# Biogas Crops - Part I: Specifications and Suitability of Field Crops for Anaerobic Digestion

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## ABSTRACT

In Germany, the growing number of agricultural biogas plants causes an increasing demand for crops as a feedstock in both mono- and co-digestion processes. Laboratory scale batch anaerobic digestion tests under mesophilic conditions according to the German Standard Procedure VDI 4630 were conducted to investigate the suitability of different plant species like barley (*Hordeum vulgare*), rye (*Secale cereale*), triticale (X *Triticosecale*), alfalfa (*Medicago sativa*), hemp (*Cannabis sativa*), Jerusalem artichoke (*Helianthus tuberosus*) and maize (*Zea mays*) for biogas production. Emphasis was placed on growing stage and maturity, respectively as well as on whole crop silage preparation without additives as a preservation method for biogas crops.

Results presented indicate that biogas yield is clearly influenced by plant species and harvest stage. Ensiled matter shows a positive effect on biomethanation with higher biogas yields and methane contents than fresh matter investigated. Hence, ensiling can be considered as pre-treatment which has also potential to improve methane production from plant matter. Analyses of digested materials reveal considerable reduction of organic matter of all crops investigated.

**Keywords:** Anaerobic digestion, biogas, methane, feedstock, silage, digestate

## 1. INTRODUCTION

In Europe, there is a significant increase in biomass cultivation for bioenergy purpose, especially for biogas production via anaerobic digestion. Methane-rich biogas is produced from a wide variety of biomass types like manure, by-products and organic waste but mainly from cultivated field crops, so-called biogas crops. Up to now maize is the preferred crop cultivated. This is mainly due to the highly developed stage of agricultural production of maize for food and fodder and consequently the widespread cultivation knowledge and availability of machinery among farmers. In Germany, most of the 3.500 biogas systems in operation have a farming background (FvB, 2007). Currently, biogas crops represent more than 46% of the input and the share of animal manure is approx. 24% of feedstock applied for biogas production (Weiland, 2006). The growing number of biogas plants causes an increasing demand for crops as a feedstock for agricultural biogas plants in both mono- and co-digestion processes.

This opens the questions which crops are suitable for biomethanation and what determines their suitability? The value of a crop as a feedstock for anaerobic digestion depends on its biomass yield capacity compared to the effort for cultivation and on its ability to produce biogas with a high methane content (50–65%). From this point of view, the most suitable plant species are those rich in easily degradable carbohydrates, such as sugar and protein matter and poor in hemicelluloses and lignin which have a low biodegradability (El Bassam, 1998). Furthermore, biogas crops shall be easy to cultivate i.e. to be tolerant to weeds, pests, diseases, drought and frost, have good winter hardiness and be able to grow with low nutrient input (Scholz and Ellerbrock, 2002).

Production on a continuous basis and an almost homogeneous feedstock is indispensable to enable an uninterrupted supply of crops for anaerobic digestion. Focussing on biogas production ensiling is the favourable and common method of whole crop preservation. Through compression of the crop material and air-tight sealing anaerobic conditions are established that promote the growth of lactic acid bacteria. This microbial conversion of free soluble carbohydrates into lactic acid and the resulting decrease in pH prevents the growth of undesirable bacteria and hence, a spoiling of the silage and a reduction in its nutrient and energy value. The production of stable silages requires a minimum of DM content in plant material of 20% and maximum should not exceed 35% (Anonymous, 2006).

Crop species show differences in lactic acid fermentation due to chemical composition and structure of material. Cereal crops like maize, barley, rye, and triticale produce high quality forage when ensiled (Rotz *et al.*, 2003). Legumes such as alfalfa have been ensiled but ensiling has relatively recently become a common means of conservation (Albrecht and Beauchemin, 2003). It is possible to produce stable preserved material from hemp if it is chopped (Pecenka *et al.*, 2007). Immature Jerusalem artichoke has forage quality equal or superior to many high-quality forage species (Buxton and O’Kiely, 2003). Considering that chemical composition and structure of crops change during their growth (Herrmann *et al.*, 2007) harvest time also plays a major role with regard to silage quality and maximum yield per hectare. Consequently, selecting plant species as feedstock for biogas production becomes a particularly important aspect.

A number of crops have been analysed for their methane formation potential (e.g. Chynoweth *et al.*, 2001; Gunnaseelan, 1997; Gunnaseelan, 2004; Amon *et al.*, 2004). Extensive screening has been carried out with different plant materials which comprise for instance tubers, stems, leaves, fruits and seeds or even whole plants. But no emphasis was put on the influence of the ensiling process in this context. The heterogeneity of crops investigated results in large variations of biogas yields and corresponding methane contents. In addition to operation modes (batch, semicontinuous or continuous) gas yields and gas qualities will be affected by digestion temperature, loading rate and retention time. However, very little is known about the influence of site-specific growth parameters on the methane potentials of crops suitable for biomass production, e.g. the growth conditions of the Brandenburg State characterised by sandy soil and almost continental climate.

This paper presents results of batch anaerobic digestion tests, which were conducted, according to the German Standard Procedure VDI 4630 (Anonymous, 2006), to determine biogas yield and specific methane content of potential biogas crops. Main focus of the underlying study was the differences in species and variety and the influence of harvest time as well as ensiling process on gas formation per unit organic dry matter. Data generated in this study are intended to be used for an ecological assessment of the provision of energy crops as feedstock in agricultural biogas plants in Brandenburg State (Plöchl *et al.*, 2009).

## 2. MATERIALS AND METHODS

### 2.1 Crops

The selection of common (maize, barley, rye, triticale and alfalfa) and less common agricultural species (hemp, Jerusalem artichoke) regards their appropriateness for anaerobic digestion and their energy yield per hectare as well as fair options of mechanisation and a good integration into farm management. Table 1 summarises species, variety and origin of crops examined.

