Reader

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IV. Conference on **Monitoring & Process Control of Anaerobic Digestion Plants**

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Poster Exhibition

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IV. Conference on **Monitoring & Process Control of Anaerobic Digestion Plants**

Background

Anaerobic digestion is a complex process of subsequent and interacting degradation steps. The requirements and standards for the operation of biogas plants are changing due to requirements of the legal side and security of supply. Thus, a precise control of this complex biological process is crucial to make the biogas production process more efficient, reliable and profitable.
Currently there is a growing need for flexibility regarding the substrate, energy and material provision (polygeneration). Thus, challenges increase for operation, monitoring and control of biogas facilities in all dimensions. Novel and optimized process monitoring and control systems are necessary to improve the performance of anaerobic digestion.
The IV. CMP International Conference on Monitoring & Process Control of Anaerobic Digestion Plants focuses on the requirements of measurement tools, best practices and practically implemented applications of monitoring and control devices.
Stakeholders in the biogas sector will have the opportunity to meet, exchange experience and get information on newest solutions to optimize the efficiency of anaerobic digestion plants from experts in the biogas field at an international level.

The IV. CMP conference is organized by

» the Research Network "Biomass energy use" of the German Federal Ministry of Economic Affairs and Energy,
» the German Biomass Research Centre (DBFZ Deutsches Biomasseforschungszentrum gGmbH),
» the Helmholtz Centre for Environmental Research (UFZ), and
» the Hessian State Laboratory (LHL)

2 DAYS
40 ABSTRACTS
29 PRESENTATIONS
& 15 POSTER FROM
8 COUNTRIES

Topics of the conference at a glance

» Modelling & simulation for process control
» AD⁺: Control of coupled processes and demand-oriented production
» Information & communication technology (ICT) and digitalization within AD processes
» Laboratory measurements: Reliability & validity
» Practical experience of process monitoring and control
» Microbiological analysis in monitoring & process control of AD plants
» Measurement technology: Sensor development & application
» Plant efficiency: Monitoring & control of the plant efficiency
» Monitoring for safety & emission reduction purposes

We wish you a most successful, enriching and instructive discussion, but also an enjoyable conference, and a very pleasant stay in Leipzig.

The organizers

PROGRAM

1ST DAY

2019-03-26

09:00
Registration

10:00
Conference opening

Session A
Laboratory measurements:

Reliability & validity
Chair: Fabian Jacobi, Hessian State Laboratory (LHL)

10:30 – 12:00
Speaker presentation 20´| Discussion 10´per each

Speaker:

1. *Francisco Raposo Bejines, Instituto de la Grasa-CSIC*
Laboratory Measurements: The Achilles´ heel for the anaerobic digestion of complex solid substrates

2. *Torsten Stefan, Christian-Albrechts-Universität Kiel /Hochschule Flensburg*
Potential of predicting Klason-lignin in digestates by calorimetry

3. *Holger Müller, BlueSens gas sensor*
Measuring instruments for determining low volume flows

12:00 – 13:00
Lunch break

Poster presentation round
Chair: Fabian Jacobi, Hessian State Laboratory (LHL)

13:00 – 13:50
5 min poster presentations

1. *Manuel Winkler, DBFZ Deutsches Biomasseforschungszentrum gGmbH*
Model-based process optimization of biogas plant operation

2. *Sasha D. Hafner, Aarhus University*
Software for measurement and prediction of methane potentia

3. *Gerhard Rettenberger, Ingenieurgruppe RUK GmbH*
Increase of safety-related requirements for biogas plants following the example of the chemical industry – development of model P&ID-flow charts with all safety-related circuits

4. *Denise Cysneiros, Jürgen Kube, Future Biogas Ltd.*
Monitoring and optimizing nine UK biogas plants: laboratory and in-situ measurements, key process indicators and data analysis and interpretation

5. *Heike Wünscher, CiS Forschungsinstitut für Mikrosensorik GmbH*
Monitoring of ammonia in biogas

6. *William Carlos Marenda, Centro Internacional de Energias Renováveis – CIBiogás – ER*
Remote monitoring of biogas plants: Brazilian case

More posters in the poster exhibition in the foyer

13:50 – 14:30
Afternoon Break and Voting for Best Poster

Session B

Modelling, Simulation & Control of ADs
Chair: Christian Wolf, Institute for Automation and Industrial IT, TH Köln

14:30 – 16:00
Speaker presentation 20´| Discussion 10´per each

Speaker:

1. *Eric Mauky, DBFZ Deutsches Biomasse-forschungszentrum gemeinnützige GmbH*
Thermodynamic modelling of gas storages for optimised demand-driven operation of anaerobic digestion plants

2. *Florian Centler, Helmholtz Centre for Environmental Research - UFZ*
Opening the Black Box: Coupling ADM1 with constraint-based methods to include intracellular activity in anaerobic digestion modeling

3. *Jürgen Kube, Future Biogas Ltd*
Optimisation of the three-stage biogas upgrading process

16:00 – 16:20
Afternoon Break and Voting for Best Poster

Session C

Batch & Interlabatory Tests
Chair: Hinrich Uellendahl, Flensburg University of Applied Sciences

16:20 – 18:30
Speaker presentation 20´| Discussion 10´per each

Speaker:

1. *Alastair James Ward, Aarhus University*
Examining the relationship between inoculum to substrate ratio and apparent hydrolysis rate in biogas batch test assays

2. *Joern Heerenklage, Hamburg University of Technology Harburger (cancelled)*
Lab tests with a mini-bioreactor test system (all-in-one) for the development of standardized and storable inocula for BMP-tests

3. *Sasha D. Hafner, Aarhus University*
Improving BMP determination with mass-based measurements

4. *Sören Weinrich, DBFZ Deutsches Biomasseforschungszentrum gGmbH*
Value of batch tests for estimating biogas potentials and degradation kinetics in anaerobic digestion

5. *Mark Paterson, Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL)*
Experiences from the KTBL/VDLUFA Inter-Laboratory Test Biogas regarding the biogas yield determination in batch tests

19:00 Guided City Walk
"Peaceful Revolution"

20:00 | Networking dinner & Winners of the BEST POSTER AWARD
Moritzbastei Leipzig
Kurt-Masur-Platz 1, 04109 Leipzig
www.moritzbastei.de

2ND DAY

2019-03-27

Session D

Microbiological analysis: Potential for process monitoring and control of AD plants

Chair: Sabine Kleinsteuber, Helmholtz Centre for Environmental Research - UFZ

09:00
Conference opening

09:15 – 10:45
Speaker presentation 20´| Discussion 10´per each

Speaker:

1. *Denny Popp, Helmholtz Centre for Environmental Research - UFZ*
Metabolism-centered predictive modeling of Anaerobic digestion of biogas production

2. *Niti B Jadeja, National Environmental Engineering Research Institute, CSIR*
Microbiome analysis to understand the biotransformation reactions responsible for conversion of food waste to energy in Biogas reactors

3. *Anko Fischer, Isodetect GmbH*
Evaluation of the process performance at commercial biogas plants using compound-specific stable isotope analysis (CSIA) during anaerobic digestion

10:45 – 11:15 | Morning break

Session E

Monitoring of Plant Efficiency in Full-sc ale

Chair: Frank Schwolwin, Institute for Biogas, Waste Management & Energy

11:15 – 13:15
Speaker presentation 20´| Discussion 10´per each

Speaker:

1. *Johan Grope, Institute for Biogas, Waste Management & Energy*
Challenges in data acquisition and application for biogas process modelling in practice

2. *Anne Geißler, Technische Universität Dresden*
Process control of a high-performance hybrid reactor as a methane stage for biomass with high nitrogen content

3. *Wolfgang Pfeiffer, University of Wismar*
Control of alkalinity of a full-scale biogas plant treating waste water from the cleaning of car tanks transporting food and fodder, adaption of biogas production to the demand and verification of Nordmann titration method for measuring VOA and alkalinity

4. *Karlheinz Meier, BayWa r.e. Bioenergy GmbH*
Monitoring of (manufacturer independent) biogas plants with evaluation of all the data of necessary data points

13:15 – 14:00 | Lunch break

Session F

Developments & Perspectives in Process Control

Chair: Alastair James, Ward Aarhus University

14:00 – 15:30
Speaker presentation 20´| Discussion 10´per each

Speaker:

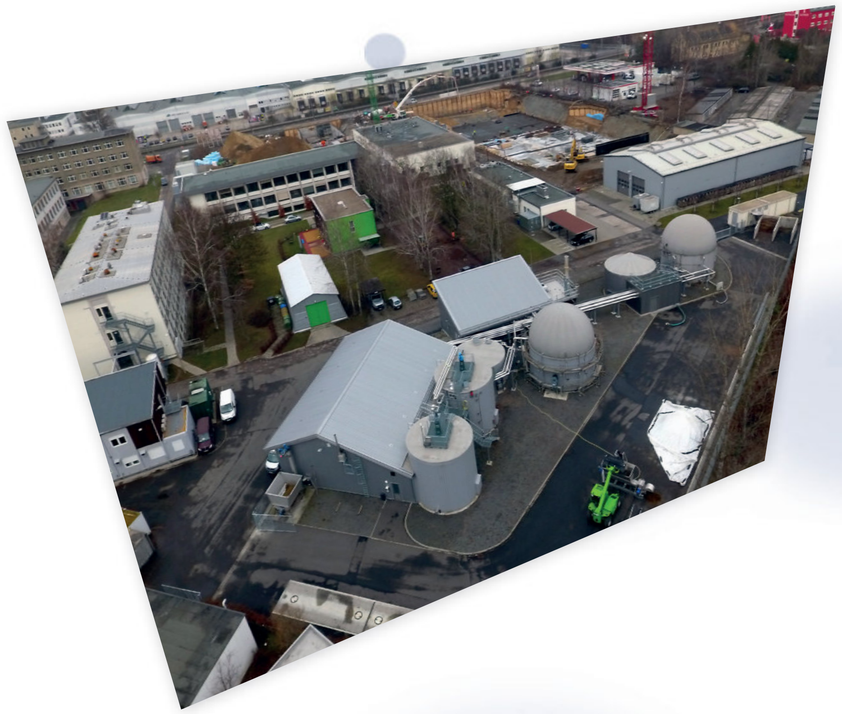
1. *Robin Eccleston, TH-Köln*
Determining conditions of intermittently fed digesters from biogas production rate data

2. *Stefan Junne, Technische Universität Berlin*
Evaluation of pre-treatment methods by in-line particle size distribution monitoring with laserlight backreflection

3. *Niloofar Raeyatdoost, TH Köln*
Flexible methane production using PI Controller with simulation based soft sensor

15:30– 15:35
Conference closing

16:00 – 17:00
Guided tour to the AD research plant
DBFZ | Torgauer Straße 116 | 04347 Leipzig
(Meeting point 15:45 at the registration desk in the KUBUS)



ABSTRACTS

Francisco Raposo Bejines

Laboratory measurements: The Achilles´ heel for the anaerobic digestion of complex solid substrates

Analytical methods, chemical oxygen demand, fat, fibre, moisture, protein

Background/motivation

The solid substrates are characterized using a few analytical methods to provide information about the content of water/ash and also for the overall organic matter (volatile solids and COD). In addition, it is usual to include more specific organic composition in form of the content of fat, fibre and protein. These determinations are carried out by wet chemistry methods that can be classified as empirical methods. Therefore, the results are obtained by indirect measurement of the analyte of interest and unfortunately, the results are in part or in whole dependent on the conditions of the assay.

