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Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations

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Abstract

Biogas production is of major importance for the sustainable use of agrarian biomass as renewable energy source. Economic biogas production depends on high biogas yields. The project aimed at optimising anaerobic digestion of energy crops. The following aspects were investigated: suitability of different crop species and varieties, optimum time of harvesting, specific methane yield and methane yield per hectare. The experiments covered 7 maize, 2 winter wheat, 2 triticale varieties, 1 winter rye, and 2 sunflower varieties and 6 variants with permanent grassland. In the course of the vegetation period, biomass yield and biomass composition were measured. Anaerobic digestion was carried out in eudiometer batch digesters. The highest methane yields of 7500–10200 m_N^3 ha^{-1} were achieved from maize varieties with FAO numbers (value for the maturity of the maize) of 300 to 600 harvested at "wax ripeness". Methane yields of cereals ranged from 3200 to 4500 m_N^3 ha^{-1}. Cereals should be harvested at "grain in the milk stage" to "grain in the dough stage". With sunflowers, methane yields between 2600 and 4550 m_N^3 ha^{-1} were achieved. There were distinct differences between the investigated sunflower varieties. Alpine grassland can yield 2700–3500 m_N^3 CH_4 ha^{-1}. The methane energy value model (MEVM) was developed for the different energy crops. It estimates the specific methane yield from the nutrient composition of the energy crops.

Energy crops for biogas production need to be grown in sustainable crop rotations. The paper outlines possibilities for optimising methane yield from versatile crop rotations that integrate the production of food, feed, raw materials and energy. These integrated crop rotations are highly efficient and can provide up to 320 million t COE which is 96% of the total energy demand of the road traffic of the EU-25 (the 25 Member States of the European Union).

Keywords: Biogas; Anaerobic digestion; Methane; Sustainable production of biomass; Energy crops

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1. Introduction

It is essential to develop sustainable energy supply systems that aim at covering the energy demand from renewable sources. Mitigation of green house gas emissions

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through renewable energy production is of rising importance. Biogas production is a key technology for the sustainable use of agrarian biomass as renewable energy source. High energy yields per hectare can be achieved through biogas production. Biogas can be produced from a wide range of energy crops, animal manures and organic wastes. Thus, it offers a high flexibility and can be adapted to the specific needs of contrasting locations and farm managements. After anaerobic digestion, the digestion residues can be used as a valuable fertiliser for agricultural crops.

Biogas production has higher demands for arable land, assets and work than other forms of renewable energy production, as e.g. RME (rape methyl ester) production (Heissenhuber and Berenz, 2005). Therefore, economic efficiency must be given particular attention. Economic biogas production requires high biogas yields. Key factors for a maximum biogas yield are species and variety of energy crops, time of harvesting, mode of conservation and pretreatment of the biomass prior to the digestion process but also the nutrient composition of the energy crop (Amon et al., 2006). Guidelines on optimum energy crop production, optimum harvesting time, optimum nutrient composition, optimum conservation and pre-treatment technology must be developed.

Biogas production from energy crops is of growing importance (Karpenstein-Machan, 2005). Maize, sunflower, grass and Sudan grass are the most commonly used energy crops. Requirements on the biomass quality are different when crops are anaerobically digested in biogas plants compared to being fed to cattle. The digester at the biogas plant offers more time to degrade the organic substance than the rumen does. In addition it is likely to assume that the micro-organism population in the digester is different from that in the rumen. Biogas plants can degrade cellulose to an extent of about 80% (Ress et al., 1998) whereas in the rumen and total digestive tract of ruminants cellulose will be broken down to a degree of approximately 40% and 59%, respectively (Gray, 1947).

With biogas production, the key factor to be optimised is the methane yield per hectare. This may result in different harvesting strategies when growing energy crops for anaerobic digestion compared to growing them as a forage source for ruminants. Specific harvest and processing technologies and specific genotypes are required when crops are used as a renewable energy source.

In addition it is of essential importance that the energy crops are grown in sustainable and versatile crop rotations. All activities must aim to use the multifaceted cultivated landscape sustainable (Buchgraber, 2003). A lasting success is only achieved, if arable land and grassland are managed after sustainable principles (Amon et al., 2006). Biomass for anaerobic digestion can be grown as preceding crop, main crop or succeeding crop. Organic by-products accumulate, when processing agricultural raw materials. They may as well be anaerobically digested.