Table 1. Species, variety and origin of investigated biogas crops

| Species | Variety | Origin |
|---|---|---|
| Barley (*Hordeum vulgare*) | Theresa | Farm, Potsdam |
| Rye (*Secale cereale*) | Ricasso | Farm, Potsdam |
| Triticale *(X Trticosecale*) | Modus | Farm, Potsdam |
| Alfalfa (*Medicago sativa*) | Europe | Trial, LVLF[2)] |
| Hemp (*Cannabis sativa*) | Feodora 19 | Energy plantation, ATB[3)] |
| JA[1)] (*Helianthus tuberosus*) | Pahlow | Energy plantation, ATB |
| | | |
| Maize (*Zea mays*) – Silage | Santiago | Farm, LVLF |
| Maize (*Zea mays*) – Silage | Banguy | Farm, LVLF |
| Maize (*Zea mays*) – Silage | Mondeo | Farm, LVLF |

[1)] JA = Jerusalem artichoke
[2)] LVLF = State Institute for Consumer Protection, Agriculture and Land Consolidation, Brandenburg, Department of Grassland and Forage Management, Paulinenaue
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Crops were harvested at different growth stages from several agricultural sites in the vicinity of Potsdam. Except maize, which was already ensiled, samples were wilted for 2 to 36 h and then applied for whole crop silage preparation. Therefore, harvested and chopped material (cereals 1-1.5 cm, others 2-3 cm) was pressed in 1.5-litre laboratory scale silos. Compression was done manually using a special pressing device that ensured same conditions for all samples. The lab-scale silos were stored at 25°C for a period of 90 days. No additives for ensiling were applied.

### 2.2 Batch anaerobic digestion tests

Biogas production and gas quality from both freshly harvested and ensiled plant material was analysed in batch anaerobic digestion tests according to German Standard Procedure VDI 4630 (Anonymous, 2006). Therefore 2-litre vessels were filled with 1.5 litre inoculum and approx. 50 g crop. Giving 50 g crop to 1.5 litre inoculum ensured the compliance of the $ODM_{feedstock}$ to $ODM_{inoculum}$ ratio being less or equal 0.5 as it is claimed in VDI 4630. The inoculum consisted of digested slurry of previous batch anaerobic digestion tests using crops as feedstock. Characteristic chemical parameters of the inoculum used are summarised in Table 2. The tests were conducted in two replicates.

The reactors were incubated at a temperature of 35°C. In order to resuspend sediments and to avoid scum layers the vessels were shaken once a day.
The biogas produced was collected in scaled wet gas meters over a defined period of 28 days and was measured daily. This duration of the test fulfilled the criterion for terminating batch anaerobic digestion experiments given in VDI 4630 (daily biogas rate is equivalent to only 1% of the total volume of biogas produced up to that time). Besides others methane content was determined at least eight times during the batch test using infrared and chemical sensors (ANSYCO). In addition to the anaerobic digestion of the crop, biogas production of the inoculum without crop was recorded as a control as well.

Table 2. Characterisation of applied inoculum: dry matter (DM), organic dry matter (ODM), volatile fatty acids (VFA), pH

| Inocculum | Parameter | | | |
|---|---|---|---|---|
| | DM [% FM] | ODM [% DM] | VFA[3] [g/kg FM] | pH [-] |
| Batch experiments; approach with | | | | |
| Barley, rye, triticale FM[1] | 3.5 | 54.5 | 1.1 | 8.1 |
| Barley, rye, triticale S[2] | 3.6 | 54.3 | 1.6 | 8.2 |
| Hemp, Jerusalem artichoke FM, S | 3.9 | 52.0 | 2.5 | 8.3 |
| Alfalfa FM S | 2.0 | 43.0 | 2.1 | 8.0 |
| Maize S | 3.1 | 54.7 | 0.8 | 7.9 |

[1] FM = Fresh matter [2] S = Silage
[3] VFA = Equivalents, the weighted sum of acetic-, propionic-, butyric-, isobutyric-, valeric-, isovaleric-, and caproic acid

Quantitative evaluation of the results included following steps:

- standardising the volume of biogas to normal litres ($l_N$); (dry gas, $t_0$=273 K, $p_o$=1013 hPa)
- correcting the methane and carbon dioxide content to 100% (headspace correction, VDI 4630)
- correcting the biogas volume of crops by subtracting the biogas volume of control

Results of batch anaerobic digestion tests are presented as cumulative biogas yields after 28 days retention time as a mean value of two replicates.
Finally, digestate was analysed with regard to reduction of plant matter and process stability.

### 2.3 Analytical methods

Samples of fresh material and of silages were stored at -18°C directly after harvest or after taking samples from lab-scale silos, respectively, for analysis and batch anaerobic digestion tests. Samples of the assigned crops were analysed according to following standard methods before the anaerobic digestion experiments:
Dry matter (DM) content of fresh material and silages was determined by drying at 105°C until the weight constancy. Organic dry matter (ODM) was characterised by specifying the ash content of dry samples in a muffle furnace at 550°C. pH-value was measured with the electrode Sen Tix 41 (WTW) after homogenizing 10 g of sample with 100 ml distilled water for a period of 20 minutes.

In order to measure the content of volatile fatty acids (VFA) samples were defrosted and extracted by cold-water extraction. Extractives were analysed for acetic acid, propionic acid, butyric acid, isobutyric acid, valeric acid, isovaleric acid and caproic acid by gas chromatography (FISIONS) using a DB-FFAP fused silica capillary column (J&W scientific, 30 m x 0.53 mm), helium as a carrier gas and a flame ionisation detector for detection. Volatile fatty acids are presented as acetic acid equivalents, i.e. the weighted sum of VFA.

For further analysis defrosted plant material was dried at a temperature of 60°C and grinded in a cutting mill (RETSCH). Starch content was quantified according to the method of EWERS as described by (Lengerken and Zimmermann, 1991), detecting the optical rotation of a specially treated and filtrated dilution of the sample with a polarimeter (WOLFGANG GLOCK KG).

The concentration of total sugar was obtained mixing 5 g of the sample with 50 ml of distilled water and Carrez I and II. After filling up to 100 ml with distilled water, the dilution was filtrated and sugar content was measured using high performance liquid chromatography.

The content of total carbon ($C_{tot}$) and total nitrogen ($N_{tot}$) was determined using an elementar analyser (vario EL, Analysensysteme GmbH) operating at the principle of catalytical combustion under supply of oxygen and high temperatures. Elementar analysis was conducted according to the DUMAS method (DIN, 2006-07).

Crude protein (XP) content was calculated by multiplying $N_{tot}$ with 6.25. Crude fat (XL) was measured gravimetrical after extracting the sample with a SOXHLET extractor according to the method of WEIBULL-STOLDT (Lengerken and Zimmermann, 1991).

Crude fibre (XF) was analysed according to AOCS Standard methods described by ANAKOM (2000) using the ANAKOM A2000 Fiber Analyser-system.

After termination of anaerobic digestion tests samples of digested output (30 g) were taken to analyse DM, ODM, VFA and pH as described above.

