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Optimal storage systems for energy crops for various climatic conditions

1 Introduction

In most EU countries energy crops for biogas production can be harvested for a limited time only, mainly from 4 to 9 months during the year. On the other hand, in many countries the consumption and the price of energy produced from biogas varies according to the season, both typically being higher in winter than in summer. Therefore storage is necessary to guarantee the supply for the continuous and economical operation of a biogas plant. In practice, the need for storage can range from few days up to one year.

The way crops can be stored is dependent on e.g. the crop type, time of harvesting, type of biogas production process, local climatic conditions, traditional storage methods, as well as existing structures and machinery in the biogas plant or/and in the farm.

Energy crops for biogas reactors are usually harvested at an earlier stage of growth as the content of lignocellulose, which is hard to degrade by anaerobic processes, rises with time. The dry matter content of typical crops like whole crop cereals, grasses, legumes etc. varies typically between 15 and 40%. Some crops are allowed to dry overnight after cutting, while crops can be taken also directly to storage. In general, moist plant material is favoured as substrate for conventional biogas reactors, e.g. drying is not wanted.

While crops are increasingly being digested in high solids (feed total solids (TS) above ca. 15 %) reactors, still the most common way is to digest crops e.g. together with manure or other substrates, in continuously stirred tank reactors (CSTR) with low dry solids concentrations (max. feed TS 5–10 %).

The storage system for biogas crops should minimise energy losses as well as losses of nutrients and also emissions should be controlled. Ideally, the storage system should act rather as a pre-treatment system to enhance methane yields and methane production rate of the crops.

Crops can be stored using methods that are common in the storage of food and feed products:

- Drying: Since drying of moist plant material requires energy, this method is only recommended for materials that initially have a high dry matter content after harvest (like cereal grains, straw, reed, miscanthus, etc.). Except cereal grains such crops are usually strongly lignified and therefore not the optimal substrate for anaerobic digestion. It should be noted that the moisture content of high solids material has to be elevated by addition of liquid during feeding when common digester types are used.

- Ensiling: Ensiling is a traditional way of preserving fodder crops and it is also applicable to energy crops that are used for biogas production. Ensiling is a biological process during which lactic acid bacteria break down the sugars and lower pH to a level that is inhibitory to other bacteria (McDonald et al. 1991). Silage preparation involves storage of compressed plant material in anaerobic conditions and is a common method for preserving crops for animal feed. Lactic acid bacteria convert

soluble sugars into lactic acid, thus causing a decline in pH. The product is stabilised by the anaerobic conditions (which prevent the growth of aerobic spoilage organisms like yeast and moulds) and low pH (preventing the growth of anaerobic spoilage organisms like Clostridium ssp.). Dry matter contents between 30 and 40% are recommended to achieve optimal results (McDonald et al., 1991). Therefore ensiling appears to be a good method to store energy crops for anaerobic digestion and is widely used in practice.

- Addition of preservatives: The addition of chemicals or bioproducts in order to prevent the growth of micro-organisms should be considered with caution. Since anaerobic digestion is a microbial process, inhibition of the digester biology is probable. On the other hand, different kinds of additives may promote the ensiling process. Addition of acid lowers the pH, but acids also cause some problems like corrosion. Enzymes have also been used to increase the sugar content of the crop, thus increasing the amount of food for lactic acid bacteria. Lactic acid bacteria inoculums can also be used to increase the amount of these bacteria (McDonald et al. 1991). Some authors suggest the use of inoculums containing both enzymes and lactic acid bacteria (Lehtomäki et al.). Enzymes may also further improve the digestibility of organic matter (McDonald et al. 1991)

1.1 Ensiling of energy crops

In principle, for ensiling of energy crops the same rules should be applied as are used for storage of animal feed. Crops are commonly stored in silos and in bales covered with plastics. The plant material is typically chopped (usually during harvesting) and compressed. In Austria, average biogas plants with an electricity production of 500 kW require 9 000 to 10 000 t of silage (fresh matter) per year, corresponding to approximately 25 t per day.

The effects of TS concentration (i.e. of the moisture content of the crop) on the ensiling process have previously been studied with fodder crops. For fodder crops an initial TSconcentration of 30-40 % is preferred. If the silage is too wet, baling might be difficult and even impossible due to leachate formation. Bales might lose their form and shape and silage is susceptible to spoiling. If the pre-wilting period is too long, respiration causes energy losses and the sugar content of the crop decreases. Dry bales are also susceptible to moulding (Buxton & O´Kiely 2003). When the crops are used for energy production, ensiling conditions do not necessarily have to be as tightly controlled as for fodder crops.

The major problems in storage of energy crops for biogas production are similar to those in storage of animal feed; however, there are differences in the size of the silos, the daily feed, and the final use of the material, which need to be considered. The main issues in silos are:

- Anaerobic spoilage

  Anaerobic spoilage is caused by anaerobic bacteria (*Enterobacteriaceae* and mainly *Clostridium* ssp.). Those microorganisms form gaseous metabolites and therefore cause losses in dry matter, which are, however, much lower than those during aerobic

spoilage. Usually these microorganisms can only develop when the plant material is very moist (<30% dry matter) or has a high buffering capacity. The biochemical reactions during anaerobic spoilage of silage correspond to the reactions that take place during the hydrolysis and acidogenisis steps in anaerobic digestion, and there are indications that such silages may lead to higher methane yields despite the losses (Neureiter et al., 2005). Problems for anaerobic digestion plants may also arise from odour emissions caused by the microbial metabolites like butyric acid.