The Division of Agricultural Engineering together with its partners investigates biogas production from a variety of energy crops and agricultural wastes with the aim to optimise methane yield and economic efficiency of sustainable biogas production. One superior aim in the research on biogas production is the development of integrated crop rotations that offer the supply with food and feed, the production of raw materials (e.g. oil, fat, organic acids) and energy (e.g. biogas, RME) and the maintenance and further promotion of a multifaceted cultivated landscape. This aim can be achieved via the following strategies:

- Food non-food switch: alternation of crops for the production of food, feed and raw materials.
- Cascade utilisation of different parts of the same crop for different options: e.g. starch from maize corns and biogas from the remaining maize plant.
- Mixed cultivation of several energy crops: e.g. sunflower and maize.
- Choice of the optimum variety and genotype: energy crops for biogas production must produce high biomass yields and contain optimum nutrient patterns.
- Choice of the optimum harvesting time.

The present paper will give an example for such an integrated crop rotation. In the research project methane yields from a range of energy crops were measured and the "methane energy value model" to estimate the methane yields from energy crops was developed.

2. Methods

A range of energy crops was grown on 60 ha in several Austrian regions (Fig. 1). The following energy crops were included in the research programme: 7 maize varieties (FAO 280-650), 2 winter wheat varieties, 2 triticale varieties, 1 winter rye varieties, 2 sunflower varieties and 6 variants with permanent grassland. Biomass yield in the course of the vegetation period and biomass composition was measured. For the development of the methane energy value model additional crop varieties were investigated: 11 maize varieties, 2 winter wheat varieties and 1 winter rye variety.

Anaerobic digestion experiments to measure the biochemical methane potential (BMP) were carried out in accordance with VDI 4630 (2006) and DIN 38414 (1987). In detail, eudiometer batch digesters of 1 l capacity were used and the temperature was set at 38 °C. In the lab experiments methane yields from each harvest and cut were measured with in replicates. All crop and grass material were used in the form of silage. The investigations covered a wide range of parameters: specific biogas and methane yield, biogas quality, transformation of biomass carbon and energy into biogas carbon and energy. The amount of biogas production was monitored every day. Biogas production is given in norm litre per kg of volatile solids (l_N kg^{-1} VS). That means the volume of biogas production is based on norm conditions: 273 K and 1013 mbar. Biogas quality (CH_4, H_2S, NH_3) was analysed 10 times during the

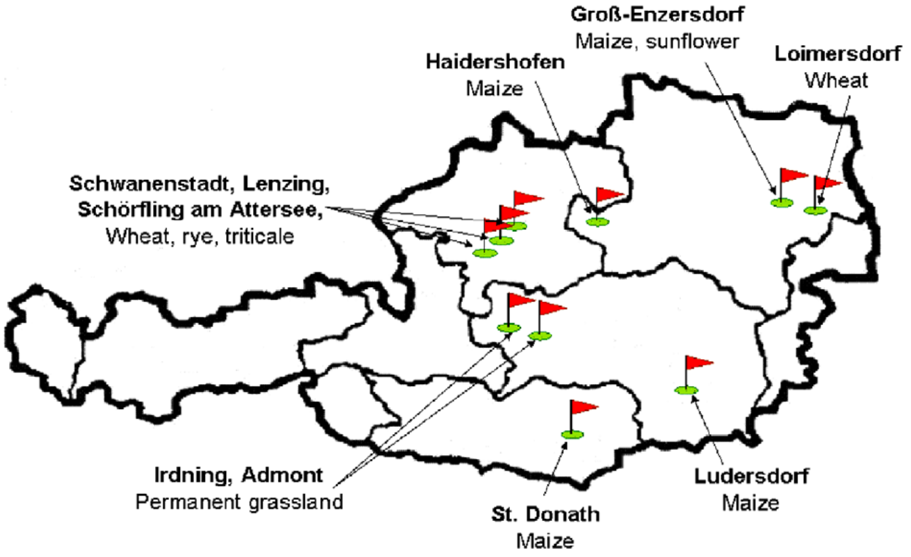

Fig. 1. Locations of the field trials in Austria.

