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Gas production potential of fresh and ensiled sugar beets in biogas production

Gas production potential of plant biomass can be evaluated by means of the parameter „content of fermentable organic dry matter" (FOM). The aim of this study was to investigate the potential gas yield from fresh and ensiled sugar beets. In contrast to other plant biomass, like forage and cereal crops, the gas yield per kg FOM from sugar beets is a varying figure. It strongly depends on the proportion of sucrose which is converted into ethanol by fermentation during storage in the silo.

Keywords
Biogas, methane, biogas yield, gas production potential, fermentable organic matter (FOM), sugar beets, silages

Abstract
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The use of sugar beets as substrate for biogas production has attracted significant attention due to high biomass yield and good biodegradability [4]. However, their limited storability results in the need to preserve them as silage in order to make this substrate available throughout the year.

The chemical composition of sugar beets and their degradation pattern in the biogas fermenter are significantly different to those of other plant biomass. In addition, changes during silage fermentation are much more evident than in other substrates. Therefore, it seemed necessary to separately evaluate sugar beets and silage thereof as substrate for biogas production.

In a previous study it was shown how the content of fermentable organic matter (FOM) of plant biomass can be predicted by using simple routine analytical procedures of feed evaluation [5]. It could also be demonstrated that it is possible to derive the potential gas yield per kg FOM by means of stoichiometric calculations [7, 8]. For the most widely used biogas substrates from forage and cereal crops, a practically constant gas yield was found of about 420 litres methane and 800 litres biogas per kg FOM, respectively.

The aim of this study was a proposal for estimating the content of FOM of fresh and ensiled sugar beets and for calculating the potential gas yield from these substrates. For this purpose, available data were used from feed science on composition and biological degradability [2, 3] as well as from own chemical analyses of sugar beet silages.

Estimation of FOM

Ensiling of sugar beets is, as known for other plant biomass, associated with the loss of organic matter, which is caused by 1) formation and release of carbon dioxide during fermentation,

2) production and drainage of effluent and 3) degradation of organic substances upon exposure of silage to air after opening of the silo during feed-out. All these mentioned processes result in an increase of the concentration of crude ash (XA) and of such organic substances, which are not biodegradable under anaerobic conditions.

Digestibility of organic matter from sugar beets is very high. As mean values of numerous trials with sheep 89 % [2] and 90 % [3] were found, respectively. It has to be stated that these digestibility refer to the apparent digestibility; the true digestibility and the fermentability are even higher. In order to obtain the content of true digestible (= fermentable) nutrients, the metabolic excretion of animals, which were used in digestibility trials, must be taken into consideration. In analogy with other substrate types [5], the following equations could be derived for the estimation of FOM in sugar beets and silage thereof:

$$FOM = 991 - XA - 0.70\ XF \quad [g/kg\ DM] \quad \text{(equation 1)}$$

$$FOM = 991 - XA - 0.50\ ADF_{org} \quad [g/kg\ DM] \quad \text{(equation 2)}$$

In equation 1, the content of crude fibre (XF) is used, whereas in equation 2 the content of ADF_{org} (organic part of Acid Detergent Fibre) is employed for estimating the non-biodegradable carbohydrates. As both equations are equally precise, they can be used as desired. The target parameter (FOM) and also the analytical figures have the dimension g/kg DM (fresh sugar beets) and g/kg DM_c (silages and effluent), where DM_c is the dry matter concentration which was corrected for the loss of volatiles during sample drying [9].

Gas production from carbohydrates

Deriving values for potential gas yield of sugar beets and sugar beet silages was carried out by means of stoichiometric calculations in the way which has already been described for forages and cereals [7; 8]. For this purpose, the equation proposed by Buswell and Mueller [1] was used for the individual chemical compounds of which FOM is composed of. Subsequently, 5 % of the calculated gas yield was subtracted from the total theoretical yield in order to compensate for the effect of incorporation of substrate into bacterial biomass [6]. Data summarized in **table 1** show the stoichiometric gas production potential of carbohydrates and of fermentation products, which may potentially be formed in the silo.

Gas production per kg substrate increases from monomers to dimers to polymers of hexoses by 5 % each. Consequently, the disaccharide sucrose delivers 5 % more gas than does the monosaccharides glucose or fructose, but about 5 % less than polymers from hexoses (e. g. cellulose and galactans). Methane content of biogas from all these carbohydrates is always 50 %. There is no difference in gas yield and methane content between glucose or fructose and the fermentation products lactic and acetic acids. On the contrary, utilization of alcohols as substrates for biogas production results in significantly higher methane production per kg substrate than that from sugars. Methan concentration in biogas from primary alcohols is always 75 %.