- Silage effluents

  According to the literature, silage effluents are a minor problem with crops like maize (Haigh, 1999). If moist plants (e.g. grass) are ensiled, considerable amounts of liquid with a high organic content (COD 100-200 g/l) can be emitted. If these effluents are not collected, they cause emissions into the environment, also odour emissions are possible. Silage effluents contain dissolved substances that can be used for the generation of biogas. Therefore effluents should be collected and fed into the biogas reactor in any case.

- Aerobic spoilage

  Aerobic spoilage of silage can occur as soon as the silage is not covered properly, which is usually during feeding. It is caused by the growth of yeasts and moulds, which metabolise the substrate to CO_2 and H_2O. The losses in dry matter (and therefore in energy) are considerable and have been estimated at 10% and more (McDonalds et al., 1991). However, the degree of aerobic spoilage is very much dependent on the composition of the silage (Danner et al., 2003), and the time of exposure to air. Silage additives that can improve the aerobic stability of silages are available and successfully used in animal feeding, where health issues are also important. It is unclear whether the reduction of losses in overall methane yields can compensate for the cost of such products (ca. € 2 per t fresh matter).

- Handling/coverage

  As has been made clear above, airtight coverage is essential in order to reduce losses during storage. This implies additional working time and material costs for the operator, however, which also contributes to the overall costs. For that reason some plant operators prefer to use a coverage that can be fed into the biogas reactor, like growing grass or cereals on top of the silage, or using solid digestate as coverage. Such coverages do not provide the exclusion of air and therefore aerobic spoilage may be higher; however, there is no cost for plastic sheeting and no additional handling is required.

2 Objectives

In this work we studied two different types of storage systems for crops. First, an experiment was designed to estimate the actual losses during the ensiling process in a full-scale bunker silo at a biogas plant in Austria. Furthermore different coverages (conventional plastic sheet and solid digestate) were evaluated. In order to confirm the results of the mass balance, chemical and microbiological analyses were performed. Secondly, the effects of storage of two common grasses/grass mixtures (timothy-clover

and ryegrass) in round bales on their chemical characteristics and methane production potential were evaluated in Finland. Also the effect of biological additives containing both enzymes and lactic acid bacteria was studied in field conditions.

3 Material and Methods

3.1 Storage in silos

The silo in Austria is located at a full-scale biogas plant. The substrate was whole crop maize. For operational reasons it was not possible to use the silage continuously. Therefore defined sectors were marked (Picture 1), from where the material was fed into the plant exclusively during a certain period of time. Within three weeks approximately 700 m^3 of silage were used. With a bulk height of 2.5 m this correlates a length of 19.30 m in the silo. The height and profile should be as uniform as possible.

Picture 1: Marking the sectors in the silo

The mass of the chaffed maize plants were recorded by a weighbridge after harvesting and it was exactly registered which loads were delivered into the selected silo. Samples were taken in order to determine TS and total VS of the original material. The volume of the silo is determined with a laser theodolite and since the volume and the mass are known, the bulk density of the silage can be calculated. The mass of fresh material in the marked sectors can be estimated using the bulk density. When the silage is taken from the silo after storage, mass is determined during the delivery into the biogas plant. In order to get exact measurements it is important to use the material from the marked sectors in a continuous period of time, without the use of co-substrate. The difference between the mass of the ensiled material after harvest and after storage can be used to calculate the mass balance. Three sectors were covered with conventional plastic sheets, while another three sectors were covered with solid digestate. Therefore a comparison between the different methods of covering was possible. Furthermore the partition in different sectors (three per coverage treatment) enables us to calculate the variation within a different treatment. Figure 1 shows how the silo was divided into different sections.

Picture 2: Silo covered with solid digestate and plastic sheet.

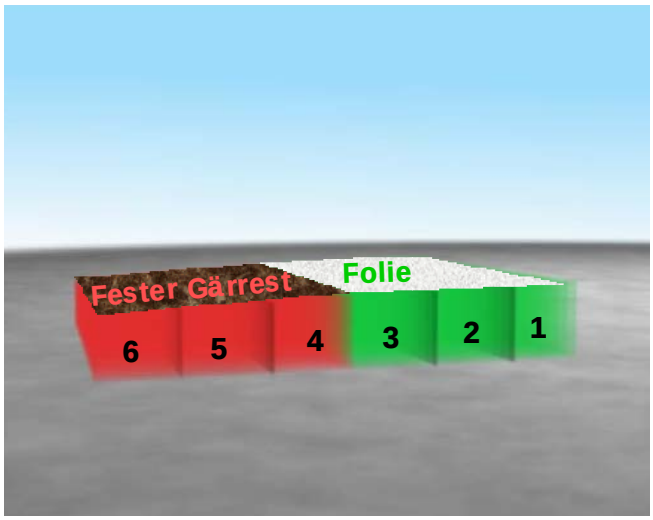

Figure 1: Division of the silo into sections. The sections covered with plastic sheet are marked in green, while the sections covered with solid digestate are marked red.

Samples were taken at least once a month from the front of the silo after removal of the material first layer (Picture 3). Before sampling approximately 0.5 to 1 m of the front layer was removed in order to obtain fresh material. Samples were taken from several defined points (Table1) in the silo in order to get a profile. In addition the temperature at the sampling spot was recorded. 2-3 kg of sample were packed in vacuum sealed plastic bags for transportation. Microbial analysis was performed on the day of sampling, for chemical analysis samples were stored at –20°C.