6-week digestion period. Methane concentrations in the biogas were analysed by a Gas Data LMS NDIR analyser (accuracy: ±1–3% of the measurement reading). The analyser was calibrated every 10th sample with a 60% CH_4 calibration gas. NDIR readings were validated at regular intervals by gas chromatographic analysis of CH_4 concentration in the biogas. H_2S concentration in the biogas was analysed with different Dräger tubes (accuracy: ±5–10% of the measurement reading). NH_3 concentration was measured with Dräger tubes Type 5/b ammonia (measurement range 5–100 ppm; accuracy: ±10–15% of the measurement reading).

Prior to anaerobic digestion the pH of the substrates was measured and the nutrient composition was analysed (dry matter (DM), crude protein (XP), crude fibre (XF), cellulose, hemicellulose, starch, sugar, lignin, crude fat (XL), and ash (XA)) according to standard procedures (Naumann and Bassler, 2004). N-free extracts (XX) were calculated and is that part of the DM not incorporated in XP, XF, XL and XA. Gross energy was measured with a calorimeter.

The methane energy value model was developed by carrying out a multifunctional analysis of full regression models (Sachs, 1992).

Biomass yields for the contrasting crop rotations were estimated with mean yields that were measured on locations that are typical of a major part of Austrian agriculture: “Mostviertel”, “Weinviertel” and a region with panonian climate, all located in “Lower Austria” (BMLFUW, 2002a,b).

3. Results

3.1. Maize

All maize varieties were grown at the same site (Haidershofen). The specific methane yield of 7 maize varieties was measured at the harvest time with the highest biomass yield. The varieties DK532, Cecilia and Doge were harvest in the vegetation stage “end milk ripeness”, the varieties Baxter and Alisun in the vegetation stage “middle wax ripeness” and Wexxil in the vegetation stage “end wax ripeness”. The average specific methane yield was 398 $l_N\ kg^{-1}$ VS with a standard deviation of 23 $l_N\ kg^{-1}$ VS (Fig. 2). There were no significant differences between the maize varieties.

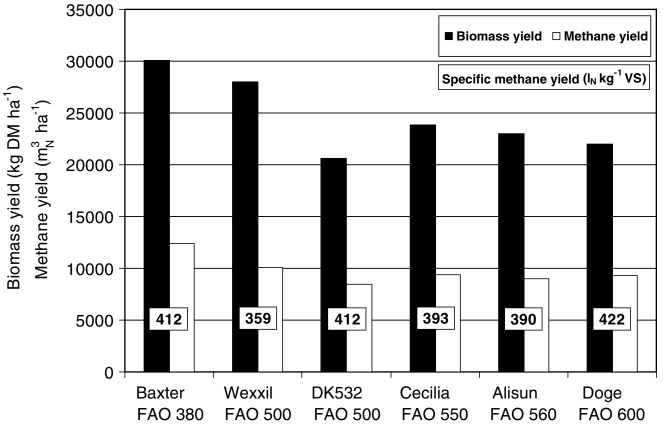

Fig. 2. Biomass and methane yield from different maize varieties.

Biomass yield was dependent on the maize variety. The biomass yield of medium ripening maize varieties like Baxter and Wexxil was higher than the biomass yield of the late ripening varieties. Because of their higher biomass yield, medium ripening varieties gave higher methane yields per hectare than late ripening varieties. The highest methane yields per hectare of 12 390 $m_N^3\ ha^{-1}$ were produced by the maize variety Baxter (FAO 380).

The time of harvesting is a key influence on the methane yield that can be produced per hectare of maize. The variety “KWS 1393” (FAO 400) was harvested at five

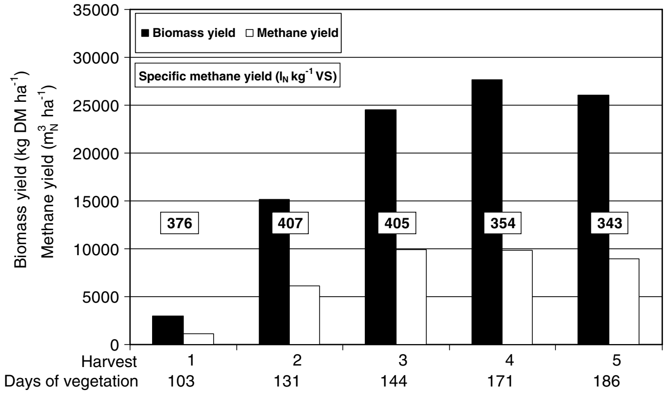

Fig. 3. Biomass and methane yield of KWS 1393 (FAO 400) in the course of the vegetation period.

