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NIRS-aided monitoring and prediction of biogas yields from maize silage at a full-scale biogas plant applying lumped kinetics

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ABSTRACT

The aim of this study was to apply near-infrared spectroscopy (NIRS), available biogas plant data and lumped degradation kinetics to predict biogas production (BPr) of maize silage. A full-scale agricultural biogas plant was equipped with NIRS-metrology at the feeding station. Continuously NIR-spectra were collected for 520 d. Substrate samples were analyzed by means of feedstuff analysis. Biogas potential of the samples was calculated from the laboratory analysis results and for a sample-subset practically assessed by "Hohenheim biogas tests". NIRS-regression-models for all mentioned parameters were calibrated. Continuously gathered spectra, NIRS-models, actual plant-feeding data and degradation kinetics were used to calculate time-series of theoretically expectable BPr. Results were validated against measured gas quantity. Determination coefficients between calculated and measured BPr were up to 58.2%. This outcome was mainly due to the positive correlation between BPr and input amount since the substrate was very homogeneous. The use of NIRS seems more promising for plants with stronger substrate heterogeneity.

1. Introduction

Optimal performance of agricultural biogas plants can only be achieved when substrate is added to the reactors such that optimal amounts of nutrients are provided. Therefore, the quantity of substrate fed to the process needs to be adapted according to substrate quality. Strategies that would predict biogas yields based on the substrates' biogas potential and on conversion rates would be helpful, especially when combined with data on the ongoing process. Despite this, currently operating biogas plants have little instrumentation and rarely use the information at hand for process control (Kujawski and Steinmetz, 2009).

1.1. Substrate characteristics

A survey of 622 German biogas plants revealed that 80% of the energy produced came from crops specifically grown for energy generation, 11% from animal manure, 7% from biowaste and 2% from other residues. Maize accounted for 76% (by mass) of the energy crops, followed by grass silage (11%), whole-plant cereal silages (7%), and grains (4%). Fodder beets are considered a future crop, but are currently not of importance (1%) (Anonymus, 2011).

The composition of these substrates varies with harvest date, conservation procedure or position in the silo. For instance, Wiese and König (2009) found that dry matter (DM) of maize silage can vary over a range of more than 10% within the vertical horizon of a stack. Specific information on substrate characteristics is usually not available to plant operators, due to a lack of appropriate online-metrology. Thus substrates are fed by weight or volume, and little attention is paid to input quality. For assessment of substrate quality and expected biogas yields, samples have to be sent to specialized laboratories. Analyses are costly, time-consuming, and results are obtained with delay so that real-time adjustments of substrate input cannot be made.

A number of studies have been carried out to determine the quality of various substrates with respect to ruminant digestibility and biogas potential using near infrared spectroscopy (NIRS). All of these studies were laboratory studies, pretreating the substrate before spectroscopical analysis. The outcomes vary and are summarized in Table 1. Works on feedstock composition analysis using NIRS with fresh material also report varying results, depending on the parameter (see Jacobi et al., 2011).

1.2. Substrate conversion rate

Deterministic and complex models like ADM1 (Batstone et al., 2002) use sets of differential equations and need multiple input values to simulate substrate conversion into biogas. Besides gas production they can estimate many more process parameters like organic acid concentrations and process inhibitions. Both are of greatest interest. However, besides the need for detailed input parameters, such models rely on a set of kinetic and rate constants to determine the course of the digestion. These can often not be

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Table 1
Compilation of NIRS-calibrations for digestibility in ruminants and for biomethane potential.

Analyte	Authors	Wavelength (nm)	n^c	PC	r^2 (%)	VE	RPD	Min	Max	Mean	SD	Silage	Unit
Digestibility	Reeves et al. (1989)	1100–2500	40 (20)	n.m.	78	2.87^{SP}	2.3	55.7	86.1	74.4	6.7	Alfalfa	% DM
	Reeves et al. (1989)	1100–2500	40 (19)	n.m.	82	1.43^{SP}	2.2	72.7	89.8	82.4	3.1	Maize	% DM
	Sinnaeve et al. (1994)	400–2500	56	4	91	2.31^{SC}	3.4	67.6	91.9	80.2	7.80	Rye, clover	% VS
	Gordon et al. (1998)[a]	1100–2500	91 (45)	n.m.	68	2.70^{SC}	2.6	53.1	80.7	67.8	7.13	Grass	% VS
	Gordon et al. (1998)[b]	1100–2500	91 (45)	n.m.	88	2.60^{SC}	2.7	53.1	80.7	67.8	7.13	Grass	% VS
	Cozzolino et al. (2006)	n.m.	90	10	53	3.0^{SC}	1.3	51.0	74.0	64.0	4.00	Maize	% DM
	Liu et al. (2008)	1100–2500	107 (35)	n.m.	71	6.1^{SC}	1.7	21.7	75.4	51.7	10.6	X	% DM
	Raju et al. (2009)	n.m.	73	9	93	2.68^{RC}	3.01	~32	~72	n.m.	n.m.	Grass	% DM
	Yue et al. (2010)	1100–2500	50 (10)	11	95	9.67^{RP}	n.m.	~50	~230	n.m.	n.m.	AP	ml gas / g
Biogas production	Raju et al. (2009)	n.m.	60	11	84	37.9^{RC}	1.83	~50	~350	n.m.	n.m.	Grass	BMP
	Lesteur et al. (2011)	1668–2500	51 (23)	7	76	31^{SC}	2.36	23[d]	400[d]	234[d]	66[d]	Y	BMP