Picture 3: Sampling the silo

Table 1: Sampling points in the silo

Layer	**Sampling point**
layer 1	30 cm from bottom, middle of silo
layer 2	170 cm from bottom, middle of silo
layer 3	50 cm from top, middle of silo
layer 4	5-10 cm from top, middle of silo
layer 5	Digestate coverage if applied
layer 6	30 cm from top, 20 cm from side wall
layer 7	thin layer between cover and silage in digestate covered samples

3.2 Storage in bales

Substrates used were grass mixture of timothy and clover (harvested in June) and ryegrass (harvested in August). Inoculum was obtained from a farm-scale digester treating cow manure.

Grass mixture was baled in plastic-covered round bales immediately or after 24 h pre-wilting in field. Biological ensiling additive (Josilac, manufacturer Josera Erbacher

GmbH & Co) containing both lactic acid bacteria (*Lactobacillus plantarum* and *Pediococcus acidlactiti*, total amount $1.5*10^{11}$ cfu/g Josilac) and enzymes (cellulase, pectinase and xylanase) was added in some (6) of the pre-wilted bales (19 g/t_{ww}). Rye grass was also baled in plastic covered round bales after 24 h pre-wilting. Josilac was added in some (3) of the pre-wilted bales (24 g/t_{ww}). Bales were weighted at the beginning and at the end of the storage trials.

Picture 4. Crops stored in bales in field conditions.

3.3 Analysis

In experiments in Finland, TS and VS were analysed according to the Standard Methods (APHA 1998). pH was measured with a Metrohm 774 pH-meter. Chemical oxygen demand (COD) was analysed according to the SFS 5504 (Finnish Standards Association 1988). Soluble COD (SCOD) from the fresh and stored crops was analysed according to modified SFS-EN 12457-4 (Finnish Standards Association 2002). Ammonium and total nitrogen were determined according to the Kjeldahl method.

Methane content was analysed with Perkin Elmer Arnel Clarus 500 gas chromatograph equipped with FID and Perkin Elmer Alumina column (30 m*0.53 mm). Argon was used as carrier gas and the temperature of the oven, detector and injector were 100 ºC, 225 ºC and 250 ºC, respectively. Amount of biogas was analysed with water displacement method. Sugars, organic acids and alcohols were analysed with HPLC after extraction with a stomacher.

For microbiological analysis (Austria) the cfu counts of lactic acid bacteria and yeasts and moulds were determined. Lactic acid bacteria were cultivated on MRS-Agar (Oxoid) at 35°C, while yeast and moulds were grown on YGC Agar (VWR) at 30°C. The microorganisms were extracted from the silage using a stomacher (IUL Instruments Masticator Silver Nr. 0420/0520). For the extraction 30 g of sample and 270 g of sterile

NaCl solution (9%) were weighed into a double chamber filter bag. The mixture was extracted for 120 sec at 6 beats per min in the stomacher. The extract was the diluted for the determination of cfus.

Methane production potential was studied in batch experiments in triplicate 1 L glass bottles. 250 mL of inoculum was added in every bottle and subsequent amount of crop to give VS-ratio of 1:1 (In laboratory conditions stored crops VS-ratio of 0.5:1 was used). Bottles were filled to liquid volume of 750 ml with distilled water and 3g/L NaHCO3 was added as buffer. Bottles were flushed with nitrogen to remove oxygen from the headspace. Bottles were closed with silicon rubber caps and biogas was collected into aluminium gas bags.

4 Results and Discussion

4.1 Storage in silos

Table 2 shows the changes in mass for each of the marked sectors in silos. The total mass of whole crop maize was recorded during ensiling of the fresh material after harvest. The mass in the sections was calculated from the volume of each sector and the density of the ensiled material. Output weight was recorded when material was taken from the silo and put into the biogas reactor. For the calculation of losses in TS and for single compounds the measured values for the different sample layers were weighted.

Table 2: Mass differences between ensiling and feeding of the silo.

Sections	Volume [m^3]	Initial weight [t]	Output weight [t]	Losses [%]	FM Initial [t]	TS Output [t]	TS Losses [%]	TS
1	245.05	229.51	202.25	12	67.48	55.44	18	
2	234.99	220.09	198.99	10	64.71	55.86	14	
3	233.36	218.55	229.43	-5	64.25	63.30	1	
4	231.87	217.16	209.59	3	63.85	53.97	15	
5	229.14	214.60	176.63	23	63.09	47.78	24	
6	395.26	370.19	362.06	2	108.84	97.39	11	
plastic cover		668.1	630.7	5.49	196.4	174.6	11.00	
digestate		802.0	748.3	9.53	235.8	199.1	16.75	
Total		**3124.3**	**2757.9**		**864.4**	**747.2**		