Aim of the work

Since the anaerobic digestion community has not yet come to a consensus on what empirical method is best suited for the analysis of solid substrates, many different empirical methods are used among laboratories and even within a single laboratory. This situation provides some lack of reliability in the analytical results due to the frequent significant variation among different laboratories.

Key research topics and novelty

This proposal is not a specific research study. It can be considered as a summary of the troubles found at the routinely laboratory work to determine the content of ash, COD, fat, fibre, moisture and protein. Also some recomendations can be provided to the most applicabble analytical methods used in the characterization of solid substrates for anaerobic digestion procedures.

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Torsten Stefan[1], René Casaretto[2]

Potential of predicting Klason-lignin in digestates by calorimetry

 # Digestates, Klason-lignin, gross calorific value, efficiency

Evaluating the efficiency of the digestion process of biogas plants based on energy inherent in the used biomass seems advantageous for comparison with other biomass conversion processes. However, for process optimization of anaerobic digestion it is necessary to quantify the portion of energy in substrates and/or digestates, which can be anaerobically converted to biogas.

Digestates from agricultural biogas plants typically contain lignin as anaerobically non-degradable organic matter. Therefore, it is necessary to know the energy content of the lignin and non-lignin portion to calculate the anaerobically available residual energy potential of digestates. Idea of this work is to predict the lignin content from the same calorimetric measurement, which is used to calculate the total energy of the material streams. This idea is based on the fact, that lignin has a distinctly higher calorific value than the residual polysaccharide fraction (hemicellulose/cellulose fibres).

According to our previous research, the content of acid detergent lignin (ADL) in digestates can be predicted by gross calorific values (GCV) in the studied range from 0.03–0.36 [kg/kg-ODM] with an accuracy of ± 0.086 [kg/kg-ODM] (± 2*RMSECV) by a linear regression model, adj. R^2=0.89 (Study submitted to Biomass & Bioenergy is in review process). However, Jung et al. (1999) reported, that the ADL-method underestimates the total lignin content, other than the Klason-method. So the aim for the present study was to try the Klason-method for the determination of lignin to improve the estimation of lignin from gross calorifc values.

Digestate samples from 34 commercial scale biogas plants were analysed for dry matter (DM), organic dry matter (ODM), gross calorific value, Klason-lignin (KL), water- and ethanol-soluble extractives and residual biomethane potential. Thirty of these samples were additionally analysed for (lignocellulosic) sugars in the hydrolysate from the Klason-lignin-extraction. Several uni- and multivariate linear regression models based on both DM- and ODM-specific parameters were tested for correlation with the Klason-lignin content. Information about the substrate composition and the hydraulic retention time of the sampled biogas plants were used additionally in some models.

Correlation between KL and GCV was significant, but low with adjusted R^2 = 0.14 (ODM-based). RMSEcv for prediction of KL is 3.7 [% ODM] and therefore better than the ADL-model from our previous study (4.3 [% ODM]). However, the smaller prediction error, despite low R^2, can be explained by the relatively small spread of the measured KL values in the examined population (95 % of all data points for KL fall in a range of ± 4.7 [% ODM] around the mean with 34.9 [% of ODM]). The measured GCV from 19.8 to 24.3 [MJ/kg-ODM] shows the low sensitivity for the prediction of KL, which ranged from 22.4 to 42.3 [% of ODM].

A possible influence of the substrate composition of the sampled biogas plants on the correlation between KL and GCV due to variation in structure of extracted KL (Horst et al. 2015) – examined by adding interactions between GCV and substrate composition to the model – was not recognizable. The best adj. R^2 was achieved using GCV, lignocellulosic sugars and extractives as explanatory variables, resulting in adj. R^2=0.61. However, further chemical analysis of the samples leads to higher analytical demand – in this case lignocellulosic sugars and extractives which contradicts the idea of the study (easy and cheap method) and does not offer any obviously benefits instead of measuring the Klason-lignin directly.

The residual biomethane potential showed no correlation with the KL-fraction (R^2 = 0.02). Therefore, KL does not seem to be a good predictor for the anaerobically degradable/non-degradable organic portion of digestates. In combination of all results, the Klason-method for lignin determination shows no advantage over ADL-methodology. Concluding from the examined data set, calorimetry is not an appropriate method for predicting Klason-lignin in digestates from anaerobic digestion.

References

Horst, D. J.; Behainne, J. J. R.; Junior, de Andrade, P. P.; Serpe, L. F. (2015): Assessing the Lignin Fraction Extracted from Brazilian Energy Crops. In: *American Journal of Environmental Sciences* 11 (1), S. 46–54. DOI: 10.3844/ajessp.2015.46.54.

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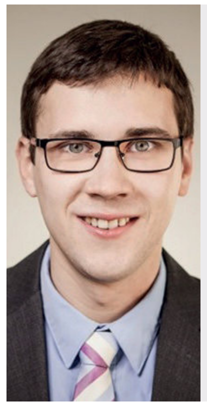

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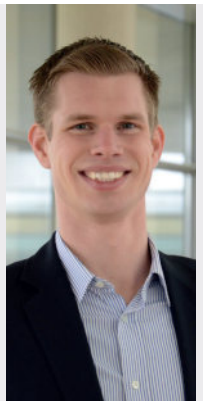

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Holger Müller[1], Udo Schmale[1], Markus Huth[2], Rainer Tölle[3]

Measuring instruments for determining low volume flows

Gas meter, Magnetic Stroke Counter, Biogas, Wastewater)

Background/motivation

In the case of metabolic processes on a microbiological basis, gas metabolisms provide information on the type and intensity of the processes taking place. For process analysis are high-resolution measurements of gas formation or gas consumption of microbiological cultures of great interest. Together with the chemical composition of the gases, which changes also over time, conclusions can be drawn on the material transformations that take place.

Aim of the work

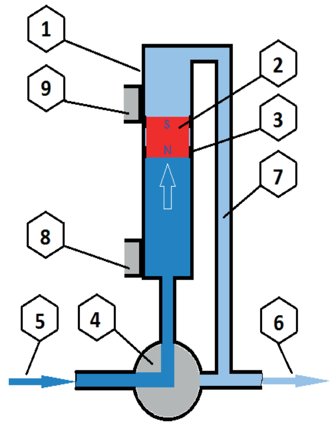
The aim of the work is the provision of gas measurement technology especially for low volume flows as they typically occur in microbiological laboratory investigations. During the measurement, the composition of the material flows consisting of different gases should not change. A large dynamic range in the volume flow of 1 to 10,000 is to be realized. At the same time, the technology must manage without a minimum volume flow.

Key research topics and novelty

The devices presented are optimized for use in biogas and wastewater laboratories. The measuring range covers a volume flow rate from 0 mL/h to 5,000 mL/h. In addition, the devices can be used with reduced accuracy up to 12,000 mL/h. The resolution of the volume measurement per measuring cycle is 1 mL standard gas. The overpressure required for operation is > 4 hPa. A pressure above 40 hPa activate a safety valve function. In special products the resolution could be scalable from 0.1 to 10 mL per measuring cycle.

Methods – Measuring principle of the magnetic stroke counter

The magnetic stroke counter works according to the principle of a positive displacement meter. The force effect caused by a gas flow on a piston in a guide tube compensates the counterforce of the piston weight. This builds up a pressure of approximate 4 hPa on the side of the gas source. This gas pressure raises the permanent magnet piston until a magnetic sensor actuates the valve and releases the gas outlet. The number of piston movements carried out periodically determines the moved gas volume. (Fig. 1)



The magnetic stroke counter works with a microcontroller, which reads the magnetic sensors and actuate the valve. The microcontroller also serves to convert the volume flow to the standard conditions of 1013.25 hPa, 0 °C and without the water vapor contained in saturation.

Results

Possibilities and limits of measurement technology are presented in the context of a method comparison. The results of a test on the residual gas potential of digested slurry are used for this purpose. The gas development of the samples was recorded for 60 days at a temperature of 20 °C and compared with conventionally determined measured values.

References

Huht, M.; Tolle, R.; Schmidt, U. (2018): Messgeräte zur Bestimmung geringer Volumenströme in Biogasversuchen. In: *Tagungsband zum 11. Biogas-Innovationskongress 2018*, pp. 69 – 75, PROFAIR Consult + Project GmbH (Ed.)

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Thermodynamic modelling of gas storages for optimised demand-driven operation of anaerobic digestion plants

Gas storage, modelling, prediction, demand-driven, emissions

The changing conditions within the energy sector in Germany force biogas plants to meet new requirements as flexible supply of electricity for compensating the divergence between energy demand and energy supply by uncontrolled sources like wind and solar power (Lund et al. 2012). In order to meet these new requirements, the biogas production needs to be increasingly adjusted to the demand of a flexible conversion rate. As shown in (Mauky et al. 2016, 2017) one part of the solution can be flexible feeding management. A feeding management requires a precise measurement of the resulting variable gas flow rates and a regulation by a precise plant-wide gas management, which optimizes the utilization of the existing storage capacity.

In the particular case of flexible plant operation, a reliable monitoring of the gas storage filling level is the crucial task of a gas management, since it specifies the switching points for CHPs and the gas flare. Furthermore, the gas utilization strategies have to be adapted to the changing weather conditions, which influencing the usable gas storage capacity. An effect of inaccurate measurements can be an overestimation of the available storage volume and consequently the unintentional blowing off of biogas by the overpressure safety device when the maximum filling level is exceeded (see Reinelt et al. 2016).

In the research project "ManBio" (BMWi Project ID: 03KB094), it was the aim to develop technical measures to improve the gas management of biogas plants. On the one hand, different measuring systems for gas storage filling levels were compared and optimized. On the other hand, influencing variables to the available gas storage capacity (e.g. temperature, wind force and solar radiation) were mapped in a thermodynamic gas storage model in order to be able to predict and control the gas storage level in a forward-looking manner. Based on weather forecasts and process data, it is therefore possible to recommend the advance adaptation of the feeding or electricity generation regime to prevent under- or over-production.

In the case of temperature measurements on the outer side of the light gray protective membrane of the DBFZ research biogas plant, surface temperatures of up to approx. 68 °C by IR-measurements were determined during direct sunlight Figure 1 (left). This consequently also led to temperature rises in the interior of the gas storage. Figure 1 (right) illustrates the dependence of the net gas storage capacity on the internal gas temperature in a computational example.