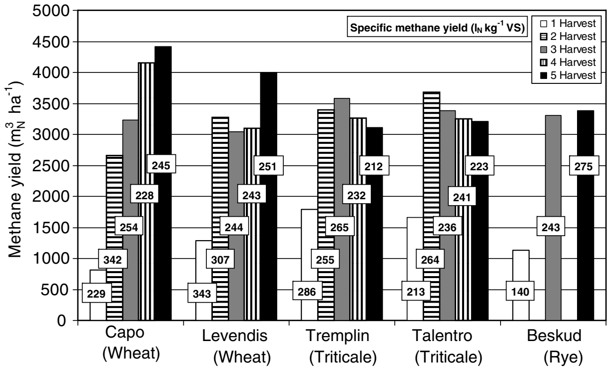

Fig. 4. Methane yield from different cereals in the course of the vegetation period.

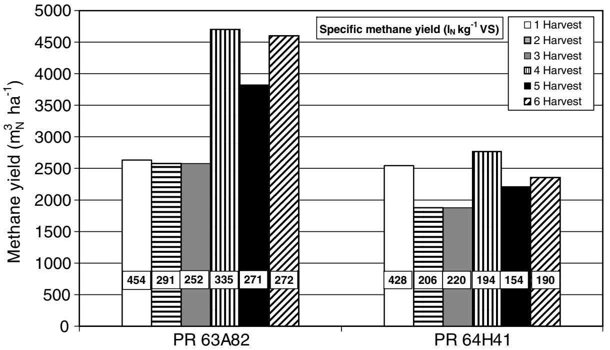

Fig. 5. Methane yield from two sunflower varieties in the course of the vegetation period.

consecutive times in the course of the vegetation period. The highest biomass and methane yield per hectare were measured 171 days after seeding (fourth harvest), at the vegetation stage "wax ripeness" (Fig. 3).

3.2. Cereals (wheat, triticale and rye)

Two varieties of winter wheat, two varieties of triticale and one winter rye varieties were grown in two locations that differed in their climate. "Lenzing" (Upper Austria) received an average of 1200 mm rainfall per year. The precipitation at "Loimersdorf" (Lower Austria) was 450 mm. The biomass yield of each crop was measured at five occasions (five harvest times) in the course of the vegetation period. The harvest time have been: (1) 3–4 node, (2) anthesis flowering, (3) grain in the milk stage, (4) grain in the dough stage, and (5) maturity complete. The highest biomass yield from winter wheat (19 t DM ha^{-1}) was achieved at the vegetation stage "grain in the dough stage" and "maturity complete", respectively (data not shown). Triticale reached the highest biomass yield (15 t DM ha^{-1}) at the vegetation stage "anthesis flowering" and "grain in the milk stage", respectively. Rye reached the highest biomass yield (15 t DM ha^{-1}) at the vegetation stage "grain in the dough stage".

The specific methane yield from wheat ranged between 140 and 343 l_N kg^{-1} VS (Fig. 4). Triticale and rye had a lower maximum in the specific methane yield than winter wheat. The highest specific methane yields were achieved during the first two harvests. In the course of the vegetation period, the specific methane yield of cereals declined, whereas the total biomass yield increased. When cereals are harvested at the optimum vegetation stage (high biomass yield and best premises for making silage) a methane yield per hectare and year of 3200–4500 m_N^3 can be achieved.

3.3. Sunflower

The experiments covered two sunflower varieties: PR 63A82 und PR 64H41. The two varieties differ in their oil composition. PR 63A82 mainly contains about 60% linoleic acid (C18:2n6) and about 30% oleic acid (C18:1n9). The oil of PR 64H41 consists of about 90% oleic acid (C18:1n9). Biomass yield in the course of the vegetation period (data not shown), specific methane yield and methane yield per hectare were measured. Fig. 5 gives the methane yields per hectare and the specific methane yield at each harvest time. The harvest times have been: (1) BBCH-57 (BBCH-identification keys, FBRCAF, 2001), (2) BBCH-65, (3) BBCH-69, (4) BBCH-79, (5) BBCH-86, and (6) BBCH-89.