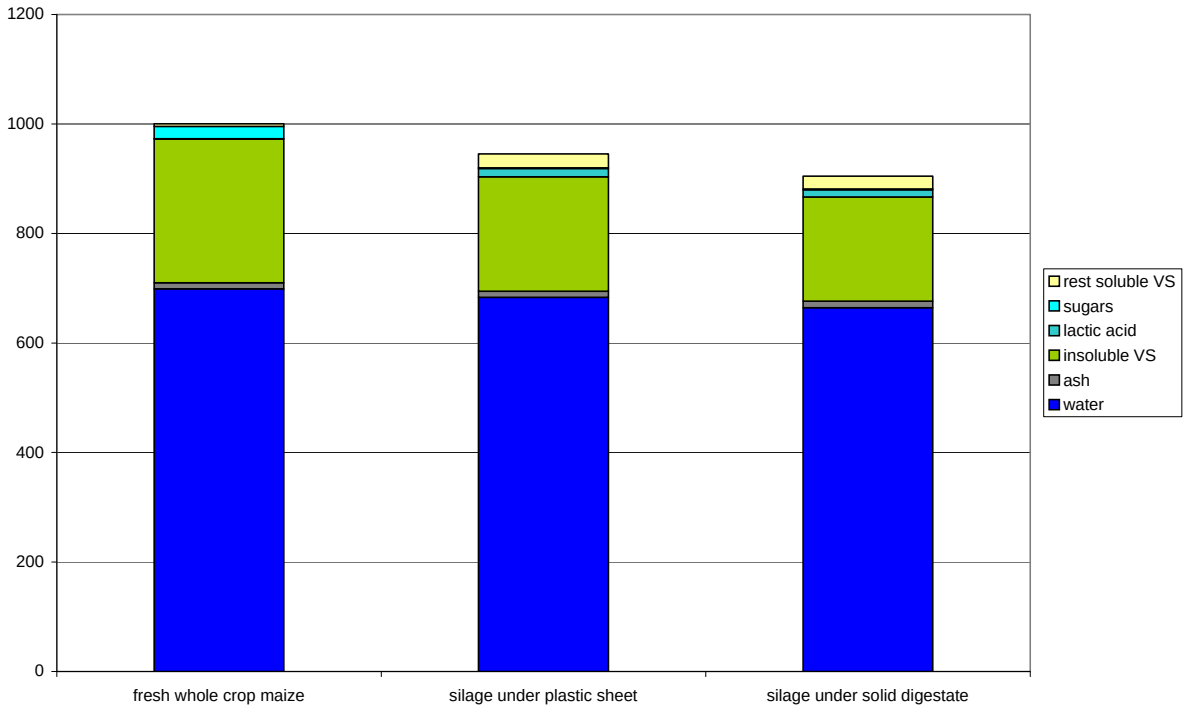

Figure 2: Changes in composition of whole crop maize after ensiling under coverage with plastic sheet or digestate, respectively. The values are based on 1 000 kg of fresh material and include the losses during the ensiling process.

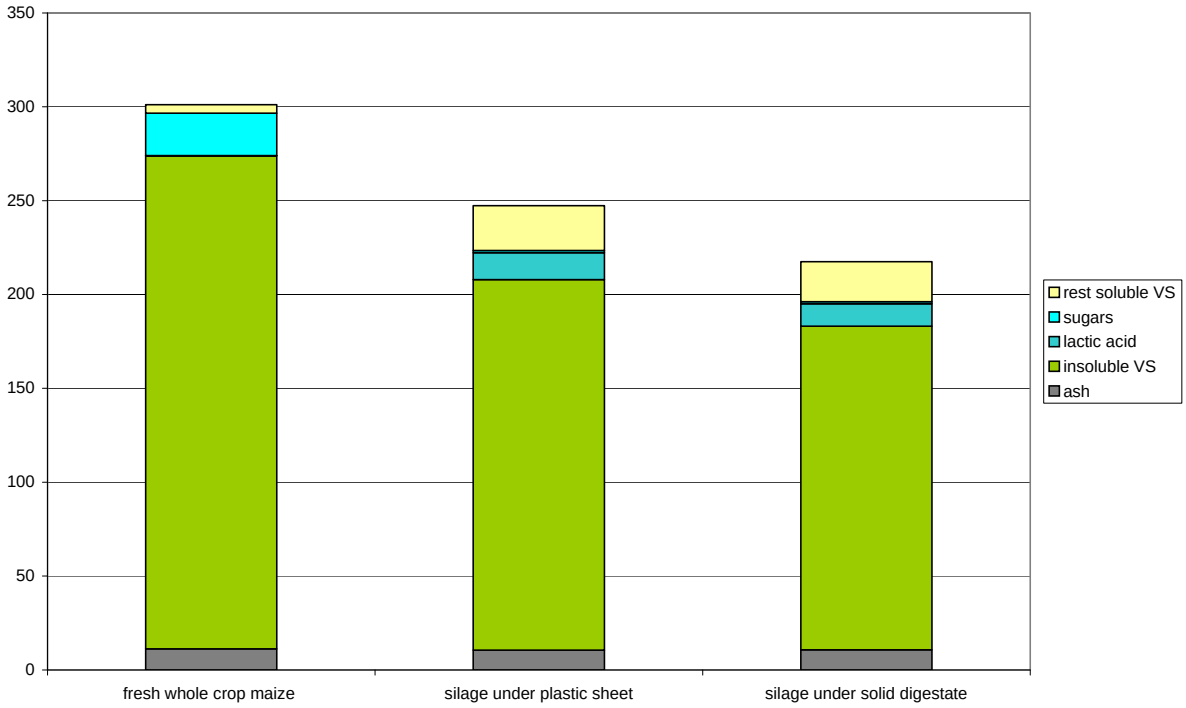

Figure 3: Changes in composition of the solids fraction in detail. The values are based on 1 000 kg of fresh material and include the losses during the ensiling process.

Figure 2 gives an overview of the changes during ensiling under plastic sheeting and under solid digestate compared to the fresh material. Since the solids fraction is of particular interest, the changes are depicted in more detail in Figure 3. It is evident that the ensiling process leads to losses irrespective of the type of coverage. In average losses in dry matter amount to 11% in the sections covered with plastic sheet and to 17% in the sections covered with solid digestate. Remarkably there are only small changes in the soluble fraction. As expected the sugars are converted to lactic acid, however, there are no losses in the soluble fraction and only small changes in the ash. Therefore, it is not very probable that substances were washed out of the silo during rainfall because one would expect the most prominent changes in these fractions. The highest changes appear to be in the fraction labelled as "insoluble VS", which refers to the substances in the VS, which could not be determined by HPLC after extraction with water. In theory this fraction should be composed of starch, cellulose, hemicellulose and lignin. It remains unclear which compound has been actually lost.