## 3. RESULTS AND DISCUSSION

### 3.1 Characterisation of Biogas Crops

#### 3.1.1 Chemical Composition

Differences in gas formation potentials of crops are mainly due to specific chemical compositions of the plant material. Results of chemical analyses for fresh matter and ensiled matter of whole crops are summarised in Table 3. For fresh matter samples the dry matter content (DM) of plant species investigated varied within a wide range (18.8-65.5%) as well as among samples of the same plant species due to different harvest times (cereals, alfalfa; cf. paragraph below). Jerusalem artichoke were harvested at lowest DM content (about 23%), followed by hemp (31%). For barley, rye and triticale - harvested at anthesis, milk and dough stage – the DM range was larger (18.8-65.5%) than for alfalfa (21.9-34.4%) which was harvested at all three cuts at beginning of florescence.

Table 3. Characterisation of applied crops as fresh matter (FM) and whole crop silages (S): dry matter (DM), organic dry matter (ODM), volatile fatty acids (VFA), pH, C:N, crude protein (XP), crude fibre (XF), crude fat (XL), sugar and starch

| Crop | DM [% FM] | ODM [% DM] | VFA [g/kg FM] | pH [-] | C:N [-] | XP [% DM] | XF [% DM] | XL [%DM] | Sugar [%DM] | Starch [%DM] |
|---|---|---|---|---|---|---|---|---|---|---|
| Barley | | | | | | | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Anthesis FM | 18.8 | 90.2 | 0.2 | 6.6 | 18.1 | 15.8 | 30.9 | 2.6 | 8.7 | 0.9 |
| Anthesis S | 38.2 | 90.2 | 5.4 | 4.7 | 18.6 | 15.3 | 31.5 | 26.9 | 0.9 | 0.5 |
| Milk FM | 27.4 | 93.2 | 0.2 | 6.6 | 22.1 | 13.1 | 21.4 | 2.2 | 9.4 | 16.3 |
| Milk S | 25.3 | 93.4 | 4.7 | 4.3 | 23.3 | 13.0 | 24.6 | 33.5 | 7.6 | 24.7 |
| Dough FM | 46.5 | 94.7 | 0.3 | 7.2 | 37.4 | 7.4 | 17.7 | 2.4 | 2.3 | 30.0 |
| Rye | | | | | | | | | | |
| Anthesis FM | 25.0 | 92.2 | 0.2 | 6.6 | 14.9 | 19.4 | 36.8 | 3.0 | 5.6 | 0.9 |
| Anthesis S | 45.9 | 91.4 | 8.3 | 5.2 | 17.9 | 16.0 | 32.2 | 27.7 | 1.1 | 0.5 |
| Milk FM | 29.3 | 93.5 | 0.3 | 6.9 | 23.6 | 12.3 | 29.3 | 2.1 | 8.8 | 9.1 |
| Milk S | 32.9 | 93.2 | 4.6 | 4.4 | 25.5 | 11.9 | 29.1 | 27.6 | 11.3 | 0.5 |
| Dough FM | 61.0 | 95.0 | 0.2 | 7.0 | 28.9 | 9.8 | 19.9 | 2.4 | 2.1 | 34.6 |
| Triticale | | | | | | | | | | |
| Anthesis FM | 35.2 | 94.3 | 0.3 | 6.5 | 24.2 | 12.3 | 29.0 | 1.9 | 11.5 | 0.9 |
| Anthesis S | 27.3 | 93.1 | 6.5 | 4.5 | 26.3 | 11.4 | 31.7 | 30.4 | 10.1 | 3.6 |
| Milk FM | 33.7 | 95.0 | 0.3 | 6.6 | 31.4 | 9.3 | 24.0 | 1.4 | 11.5 | 7.4 |
| Milk S | 41.2 | 94.6 | 3.8 | 4.2 | 34.5 | 8.8 | 25.6 | 21.0 | 22.0 | 0.6 |
| Dough FM | 65.5 | 97.4 | 0.3 | 7.1 | 30.3 | 9.5 | 18.1 | 1.4 | 1.3 | 40.4 |
| Alfalfa | | | | | | | | | | |
| 1. cut FM | 21.9 | 88.8 | 0.5 | 6.4 | 15.9 | 17.8 | 33.8 | 11.0 | 2.8 | 2.9 |
| 1. cut S | 14.4 | 83.8 | 25.5 | 5.8 | 20.6 | 14.8 | 41.0 | 38.0 | 1.8 | 1.8 |
| 2. cut FM | 22.9 | 88.8 | 0.5 | 6.3 | 13.2 | 21.6 | 29.3 | 11.9 | 3.8 | 2.6 |
| 2. cut S | 34.8 | 87.8 | 10.0 | 5.3 | 14.1 | 20.4 | 35.9 | 22.6 | 2.1 | 4.6 |
| 3. cut FM | 39.8 | 89.1 | 0.5 | 6.2 | 11.6 | 24.8 | 20.8 | 19.9 | 3.9 | 2.8 |
| 3. cut S | 34.4 | 87.8 | 4.4 | 5.5 | 14.1 | 20.4 | 35.9 | 22.6 | 3.4 | 4.0 |
| Hemp | | | | | | | | | | |
| Anthesis FM | 31.1 | 92.2 | 0.7 | 7.6 | 28.8 | 13.1 | 40.9 | 1.2 | 16.2 | 4.8 |
| Anthesis S | 27.8 | 91.9 | 18.0 | 5.5 | 35.2 | 8.5 | 51.0 | 1.1 | 2.4 | 1.1 |
| Jerusalem artichoke | | | | | | | | | | |
| Haulm FM | 23.4 | 86.9 | 1.0 | 8.4 | 16.8 | 17.1 | 24.8 | 0.6 | 26.3 | 0.9 |
| Haulm S | 26.8 | 91.0 | 3.6 | 4.1 | 29.8 | 9.8 | 35.1 | 1.2 | 18.8 | 1.7 |
| Tuber FM | 23.6 | 86.3 | 0.3 | 6.4 | 19.6 | 13.4 | 4.5 | 0.1 | 51.7 | 0.5 |
| Maize | | | | | | | | | | |
| V1[1] D[2]1 S | 25.1 | 95.0 | 2.0 | 3.7 | 30.1 | 9.9 | 23.2 | 31.1 | 5.9 | 29.8 |
| V1 D2 S | 32.6 | 95.7 | 3.9 | 3.8 | 28.8 | 10.2 | 18.6 | 31.8 | 4.3 | 27.6 |
| V1 D3 S | 32.8 | 96.2 | 4.7 | 3.8 | 29.2 | 9.9 | 21.3 | 29.6 | 3.1 | 29.1 |
| V2 D1 S | 28.8 | 96.2 | 2.5 | 3.7 | 33.0 | 9.1 | 20.3 | 28.1 | 8.7 | 26.1 |
| V2 D2 S | 35.3 | 96.5 | 2.9 | 3.7 | 31.5 | 9.3 | 19.7 | 28.9 | 3.7 | 33.0 |
| V2 D3 S | 34.2 | 96.2 | 3.6 | 3.7 | 32.0 | 9.2 | 19.5 | 32.4 | 3.6 | 34.1 |
| V3 D1 S | 29.2 | 96.0 | 2.8 | 3.7 | 32.2 | 9.3 | 21.8 | 28.1 | 5.3 | 25.1 |
| V3 D2 S | 37.0 | 95.9 | 2.0 | 3.8 | 31.1 | 9.4 | 22.0 | 27.6 | 3.1 | 26.2 |
| V3 D3 S | 37.0 | 95.8 | 2.9 | 3.8 | 33.2 | 8.8 | 21.6 | 23.7 | 2.0 | 29.8 |