Sunflowers were first harvested at BBCH-57 ("Inflorescence clearly separated from foliage leaves"). In the first harvest PR 63A82 and PR 64H41 yielded 454 l_N CH_4 kg^{-1} VS and 428 l_N CH_4 kg^{-1} VS, respectively. From the second harvest (BBCH-65, "Full flowering") onwards, the specific methane yield was on a much lower level. The methane yield per hectare of the variety PR 64H41 was highest at the first and fourth harvest. With the variety PR 63A82 a different development of the methane yield per hectare was observed. Here, the highest methane yields per hectare were measured at the fourth and sixth harvest. With both varieties, the maximum methane yield per hectare was achieved at a dry matter content of 15%. At that time, PR 63A82 yielded 4695 m_N^3 CH_4 ha^{-1} and PR 64H41 2771 m_N^3 CH_4 ha^{-1}, respectively. Further investigations are needed to clarify whether the considerable difference in the methane yield per hectare between both varieties depends on the different fatty acid composition of the oils.

3.4. Grass

Six grassland variants were grown in two Alpine regions: “Admont”, a low input mountainous region (three variants: “Hill site” with one, two or three cuts) and “Irdning”, an intensive valley area (three variants: “Valley site” with three or four cuts). Experimental set up and sampling allowed a differentiation between management intensity and vegetation stage at harvesting. More details on the two locations, on the climatic conditions and on the grassland composition can be taken from (Amon et al., 2005).

The hill site yielded 4.2 t DM ha^{-1} a^{-1} when cut once and 6.4 t DM ha^{-1} a^{-1} when cut twice (data not shown). The variants with three cuts resulted in a decline in total biomass yield (5.9 t DM ha^{-1} a^{-1}). The variants grown at the valley site were cut three to four times and yielded more biomass. The “three-cuts variants” were further differentiated into “early first cut” (cut at the 1st June, variant 4) and “late first cut” (cut at the 15th June, variant 5). The variant “early first cut” yielded much less biomass than the variant “late first cut”. The difference in the biomass yield of the first cut of these two variants was not compensated by variant 4 although it had slightly higher biomass yields in the second and third cut. This means, that the timing of the first cut is of key importance for the total biomass yield from a full vegetation period.

The specific methane yields of grassland from the mountainous and from the valley region showed significant differences (Fig. 6). Independent of the number of cuts only a low specific methane yield (128–221 l_N kg^{-1} VS) was measured from the biomass coming from the hill site. The grass grown at the valley site produced 190–392 l_N CH_4 kg^{-1} VS. The highest specific methane yield was measured for the biomass from the second cut from the “four-cuts variant” (variant 6).

The methane yield per hectare and year increased when the number of cuts increased. However a fourth cut seems not sensible since with this cut only 81 m_N^3 CH_4 ha^{-1} were achieved. The highest methane yield with one cut was reached with the late first cut in the three-cuts system namely 1872 m_N^3 ha^{-1}. On average the methane yield of the hill site was 910 m_N^3 ha^{-1} a^{-1}, which only is one third of the average methane yield at the valley site.

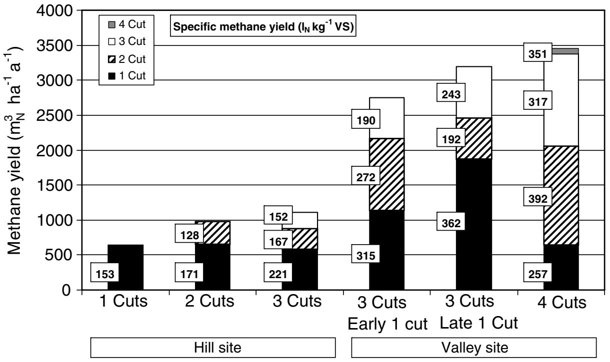

Fig. 6. Methane yield from permanent grassland at two sites (hill and valley) and under different management intensity.

4. Methane energy value model (MEVM)

4.1. Development of the methane energy value model

A new model – the methane energy value model – was developed, which estimates methane yield from the nutrient composition of energy crops in mono fermentation via regression models. Existing models concentrate on picturing the kinetics of anaerobic digestion for organic wastes (Angelidaki et al., 1993; Batstone et al., 2000; Henze et al., 1986; McCarty and Mosey, 1991; Pavlostathis and Gossett, 1986). They show the effects of e.g. pH value, NH_4–N content, or content of volatile fatty acids on the digestion process. Buswell (1936) and Boyle (1977) developed a model that estimates biogas composition (CH_4, CO_2, H_2S und NH_3) from the chemical composition (C, H, N, S) of the organic substrates.