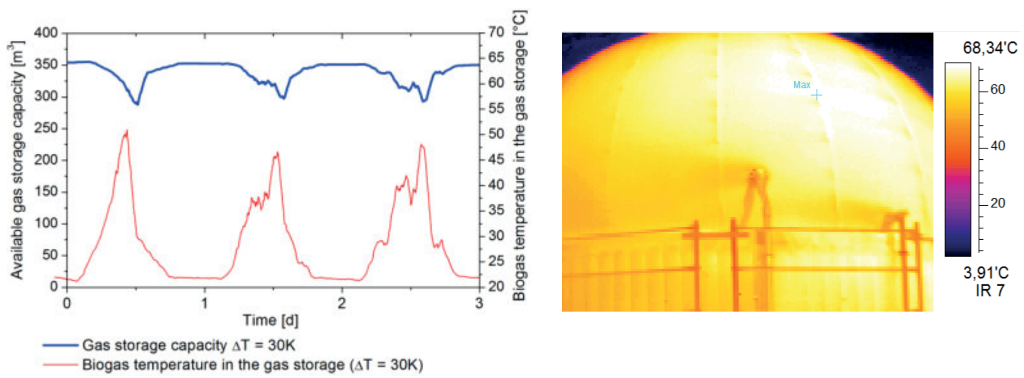

Figure 1 (right) Temperature effects on the available gas storage capacity; (left) surface temperatures of up to approx. 68 °C on the outer side of the light gray protective membrane of the DBFZ research biogas plant / Picture by IR- camera (Mauky/DBFZ).

A reduction in the net gas storage capacity by up to 20 % results for a temperature change of 30 K in the gas storage interior during the course of one day.

These measured temperature spreads can be transferred to other practical biogas plants. Under certain operating conditions, this can lead to an unscheduled reaching of technically full gas storage with a triggering of the overpressure relief. Therefore, the targeted management by predictive thermodynamic models of the gas storage tank contributes to a reduction in the losses caused by flare-off or blow-off of potential gas overproductions. A advanced feeding and gas management are recommended, as this makes it possible to optimize flexibility, operational safety and efficiency. Biogas plants can offer a wide range of services to balance demand and production, but also to stabilize the grid.

The presentation will be focus on the Model description and the discussion of monitoring Results from the used research biogas plant.

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Opening the Black Box: Coupling ADM1 with constraint-based methods to include intracellular activity in anaerobic digestion modeling

 # Anaerobic Digestion Model No.1 (ADM1), flux-balance-analysis (FBA), constraint-based modeling, meta-omics

Since more than 15 years anaerobic digestion has been modeled predominantly by ordinary-differential-equation-based (ODE) models such as ADM1. These models resolve individual process steps but do not consider the phylogenetic diversity at these steps and neglect species-specific microbial activity. In the meantime, meta-omics techniques including metagenomics, metatranscriptomics, and metaproteomics have led to the elucidation of microbial activity down to the enzyme level for individual genera, providing an unprecedented view on the intracellular activity of microbes embedded in complex communities. However, such data is difficult to integrate with common ODE-type models covering anaerobic digestion. Instead, they can be incorporated with constraint-based modeling techniques such as Flux-Balance-Analysis (FBA) that consider the intracellular metabolic network of microbes up to the genome-level. FBA allows for the prediction of specific growth rate and metabolic turnover for individual species based on its metabolic network, its biomass composition, and available substrates. This genotype to phenotype mapping relies on the assumption that intracellular metabolites are at steady state and that the cell orchestrates its metabolic flux distribution for optimal growth. A FBA simulation additionally delivers flux values for all enzymatic reaction steps contained in the metabolic network, providing a rich data set which can be compared to omics data sets delivering information on enzymatic activity. To harness the power of this modeling technique in anaerobic digestion research, we constructed a hybrid model that, relying on a mass-based version of ADM1, considers acetoclastic and hydrogenotrophic methanogenesis by FBA models of *Methanosarcina barkeri* and *Methanococcus maripaludis*. We first compare simulated steady-state results of ADM1 with our novel hybrid model and then consider a dynamic simulation in which a continuous feeding of maize silage is switched to a pulsed daily feeding. While both the ADM1 and the hybrid model agree well regarding predictions of process performance, differences regarding microbial activity predictions are observed for the dynamic simulation, which remain to be confirmed by experimental evidence. Demonstrating the technical feasibility of coupling ADM1 with constraint-based modeling, we envision a new era of simulation models for complex microbial communities which do no longer merely focus on individual chemical conversion steps, but are able to explicitly take into account microbial diversity and metabolic capacities of individual community members. Such models incorporate a more faithful representation of microbial activity in complex communities and will be elemental in gaining a better control of processes driven by these systems.

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Optimisation of the three-stage biogas upgrading process

 # Biogas upgrading, Gas permeation, Membrane separation, Non-linear optimisation, boundary value problem

The energy demand of a biogas upgrader is one of the largest cost items of a biogas plant. Typical upgrader processes driven by electric energy require 0.20 to 0.30 kWh per Nm³ raw biogas processed. An average sized gas-permeation, water-scrubber or organic scrubber-upgrader therefore uses 200 to 400 kW electric energy. Part of operating excellence is the identification of optimisation potentials for new and existing upgrader plants. Reducing the power demand of the upgrader while maintaining or improving the recovery rate will lead to significant economic savings and will improve the sustainability of the biogas plant.

Two methods for the optimisation of biogas upgraders are described. The first method is the mechanical modelling of a gas-permeation process and the optimisation of the model using non-linear optimisation with batch The three-stage gas permeation process for a gas mixture of four components (CH_4, CO_2, N_2, O_2) is modelled as a system of 12 coupled boundary value equations. The equations have a singular boundary value at the retentate outlet side of the membrane, when the permeate flow becomes zero, requiring simultaneous solving of the BVP and a nonlinear algebraic equation system. The solution is then subjected to a non-linear optimisation routine using the fmincon-algorithm in MATLAB.
The result of the optimisation is a set of optimal temperatures and number of membranes per stage plus two pressures governing the process and controlling the gas qualities of the product and lean gas (see figure 1). Further the impact of increased membrane surface and selectivity, changes of setpoints or the addition of permeate compression can be investigated under optimal conditions.

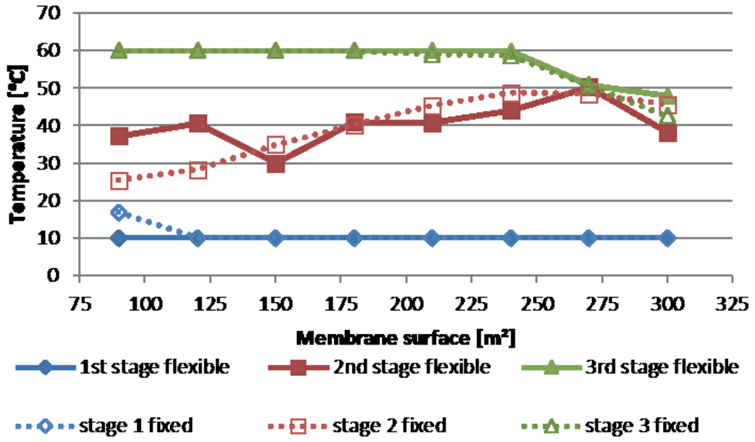

Figure 1 Optimal inlet temperatures of every stage as a function of overall installed membrane surface for a inlet gas flow of 900 Nm³/h biogas with 50 % CH_4. The constraints are 1.5 % CO_2 in the product gas and 1 % CH_4 in the lean gas. Optimisation parameters are the temperatures at the inlet of every stage, the retentate pressure of the second and third stage. The number of membranes per stage are either fixed in a ratio of 1:1:1 (open symbols) or optimisation parameters as well (closed symbols).

The optimal configuration of a three-stage upgrader is surprisingly straightforward. The first stage should be operated at low temperatures at high selectivity, the third stage should operate at low selectivity and high capacity, i.e. high temperatures. The distribution of membranes amongst the stages barely has an impact on the power uptake, they can be distributed in a ratio of 1:1:1. Existing gas-permeation upgraders can be easily readjusted to optimal process parameters for a reduction of energy demand.

If no mechanical model of the upgrader process can be obtained or it is too complicated for calculation, a new method (Kube 2018) can be used to optimise existing upgrader units. The method is based on the gradient descent method, but it is extended to fulfil constraints, so the energy demand of the upgrader can be optimised while maintaining or even improving gas qualities of product and lean gas. The method can be used on all kind of upgraders and is not limited to gas permeation. It can be implemented as an on-line process control function to allow the upgrading unit to automatically adjust its operation parameters to optimize power uptake or throughput.

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Examining the relationship between inoculum to substrate ratio and apparent hydrolysis rate in biogas batch test assays

Biogas, process control, spectroscopy

Finding the apparent hydrolysis rate khyd (measured as the gas production rate) of a continuous biogas process takes a lot of time and measurement. Simple batch tests provide useful data in terms of the methane potential, but the apparent hydrolysis rate is dependent on the interaction between the inoculum microbial community and the physical and chemical nature of the substrate. For the same substrate and inoculum source, the inoculum to substrate (I:S) ratio is a very important parameter in batch tests. Standardised batch test protocols (Angelidaki et al. 2009) suggest an I:S of 2:1 (in terms of volatile solids or chemical oxygen demand) will ensure there is a sufficiently high microorganism density to achieve digestion without inhibition. However, the relatively high single organic load certainly reduces the apparent hydrolysis rate when compared to the smaller organic load experienced at a higher I:S ratio (Ward et al. 2018). Using a higher I:S in batch assays will give a k_{hyd} that is comparable to a continuous process (Ward et al. 2018) but tends to increase the error in the results. This is because of the natural biogas production from the inoculum, despite attempts to “de-gas” prior to preparing the batch assay bottles. Biogas production from substrates is calculated by subtracting the inoculum gas production measured in control assays, therefore with a greater proportion of inoculum there will be a corresponding increase in the proportion of inoculum gas production relative to gas production derived from the substrate.

As shown by Ward et al. (2018) in an experiment using cattle manure, high I:S ratios of 6:1 and 12:1 showed very small differences to each other in terms of k_{hyd}, whereas a 1:1 ratio showed a khyd value that was considerably lower than a 2:1 ratio, which in turn was considerably lower than 6:1 or 12:1 ratios. It was therefore hypothesized that khyd will reach a maximum at an I:S where microorganism density is not rate limiting. This study examines the relationship between I:S ratios and khyd with the aim of producing a conversion factor to adjust measured khyd in batch assays at the recommended (and relatively low) I:S of 2:1 to a k_{hyd} where microorganism density is not rate limiting. The work is intended as a follow up to Ward et al. (2018) where k_{hyd} values were established for estimation of continuous process yields.

Batch assays have been prepared using three substrates (maize silage, meadow grass and wheat straw) and six different I:S ratios. I:S ratios were: 1:1, 2:1, 4:1, 6:1, 8:1, 12:1, and 16:1, the 1:1 ratio reflecting methodology used by some authors. The assays were set up in 1 litre bottles with butyl rubber caps, with a total inoculum and substrate mass of 500 g in each bottle. Control bottles containing inoculum only were also included. All assays were conducted in triplicate and incubated at 35 °C until gas production became negligible. Produced gas volume was measured by acidified water displacement (3) at intervals dependent on the rate of gas production. Sub samples of biogas were collected for compositional analysis by gas chromatography.

Results are not available at the time of writing, but first order models will be fitted to the gas production data to provide k_{hyd} values. The k_{hyd} values will be examined in relation to the I:S ratio and curves will be fitted to establish a relationship between these two parameters. Special attention will be given to the error between triplicates, as it is expected that this value will increase at higher I:S.