Table 1

Table 1: Stoichiometric gas production potential of nitrogen-free organic compounds

Substrate	Litres/kg		Methane content
	Methane	Biogas	%
Carbohydrates			
Monomers of hexoses	355	709	50.0
Dimers of hexoses	373	746	50.0
Polymers of hexoses	394	788	50.0
Polymers of pentoses	403	806	50.0
Polymers of galacturonic acids*	364	784	46.4
Fermentation acids			
Lactic acid	355	709	50.0
Acetic acid	355	709	50.0
Propionic acid	503	862	58.3
Butyric acids	604	967	62.5
Alcohols			
Methanol	498	664	75.0
Ethanol	693	924	75.0
Propanols	797	1063	75.0
Butanols	862	1149	75.0
Propandiols	559	839	66.7
Butandiols	650	945	68.8

*completely methylated

Based on these stoichiometric gas yields and typical concentrations of each individual chemical compound in fresh and ensiled sugar beets, the potential gas yields were calculated for each fraction of fermentable carbohydrates (including the in silo formed fermentation products) (**table 2**).

As is well known, sucrose is the main component of carbohydrates in sugar beets. Cell walls contain cellulose, hemicelluloses and pectins where the latter are the major component here. During fermentation, sucrose is hydrolysed and the resulting monomers glucose and fructose are utilized for formation of lactic and acetic acids. Due to the low buffering capacity of sugar beet tissue, already low concentrations of acids are sufficient to reduce pH to a level lower than 4.0, which in turn leads to the cease of acid production. Other short-chain organic acids, e. g. propionic and butyric acids, occur only in minute amounts and can therefore be neglected. Especially after the cease of lactic acid fermentation, an increasing proportion of the residual sugar is utilized by yeasts to produce ethanol, whereby about one half of the weight of the fermented sugar is released from the silo as carbon dioxide. The amount of organic substance which remains in the silo decreases by this fermentation process and

Table 2

Table 2: Gas production potential of fermentable carbohydrates and fermentation products from fresh and ensiled sugar beets

	Proportion of fermentable carbohydrates %	Methane		Biogas		Methane content
		Litres/kg of the fraction	Litres/kg of fermentable carbohydrates	Litres/kg of the fraction	Litres/kg of fermentable carbohydrates	%
Sugar beets, fresh						
Sucrose	78	373	291	746	582	50.0
Polymers of hexoses (cellulose, galactans and others)	5	394	20	788	39	50.0
Polymers of pentoses (arabans, xylans and others)	5	403	20	806	40	50.0
Polymers of galacturonic methyl esters (pectins)	12	364	44	784	94	46.4
Total	**100**		**374**		**756**	**49.5**
Sugar beet silage, storage period up to 6 months						
Sucrose	50	373	187	746	373	50.0
Glucose, fructose, lactic acid, acetic acid	6	355	21	709	43	50.0
Ethanol and other alcohols	10	693	69	924	92	75.0
Polymers of hexoses (cellulose, galactans and others)	7	394	28	788	55	50.0
Polymers of pentoses (arabans, xylans and others)	7	403	28	806	56	50.0
Polymers of galacturonic methyl esters (pectins)	20	364	73	784	157	46.4
Total	**100**		**406**		**776**	**52.3**
Sugar beet silage, storage period more than 6 months						
Sucrose	30	373	112	746	224	50.0
Glucose, fructose, lactic acid, acetic acid	8	355	28	709	57	50.0
Ethanol and other alcohols	20	693	139	924	185	75.0
Polymers of hexoses (cellulose, galactans and others)	9	394	35	788	71	50.0
Polymers of pentoses (arabans, xylans and others)	9	403	36	806	73	50.0
Polymers of galacturonic methyl esters (pectins)	24	364	87	784	188	46.4
Total	**100**		**438**		**797**	**55.0**

the proportion of cell wall substances consequently increases. Seepage of effluent, which is produced in high amounts and contains high concentrations of sugar, has similar effect on cell wall content as carbon dioxide release does.

In addition to its high ethanol content, sugar beet silages always contain some methanol, which is formed during degradation of pectins. Furthermore, some higher alcohols may be formed. Nevertheless, for the entirety of alcohols, specific gas production potential of ethanol can be generalized.