1) V = Variety
2) D = Date of harvest

Organic dry matter (ODM) values depicted minor differences between the species. Lower ODM contents were determined for Jerusalem artichoke and alfalfa (87 and 89%, respectively), higher values for hemp (92%) and cereals.
Further parameters characterised alfalfa as a protein-rich species (21 ± 3%) associated with high fat content and hemp as a fibre plant (41%) combined with noticeable sugar content (16%). Highest sugar contents were analysed for Jerusalem artichoke haulm and tuber (26 and 52%, respectively). Barley, rye and triticale were confirmed as starch-rich cereals.

### 3.1.2 Impact of Harvest Time

Several parameters that are relevant for the biogas production process alter significantly during plant growth. Generally, contents of DM and crude fibre as well as C:N-ratio increase while contents of crude protein, crude fat and sugar decline as parameters are interrelated (Table 3). Barley, rye and triticale showed these described trends of parameters except for crude fibre. Second and third cuttings of alfalfa presented regrown biomass harvested at beginning of florescence and therefore the depicted impacts of maturity were not as clear as for cereals. Consequently, not only growth also timing and frequency of harvest plays an important role for anaerobic digestion.

Besides the effect on biomass yield, harvest time determines the amount of digestible compounds. One of the main parameters depending on harvest time is the DM content of plant material. As mentioned above, DM content varied extremely between some samples of the same plant species. In addition to the impact on chemical composition, harvest time also affects storage of the plant material due to the fact that DM content is one of the main influences considered in silage preparation.

### 3.1.3 Impact of Ensiling Process

As presented in Table 3 silage parameters determined (DM, pH, VFA) indicate that whole crop samples were ensiled properly.
The preparation of whole crop silage at dough stage is unviable due to the high DM (46.5-65.5%) and hence, leads to difficulties in the natural ensilage process. Typically silages have pH values of approximately 4-5. Considering that no additives were used in our model silo experiments, in some cases pH values were higher than usual. Generally, legumes have a higher buffering capacity than other crops, so the pH of alfalfa silage is not reduced during ensiling as much as occurred for the other species (Buxton and O'Kiely, 2003). Complex biochemical and microbiological processes during ensiling result in the fermentation of plant sugars to lactic acid and other compounds like acetic acid, propionic acid and butyric acid, indicated by the parameter volatile fatty acids (VFA; Table 3). Most remarkable are the very high VFA values of alfalfa and hemp silages (18-25 g VFA $kg^{-1}$ FM; Table 3). However, the carbohydrate and protein fractions of silages are markedly different from that of fresh material. These differences might influence methane formation process when silages are used as feedstock for digestion.

Selection of maize silages – which were taken from a large-scale bunker silo - (Table 3) represented silage-specific varieties, chosen from a group well adapted for drought tolerance and maturity behaviour. Comparing the silage samples of the three maize varieties the most obvious differences are in the content of DM, VFA (D3), sugar, and starch, to a certain extent modified also by harvest time.

### 3.2 Biogas yields and methane contents

Highest biogas yields were obtained from barley and rye harvested at milk stage with 730-932 $l_N$ biogas $kg^{-1}$ ODM and 618-743 $l_N$ biogas $kg^{-1}$ ODM, respectively (Figure 1). Triticale produced highest yields (733-819 $l_N$ biogas $kg^{-1}$ ODM) harvested at anthesis. Due to a non-representative straw to grain proportion (DM values in Table 3) of the material investigated, this result seems to be misleading. The crops investigated show the lowest biogas values if harvested in dough stage.

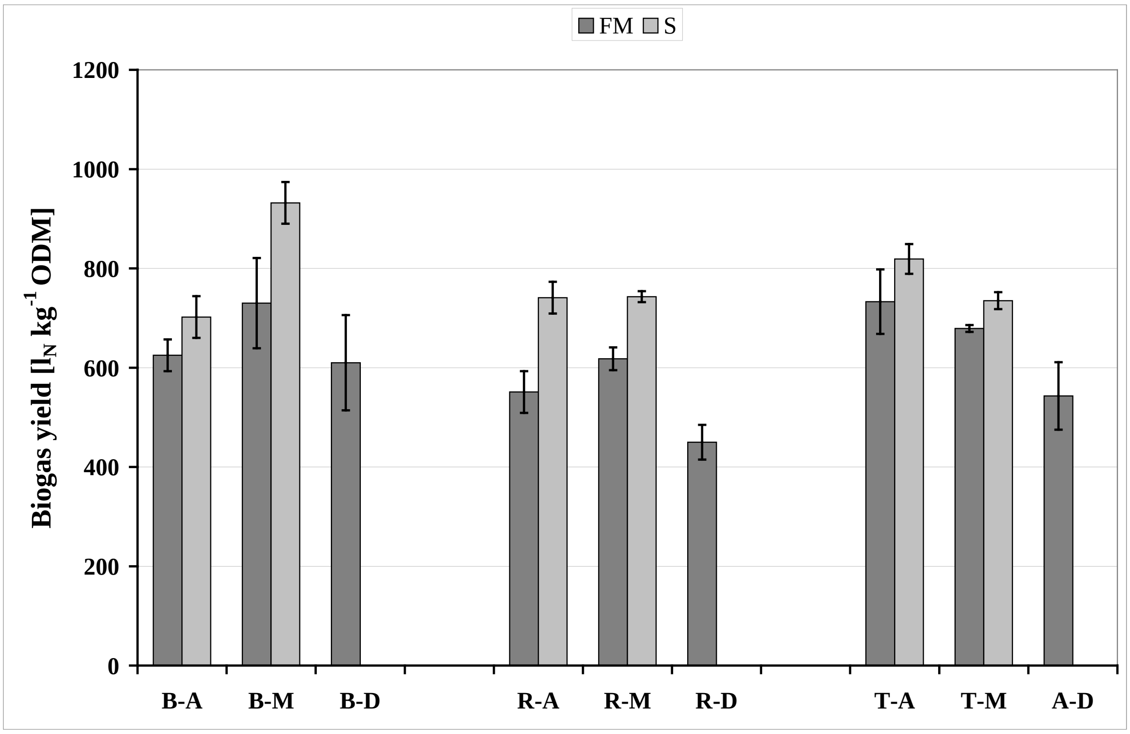


Figure 1: Biogas yields after 28 days in batch anaerobic digestion test. Fresh matter (FM) and silage (S) from barley (B), rye (R), and triticale (T) harvested at anthesis (-A), milk (-M) and dough (-D) stage. In this case error bars don’t indicate standard deviation but the both values measured