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Lab tests with a mini-bioreactor test system (all-in-one) for the developement of standardised and storabel inocula for BMP-tests

BMP-Tests, biogas, mini-bioreactor, test system, inocula

In the context of anaerobic batch tests (BMP), different origin of inocula might cause significant variations of test's results (Raposo et al. 2011; Hagen et al. 2015; Holliger et al. 2016; Koch et al. 2017), preventing from acquiring reproducible and uniform applications. The Hamburg University of Technology (TUHH) intends to develop a method to produce standardised and storable inocula for BMP tests. The aim is to provide a range of inocula for different substrates and research methods, which can be applied in research as well as in industrial applications (Heerenklage et al. 2017). As a long term preservation method for anaerobic inocula, freeze-drying was examined. Comprehensive studies of preservation through lyophilisation were implemented using two anaerobic inocula (mesophilic and thermophilic), which were produced on the basis of thin sludge under standardised conditions and a selected sludge of a wastewater treatment plant (mesophilic). For the investigation of the different treatment steps a so called "All-in-one" mini-bioreactor test system (MBR) was developed with specific requirements
» Low volume assay system for inoculum screenings, » Anaerobic conditions and gas tightness within all process steps, » Possibility of obtaining parallel quantity and quality assessments of solid, liquid and gas phases a various treatment and cultivation steps, » Simple and cost-effective analysis of biogas production.

The identified requirements could be fulfilled by "All-in-one" test system that consists of mini-bioreactors (MBR) with a maximum volume of V = 25–50 mL. The main advantage of such a system is the realization of all process steps, namely: sample preparation (incubation and centrifugation), lyophilisation and anaerobic digestion according VDI 4630 (2016) in the same reactor. Moreover, the different preparation steps and procedures were continuously optimized within the frame of this research. A general and simplified scheme of "All-in-one" MBR – test system is shown in Figure 1.

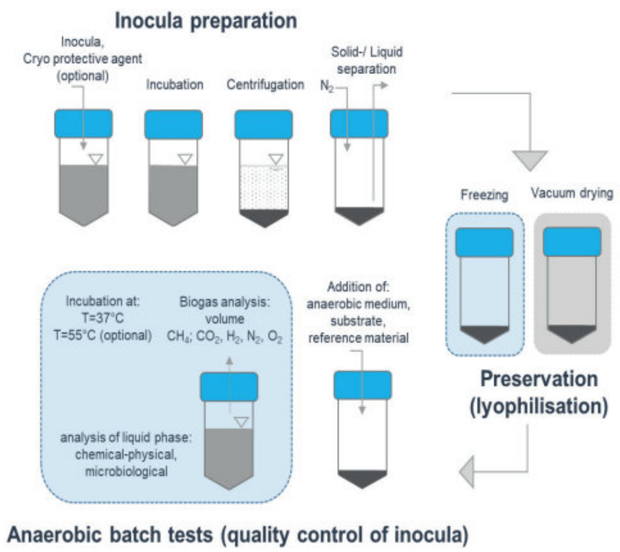

Figure 1 General and simplified scheme of "All-in-one" mini-bioreactor test system (MBR)

The test results showed that a preservation of inocula, which are produced under standardised conditions, is possible. The following anaerobic batch tests of the resuspended inocula showed a high recovery of expected methane production. However, obtained results indicated a lag phase of 7–10 days within the methane production, which is possibly occurring due to the cell damage of microorganisms, as a consequence of the preservation process. Research activities of Bhattad et al. (2017) reported similar lag phase duration. Further investigations will be carried out to optimise the preservation process of the produced inocula for the aim of decreasingthe lag phase.

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Improving BMP determination with mass-based measurements

 # Biogas, biochemical methane potential (BMP), gravimetric, laboratory methods, gas density

Measurement of biochemical methane potential (BMP) is essential for both research and optimal operation of biogas plants. But multiple blind comparisons have shown that large biases in BMP measurement exist among laboratories. Although the use of commercial, automated systems can reduce variability, purchase costs are high. Conversely, simple manual methods require less expensive equipment, but accuracy may be poor, and labour costs can be high. The aim of this work is to describe recent developments in mass-based measurements of BMP that can improve the accuracy of BMP measurements and reduce costs.

Measurement of BMP bottle mass loss in response to removal of biogas provides accurate and relatively sensitive determination of CH_4 production (detection limit of 10 mL). The general approach was first described nearly 30 years ago (Richards et al. 1991), and recently refined (Hafner et al. 2015). Free software provides access to data processing algorithms (Hafner et al. 2018a). A typical laboratory scale with a readability of 10 mg and limit of 2 kg is more than sufficient for most BMP trials. Unlike conventional manometric and volumetric methods, this gravimetric approach is not affected by leaks, and is much less sensitive to headspace pressure and temperature. One drawback is a higher sensitivity to error in CH_4 concentration (ca. 8 % error in CH_4 production for an error of 3 % volume). The method also has lower sensitivity than conventional volumetric and gravimetric alternatives, but this difference is less important than differences in accuracy. New measurements comparing manometric and gravimetric approaches showed similar random error, but much smaller effects of headspace pressure and volume in gravimetric results (Fig. 1).

In many BMP methods it is taken as a matter of faith that biogas leakage is not significant, but recent work shows this may not be true. Measurement of mass loss during bottle incubation provides a simple way to detect, and even correct for, leakage (Hafner et al. 2018b). In general, losses as low as 10 % of total biogas production can be detected. Application of the method in three trials showed some detectable leakage in each trial, suggesting that researchers should regularly check for leakage. New results comparing three types of 20 mm setpa show that common thin (3 mm) butyl septa may leak above a pressure of 1 bar (gauge), while thicker (13 mm) butyl septa are more reliable (Fig. 1).

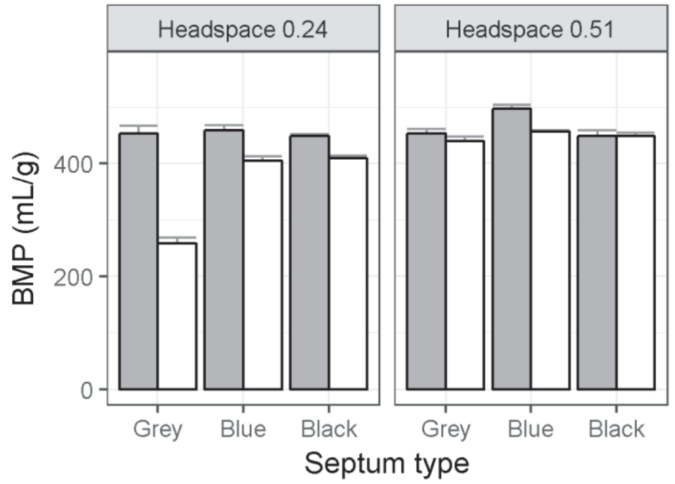

Figure 1 Comparison of manometric (light grey) and gravimetric (dark grey) measurement of BMP of primary wastewater sludge (n = 3 bottles, bars show standard deviation). Measurements were made using three types of septa and two headspace fractions (headspace was 24 % or 51 % of the total bottle volume). Grey septa used with the lower headspace volume (and higher headspace pressure) lost 25 % of biogas production to leakage.

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The latest developments in gravimetric BMP measurements have been focused on elimination of the need for gas analysis. Gas chromatography requires relatively expensive equipment and is not an option for research groups or companies without sufficient funding. By adding simple volumetric measurements to the gravimetric BMP method, resulting estimates of gas density can be used to calculate CH_4 concentration. New results comparing this proposed gas density (GD) approach to a conventional volumetric approach show the new method has promise: BMP values calculated with the two methods were generally within 6 % of each other, with a maximum difference of 9 % for ethanol (Table 1). Sampling effort is low in the GD method: 2–3 min. per bottle per sampling event.

In conclusion, gravimetric approaches have the potential to improve BMP measurement through: 1) better accuracy, by eliminating the effect of leaks and biases related to manometric and volumetric measurement, 2) lower cost, by reducing equipment and labour needs, and 3) accessibility, by eliminating the need for biogas analysis.

Table 1 Biochemical methane potential (BMP) of five substrates measured using a conventional volumetric method and the new gas density (GD) method. For all conditions, n = 3 bottles. Substrates A, B, and C were animal feed ingredients.

	Volumetric BMP (mL/g)		GD BMP (mL/g)	
Substrate	**Mean**	**Std. dev.**	**Mean**	**Std. dev.**
A	378	15.0	369	29.5
B	371	17.4	357	53.4
C	517	33.4	488	73.0
Cellulose	380	63.6	381	63.1
Ethanol	710	37.6	651	74.0

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Value of batch tests for estimating biogas potentials and degradation kinetics in anaerobic digestion

 # Anaerobic batch test, biomethane potential (BMP), degradation kinetics

Introduction

The maximum methane potential as well as the effective degradation kinetics of individual substrates are key parameters for profound substrate characterisation and efficiency evaluation of anaerobic digestion plants. They are crucial quality criteria for monetary rating of different substrate types or pre-treatment methods and enable reliable process balancing or design.
Commonly, the methane potential and the degradation kinetics (e.g. first-order reaction constants) of utilised substrates are determined based on laboratory batch tests. Due to extensive research and comparative inter-laboratory tests the standard protocols (such as VDI 4630) for the conduction of anaerobic batch tests have been optimise and standardised in the past years. However, the results of biomethane potential (BMP) tests are still affected by numerous influencing factors (Holliger et al. 2016). Furthermore, the validity of batch tests to describe effective degradation kinetics (and underlying methane potential) of continuous operated anaerobic digestion processes is rarely investigated or proven in detail (Batstone et al. 2009, Jensen et al. 2011).
The current contribution presents a critical comparison and detailed evaluation of batch test results, continuous operated laboratory experiments and available calculation procedures for estimation of the BMP and kinetic parameters during anaerobic digestion of maize silage.

Material and methods

To depict inter-laboratory variation parts of the presented investigation is based on the comprehensive database of the KTBL/VDLUFA Proficiency Test Biogas (2018). In the national inter-laboratory test results from experimental batch tests and nutrient analysis of various substrates were measured in participating laboratories. Basic requirements for the conduction of BMP test are in compliance with the VDLUFA (2011) or VDI 4630 (2016) guideline. Analytical determination of individual nutrients is based on Weender and van Soest method (Liebetrau et al. 2015) which both originated from feedstock characterisation for livestock husbandry.

<u>Comparison of batch test result and available calculation procedures for BMP determination</u>
For a comparison of available methods for BMP determination a single sample of maize silage was analysed in batch trials and also evaluated utilising calculation procedures (digestibility analysis and regression models in Weinrich et al. 2018) based on nutrient analysis measured in participating laboratories during the KTBL/VDLUFA Proficiency Test Biogas (2018).

<u>Comparison of degradation kinetics measured in discontinuous (batch) and continuous operation</u>
Furthermore, the same sample of maize silage was also digested in continuous operated laboratory reactors (10 L) until steady state conditions were attained. Methane production rates were logged during continuous experiments. Standard process analytics (such as pH, total VFA or NH4-N concentrations) were measured weekly to ensure uninhibited process conditions. To assess degradation kinetics in batch and continuous operation mode a simplified model based on first-order kinetics was applied to simulate methane production.