A detailed analysis of the different sampling points yielded different patterns of losses depending on the position of the sample in the silo. In the layers close to the surface (layer 4 and layer 3 on top and layer 6 on the margin of the silo) soluble substances like lactic acid or ethanol were degraded. In these layers a higher activity of yeasts and moulds could be observed (data not shown), therefore these compounds have probably been degraded due to the activity of aerobic microorganisms. It could be shown as well that the solid digestate contains a high number of yeasts and moulds, which were probably infiltrating the top layers. To give an example, the time courses of the layers for lactic acid (Figure 4) and ethanol (Figure 5) are shown below. Ethanol in silage can be formed either by heterofermentative lactic acid bacteria or by yeasts. Figure 6 depicts the ethanol concentrations in the different layers with respect to the coverage of the silo. In this case it also becomes evident that there is a significantly larger reduction in ethanol in

the top layers when the silo is covered with digestate instead of plastic sheet. However, the highest reduction in lactic acid and ethanol took place at the side margin of the silo (layer 6), irrespective of the coverage.

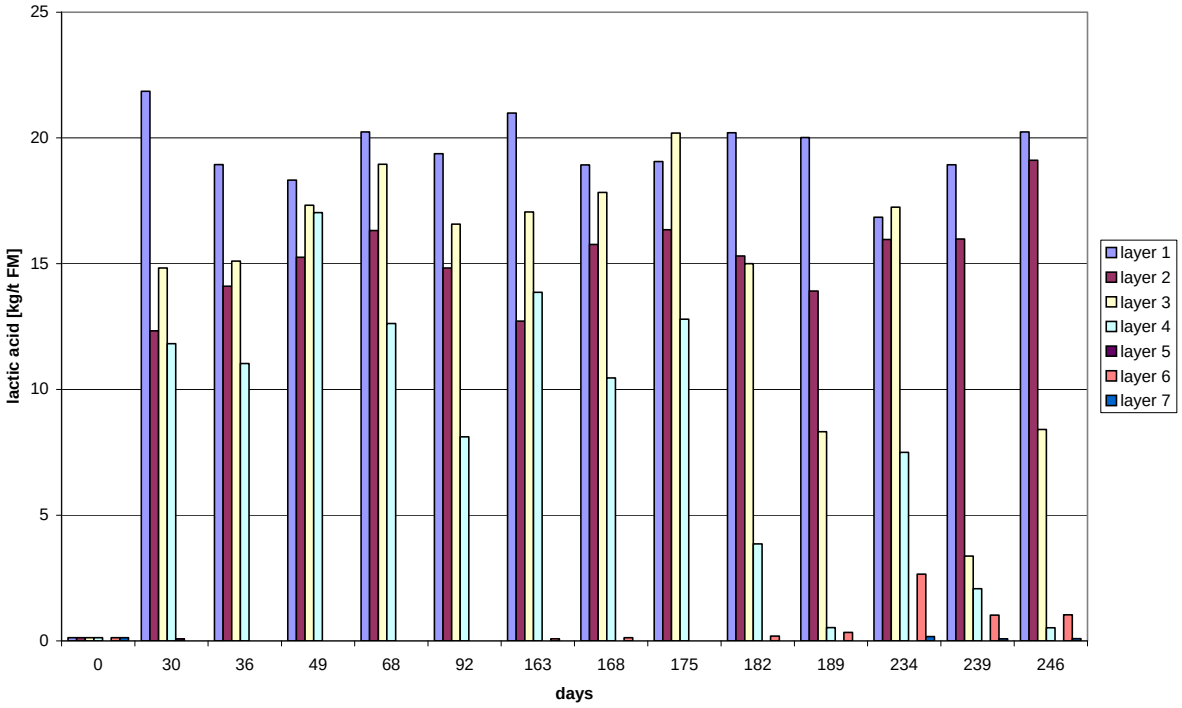

Figure 4: Time course of lactic acid concentration [kg/t FM] in the different sampling layers over the ensiling period.