Methane production from organic substrates mainly depends on the content of nutrients (crude protein, crude fat, crude fibre, N-free extracts) which can be degraded to CH_4 and CO_2. The content of these nutrients determine the degradability and thus the methane yield that can be produced through anaerobic digestion. There is a difference in the specific methane yield of crude fat (850 l kg^{-1} VS), crude protein (490 l kg^{-1} VS), and carbohydrates (crude fibre and N-free extracts, 395 l kg^{-1} VS) (Karpenstein-Machan, 2005). The methane energy value model investigates and considers the impact of the content of crude protein, crude fat, crude fibre, N-free extracts on the methane formation (MEV, methane energy value) with the following equation:

$$
\begin{aligned}
&\text{MEV } (l_N\ CH_4\ kg^{-1}\ VS)\\
&\quad = x1 \times \text{crude protein (XP)} \quad \text{(content in \% DM)}\\
&\qquad + x2 \times \text{crude fat (XL)} \quad \text{(content in \% DM)}\\
&\qquad + x3 \times \text{crude fibre (XF)} \quad \text{(content in \% DM)}\\
&\qquad + x4 \times \text{N-free extracts (XX)} \quad \text{(content in \% DM)}
\end{aligned}
$$

The present methane energy value model helps to optimise biogas production by the following capabilities:

- estimation of the specific methane yield of organic substrates;
- estimation of the nutrient requirement of micro-organisms that are responsible for anaerobic digestion;
- estimation of the producible power of agricultural biogas plants in dependency of available amount and composition of organic substrates;

- estimation of the methane yield per hectare of energy crops (species and varieties) and crop rotations;
- recommendations on optimum harvesting time of energy crops (species and varieties).

4.2. Methane energy value model for maize

Table 1 shows coefficients of regression and level of significance of the regression model for the estimation of methane yield from anaerobic digestion of maize. The nutrients crude protein (XP), crude fat (XL), crude fibre (XF) and N-free extracts (XX) proved to have a significant influence on the level of methane production. From their content – expressed as % in dry matter – the specific potential of maize to produce methane is estimated. The regression equation is based on 95 observations. Crude fat and crude protein contribute most to the MEV of maize.

Specific methane yields measured in the eudiometer batch digesters were compared with the values estimated with the methane energy value model (Table 2). Estimated values differed between 0.1 and 52 l_N CH_4 kg^{-1} VS from the measured values. This corresponds to a difference of 0–15%. The mean difference was 0.7%. The Methane Energy Value for maize is currently validated at commercial biogas plants. First results showed a good agreement between estimated and measured values with a difference of 2–5%.

Table 1
Coefficients of regression and level of significance for the estimation of the methane yield of maize from the nutrient content

Parameter (content in % DM)	Coefficient of regression	Level of significance
Crude protein (XP)	15.27	0.000
Crude fat (XL)	28.38	0.001
Crude fibre (XF)	4.54	0.000
N-free extracts (XX)	1.12	0.008

Quality parameters of the whole equation:
$R^2 = 0.968$; F value = 1583.027; Durbin–Watson value = 1.176; level of significance = 0.000; $n = 95$

Table 2
Examples for the specific methane yield of maize: comparison between measured values and values estimated with the methane energy value model

Maize variety/harvest	Specific methane yield (l_N kg^{-1} VS)		Difference between measured and estimated value	
	Measured	Estimated	l_N	% of measured
Tonale/first	333.7	339.4	5.7	1.7
Tonale/second	283.2	324.8	41.6	14.7
Tonale/third	280.4	266.0	−14.4	−5.1
PR34G13/first	365.9	313.6	−52.3	−14.3
PR34G13/second	302.1	320.7	18.6	6.2
PR34G13/third	268.2	311.4	43.2	16.1
LZM/first	312.6	296.4	−16.2	−5.2
LZM/second	325.6	300.6	−25.0	−7.7
LZM/third	286.8	286.9	0.1	0.0
Mean difference				0.7

4.3. Methane energy value model for cereals

For cereals, the methane yields of 20 observations were correlated with their nutrient composition. Table 3 gives the coefficients of regression and level of significance of the regression model for the estimation of the methane yield from cereals. Crude protein (XP) and crude fibre (XF) contributed most to the methane yield from cereals. So far, the statistical analysis did not show a significant influence of the fat content of the cereals on the methane yield. It may be assumed that the reason for this lies in the contrasting quality of the different fats present in the investigated cereals. Further experiments have to be done.