Results and Conclusions

The batch test is an established laboratory test setup for the determination of the biogas potential and degradation kinetics in anaerobic digestion. However, due to numerous influencing factors the general validity and comparability of batch test results are still not proven or rarely investigated in detail.

Comparison of batch test result and available calculation procedures for BMP determination
Depending on the utilised inoculum, measuring equipment and experiment conduction inter-laboratory investigations still reveal a significant variability of BMP test results (Weinrich et al. 2018). Calculation procedures for the determination of the BMP based on nutrient analysis show a significant lower variability in the results, but limited correlation with batch tests. Furthermore, mean values and respective ranges of utilised regression models scatter widely as well. In accordance to the investigation of Rath et al. (2015) the method of Weissbach (2008) based on degradability analysis shows the best accordance to the mean value of the inter-laboratory tests results. Generally, chemical analysis come with less effort than the biological batch test and are consequently an easier way to analyse the inhomogeneity and the variability of the substrate characteristics over time. However, any chemical analysis needs information on the substrate type and the availability of reference values to determine the degradable fraction of the substrate and the share of biomass consumption for microbial growth.

Comparison of degradation kinetics measured in discontinuous (batch) and continuous operation
Kinetic constants estimated in individual batch trails during inter-laboratory testing tend to underestimate the biogas potential and degradation kinetics in continuous operation mode. These findings are partly confirmed in literature. Thus, Batstone at al. (2009) or Jensen at al. (2011) also report higher specific methane yields and faster degradation kinetics during continuous operations in comparison to results of anaerobic batch test of the utilised substrates.
A further revision of available protocols and identification (and elimination) of causes for variability is needed. Additional inter-laboratory tests (including continuous experiments and chemical analysis) are necessary for further improvement of BMP test execution.

Thus, the presented evaluation procedure demonstrates an objective methodology to assess general validity and comparability of batch test results, available calculation procedures or continuous experiments for a reliable and precise determination of biogas potentials and degradation kinetics in anaerobic digestion.

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Experiences from the KTBL/VDLUFA Inter-Laboratory Test Biogas regarding the biogas yield determination in batch tests

Inter-laboratory test, biogas potential, residual methane potential, batch tests

Background/motivation

Since 2006, the German Association for Technology and Structures in Agriculture (KTBL) together with VDLUFA Quality Assurance NIRS carries out the proficiency test biogas (also referred to as inter-laboratory test) for biogas laboratories with different experimental setups (batch tests) on a regular basis. The number of participating laboratories from Germany and abroad varies between 20 and 30 per year

Aim of the work

The aim of the KTBL/VDLUFA-Proficiency Test Biogas is essentially a comprehensive quality-assurance of biogas laboratories in the determination of biogas yield and residual methane potential by means of discontinuous laboratory tests. To this end, possible influencing factors and causes of deviations in the measurement results are analysed in order to increase the measurement accuracy of the biogas laboratories. This improves the comparability of the results of fermentation tests.

Methods

In order to obtain a uniform procedure and a good basis for the comparison of the test results, the VDI Guideline 4630 “Fermentation of organic substances; substrate characterisation, sampling, collection of material data, fermentation tests” (2016) or the VDLUFA Association Method “Determination of biogas and methane yield in fermentation tests” (2011) procedures are were specified. The evaluation is carried out according to DIN ISO standard No. 5725-1 (1997) “Accuracy (correctness and precision) of measuring methods and results” (DIN ISO 5725-1, 1997 and DIN ISO 5725-2, 2002) and DIN standard No. 38402-45 (2014) “Standard methods for water, wastewater and sludge analysis – Part 45: inter-laboratory tests for suitability testing of laboratories”. The evaluation of the proficiency test serves to describe the possibilities of the method and in particular the comparability of the results across the laboratories.

Results

The study of the inter-laboratory test data sets from 2006 till 2017 show that the results of the analysis have improved significantly regarding the biogas and methane yield determination over the past years. Despite the increasing demands on the measurements, changing laboratories among the participants and varying numbers of participants over the years (Weinrich & Paterson 2017). Since the composition of the laboratories participating in the proficiency test changes annually, a comparison of the evaluation over the duration of the test is only possible to a limited extent.
The inter-laboratory precision is represented by the variation coefficient of repeatability (CV_r) and variation coefficient of reproducibility (CV_R) for microcrystalline cellulose (reference standard) and maize silage samples (see Figure 1).
It is striking, that at the first run in 2006 the results for cellulose showed a relatively wide spread (CV_R of 19.5-%), although a standardized and very homogeneous test substrate was used. When comparing the test setups and the results, it became clear that the deviations were not related to the type and size of the respective test facilities.
Rather, the procedure of data collection, the accuracy of methane measuring instruments, their regular calibration,

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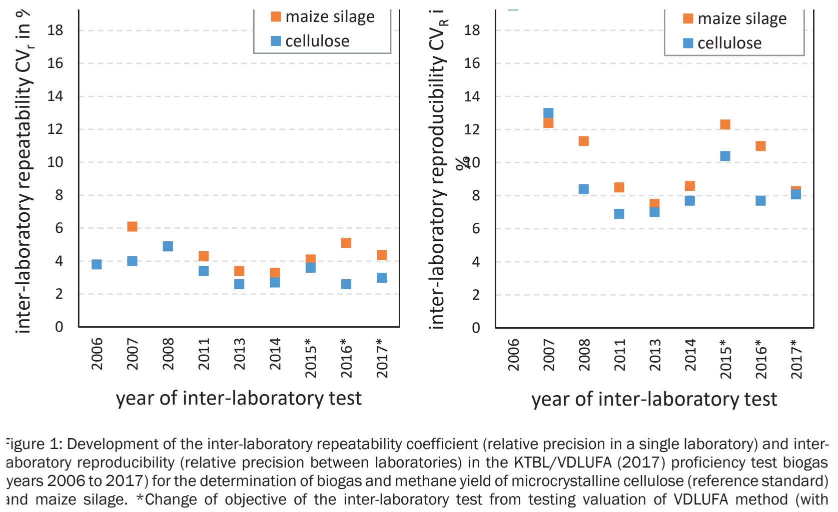

Figure 1 Development of the inter-laboratory repeatability coefficient (relative precision in a single laboratory) and inter-laboratory reproducibility (relative precision between laboratories) in the KTBL/VDLUFA (2017) proficiency test biogas (years 2006 to 2017) for the determination of biogas and methane yield of microcrystalline cellulose (reference standard) and maize silage. *Change of objective of the inter-laboratory test from testing valuation of VDLUFA method (with plausibility control of incoming laboratory data) to quality assessment of laboratories (without plausibility control)

the mathematical evaluation considering the reference values for standard conditions and the consideration of water vapour correction in the event of deviations played a clearly more recognizable role. In the meantime, the CV_R values for the methane yield for cellulose are around 8 %. The CV_r, which describes the accuracy of the values within a single laboratory, was reduced to less than 3 % for the methane yield in the years of the test runs.
A slightly different picture emerges by looking at the results of determining the methane yield of maize silage. The CV_r of the laboratories could be improved from initially more than 6 % to about 4 % in 2017. The CV_R began with high values of over 12 % and over the years of the inter-laboratory test the scattering for this sample material has reduced to around 8 %.
In the meantime, however, these values rose again slightly in some cases. For such a substrate, possible natural quality differences between the cultivation years, the influence of comminution technology and the influence of silage play a role in the development of the results. It has to be mentioned, that correction for volatile fatty acids was not mandatory and therefore not included in all test results. This can also lead to certain distortions of the results. Furthermore, in 2015, the objective of the inter-laboratory test was changed towards the quality assessment of the laboratories. Thus, the plausibility check of the incoming laboratory data applied up to then was omitted, which partly explains the deterioration in the evaluation in the final years of the comparison.
Also the homogeneity of the sample has had an influence on the comparison of the test evaluations over the years; maize silage is sent to the laboratories without precomminution and the sample is prepared as is customary in the respective laboratory. For this reason, higher and more fluctuating CV_R values are generally plausible for maize silage compared to cellulose.

The study of the results from 2006 till 2017 show that, despite the established methodological regulations, the regular participation of laboratories on laboratory-wide quality improvement measures is essential in order to hold and improve their performance. Because the analytical performance of a laboratory can best be tested in an inter-laboratory test in comparison with other laboratories.

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Metabolism-centered predictive modeling of anaerobic digestion of biogas production

Omics techniques, next-generation sequencing, flexible feeding, flux balance analysis, Anaerobic Digestion Model No.1 (ADM1)

Biogas produced from waste materials is an environmentally friendly and sustainable source of energy. The process is driven by complex microbial communities, and while the general process steps are known, the ultimate relationship between community composition, its dynamics, and process performance is yet uncovered, leading to biogas reactors being operated within broad safety margins at the cost of efficiency. In order to elucidate the link between the microbial communities and process performance in more detail, the aim of our work is to build computational models describing the full process both at the community level and the enzyme level.

Towards this aim, three lab-scale biogas reactors (A, B, and C) were established which implement acetogenesis and methanogenesis as the last two steps of anaerobic digestion. CSTR A and B were continuously fed at a mean hydraulic retention time (HRT) of 20 d and 14 d, respectively, and CSTR C was operated at an HRT of 14 d and fed discontinuously (once a day). Using propionate as the sole carbon source at mesophilic conditions, reactor performance (methane production) and dynamics of the microbial community were recorded via a combination of experimental techniques like amplicon sequencing, metagenomics, and metaproteomics.

In all reactors propionate was converted very efficiently (> 95 %) and similar amounts of methane were produced despite the different feeding regimes. The bacterial communities were dominated by the known propionate degrader *Syntrophobacter* with the highest abundance in CSTR B (47 %). Together with the second identified propionate degrader *Pelotomaculum* they accounted only for 29 % to 48 % of the bacterial communities. As not even half of the bacterial communities were known as propionate degraders, other bacteria might degrade propionate as well, which still need to be elucidated.

Therefore, metagenomic and metaproteomics were applied. To reconstruct genomes of individual community members a hybrid approach using short-read sequencing (Illumina) and long-read sequencing (Oxford Nanopore Technologies) was applied. Experiments with stable isotope labelled propionate indicated that the degradation of propionate exclusively occurred via the methyl-malonyl-CoA pathway in all reactors, which is in agreement with the detected propionate degrading species. Accordingly, the metagenomes were searched for genes for the methyl-malonyl-CoA pathway and their taxonomic affiliation. Other genera apart from *Syntrophobacter* and *Pelotomaculum* that had almost all genes for this pathway were *Desulfacinum, Desulfobulbus, Desulfotomaculum, Geobacter,* and *Thauera*. However, each of these taxa was found only in low abundance in all three reactors (< 0.5 %) and hence, would only contribute little to overall propionate degradation.

The methanogenic community showed clear differences between continuous and discontinuous feeding. *Methanosaeta* as a strict acetoclastic methanogen and the hydrogenotrophic *Methanoculleus* were dominant in the continuously fed CSTRs with a combined relative abundance of at least 87 %. Beside those two methanogens, *Methanospirillum* was found as an important methanogen in the discontinuously fed CSTR with a relative abundance of about 13 %.