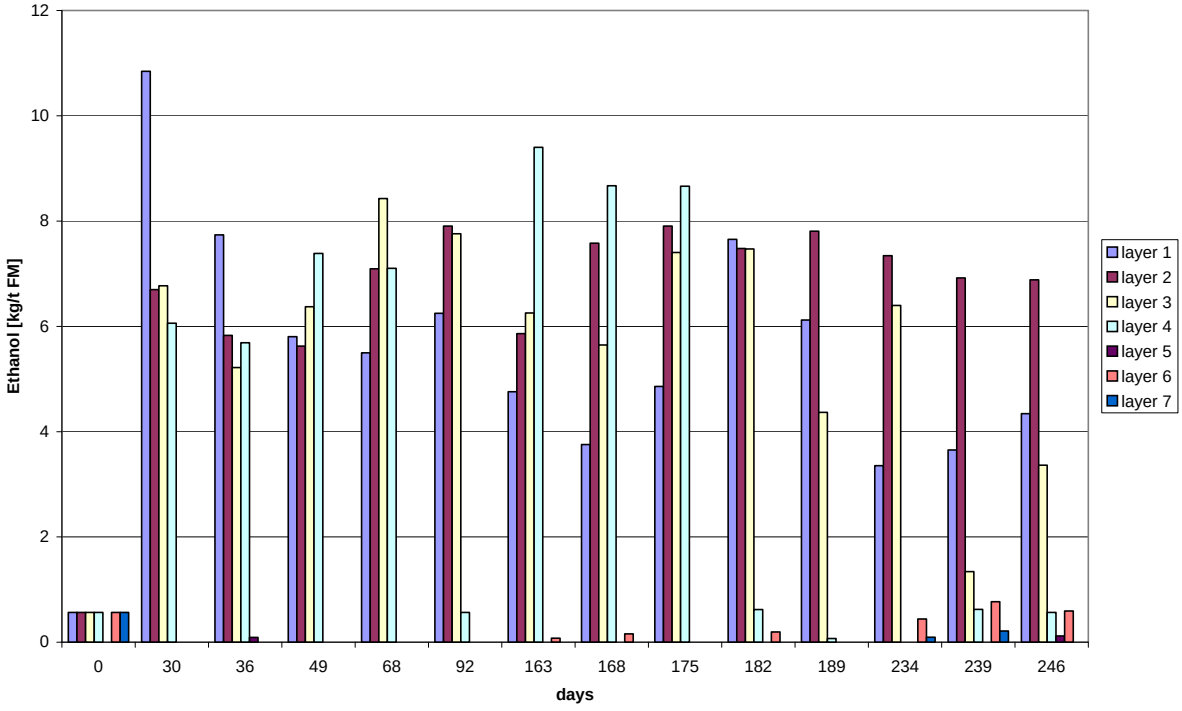

Figure 5: Time course of ethanol concentration [kg/t FM] in the different sampling layers over the ensiling period.

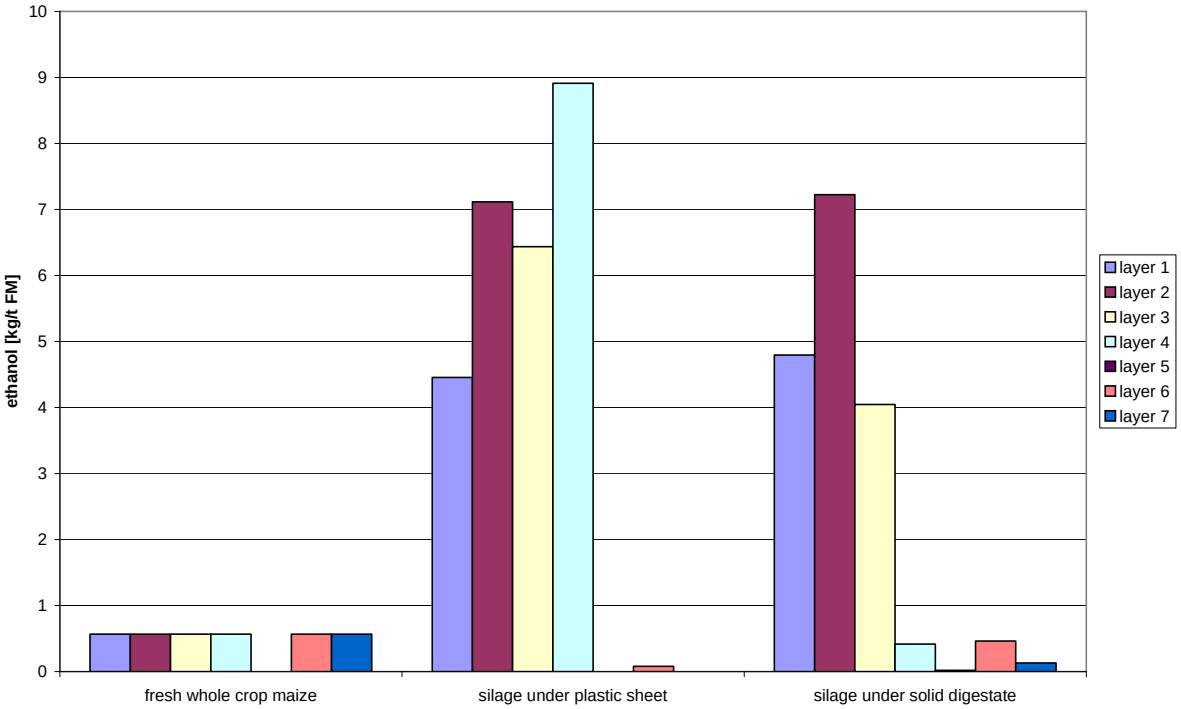

Figure 6: Changes in ethanol concentration in dependence on the coverage in the different sampling layers

In the lower layers of the silo, which contribute the largest part to the overall mass, no reduction of the soluble component could be observed; however, there was a reduction of the insoluble fraction of VS. Since it is assumed that these parts of the silo are strictly anaerobic, it remains unclear how these compounds were degraded, since no evidence for anaerobic degradation such as metabolites (butyric acid, etc.) was found.

4.2 Storage in bales

The effects of storage time and biological additives on the chemical characteristics of the grass mixture (Table 3) and ryegrass (Table 4) were studied in bales stored in field conditions (Figure 8). With grass pH decreased in all conditions from initial 6.0-6.2 to 4.7-5.2 within one month of storage and remained at about that level during the 11 months storage. Until six months storage pH was about 0.2 units lower with crop stored without pre-wilting or additive. Some individual high (7.3-8.8) pH values were observed in some bales indicating apparent spoilage of the bales. With ryegrass the storage additive decreased pH from 6.2 to 5.8. After one month storage pH had increased in all bales to 7.1-7.5, but decreased to 4.5-4.9 with three months' storage. With grass pre-wilting resulted in higher TS and VS compared to wet grass. No major decreases in TS or VS were recorded with grass even though some variation was noticed during storage. With ryegrass the measured variation in TS during storage was significant and no clear trends could be concluded. Apparently the high variation is also due to differences in

bales (initial material, air tightness, leachate leaks, freezing) also due to difficulties in sampling the bales under the quite extreme field conditions.