Values were rounded and units were modified if appropriate, missing values were calculated if possible.
AP = Aquatic plants; BMP = biomethane potential (ml CH_4 g^{-1} VS); DM = dry matter; FM = fresh matter; *n* = number of samples; n.m. = not mentioned; PC = principal component; r^2 = correlation coefficient of *calibration* or validation; RMSECV = root mean square error of cross validation; RMSEP = root mean square error of prediction; RPD = SD/SECV or SD/SEP; SD = standard deviation; SECV = standard error of cross validation; SEP = standard error of prediction; VE = validation errors (RP = RMSEP; RC = RMSECV; SC = SECV; SP = SEP); VS = volatile solids; X = maize, rice, wheat, sorghum; *Y* = different wastes, mainly municipal solid waste.
[a] Not ground.
[b] Ground.
[c] Test set in brackets.
[d] Calibration only.

measured and may require case dependent calibration (Wichern et al., 2007). Despite the advantages of the models' multiple output parameters until now this stands against their broad implementation in process control. A less complex approach to simulate gas production is to only consider the kinetics of the rate limiting step, e.g. hydrolysis or disintegration. These parameters have been experimentally determined in batch-assays and also for continuous laboratory or full-scale processes (e.g. Batstone et al., 2009; Mähnert, 2007).

1.3. Process state information

Biogas plants are generally equipped with metrology to continuously measure the substrate input amounts by volume and/or by weight as well as the plant output (gas flow and composition, electricity generated). Moreover temperature regulation is widely implemented, being a prime prerequisite. Information about the process itself is sometimes available in the form of continuous pH-measurements, while mostly only occasional information on biological/chemical parameters such as volatile fatty acids, nitrogen compounds and buffer capacity is gathered. Continuous monitoring of biogas plants with near-infrared spectroscopy (NIRS) has been attempted (e.g. Jacobi et al., 2009; Lomborg et al., 2009) and it was concluded that the detection of fatty acids is possible.

The objective of this study was to develop NIRS models for the prediction of the biogas potential (BP) of maize silages, based on Jacobi et al. (2011) and additional work by the authors. The models were used to predict BP of continuously gathered NIR-spectra from the feeding station of a full-scale biogas plant. From the NIRS-predicted BP-values, feeding data and simplified, lumped degradation kinetics the expected biogas yields were calculated. For validation of the results, the dynamics of such biogas yield estimates were compared with actually observed gas production dynamics of the plant through correlation analysis.

2. Methods

2.1. Biogas plant

The agricultural biogas plant (1.1 MW) consists of three process stages and is fed with maize silage 18 times per day. The daily ration is mainly fed to the main fermenter (12 feedings per day) and a smaller amount is fed to the secondary fermenter (6 feedings per day). At the plant several process parameters are measured and logged (Table 2), those relevant for this publication are explained in Section 2.8.

2.2. Sampling and sample analysis

During the period of investigation (520 d), silage samples were taken in weekly intervals and 65 of these were used for reference analysis and comprised most of the sample set. Another 20 silage samples taken from other biogas plants were also analyzed and added to the sample set. All samples of this reference sample set were kept frozen at −20 °C until analyzed. Weender analysis (Jeroch et al., 1999) was carried out yielding values for content of dry matter (DM), volatile solids (VS), crude protein (XP), crude fat (XL), crude fiber (XF) and nitrogen-free extracts (NfE) in a commercial laboratory following the methods described in VDLUFA methods book vol. III (VDLUFA, 1976–2007).

2.3. Laboratory biogas potential estimation (Hohenheim biogas test)

For experimental assessment of the samples' BP, a modified Hohenheim biogas test (HBT) (Anonymus, 2006; Ohl and Hartung, 2010) was carried out. To be able to keep the number of trials as low as possible, a subset of 30 samples evenly distributed over the range of VS-contents was selected from the reference samples.

For the HBT, samples were digested anaerobically in 100 ml-syringes, filled with 30 ml of inoculum and substrate was added to yield a proportion of 2:1 (VS inoculum/VS substrate). The substrate was milled to pass a 1 mm-mesh. In contrast to the usual

Table 2
Parameters logged at the biogas plant under investigation.

	Parameter	Units	Logging interval
Feeding events	Start time	Time and date	Every feeding (18/d)
	End time	Time and date	
	Amount fed	t	
Biogas production	Biogas flow	m^3/h	1/5 min
	Biogas temperature	°C	1/h
	Methane content	%	1/h
NIRS	Reflection spectra	% reflection	Average of 10 s/min