Crops harvested in dough stage were not appropriate for ensiling due to low moisture content (34.5-53.5%), hence, biogas yield could not be determined for this material. Generally, ensiled material showed higher biogas values than fresh matter. The mean methane content of biogas ranged from 55 to 62% (Table 4), highest values were obtained for ensiled material.

Table 4. Methane contents determined in batch anaerobic digestion test as a mean of the both values measured after 28 days retention time

| Crop<br>Variant | Methane content [Vol.%]<br>Harvest stage | | |
|---|---|---|---|
| | Anthesis | Milk | Dough |
| Barley FM | 57 | 55 | 56 |
| Barley S | 56 | 59 | - |
| Rye FM | 57 | 58 | 58 |
| Rye S | 59 | 61 | - |
| Triticale FM | 59 | 57 | 56 |
| Triticale S | 61 | 62 | - |
| | 1. cut | 2. cut | 3. cut |
| Alfalfa FM | 54 | 54 | 59 |
| Alfalfa S | 57 | 59 | 59 |
| Hemp Anthesis FM | 53 | - | - |
| Hemp Anthesis S | 57 | - | - |
| Jerusalem artichoke - haulm FM | 52 | - | - |
| Jerusalem artichoke - haulm S | 53 | - | - |
| Jerusalem artichoke - tuber FM | 54 | - | - |
| | D1 | D2 | D3 |
| Maize V1 S | 57 | 56 | 55 |
| Maize V2 S | 58 | 57 | 55 |
| Maize V3 S | 57 | 56 | 54 |

Alfalfa (Figure 2) was digested as fresh matter and formed 777 to 516 $l_N$ biogas $kg^{-1}$ ODM. There was no trend observable for selected cutting dates. The biogas yields from silages of alfalfa showed a similar range (735-507 $l_N$ biogas $kg^{-1}$ ODM). Minor differences were analysed for methane content with 54-59% (Table 4). Variation in biogas yields might be due to varying plant matter quality. Alfalfa is known for changing the leaf/stem ratio from 1.5 to 0.5 during growing season caused by several factors (e.g. moisture conditions) and hence, reduction of forage quality (Albrecht and Beauchemin, 2003).

Hemp (Figure 3) produced higher yields of biogas (567 $l_N$ biogas $kg^{-1}$ ODM) as fresh material than as ensiled material (453 $l_N$ biogas/kg ODM), whereas for the methane content higher values were obtained for ensiled material (57%) than for fresh matter (53%) (Table 4). Biogas yields of Jerusalem artichoke (Figure 3) showed a clear dependence on the energy content of the plant parts investigated. The tuber, which contains the polysaccharose inulin, produced the 1.5 fold biogas yield (700 $l_N$ biogas $kg^{-1}$ ODM) than the haulm. Tuber reaches similar methane values like haulm (52 and 54%, respectively) (Table 4).

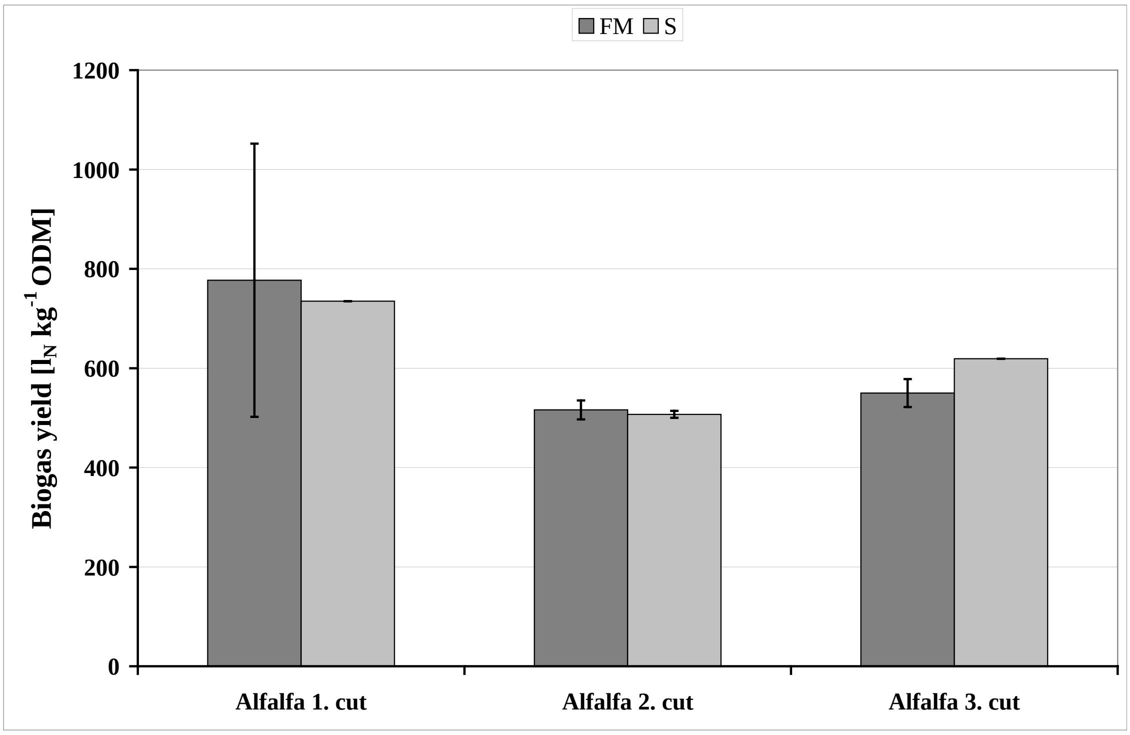


Figure 2: Biogas yields after 28 days in batch anaerobic digestion test. Fresh matter (FM) and silage (S) from alfalfa at three cuts at beginning florescence. In this case error bars don't indicate standard deviation but the both values measured