As the ultimate result of all fermentation processes, the average specific gas production potential of ensiled sugar beets is markedly higher than that of fresh sugar beets. As storage length affects the content of fermentation products, two scenarios are given for silages which differ in the extent of sucrose degradation. The storage lengths given in **table 2** should not be considered generally valid. They were rather made to stress the effects of sucrose fermentation with progressing storage length until the summer. Since fermentation intensity is strongly related to ambient temperature, the described stages of development can certainly be reached also after shorter or longer storage periods.

Gas production potential of FOM

Gas production potential per kg FOM, as given in **table 3**, was calculated including the other two nutrient fractions than carbohydrates. For fermentable fat and protein, which are contained only in low concentrations in sugar beets, the mean gas production values calculated for other vegetative plant biomass (grass silage) were adopted. Gas production from fat and protein in those substrates was found to be 945 litres methane in 1,340 litres of biogas per kg fermentable fat and 365 litres methane in 714 litres of biogas per kg fermentable protein [7; 8].

Gas production potential of FOM from fresh sugar beets was found to be markedly lower than that of forages and cereals [7; 8]. This is caused by the fact that the main source of fermentable substrate in sugar beets is the disaccharide sucrose, whereas in forages and cereals the main part of fermentable organic matter consists of polysaccharides. Due to the increasing formation of ethanol during fermentation, this disadvantage of sugar beets is compensated for. Especially methane production from sugar beet silage can be substantially higher than that from other plant biomass.

The potential gas yield of fresh sugar beets can be stated to be about 375 litres methane in 750 litres biogas per kg FOM (volumes at standard temperature and pressure (STP)). Consequently, the equations for calculating the potential gas yield at STP of fresh and ensiled sugar beets are:

Biogas [litres /kg DM] = 0.750 FOM [g/kg DM] (equation 3)

Methane [litres /kg DM] = 0.375 FOM [g/kg DM] (equation 4)

For evaluating the gas yield of sugar beet silages, alcohol content has to be included in the calculation. Therefore, it is absolutely necessary to analyse the alcohol content of ensiled sugar beets. Stoichiometrically, ethanol per weight unit gives about 24 % more biogas and about 86 % more methane than does sucrose (924/746 litres per kg = 1.24 and 693/373 litres per kg = 1.86, respectively; see **table 1**).

If analysed alcohol concentrations (sum of all alcohols = AL) are given in g per kg corrected DM (DM_c), then the equations can be amended:

Biogas [litres /kg DM_c] =
0.750 (FOM + 0.24 AL) [g/kg DM_c] (equation 5)

Methane [litres /kg DM_c] =
0.375 (FOM + 0.86 AL) [g/kg DM_c] (equation 6)

Consequently, the following final equations may be proposed for calculation of the potential gas yield at STP from sugar beet silage and effluent:

Biogas [litres/kg DM_c] =
0.750 FOM + 0.18 AL [g/kg DM_c] (equation 7)

Methane [litres/kg DM_c]=
0.375 FOM + 0.32 AL [g/kg DM_c] (equation 8)

Conclusions

Organic matter of sugar beets is highly fermentable. But the gas yield per kg FOM from fresh and ensiled sugar beets is 375 litres methane in 750 litres biogas, and thus is lower than that of forages and cereals. However, during the process of fermentation, gas production potential markedly increases due to the conversion of sugar into ethanol. As a consequence, gas yield per kg FOM and particularly methane content in the biogas from ensiled sugar beets will be much higher than those from fresh sugar beets. Methane content of biogas can also be higher than in biogas from other sources of plant biomass. As the extent of sugar fermentation in the silo is subjected to significant variation, the correct evaluation of sugar beet silages (and produced effluent) for biogas production crucially requires the determination of the concentrations of alcohols and other volatile compounds, which are lost during drying.

Table 3

Table 3: Gas production potential of fermentable organic matter (FOM) from fresh and ensiled sugar beets

Fermentable nutrients	Content	Litres/kg nutrient		Methane content
	g/kg DM	Methane	Biogas	%
Sugar beets, fresh				
Carbohydrates	835	374	756	49.5
Fat	5	945	1340	70.5
Protein	50	365	714	51.1
Total (FOM)	890	**377**	**757**	49.8
Sugar beet silage, storage period up to 6 months				
Carbohydrates	835	406	776	52.3
Fat	5	945	1340	70.5
Protein	50	365	714	51.1
Total (FOM)	890	**407**	**776**	52.4
Sugar beet silage, storage period more than 6 months				
Carbohydrates	835	438	797	55.0
Fat	5	945	1340	70.5
Protein	50	365	714	51.1
Total (FOM)	890	**437**	**795**	54.9

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