With timothy grass some variation in specific methane yields was observed while in general no clear decreasing or decreasing trend could be confirmed. Some individual exceptional values might indicate spoilage or the heterogenous nature of the sampled material. The specific methane yields of the ryegrass showed high variation during the storage, and in fact the measured initial yields were highly different from those observed during the storage. Anyway it appears that there is no clear trend in methane potential during the storage, e.g. after 11 month storage the yields were higher than after one month storage.

With both grass mixture and ryegrass the methane yields (m^3 methane) per t_{ww} initial varied during the storage with some highly exceptional values (Tables 3, 4; Fig. 7) but did not show a decreasing trend along the storage time. The effects of wilting or storage additives were not evident.

Table 3. Effect of storage on chemical characteristics and methane production potential of timothy-clover.

Timothy-clover	Storage time (months)	pH	TS (%)	VS (%)	CH_4 (m^3/kgVS)	CH_4(m^3/t_{ww})	CH_4 (m^3/t_{ww})
Wet	0	6.08	14.6	13.4	0.47	62.6	62.6*
pre-wilted		6.02	18.2	16.8	0.41	68.3	54.6*
pre-wilted+LAB		6.22	17.0	15.7	0.50	78.8	67.5*
Wet	1	4.72	17.1	15.7	Nd	Nd	Nd
pre-wilted		5.05	20.0	18.3	0.48	87.1	Nd
pre-wilted+LAB		5.44	17.0	15.2	0.38	58.0	Nd
Wet	3	5.02	17.1	15.7	0.49	76.4	Nd
pre-wilted		5.22	17.4	15.7	0.42	66.2	Nd
pre-wilted+LAB		7.3 & 5.12	17.5 & 20.3	15.6 & 18.5	0.39 & 0.36	60.4	Nd
Wet	6	4.79	17.3	16.0	0.43	68.7	Nd
pre-wilted		8.79	17.9	15.9	0.26	40.9	Nd
pre-wilted+LAB		5.44	17.9	16.5	0.37	61.2	Nd
Wet	11	5.38	16.4	15.0	0.49	73.0	63.4 ♦
pre-wilted		5.27	17.7	16.2	0.48	78.0	59.5 ♦
pre-wilted+LAB		5.03	21.5	20.0	0.44	87.9	56.9 ♦

* mass loss during the pre-wilting taken into account.

♦ mass change during the storage taken into account.

nd=not determined

Table 4. Effect of storage on chemical characteristics and methane production potential of ryegrass.

Ryegrass	Storage time (months)	pH	TS (%)	VS (%)	CH_4 (m^3/kgVS)	CH_4 (m^3/t_{ww})	CH_4 (m^3/t_{ww}) *
pre-wilted	0	6.2	44.4	39.6	Nd	Nd	Nd
pre-wilted+LAB		5.81	42.2	37.8	0.47	177	177
pre-wilted	1	7.47	30.3	26.0	0.32	82.8	Nd
pre-wilted+LAB		7.09	27.6	24.4	0.32	78.0	Nd
pre-wilted	3	4.88	44.4	39.9	0.44	177	Nd
pre-wilted+LAB		4.49	26.6	22.6	0.39	88.3	Nd
pre-wilted	11	4.51	37.4	32.9	0.39	127	129
pre-wilted+LAB		4.32	33.3	29.0	0.36	105	108

* mass change during the storage taken into account.

-=not measured

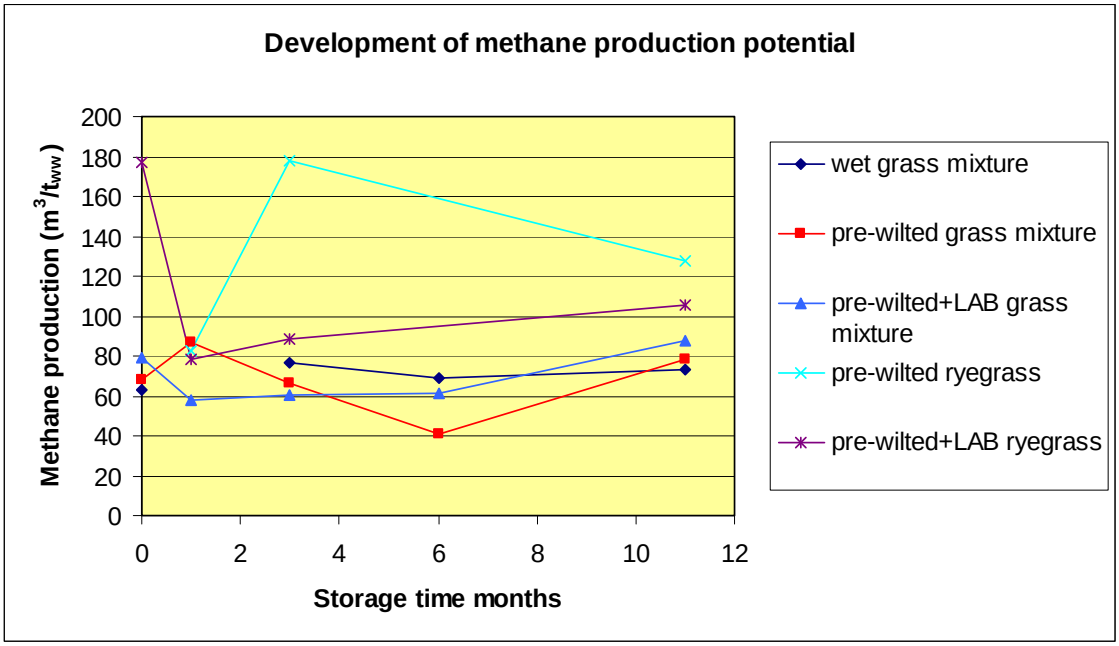

Figure 7: Change of methane production potential (m^3/tww) during storage of grass and ryegrass in bales. Mass loss during pre-wilting was taken into account.