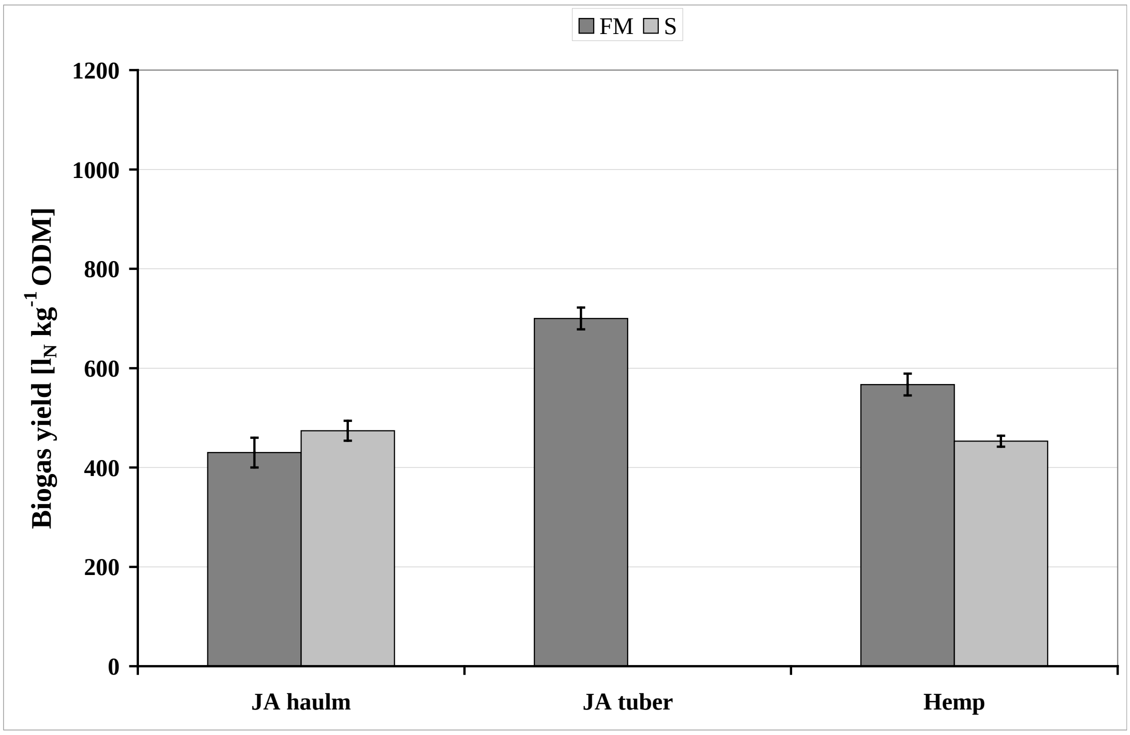


Figure 3: Biogas yields after 28 days in batch anaerobic digestion test. Fresh matter (FM) and silage (S) from hemp and Jerusalem artichoke. In this case error bars don't indicate standard deviation but the both values measured

The biogas yields from the maize varieties investigated showed only minor differences in quantity (Figure 4). The variety 1 (medium-early) produced relatively more biogas with values of 825-1048 $l_N$ biogas $kg^{-1}$ ODM, than variety 2 (medium-early) and variety 3 which produced similar values in a lower range of 826-970 and 831-950 $l_N$ biogas $kg^{-1}$ ODM, respectively. Regarding the final harvest date (D3) the maize silages investigated showed a clear effect of variety on biogas production. This is due to the fact that within one variety biogas yields are determined by the variety-specific differences in harvest period in which the DM content is within the appropriate range for ensiling as well as the final date of starch incorporation. Gas quality remains between 54 and 58% methane with decreasing values regarding harvest date: D1 > D2 > D3 (Table 4).

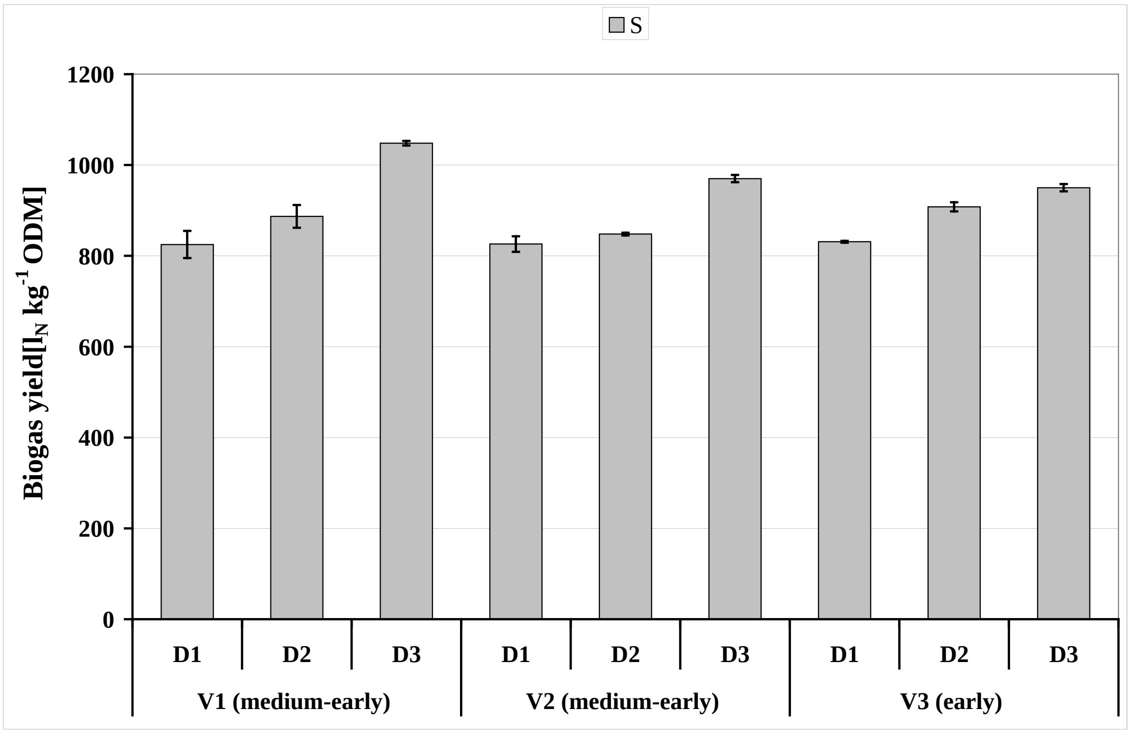


Figure 4: Biogas yields after 28 days in batch anaerobic digestion test. Silages (S) from different maize varieties (V1, V2, V3) at three harvesting dates (D1, D2, D3). In this case error bars don't indicate standard deviation but the both values measured

