biogas production. After a steep increase, biogas production decreased resulting in a plateau of the cumulative curve. The maximum biogas rate was already achieved on the second day of digestion experiment (Figure 1). More than 90% of the biogas yield were obtained after 9 to 11 days of anaerobic digestion. Moreover, analysis of digested residues showed a high degradation of substrates for the batch experiments conducted.

Measured biogas yields ranged from 0.65-0.86 m³/(kg VS) after 28 days digestion time. Therefore, the measured biogas yields lay in between the values from the literature for fresh and ensiled grass. Hence, measurements for fresh cut grass were reported recently of 0.5-0.6 m³/(kg VS) by Baserga and Egger (1997) and of 0.6 m³/(kg VS) (KTBL, 2005) and for grass silage of 0.54 m³/(kg VS) by Linke et al. (2003), 0.58 m³/(kg VS) by Niebaum and Döhler (2004), 0.63 m³/(kg VS) (KTBL, 2005) and 0.81 m³/(kg VS) by Jäkel (2000).

Both, fresh and ensiled, the perennial ryegrass achieved the highest biogas yields in the experiments with 0.83 and 0.86 m³/(kg VS), respectively, and cocksfoot fresh matter and silage the lowest (0.72 and 0.65 m³/kg VS). Biogas yields for meadow foxtail were obtained with 0.74 m³/(kg VS) at a medium level and varied considerably. The results presented show no clear differences in biogas production between the grass species investigated because the difference between the two replicates of the meadow foxtail is more distinctive than the difference to the averages of the other grass species. On the other hand the replicates of perennial ryegrass as fresh matter and silage and of the cocksfoot silage showed deviations of about 2%, 10% and 1%, respectively, whereas the difference between the averages of these grass species amounted about 25%. Almost no difference could be detected for ensiled material compared to fresh matter. In the case of perennial ryegrass the averages of the fresh matter and the silage differed of about 3.5% and in the case of cocksfoot of about 9.7%. But it should be mentioned that in all cases only two replicates have been applied, which is not enough to draw general conclusions. The grass silages produced for these experiments could have a minor quality compared to quality forage silages, because no silage additives were used, in order to avoid any possible additional effect on the biomethanation process. These quality differences may be the cause of greater variability of the associated biogas production. In general, ensiling is an appropriate method to preserve grasses for later anaerobic digestion (Mähnert et al., 2002).