Ultimately, predictive models resulting from the reconstructed genomes will both elucidate ecological principles providing stability, resistance, and resilience of the community, as well as help to identify key processes, bottlenecks, and easy measureable indicators of process stability during biogas production. This will be useful in optimizing reactor design and operational regimes, and in devising intervention strategies during critical reactor states. The model will finally be simplified to only consider relevant processes to become applicable as an online tool for biogas reactor monitoring and optimal control.

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Microbiome analysis to understand the biotransformation reactions responsible for conversion of food waste to energy in biogas reactors

Extended Kalman filter, soft sensor, monitoring, parameter estimation, simplified kinetic model

Background

Microbiome analyses were performed to assess the anaerobic digestion process for conversion of food waste to biogas in lab scale fed batch reactor. The report of ammonical nitrogen accumulation leading to process failure at an industrial Biogas plant inspired us to perform some comparative studies by altering process parameters in a lab scale bioreactor. Efficiency of hydrolysis of food waste was assessed in a fermenter of 35 L capacity operated at previously optimized conditions (pH 7.2–7.5, temperature 43 °C, aeration 0.19–0.22 vvm) with a retention time of 24 h.
The aim of the study was to assess the anaerobic digestion process by analysing the functional diversity responsible for process efficiency. High throughput DNA sequencing techniques provide extensive inputs into the biotransformation reactions undertaken by distinct microbial populations governing the process.

Methods

The biogas plant situated at Nagpur runs on cattle manure and food waste was reported for process failure in June 2015. The operational conditions of this plant were simulated in a lab scale reactor using identical inoculum and food biomass. To enhance the hydrolysis of food waste, temperature was gradually increased from 43 °C to 48 °C. Total metagenome extractions were performed from the insitu sample at the plant (BGR-A), and reactor samples at initial (BGR-B, 43 °C) and final time point (BGR-C, 48 °C) which were used in subsequent microbiome studies. Total DNA extractions from reactors were used for whole metagenome sequencing task using Illumina platforms. Raw reads were assembled, datasets were annotated and analysed using methods reported earlier (Jadeja et al. 2014). The metagenomic data sets used in this study have been submitted in National Center for Biotechnology Information; Sequence Read Archive under the Bioproject number PRJNA357876.

Results

The results suggested minimized ammonical nitrogen accumulation during hydrolysis (net removal up to 75 %) with 3589±469 mg/L soluble COD and 1419 ±136 mg/L TVFA concentration at pH 7.5 and temperature 48 °C (compared to 43 °C, initially). This led to reduction in ammonia accumulation up to 66 % indicative of optimized hydrolysis conditions compared to earlier bioreactor runs performed at 43 °C. Comparative metagenomics revealed the shifts in microbiome functions responsible for improvement of the process efficiency. Functional gene hits classified for methanogenesis function increased from 65 % to 72 % in BGR-C sample metagenome (Figure 1).
Noteworthy changes were observed in the Bacterial/Archaeal populations during the anaerobic digestion process. In sample BGR-C, Archaeal population increased to 10.5 % which was 2.24 fold higher level as compared to samples from reactor operated at lower temperature (BGR-B). In sample BGR-C, abundance of phyla Proteobacteria and Bacteroidetes reduced to 22.6 % and 17.7 % of respectively accompanied by increased levels of Firmicutes (abundance 15.7 % of total bacterial population). Abundance of Thermotogae phylum increased to 11.8 % in BGR-C sample from 0.96 % as compared to BGR-A sample. At genera level, sample

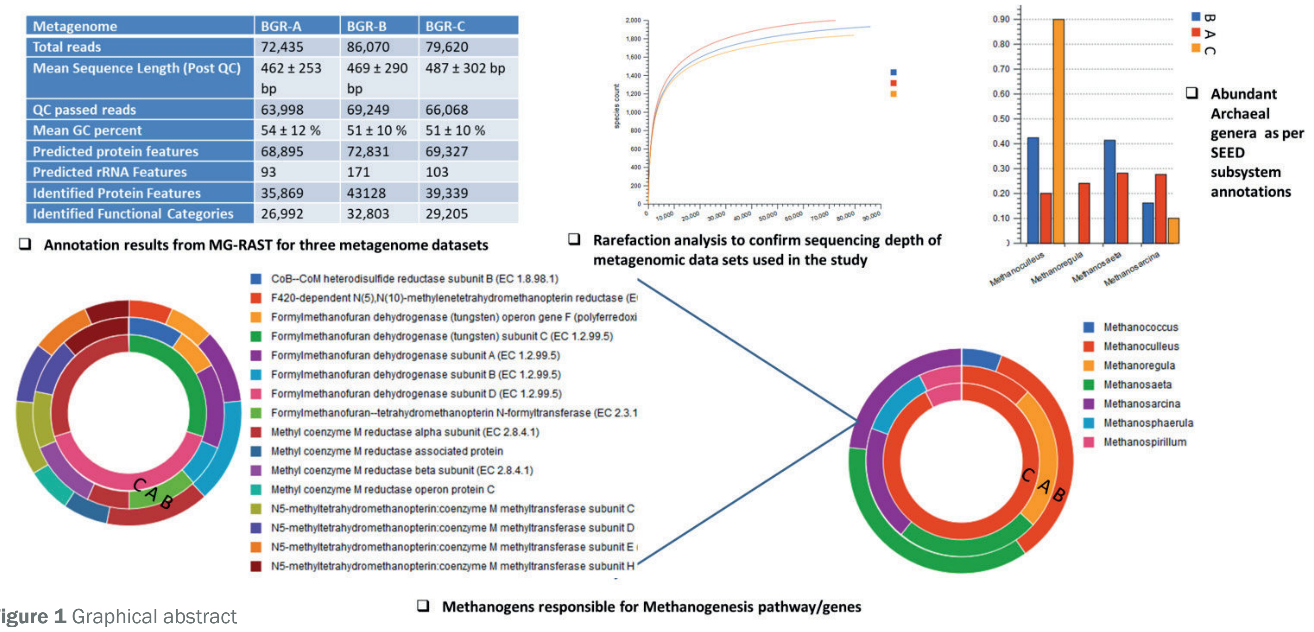

Figure 1 Graphical abstract

BGR-B depicted *Candidatus Cloacamonas* (7.2 %), *Bacteroides* (6.6 %), *Syntrophus* (2.9 %), *Clostridium* (2.7 %), *Geobacter* (2.4 %), *Prevotella* (1.7 %), *Parabacteroides* (1.7 %); the dominating microbial populations. Bacteroides (7.4 %), *Methanoculleus* (6.0%), unclassified genera derived from Thermotagales family (5.3 %), *Clostridium* (2.8 %), *Kosmotoga* (2.6 %), *Geobacter* (2.1 %) and *Thermotoga* (1. 8 %) were the dominating genera observed in sample BGR-C. The hyperthermophilic and anaerobic bacterium Thermotoga is known to ferment a wide variety of carbohydrates, producing acetate, CO_2, and H_2 (Schut and Adams 2009).

Optimization of temperature resulted in efficient hydrolysis of the food waste used in the bioreactors. Despite the drastic shifts in microbial community with respect to the increasing temperature, the methanogenesis process was sustained by key microbial populations identified in this study.

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Evaluation of the process performance at commercial biogas plants using compound-specific stable isotope analysis (CSIA)

 # CSIA, isotope, monitoring, biogas plant

Laboratory studies indicated that compound-specific stable isotope analysis (CSIA) is an appropriate monitoring tool for process failure and optimisation of biogas production (Laukemann et al. 2010, Nikolausz et al. 2013, Lv et al. 2014a&b, Leite et al. 2015, Mulat et al. 2016, Lia et al. 2018, Lv et al. 2018). Moreover, CSIA was applied for pilot-scale biogas plants, successfully (Gehring et al. 2015, Polag et al. 2015). However, studies on the application of CSIA at commercial biogas plants are limited.
The aim of our study was to test the applicability of CSIA for evaluating the process status of commercial biogas plants. Thus, practical basics were generated for the implementation of CSIA as monitoring tool for early warning of process failures in biogas plants and for optimisation of the biogas production.

Carbon and hydrogen stable isotope ratios of methane ($^{13}C/^{12}C$ and $^{2}H/^{1}H$ obtained as delta-notation: $\delta^{13}C_{CH4}$- and $\delta^{2}H_{CH4}$-values) as well as carbon stable isotope ratios of carbon dioxide ($\delta^{13}C_{CO2}$-values) were measured at six biogas-plant fermenters, which exhibited differences in biogas substrates, process conditions (mainly temperature) and construction. Sampling occurred four to six times over a period of six months. Additionally, carbon stable isotope ratios of the biogas substrate ($\delta^{13}C_{substrate}$-values) and digestate ($\delta^{13}C_{digestate}$-values) were determined, in order to examine their influence on the carbon stable isotope ratios of biogas ($\delta^{13}C_{CH4}$, $\delta^{13}C_{CO2}$). For the verification of the assessment of methanogenic pathways based on CSIA, the pattern of the methanogenic community was gathered by the Terminal restriction fragment length polymorphism (T-RFLP) analysis of methyl coenzyme M reductase (*mcrA*) genes.

Based on the comparison of $\delta^{13}C_{CH4}$- and $\delta^{2}H_{CH4}$-values, the biogas plants could be differentiated. The isotope ratios of the biogas plants J and T1 clustered together, while they significantly differed from those of the biogas plants T2, S, Q1 and Q2. The negative $\delta^{13}C_{CH4}$-values of J and T1 could be attributed to the high amount of C3-plant-based substrates used in these biogas plants. The more positive $\delta^{13}C_{CH4}$-values of T2, S, Q1 and Q2 indicated the usage of C4-plant-based substrates, which could be confirmed by the obtained $\delta^{13}C_{substrate}$- and $\delta^{13}C_{digestate}$-values. Since the carbon isotope ratios of the biogas substrate influences those of the biogas, $\delta^{13}C_{substrate}$- or $\delta^{13}C_{digestate}$-values need to take into account for the interpretation of $\delta^{13}C_{CH4}$- and $\delta^{13}C_{CO2}$-values.

For all biogas plants, $\delta^{13}C_{CH4}$-, $\delta^{13}C_{CO2}$- and $\delta^{13}C_{CH4}$-values were relative consistent over time. This indicated that there were no clear shifts in the proportion of the methanogenic pathways. Thus, a quite stable performance of the biogas production could be expected, which was confirmed by the relative consistent structure of the methanogenic community over time.

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Among other process parameters, the $\delta^{13}C_{CH4}$-values showed the highest correlation with the ammonia content. High ammonia concentrations were associated with negative $\delta^{13}C_{CH4}$-values. This correlation had already been observed in laboratory studies on the ammonia inhibition of the biogas production (Lv et al. 2014a & 2018). Our current findings confirmed the observation at commercial biogas plants and approved that CSIA has the potential as monitoring tool for ammonia stress. More negative $\delta^{13}C_{CH4}$-values suggest a higher content of hydrogenotrophic methanogenesis (Laukemann et al. 2010, Nikolausz et al. 2013, Gehring et al. 2015, Mulat et al. 2016). Obviously, hydrogenotrophic methanogenesis is more resistant against ammonia stress than acetoclastic methanogenesis (Mulat et al. 2016).