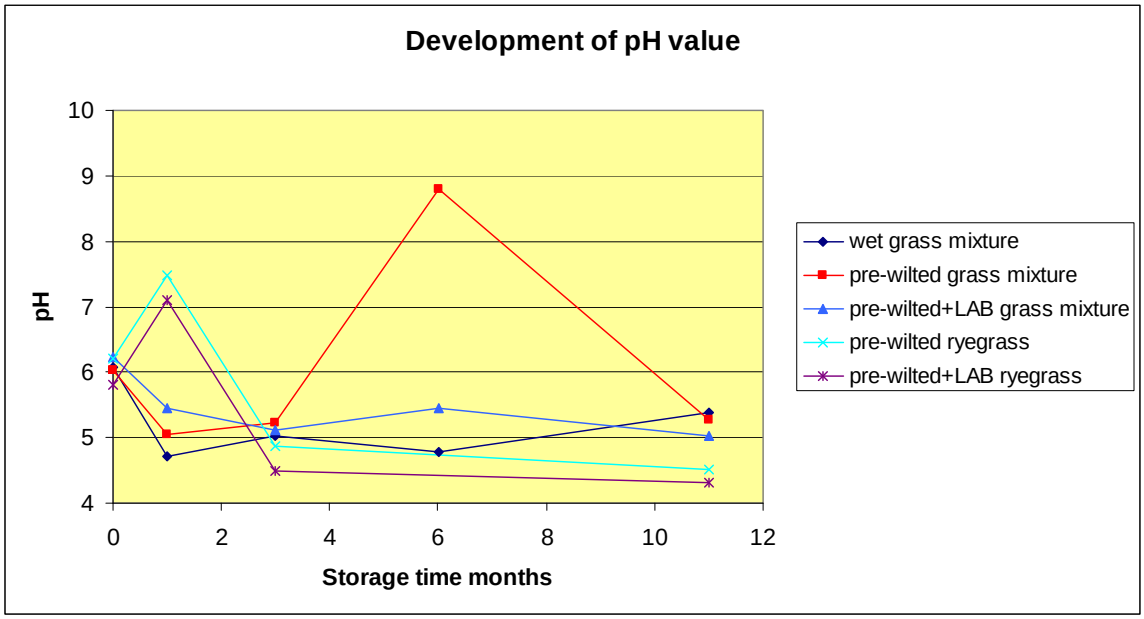

Figure 9: Change of pH during storage of grass and ryegrass in bales.

5 Conclusions

Losses in total solids are critical in silage management for energy crops because they are related to energy losses during storage. With maize considerable losses were observed in solids in silos after ensiling independently of the coverage. Covering silage silos (maize) with solid digestate may save time and resources, however, microbial decay of the surface layers can be expected due to the activity of yeast and moulds that are present in the digestate and will infiltrate the silage. The greater part of the observed losses belongs to the fraction of insoluble volatile solids. It has still to be determined which compound is actually degraded and by what means the degradation is taking place.

Storage of grass in bales (weight ca 400-600 kg) covered with plastics is commonly used e.g. in Finland besides silos. The present results suggest that timothy grass stored in this way (at 15-18 % TS) apparently could maintain its methane potential without major losses. Ryegrass, which was stored at about 40 TS %, seemed to lose some TS during the storage, and lost apparently also some methane potential, even though the data was scarce. Anyway, the practical experience gained indicated that care must be taken of the bales during the storage to avoid physical breakage of the plastic cover material, which may lead to spoilage of the silage. The effects of wilting and storage additives on the storage of grass were not apparent, and should be analysed more in details case by case.

The above report describes the work carried out in the CROPGEN project. To disseminate the detailed results, it is planned to publish two academic journal papers.

6 References

Buxton D.R. and O'Kiely P. (2003). Preharvest plant factors affecting ensiling. In: *Silage Science and Technology*, Al-Amoodi L, Barbarick K.A., Volenec J.J. and Dick W.A. (eds.), American Society for Agronomy, Inc., Madison, USA, pp. 199-250.

Haigh, P.M. (1999). Effluent production from grass silages treated with additives and made in large-scale bunker silos. *Grass and Forage Science* **54**, 208–218

Danner, H., Holzer, M., Mayrhuber, E. and Braun R. (2003). Acetic acid increases stability of silage under aerobic conditions. *Applied and Environmental Microbiology* **69**(1), 562–567

Neureiter M., Teixeira Pereira dos Santos J., Perez Lopez C., Pichler H., Kirchmayr R. and Braun R. (2005). Effect of silage preparation on methane yields from whole crop maize silages. In: Ahring B.K. and Hartmann H. (eds.): 4th International Symposium on Anaerobic Digestion of Solid Waste, Copenhagen, August 31–September 2, 2005, Volume 1 Oral Presentations, 109–115

McDonald, P., Henderson, A.R. and Heron, S.J.E. (1991). The Biochemistry of Silage, Second Edition, Chalcombe Publications, Marlow