As an example, Table 4 compares the specific methane yields measured in the eudiometer batch digesters and the values estimated with the Methane Energy Value Model for the triticale variety Tremplin. Even without inclusion of crude fat, the model gives very good results. The mean difference between estimated and measured value is 0.5%.

4.4. Methane energy value model for grass

The methane energy value model for methane production from anaerobic digestion of grass is currently under

Table 3
Coefficients of regression and level of significance for the estimation of the methane yield of cereals from the nutrient content

Parameter (content in % DM)	Coefficient of regression	Level of significance
Crude protein (XP)	5.904	0.004
Crude fibre (XF)	3.791	0.001
N-free extracts (XX)	1.352	0.015

Quality parameters of the whole equation:
$R^2 = 0.985$; F value = 371.739; Durbin–Watson value = 2.442; level of significance = 0.000; $n = 20$

Table 4
Example for the specific methane yield of cereals: comparison between measured values and values estimated with the methane energy value model

Tremplin (triticale)	Specific methane yield (l_N kg^{-1} VS)		Difference between measured and estimated value	
	Measured	Estimated	l_N	% of measured
First harvest	286	259	−27	−9.4
Second harvest	255	265	10	3.9
Third harvest	265	272	7	2.6
Fourth harvest	232	235	3	1.3
Fifth harvest	212	221	9	4.2
Mean difference				0.5

Table 5
Coefficient of regression and level of significance for the estimation of the methane yield of grass from the nutrient content

Parameter (content in % DM)	Coefficient of regression	Level of significance
Crude protein (XP)	2.19	0.602
Crude fat (XL)	31.38	0.017
Crude fibre (XF)	1.48	0.457
N-free extracts (XX)	1.85	0.217

Quality parameters of the whole equation:
$R^2 = 0.935$; F value = 126.976; Durbin–Watson value = 0.804; level of significance = 0.000; $n = 40$

development. Table 5 gives preliminary results on coefficient of regression and level of significance of the regression model. The complete regression model is highly significant. However the single parameters are currently not significant. The methane energy model for grass needs further refinement.

5. Sustainable crop rotation systems

Energy crops for biogas production need to be grown in sustainable crop rotations. Table 6 gives an example of a sustainable crop rotation in Lower Austria. Biomass yields are longtime mean values (BMLFUW, 2002a,b). They are similar to mean EU-25 biomass yields (EUROSTAT, 2005). The specific methane yields given in Table 6 were measured in own lab experiments or are from KTBL (2005). The methane yield per hectare was calculated by multiplication of the biomass yield and the specific methane yield. Methane yields per hectare are given separately for each crop and in total for the complete crop rotation as an annual average. The crop rotation outlined in Table 6 produces 4149 m_N^3 CH_4 ha^{-1} a^{-1}. At the same time, it is assumed that the crop rotation covers food and feed demands. It is essential that the intensity level of production is adapted to the pre-requisites of the location where energy crops, food and feed are grown.

Table 7 compares methane yields from specialised and integrated crop rotations from arable land in EU-25. The total arable land is 93 million ha (EUROSTAT, 2005). In the specialised crop rotation, it is assumed that 20% of arable land is used for energy crop production and that a mean of 6500 m_N^3 CH_4 ha^{-1} a^{-1} is produced. This results in a methane production in EU-25 of 120,900 million m^3 CH_4 a^{-1}. This amount of methane corresponds to 104 million t crude oil equivalents (COE) a^{-1}.