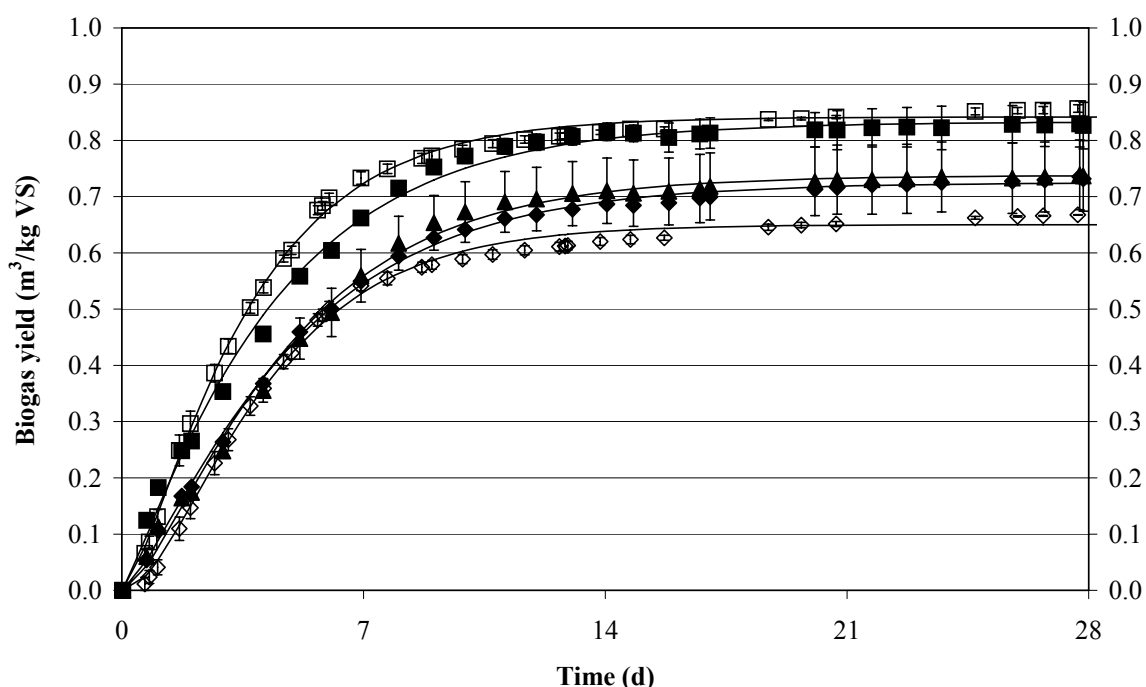


Figure 1. Cumulative biogas yield y_B (m³/kg VS) of selected fresh grass species (FG) and their silages (S): (◆;◇) Cocksfoot-FG (n = 1) and -S; (■;□) Perennial ryegrass-FG and -S; (▲) Meadow foxtail-FG; symbols are averages and bars indicate value of each replicate

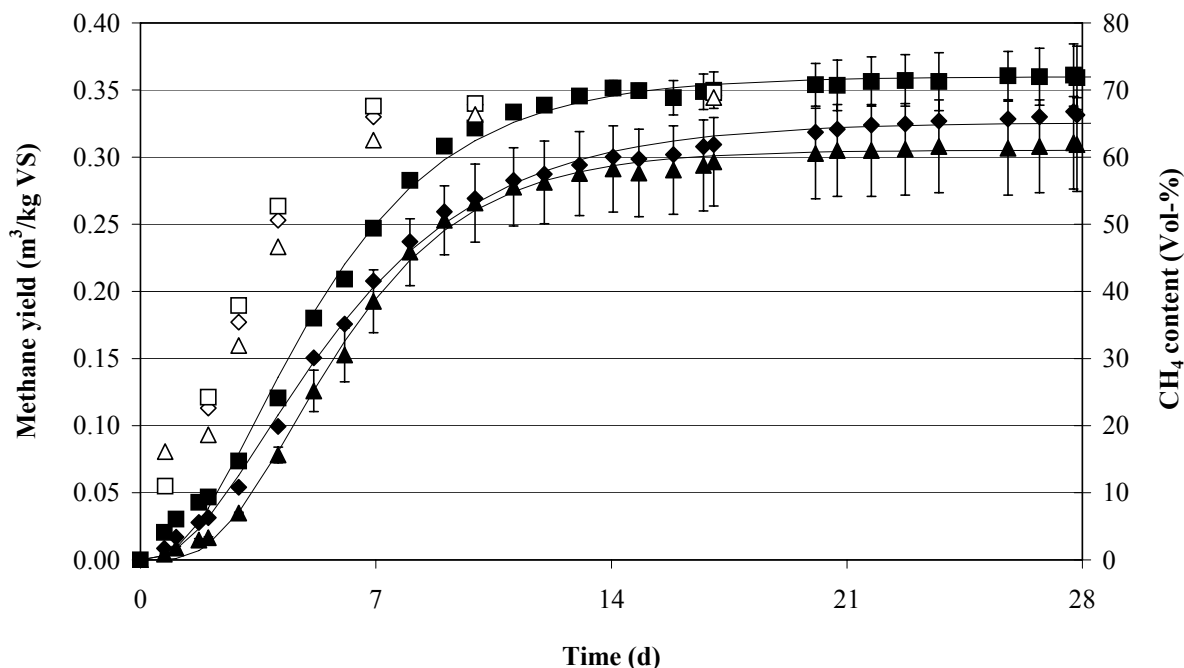


Figure 2. Cumulative methane yield y_{CH_4} (m^3/kg VS) and methane content in the biogas p_{CH_4} (Vol-%) of selected fresh grass species: (\blacklozenge ; \diamond) Cocksfoot y_{CH_4} and p_{CH_4} ; (\blacksquare ; \square) Perennial ryegrass y_{CH_4} and p_{CH_4} ; (\blacktriangle ; \triangle) Meadow foxtail y_{CH_4} and p_{CH_4} ; symbols are averages and bars indicate value of each replicate

For the investigated fresh cut grass species, methane content of the biogas increased during the first days of the experiment and then approximated to an average of 66% to 71% in the middle of the period investigated (Figure 2). Furthermore, there were no great differences in the methane production from fresh matter or from silage. With respect to the high level of methane formation, it should be mentioned that these measurements are optimum values explored under optimum conditions in the laboratory.