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Challenges in data acquisition and application for biogas process modelling in practice

 # Biogas process modelling, practical experiences, plant efficiency

Background / motivation

With a funding from the European Regional Development Fund, the Institute for Biogas, Waste Management and Energy is developing a tool to improve efficiency and process monitoring of biogas plants based on a daily accurate target-actual comparison of the biogas yield. In order to simulate the daily biogas production (target value) a model, based on a reaction model, is being applied. The simulated daily biogas production is being compared with the actual measured biogas quantities (actual value). Through this daily efficiency and process monitoring of large-scale biogas plants disturbances of the process and equipment technology can be identified much more reliable and timely as by the monitoring based on a monthly sum and average values, which is common practice today. This allows the implementation of countermeasures much more quickly and therefore to reduce system failures as well as efficiency losses.

Aim of the work

A major challenge in simulating the biogas process in a large-scale biogas plant is the quality of the available data. These are often inaccurate, incomplete or not high enough resolved. Therefore, the aim of this work is:

a) to identify and quantify the most relevant sources of error regarding the above-mentioned comparison of modelled and measured biogas values in a large-scale biogas plant and
b) to estimate influence on the accuracy of the result of the target-actual comparison of the biogas yield in a large-scale biogas plant.

Key research topics

The key research topics are:

» identification and quantification of the main errors in data acquisition for biogas process simulation and modeling as well as the measurement of biogas production quantities in practical large-scale biogas plants,
» quantification of the influence of those errors on a target-actual comparison of the biogas yield based on the simulation of the biogas yield on the one hand and its measurement on the other hand.

With this work, a much better understanding about the main challenges with regard to the acquisition of data for biogas process simulation and modeling in practical large-scale biogas plants will be given.

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Methods

In order to be able to evaluate the influence of the data quality on the simulation result and the validity of the results for efficiency and process monitoring, the main sources of error are summarized, e.g.:

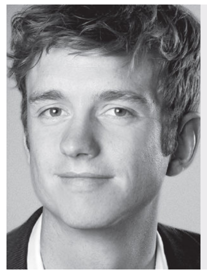
» sampling and analysis of substrates
» recording of operating data such as feeding quantities and qualities
» gas quantities and gas storage levels

Based on technical data (e.g. measurement accuracies) and the experience during data acquisition at a large-scale biogas plant, which serves as the practical example for the project, the identified errors are quantified (maximum of deviation). A sensitive analysis is performed in order to quantify the influence of each error on the daily simulated biogas yield of the plant. The errors with the highest influence on the result of a daily accurate target-actual comparison of the biogas yield are identified and recommendations for reducing those errors are proposed.

Results

So far, data acquisition at the biogas plant have shown the following major sources of errors, which may have an influence on the result of the daily accurate target-actual comparison of the biogas yield:

» Inaccuracy concerning sampling, transporting of the samples and laboratory analysis are having an influence on substrate analysis being performed to determine adequate input values (biogas potential and kinetic parameters) for the model being used in the project.
» The substrates being used often vary with regard to their actual composition, but are always labelled the same (e.g. surface cover of silage, claimed as grass silage).
» The order at which substrates are being put into the bunkers (before being carried into the digesters) is not known.
» Gas storage levels are only monitored as graphics – the actual values can only be estimated roughly.



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Process control of a high-performance hybrid reactor as a methane stage for biomass with high nitrogen content

 # Nitrogen, high-performance, sewage sludge, process control, process stability

The possibility to develop a complex, modular high-performance methane stage for flexible use in the field of biogas technology as well as in the field of wastewater treatment as a supplementary module is the subject of the following work. Biomass like manure and sewage sludge have high nitrogen and chemical oxygen demand (COD) concentrations. This can cause disturbances in the anaerobic digestion process, by ammonia as well as accumulation of volitaile fatty acids (VFA). Therefore, the target is to develope a high-performance methane stage for mesophilic monofermentation of these substrates. Hence a stepwise increase of the reactors, trickle bed reactor (RB), upflow anaerobic sludge bed reactor (UASB), and anaerobic filter reactor (AF) was done. To adapte the microorganizmen to nitrogen and organic loads plastic pellets have been adapted in RB and AF. The UASB enriches biomass by forming natural pellets through accumulation of the microorganism and the subsequent sedimentation. Altogether, to find out the weakness in the acetogenesis/methanogenesis the feeding process was done with a modelsubstrate.

While operating the reactors especially in the lab-scale there is a big gap between the process parameters to achieve and the real conditions. Also the sampling point in each reactor cannot always be considered as represented. The challenge is to guarantee a stable process while increasing the performance in real conditions and for different reactor types likes trickle bed reactors or UASB reactors.

Result

Experience in how parameters interact with each other and how process control in practical conditions looks like.

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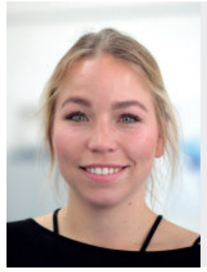

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Control of alkalinity of a full-scale biogas plant treating waste water from the cleaning of car tanks transporting food and fodder, adaption of biogas production to the demand and verification of Nordmann titration method for measuring VOA and TIC

Anaerobic treatment of wastewater from cleaning of tank cars, physicochemical model of anaerobic digestion, measurement of volatile organic acids and alkalinity, biogas production on demand

Background/motivation

The car tanks transporting food and fodder need to be cleaned and disinfected regularly. Germany has some 100 cleaning stations for cleaning car tanks, Europe some 1,600. Car tanks are often pre-cleaned with steam and hot water producing a strongly polluted wastewater. The rinsing and the cleaning of only moderately polluted tanks generates only moderately polluted wastewater (WW).
TS-Clean company cleans some 450 car tanks a week in 3 cleaning stations (Fahrbinde, Kavelstorf, Neudietendorf). In TS Clean the strongly polluted WW was transported to a wastewater treatment plant (WWTP) for co-digestion and the moderately polluted WW was and is discharged indirectly after passing a grid chamber system. TS-Clean had the idea of an anaerobic treatment of the strongly polluted WW in Fahrbinde in order to reduce cost for natural gas by substituting natural gas consumed in the steam generator with biogas and reduce costs for wastewater disposal by indirect discharge of the effluent of the anaerobic treatment and contracted the University of Wismar to do the necessary investigations. In extensive bench and pilot scale experiments was shown that a stable anaerobic treatment of the strongly polluted WW and the sludge from the grease traps with more than 85 % COD reduction was possible and that in combination with a flocculation and solid separation of the effluent indirect discharge standards could be met and that the effluent of the solid separation had no adverse effects on the biological treatment in the communal WWTP. On the basis of these findings the anaerobic treatment plant with flocculation and solid separation was planed and built by Rotaria – Energie- und Umwettechnik GmbH, Rerik and commissioned in November 2017.

Aim of the work

The aim of our research was to find out if and how we can treat the strongly polluted WW with anaerobic digestion producing biogas that can substitute the natural gas used in the steam generator and producing an effluent that can be discharged indirectly with no adverse effects on the WW treatment in the WWTP.

Key research topics and novelty

Our research topics were:

- Development of a physicochemical model for calculating and controlling the addition of $NaHCO_3$ in order to stabilize the digestion process of highly polluted wastewater from the cleaning of car tanks transporting food and fodder
- Investigation of the effect of the addition of micronutrients on the digestion process stability and efficiency

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- Verification of the Nordmann titration method for measuring volatile organic acids (VOA) and alkalinity (TIC) with FOS/TAC 2000 Pronova device
- Controlling the anaerobic digestion process by measuring VOA and TIC
- Controlling biogas production by feeding regime in order to meet demand

Methods

Due to the softened water used in the cleaning of the tank cars, the WW is low in alkalinity and buffer capacity which potentially effects the anaerobic digestion process. A physicochemical model was developed in order to investigate the relation of alkalinity and pH in the anaerobic digester. The model is based on the CO_2-absorption equilibrium (Henry´s law) and the chemical equilibria for ammonia, carbonic and phosphoric acid and the balance of the ion charges. The alkalinity equation was adapted from Bruce E. Rittmann and McCarty (2012). In order to evaluate the exactness of the measurements of volatile organic acids (VOA) and TIC with the FOS/TAC 2000 (Pronova 2015) using the Nordmann titration and the McGhee empirical equations the analysis was tested and verified with synthetic digestate, diluted disgestate and digestate spiked with acetic acid and $NaHCO_3$.

Results

The highly polluted WW from the cleaning of tank cars transporting food and fodder is suitable for anaerobic digestion if OLR is controlled below 4 kgCOD/m³/day, and micronutrients and $NaHCO_3$ are added. The physicochemical model showed that 2.4 kg$NaHCO_3$/m³ of wastewater has to be added in order to control the digester pH at 7.2 and to maintain the digester alkalinity at 3.1 g$CaCO_3$/L. These model results are in a good correlation with the experimental and full scale observations. The addition of micronutrients is also required in order to avoid a deficit of the trace elements in the digester. Without trace element dosage the digestion process failed in less than one year of operation.
The Nordmann titration method was verified. The FOS/TAC 2000 has a good performance measuring VOA and TIC.
The 1,200 m³ full scale biogas plant in Fahrbinde produces in average 800 m³ biogas from 12 m³ WW with 62 % CH_4. The biogas substituting natural gas in the steam generator saves about €8,500/month. The return on investment of the biogas plant is therefore less than 5 years.
The operators are trained for monitoring and controlling the digestion process analysing daily VOA and TIC with FOS/TAC 2000. The VOA/TIC ratio is stable in the range of 0.1–0.3, indicating a stable digestion process (Drosg et al. 2013). Biogas production is successfully adapted to the biogas demand by the wastewater feeding regime.

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Monitoring of (manufacturer independent) biogas plants with evaluation of all the data of necessary data points

BayWa r.e. Bioenergy GmbH, biogas information system, manufacturer independent, evaluation of data points, biogas and upgrading plants

Aim of the work

A measuring system for operating data of biogas plants (read from the PLC of the plants) is developed by BayWa r.e. Bioenergy, to which additional sensors can be connected and manual values can be entered. On the basis of this complete data situation, the consumption of electricity, biogas and process heat can be compared (benchmarking) in comparison to other plants, in order to see potential savings and to increase these through process and component changes.

Innovation / novelty of the project

The system can handle plants of various sizes and manufacturers, necessary additional sensors can be added, even for plant manufacturers, which are not existing anymore. With a learning algorithm datapoints of various components can be detected, whereby the connection in a short period of time can be done. A frequent reading of the data (96–43,000 per day) reveals even small changes.

Methods

Using data aggregation 1,000 manually entered existing datapoints of biogas plants were analysed.
The manually entered datapoints are measured regularly and can be analysed further in their biogas context inside the Pimos Software.

Results

Our findings conclude that there is no clustering in the datapoints, which means that the different vendors do not use the same position of data for access in the PLC. This also is true for plants of the same vendor as the position of the data points seem to have a technical reason.
The manually entered data points lead to deeper insights of biogas plant data. Using data of various plants metrics can be generated like the average energy consumption per output kilowatt hour.
Finaly we will show how animated daily aggregated heat measurement data can – along with weather data and GEU data - can lead to a deeper understanding of heat consumption over a yearly period.