The integrated crop rotation uses the total arable area for an integrated production of food, feed and energy crops. In this system, it is assumed that on average 4000 m_N^3 CH_4 ha^{-1} a^{-1} can be produced on the whole agricultural area of EU-25. This results in a methane production of 372,000 million m^3 CH_4 a^{-1} or 320 million t COE a^{-1}. The road traffic in EU-25 has a total annual energy demand of 334 million t COE (EUROSTAT, 2005). That means up to 96% of this energy demand could be covered by biogas plants using biomass from integrated

Table 6
Example of biomass and methane yields from a sustainable crop rotation in Lower Austria that integrates food, feed and energy crop production

Year	Crop	Biomass yield ($t\ VS\ ha^{-1}$)	Specific CH_4 yield ($l_N\ kg^{-1}\ VS$)	CH_4 yield per hectare ($m_N^3\ ha^{-1}\ a^{-1}$)	
				Crop only	Crop rotation
1	Maize (whole crop silage)	15.12	390	5897	1179
2	Winter wheat (straw)	5.44	189	1028	206
	Intercrop (clover grass)	2.71	335	906	181
3	Summer barley (straw)	3.81	189	720	144
4	Sugar beet (leaves)	7.20	210	1512	302
	Pressed beet pulp silage	14.36	430	6173	1235
5	Sunflower (whole crop silage)	11.02	300	3300	660
	Intercrop (lucerne)	3.61	335	1208	242
Methane yield of the whole crop rotation ($m_N^3\ ha^{-1}\ a^{-1}$)					4149

Table 7
Annual methane yields and energy production of specialised and integrated crop rotation from arable land in EU-25

Specialised crop rotation Arable land in EU-25: 93 million ha	Integrated crop rotation
Specialised energy crop production on 20% of the arable land: 18.6 million ha	Integrated energy crop production on the whole arable land: 93 million ha
Methane yield: 6500 $m^3\ ha^{-1}\ a^{-1}$	Methane yield:[a] 4000 $m^3\ ha^{-1}\ a^{-1}$
Energy production:	Energy production:
120,900 million m^3 CH_4 a^{-1}[b]	372,000 million m^3 CH_4 a^{-1}[b]
104 million t COE a^{-1}[c]	320 million t COE a^{-1}[c]
Total energy demand of road traffic in EU-25: 334 million t COE a^{-1}	

[a] See Table 6.
[b] 1 m^3 CH_4 = 10 kW h (Dubbel, 1987).
[c] 1 kg COE = 11.63 kW h (Ag Energie, 2005).

sustainable crop rotations. This calculation still excludes the additional energy production that can be achieved from anaerobic digestion from grass land and animal manures.

6. Conclusions and outlook

Energy crops are very suitable substrates for anaerobic digestion. To be able to run biogas plants economically the methane yield from energy crops needs to be known. The present data show that the methane yield of energy crops depends on their nutrient composition. A wide range of energy crops was anaerobically digested in eudiometer batch digesters. From the digestion experiments, the methane energy value model (MEVM) for the different energy crops in mono fermentation was developed. The statistical analyses have given very good results for the estimation of methane yields from maize and cereals. The MEVM for grass needs further refinement. Also for sunflower, more data have to be collected to be able to develop a MEVM. In future, the MEVM should be developed for a wide range of energy crops. The present data show that the MEVM is a suitable tool to optimise methane yields from energy crops in the biogas production.

In the cultivation of energy crops the following should be considered:

Maize: Locally suitable varieties with a high biomass yield should be used. The maize should be harvest in the vegetation stage milk to wax ripeness. Under suitable climatic conditions methane yields of 7500–10200 m_N^3 ha^{-1} can be achieved.

Cereals: Fast growing varieties with a high biomass yield should be used. Cereals should be harvest in the vegetation stage “grain in the milk stage” to “grain in the dough stage”. Methane yields of 3200–4500 m_N^3 ha^{-1} can be achieved. Rye and triticale are very suitable as intercrops.

Sunflowers: With sunflowers, methane yields between 2600 and 4550 m_N^3 ha^{-1} can be achieved. The used variety has an important impact on the methane yield. This might depend on the oil composition of the sunflower varieties which has to be investigated in further studies.

Grass: The first cut should not be made before the vegetation stage “ear emergence” since an early first cut reduces the methane yield per hectare for the whole vegetation period. In Alpine valley regions the “three-cuts system” with a “late first cut” gave almost similar high methane yields per hectare and year as the “four-cuts system” (3200–3500 m_N^3 ha^{-1} a^{-1}).

Currently, biogas production from energy crops is mainly based on the anaerobic digestion of maize. In the near future, biogas production from energy crops will increase (Karpenstein-Machan, 2005) and it has to be considered that energy crops are grown in versatile, sustainable crop rotations. Sustainable biogas production from energy crops must not be based on maximum yields from single crops, but on maximum methane yield from the whole system of sustainable and environmentally friendly crop rotation.

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