Means of methane yield (Figure 2) range from 0.31 to 0.36 $m^3/(kg$ VS) for fresh cut meadow foxtail and perennial ryegrass, respectively. Values obtained are in good accordance to Oechsner (2001) who observed similar values for fresh grass of 0.23-0.41 $m^3/(kg$ VS) and Amon et al. (2004) who observed 0.25 $m^3/(kg$ VS). Results from Jäkel (2000) indicate clearly higher methane yields of 0.5 $m^3/(kg$ VS).

3.3 Semi-continuous experiments

The weekly reactor performance data for biogas yield and organic loading rate from semi-continuous lab-scale digesters are shown in Figure 3 for grass as mono-substrate, single cattle slurry, and the co-digestion of 67% grass and 33% cattle slurry on VS-basis.

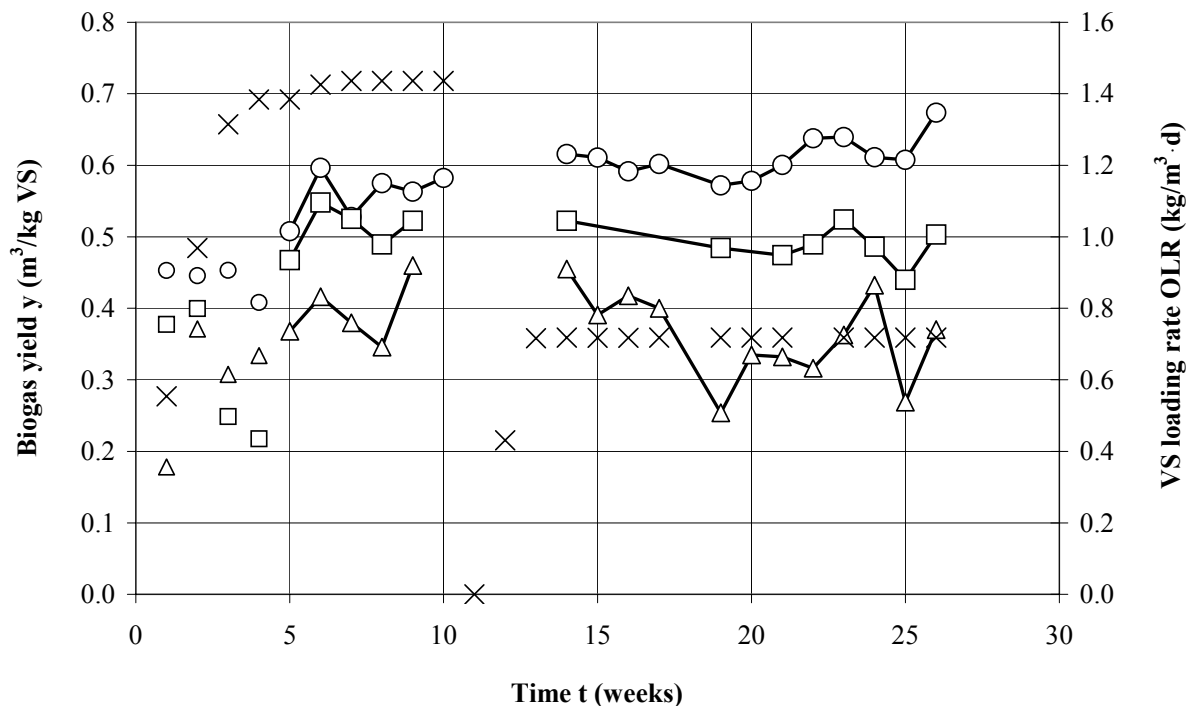


Figure 3. Biogas yield y ($\text{m}^3/\text{kg VS}$) and organic loading rate OLR ($\text{kg VS}/(\text{m}^3 \text{d})$) in course of time from semi-continuous operating fully mixed lab bioreactors digesting forage grass and cattle slurry: (O) y forage grass, (□) y 67 % forage grass and 33 % cattle slurry (VS basis), (Δ) y cattle slurry, (x) OLR for all substrates