## 3.3 Digestate

Generally, the organic residue left from anaerobic digestion is made up of recalcitrant plant residues and microbial biomass and metabolites formed during anaerobic digestion. Table 5 summarises measurements of DM and ODM content as an indicator of degradability of plant matter as well as the parameters VFA and pH as process state indicators. Samples of the digested output showed an increased pH (7.7-8.0) compared to initial plant matter samples (FM 6.2-7.6; S 3.7-5.8), and almost no differences between output and inoculum used (7.9-8.3) (cf. Table 1, Table 3, Table 5). Due to the high buffering capacity of slurry the pH was not mainly influenced by adding acidic silages. Usually, an almost constant pH value is necessary to provide optimum conditions for the balanced growth of bacteria. The concentration of VFA is an important parameter as this can be the first indicator that digestion is not progressing normally. Usually, VFA are present in feedstock, especially in silages or produced during anaerobic digestion process as intermediate products e.g. acetate and propionate. But high concentrations of VFA have an inhibitory effect on the hydrolysis process and thus on the production of biogas. Data presented in Table 5 confirm good process conditions: The very high VFA concentrations in alfalfa and hemp silages (18-25 g VFA $kg^{-1}$ FM; Table 3) degraded to normal concentrations within the range of 1.3-2.5 g VFA $kg^{-1}$ FM.

Table 5. Characterisation of digested output (day 28) from crops applied as dry matter (DM), organic dry matter (ODM), volatile fatty acids (VFA), and pH

| Crop | DM [% FM] | ODM [% DM] | VFA [g/kg FM] | pH [-] |
|---|---|---|---|---|
| Barley | | | | |
| Anthesis FM | 3.6 | 54.8 | 1.7 | 7.8 |
| Anthesis S | 2.6 | 47.0 | 2.5 | 7.8 |
| Milk FM | 3.8 | 56.1 | 1.5 | 7.8 |
| Milk S | 2.2 | 45.0 | 2.1 | 7.8 |
| Dough FM | 3.3 | 52.6 | 1.9 | 7.8 |
| Rye | | | | |
| Anthesis FM | 3.6 | 55.5 | 1.7 | 7.7 |
| Anthesis S | 2.3 | 45.9 | 2.2 | 7.7 |
| Milk FM | 3.4 | 55.4 | 1.7 | 7.8 |
| Milk S | 2.1 | 41.5 | 2.2 | 7.7 |
| Dough FM | 3.0 | 53.6 | 1.7 | 7.7 |
| Triticale | | | | |
| Anthesis FM | 3.5 | 56.0 | 1.7 | 7.8 |
| Anthesis S | 2.0 | 44.8 | 2.2 | 7.8 |
| Milk FM | 3.5 | 55.1 | 1.4 | 7.8 |
| Milk S | 2.9 | 53.6 | 2.5 | 7.8 |
| Dough FM | 4.2 | 59.9 | 1.5 | 7.7 |
| Alfalfa | | | | |
| 1. cut FM | 3.1 | 49.0 | 1.8 | 7.9 |
| 1. cut S | 3.3 | 49.5 | 2.1 | 8.0 |
| 2. cut FM | 3.0 | 50.0 | 1.8 | 7.9 |
| 2. cut S | 2.9 | 49.2 | 1.8 | 8.0 |
| 3. cut FM | 3.4 | 51.7 | 1.9 | 7.9 |
| 3. cut S | 3.4 | 51.1 | 1.6 | 7.9 |
| Hemp | | | | |
| Anthesis FM | 3.7 | 52.2 | 1.3 | 7.8 |
| Anthesis S | 3.6 | 52.7 | 1.6 | 7.8 |
| Jerusalem artichoke | | | | |
| Haulm FM | 3.8 | 52.0 | 1.5 | 7.8 |
| Haulm S | 3.6 | 52.2 | 1.3 | 7.8 |
| Tuber FM | 3.2 | 48.6 | 2.1 | 8.0 |
| Maize | | | | |
| V1[1)] D[2)]1 S | 2.8 | 53.6 | 2.3 | 7.8 |
| V1 D2 S | 2.8 | 54.0 | 2.2 | 7.8 |
| V1 D3 S | 2.3 | 48.1 | 2.4 | 7.8 |
| V2 D1 S | 2.2 | 49.1 | 2.5 | 7.7 |
| V2 D2 S | 2.8 | 53.5 | 2.5 | 7.8 |
| V2 D3 S | 2.9 | 54.8 | 2.2 | 7.7 |
| V3 D1 S | 2.4 | 49.2 | 2.3 | 7.8 |
| V3 D2 S | 2.3 | 49.0 | 2.4 | 7.7 |
| V3 D3 S | 2.9 | 55.3 | 2.3 | 7.8 |

Biomethanation of plant materials resulted in a clear decrease of DM and ODM content. Measurements of digested output revealed that feedstock was reduced to 5-19% of initial DM content (18.8-65.5% DM; Table 3). The ODM content in final samples (45-56% ODM) showed a reduction of about 39-55% in comparison to feedstock (87-96% ODM). Regarding the reduction of ODM in correlation to chemical composition and biogas yield there is a clear coherence of data for cereals investigated. Maize records show a limited correlation between harvest date and biogas yield. But there is no relationship among ODM reduction and biogas yield which is confirmed by data of Jerusalem artichoke and hemp, too. Despite time-dependent variable chemical characteristics of alfalfa plant matter no correlation between biogas yield and ODM reduction exists. Results suggest that the ensiling process has a much larger influence on ODM degradability and hence, on biogas yield than the aspects previously mentioned. This is most notable for barley, rye and triticale (Figure 5). The degradation of ODM in ensiled matter is at least 10% higher than in fresh matter. (Neureiter *et al.*, 2005) explained this aspect as follows: "[…] the biochemical processes during ensiling include hydrolysis and acidification. The microbial degradation of crop compounds may lead to a faster conversion or to a better availability of recalcitrant compounds during the anaerobic digestion process so that ensiling can be regarded as a pre-treatment method."