At semi-continuous experiments biogas yields of investigated grass species with an average of 0.61 and $0.56 \text{ m}^3/(\text{kg VS})$ at an OLR of 0.7 and $1.4 \text{ kg VS}/(\text{m}^3 \text{d})$, respectively, were observed slightly lower than $0.76 \text{ m}^3/\text{kg}$ of batch-experiments. Consequently, biogas yield also depends on the organic loading rate with 80% and 74% of maximum potential biogas yield at an OLR of 0.7 and $1.4 \text{ kg VS}/(\text{m}^3 \text{d})$, respectively. Baserga (1998) reported similar results. In a continuously fed pilot plant about $80\text{-}85\%$ of biogas yield was measured compared to batch-experiments. Krieg (2000) also indicates that for grass it is feasible to generate biogas yields of about $0.65 \text{ m}^3/(\text{kg VS})$ at an OLR of $0.4 \text{ kg VS}/(\text{m}^3 \text{d})$ and $0.31 \text{ m}^3/(\text{kg VS})$ at an OLR of $3.2 \text{ kg VS}/(\text{m}^3 \text{d})$.

In co-digestion of grass with slurry (mixture) as well as experiments with single cattle slurry, differences in measured VS-biogas yield due to OLR were not observable at very low OLR. VS-biogas yield for co-digestion ranged from 0.51 and $0.49 \text{ m}^3/(\text{kg VS})$, respectively, and for anaerobic digestion of cattle slurry from 0.38 and $0.39 \text{ m}^3/(\text{kg VS})$. In figure 4, the biogas yields from the three experiments at an OLR of $0.7 \text{ kg VS}/(\text{m}^3 \text{d})$ are plotted against the VS-portion of grass in the mixture with cattle slurry. With increase of the VS-portion of grass up to the mono-digestion, the biogas yields rise linear. Thus, biogas yield of grass-slurry-mixture is equivalent to the total sum of biogas yield of proportionate single substrates.

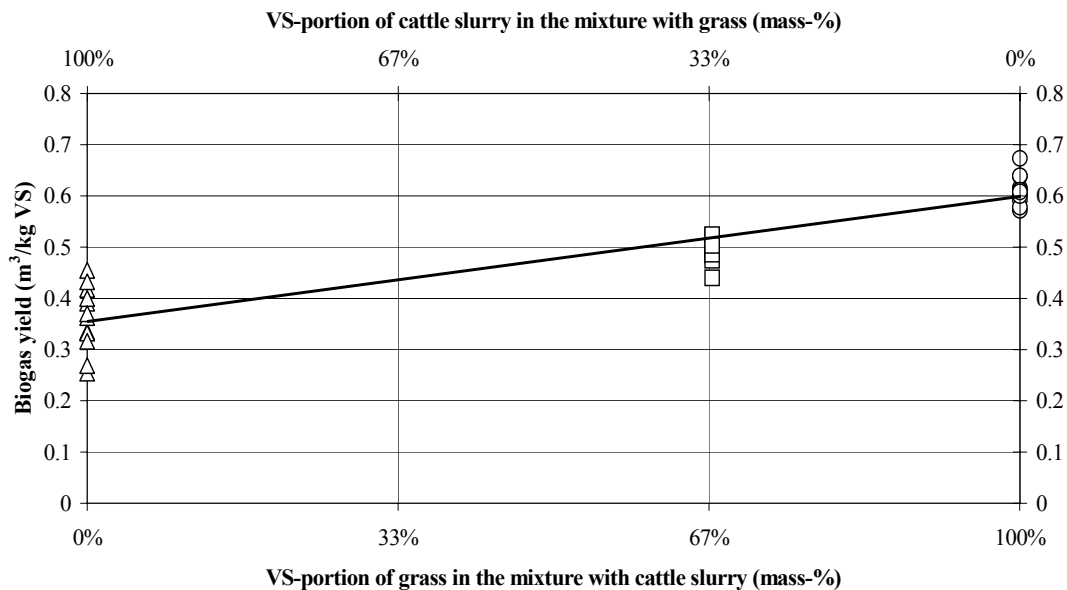


Figure 4. Effect of VS-portion of grass in the mixture with cattle slurry on biogas yield from the continuous fermentation of (Δ) forage grass as mono-substrate; (\square) grass as co-substrate; (\circ) single cattle slurry

Results have shown, that the impact of OLR on the methane content in the biogas is not significant. This parameter seems to be substrate specific rather than specific to OLR. During the first phase of the semi-continuous experiment with grass species, the methane content ranged from 52-56%. This is slightly lower than values from the grass-slurry-mixture (53-59%) and cattle slurry (59-63%). Corresponding methane contents as a result of anaerobic digestion of slurry (57-60%) and of co-digestion of grass and maize with slurry (54-57%) are described by Lemmer and Oechsner (2001). In semi-continuous experiments, methane yield was calculated through multiplication of the biogas yield and the according methane content. The resulting values range between 0.30-0.32 m³/(kg VS) for mono-digestion of grass and 0.22-0.23 m³/(kg VS) for cattle slurry, respectively. Generally, with an increasing methane content of produced biogas, the calorific value increases. But mono-digestion or co-digestion of grass may lead to a more efficient operation of the biogas plant due to higher maximal biogas production potential of grass.

3.4 Grass as Co-substrate

A comparison of the averaged biogas yield of the forage grass species investigated (0.76 m³/kg VS) with different energy feedstock tested in batch experiments (Linke et al., 2003) reveals that biogas yield range clearly at a higher level than cattle and pig slurry with 0.41 and 0.42 m³/(kg VS), respectively. It shows a range similar to that of apple pomace and maize silage with 0.68 and 0.77 m³/(kg VS), respectively, and a lower level than barley silage with 0.92 m³/(kg VS).

The supply of a high quality feedstock is an essential prerequisite to obtain optimal gas yields (Heiermann and Plöchl, 2004). The production system and the management of grassland mainly influence the botanical composition of crop species. For example, grasslands intensively managed for silage will normally consist of high yielding varieties of perennial ryegrass. Haymaking is

particularly a feature of meadow foxtail. Results of perennial ryegrass, cocksfoot and meadow foxtail presented here do not reflect variety specific differences in biogas production potential, but indicate dependence on the quality of the silage. While ensiling, farmers aim to achieve the best possible compromise between crop yield (dry matter production) and crop quality (digestibility) both for livestock and biogas plant. An increase in dry matter content of the crop decreases its ensiling ability as measured by pH and short-chain fatty acid content. Furthermore, hemicelluloses and lignin have a low biodegradability, and for the latter, the breakdown is hardly noticeable under anaerobic conditions (Klaas, 1998). Thus, the timing of grass cutting as well as the sequence of grass cutting strongly influence biogas yield. Some examples of biogas plants conducting the digestion of grass and energy crops are given by Fischer and Krieg (2005).

4. CONCLUSIONS

Forage grass can be used in an ecologically sound way as co-substrates for the anaerobic digestion. The three fresh and ensiled grass species investigated in lab-scale batch-experiments and semi-continuous biomethanation are appropriate to anaerobic digestion. In comparison to cattle slurry, they produce higher biogas yields.

According to Mähnert et al. (2002), the maximum biogas and methane yields from the three grass species investigated in this study and five more grasses were independent both of species and of conservation. Measurements for semi-continuous biogas production from forage grass as mono-substrate depends on the organic loading rate. Even at low values of 0.7 and 1.4 kg VS/(m³ d) the biogas yield decreased with increasing OLR. Therefore, the biogas yield amounted to 80% and 74% of maximum potential biogas yield, respectively. Whereas, at the co-digestion of grass and the biogas production from single cattle slurry the two OLR investigated do not have any effect on the biogas yield. Other lab-scale experiments (Krieg, 2000) and full-scale experiences (Fischer and Krieg, 2005) indicate that higher OLR of about 3 kg VS/(m³ d) are possible, even at the mono-digestion of grass. Further work is needed to find the correlation between the biogas production from grass as mono- and co-substrate and the organic loading rate.

At low OLR, the biogas yield of a grass-slurry-mixture is equivalent to the total sum of biogas from the proportionate single substrates. Therefore, the biogas yield from a mixture of grass and slurry can be calculated by the VS-biogas yield of grass and of slurry and the VS-portion of the grass in the mixture. The impact of OLR on the methane content is not distinctive, but seems to be substrate-specific. Also, the methane content decreased with increasing proportion of grass from 59-63% to 53-59%.

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