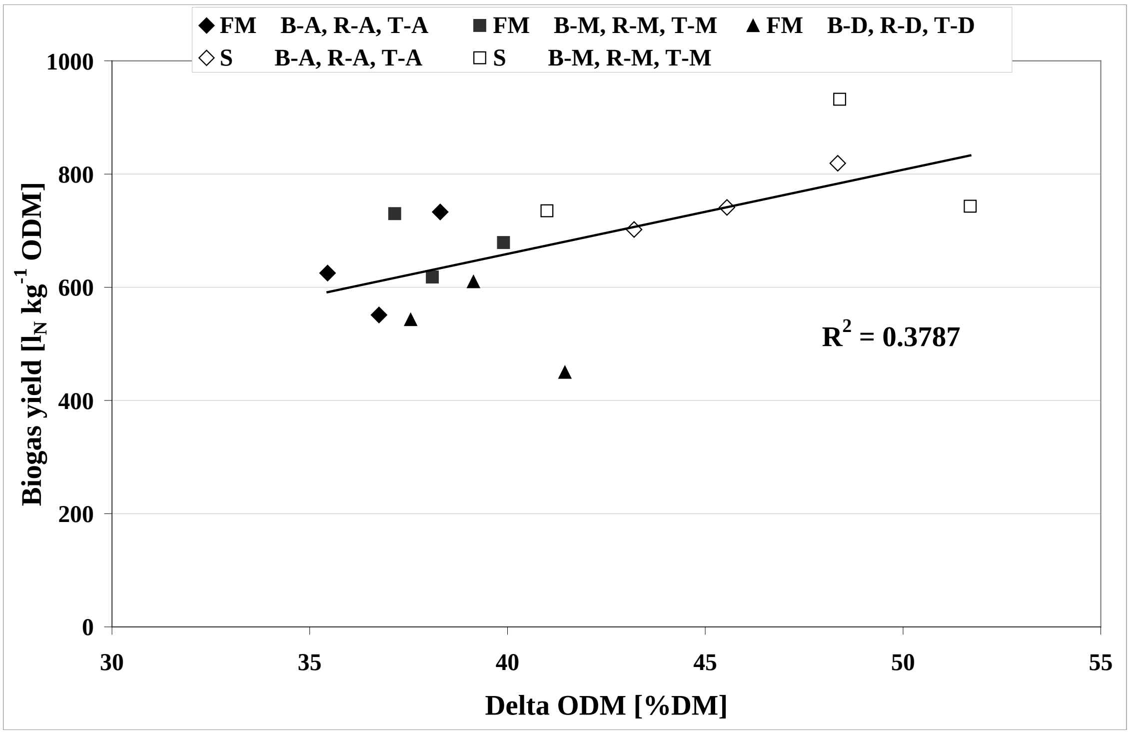


Figure 5: Biogas yield after 28 days related to reduction of organic dry matter (expressed as Delta ODM) from barley (B) , rye (R) and triticale (T) at anthesis (-A) milk (-M), dough (-D) as fresh matter (FM) and silage (S) during batch anaerobic digestion test under mesophilic conditions

### 3.3 Suitability

There are significant differences in the methane potentials of the potential biogas crops investigated. Table 6 gives an overview of methane yields calculated on the basis of biogas yields and methane contents determined in the batch anaerobic digestion tests. All species are suitable for practical use in biogas plants although results confirm the considerable influences of harvesting time, variety, and ensiling on methane yield (220-581 $l_N$ biogas $kg^{-1}$ ODM). Cereals and maize support the assumption that harvesting time and hence, composition of constituents can optimise biogas production and methane formation, respectively. Further potential remains in the appropriate selection of variety, cf. maize samples. From livestock production it is already known that the digestibility of starch in maize silage is affected by maturity at harvest and hybrid genetics (Allen *et al.*, 2003). With regard to crop diversification alfalfa and the less common agricultural species hemp and Jerusalem artichoke show potential as alternative biogas crops. Both the economic and ecological compatibility have to be proven in further research.

Table 6. Methane yields determined in batch anaerobic digestion test under mesophilic conditions (28 days)

| Crop | Methane yield [$l_N$ $kg^{-1}$ ODM] | | |
|---|---|---|---|
| | Anthesis | Milk | Dough |
| Barley FM | 358 | 395 | 337 |
| Barley S | 395 | 552 | - |
| Rye FM | 316 | 356 | 262 |
| Rye S | 440 | 456 | - |
| Triticale FM | 435 | 388 | 305 |
| Triticale S | 504 | 467 | - |
| | 1. cut | 2. cut | 3. cut |
| Alfalfa FM | 464 | 275 | 324 |
| Alfalfa S | 415 | 297 | 374 |
| Hemp Anthesis FM | 301 | - | - |
| Hemp Anthesis S | 259 | - | - |
| Jerusalem artichoke - haulm FM | 220 | - | - |
| Jerusalem artichoke - haulm S | 252 | - | - |
| Jerusalem artichoke - tuber FM | 374 | - | - |
| | D1 | D2 | D3 |
| Maize V1 S | 471 | 500 | 581 |
| Maize V2 S | 477 | 480 | 531 |
| Maize V3 S | 468 | 495 | 538 |

In order to supply biogas crops over the entire year it is necessary to preserve the material. In our experiments, ensiling showed a positive effect on anaerobic digestion, hemp being the only exception. Studies reviewed in (Lehtomäki, 2006) confirm that crops preserved as silages resulted in higher methane yields than the fresh matter. Hence, storage as silages can be considered as pre-treatment which also has potential to

improve methane production from plant matter (Lehtomäki, 2006; Neureiter et. al, 2005).
It is obvious that ensiling without application of additives produces less quality silages. Nevertheless, the quality was sufficient for batch experiments but may also be responsible for the large dispersal of results (Mähnert *et al.*, 2002). Ensiling quality might also be a reason for the low methane yield of hemp silage.

## 4. CONCLUSIONS

Among farmers and researchers there is an increasing interest in alternative suitable crops for bioenergy production. As presented here, numerous crops are available for biogas production. Not only genetic characteristics which can be modulated by soil and climate conditions but also technical factors and management practise have a considerable influence on biomass and gas yield potentials. Since methane yield is influenced by the harvest time cropping systems as well as crop rotations are affected and have to be adjusted. Furthermore, harvest time plays a major role with regard to silage quality and maximum methane yield per unit ODM. An increase in dry matter content of the crop decreases its ensiling ability. Therefore, farmers have to achieve the best possible compromise between crop yield (dry matter production) and crop quality (digestibility).
The selection of the appropriate plant species as feedstock for biogas production is an important aspect in decision-making. Along the entire production chain (cultivation, harvest, storage and biogas production) additional factors offer a big potential for improving the efficiency of anaerobic digestion in agricultural biogas plants. Generally, the conversion of biomass to energy should be economically efficient and optimise the environmental benefits. Biogas crops should have characteristics like high yields and low production inputs. Data generated in this study will be used as basis for a thorough ecological assessment of the provision of energy crops as feedstock in agricultural biogas plants in Brandenburg State (Plöchl *et al.*, 2009).

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