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Determining conditions of intermittently fed digesters from biogas production rate data

Intermittent feeding, process control, demand driven biogas

There has been a reduction in subsidies for electricity generated from anaerobic digestion in recent years, which will lead to challenges to ensure profitability. As the electricity grid shifts to a larger proportion of renewable energy, there are larger uncontrolled swings in electricity generation due to the intermittent nature of wind and solar power sources. In the electricity spot market, quick responding generators can charge a premium in such times. A possibility to increase income for AD plants is to produce energy on demand in order to fill the gaps in generation from solar and wind. Flexible feeding is possible without negatively effecting process stability (Mauky et al. 2016). Previous work has shown that using the step response of an AD plant to feeding variation can provide information about the process and be used for process control (Steyer et al. 1999).

This work considers the situation of an intermittently fed biogas plant, generating electricity for a limited part of the day, and uses the variations observed in the biogas production rate data to make control decisions on whether to increase or decrease the feeding amount for the following day.
Testing was performed at the laboratory scale (5 L CSTRs) feeding grass silage, and pilot scale (1,000 L) feeding maize silage. The production rate of biogas was measured as the organic loading rate was increased. As the digester was fed with higher loading rates there was a noticeable change in the characteristics of the response in the gas production. Using the gas production rated data, a number of statistical analysis techniques were performed in order to attempt to quantify the observed changes. A suitable technique was found which correlated well with the reference data. Thresholds were set per litre, meaning that the same thresholds were applicable to both the 5 L and 1,000 L scale tests.

A PID controller was then implemented in order to control the daily feeding amount on a biogas plant model, with the biogas plant model using the ADM1. The input used for the controller was the statistical analysis previously described, and the output was the feeding rate. The PID controller was tuned manually. Simulations were then performed using the ADM1 and PID controller, and ran for 365 days. After this, the loading rates were increased until the ADM1 simulations failed due to the high loading rate.
The simulation results showed that the control technique performed well, with very little variation in the total produced methane content each day during the operation with the PID controller. When increasing the loading rate at the end of the test period, the produced methane started to vary significantly for a fixed feeding amount, indicating instability in the process, and further increases lead to inhibition of the process.

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Evaluation of pre-treatment methods by in-line particle size distribution monitoring with laserlight backreflection

Particle size distribution, laserlight backreflection, ultrasound, enzyme addition, feedstock pre-treatment

Background/motivation

Pre-treatment for a better conversion of feedstock in bioprocesses is frequently applied. Among typical methods are i) mechanical treatments with high shear forces to disrupt fibre structures with milling and ultrasound, ii) chemical treatments during hydrolytic steps like enzyme or base addition, and iii) biological treatment through bioaugmentation of hydrolytic microbes, among others. The evaluation of such methods for anaerobic digestion can be made based on the conversion efficiency to biogas, although this method is time-consuming. Effects are often just detectable whithin several weeks or months of operation. In order to achieve a rapid analysis of the effect of pre-treatment methods (or methods applied in the digester), a method to rapidly assess the particle size distribution was adjusted to be applicable directly in culture broth: the laserlight-based focused beam backreflection is applied for the determination of the particle and cell-size size distribution to optimize feedstock pre-treatment and measurement of the fluid phases of anaerobic digestion bioprocesses. Due to the different patterns of back reflection at the edges and cores of particles and multi capture signal interpretation, sizes of them can be determined directly in the culture broth. .

Methods

Laserlight backreflection allows to determine size distributions at typical compositions of the culture broth, if biogenic raw and residual material is used as feedstock. The resolution of the technology reaches up to < 0.5 µm, which makes it also applicable to track sizes of bacterial cells. In this study, the course of the size distribution was monitored during digestion with various pre-treatment methods, e.g. an oscillating exposure to ultrasound in scale-down experiment of industrial conditions, and enzymatic treatment.

Results

Results show that it is possible to distinguish the cell size distribution before and after various treatments. Data was compared and correlated to process parameters, like the metabolite fraction in the liquid phase, the methane formation, and viscosity, respectively. They show that the method is robust and allows the rapid identification of suitable operation conditions for substrate pre-treatment, e.g. milling or ultrasound exposure, w/o the requirement of time-consuming monitoring of the process performance, e.g. carboxylic acid production or methane formation.

In particular, the impact of the size distribution is compared to results of batch digestion tests in lab scale. A correlation between the size distribution and methane production efficiency from various feedstock are found: smaller particle sizes during certain stages in the batch process indicate clearly conditions that lead to a higher methane production rate. In case of feedstock made of fibres, a distinct size distribution indicates an improved digestibility.

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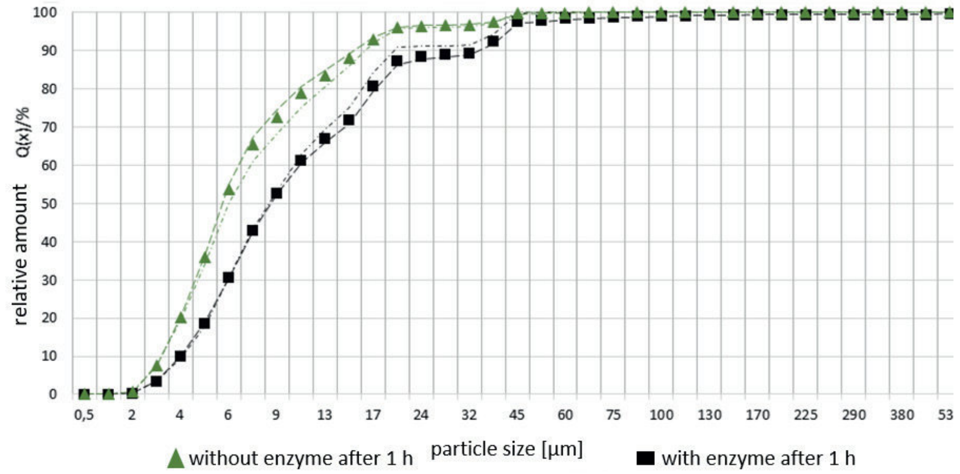
Usually, the sensitive size range of solid material is different from the typical size range of microorganisms, so that the impact of pretreatment methods on feedstock can be distinguished from microbes and agglomerates of them. Effects of pretretament are seen directly within minutes, which results in a very fast evaluation method. In case of ultrasound treatment, a clear effect on the cell size distribution is seen and suitable power input settings can be made.

While the method works well if the feedstock remains similar, investigations are needed for alternating feedstock compositions in order to be able to extract data specific for each substrate and to reduce random distributions, which decrease the specificity of the size distribution, and thus lower predictability of the measurement for methane production. Studies directly at industrial plants, which are operated continuously with alternating feedstock composition, are currently performed to demonstrate the suitability also in the large scale.



Example: **Figure 1** Particle size distribution measured with laserlight backreflection in culture broth with and without enzyme addition

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Further information

https://www.energetische-biomassenutzung.de/en/projects-partners/details/project/show/Project/lasersize-490/

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Minimizing negative effects of liquid digestate recirculation on methane production and system stability in anaerobic digestion of livestock bio-wastes

Biogas, Process stability, Recirculation, Livestock manure, Stable isotope

The recycled utilization of digestate has preliminarily been demonstrated as an efficient method for recovering energy and reducing digestate discharge from some AD plants. The recycling operation could introduce the residual methane potential and methanogenic bacteria back to the AD plant, which can theoretically significantly improve the methane production of the applied AD plant. However, the concerns surrounding recycling of digestate in AD plants are the accumulation of key chemical inhibitors to methane production in AD plant, such as ammonia and volatile fatty acids (VFAs). It is commonly accepted that excessive ammonium accumulation can increase the proportion of free ammonia, which is toxic for methanogenesis and results in lower methane production. However, this process might also be highly dependent on feeding materials. For example, Estevez et al. 2014 observed a 16 % increase in methane yield with liquid digestate recycling of cow manure with Salix, whereas Wu et al. 2016 reported a decrease of 43 % in methane production under liquid digestate recycling of chicken manure due to ammonia accumulation. In addition, viscosity may also increase with digestate recirculation and decrease methane production due to imperfect substrate movement in AD plants. Until now, the implications of digestate recirculation have been studied in AD of dairy manure, chicken manure and co-digestion of cow manure with salix or grass silage. To our knowledge, the dynamics of how ammonium accumulates during the digestion of chicken manure under long-term recycled unitization of liquid digestate as well as its influence on microorganism activity and biogas production are still not comprehensively understood. It should also be determined whether or not the use of ammonium removal technology, such as ammonia striping, on the liquid digestate before its recycled utilization can effectively perform ammonium mitigation.
Besides the energy production efficiency, the deep understanding of methane generation mechanisms change under the digestate recycled utilization would be important to support the recycling application in AD plant. Another knowledge gap hypothesis is the dynamics of heavy metals in digestate from AD plants might also influence the operation of digestate recirculation; heavy metal concentration will regulate the digestate application by agriculture. Thus, to achieve the full success application of this optimized digestate recycled AD plant, the accumulation and mobilization of heavy metals in digestate effluent under liquid digestate recirculation need to be monitored.

The aims of the study presented here were to assess the liquid digestate recirculation operation on the energy production performance and mechanisms of livestock biowaste anaerobic digestion, including pig manure, cow manure and chicken manure. For this purpose, laboratory-scale CSTRs for treating different manures at variable organic loadign rates were implemented under mesophilic conditions. The influences of AD reactor digestate recirculation on methane production, and the characteristics of the digested substrate, were investigated to evaluate methane production and system stability. Additionally, to assess the risk potential for agricultural utilization of the final digestate effluent, the dynamics of heavy metals accumulation and mobilization were determined in both the liquid and solid fractions. Moreover, to understand the impact of recirculation on predominantly methanogenic pathways, the composition of $\delta^{13}C_{CO2}$ and $\delta^{13}C_{CH4}$ associated with the molecular analysis method were monitored. The integration of air stripping with ammonium mitigation of liquid digestate before recycled utilization was investigated in order to maintain the ammonium concentration below the inhibition level.

The manures used in this study was collected from larger-scale farms located in Beijing, China. The raw manure was naturally dried, followed by pulverization treatment. Then, the homogenized samples were frozen at -20 °C to prevent biological decomposition. The sludge inoculum was collected from a biogas plant (located in Shun Yi district, Beijing, China) with mesophilic pig manure AD by CSTRs. Laboratory-scale CSTRs were implemented in two identical glass cylinders with a total volume of 15 L and effective volume of 10 L. The feeding and discharge ports were set at the top and bottom of the reactors, respectively. The gas outlet was at the top and connected with a plastic gasbag. All CSTRs were intermittently stirred at 120 r/min for 1 h on and 1 h off. The experiment was maintained at 37 ± 1 °C in a temperature-controlled chamber. To investigate the effect of various OLRs and recirculation on the performance of the CSTR reactors, the experiment was divided into many different phases with various OLR levels. Some CSTR reactors were established as control without recirculation, while some were set to 60 % effluent liquid digestate recirculation.
The pH, methane production volume, CH_4 and CO_2 contents, Total solids (TS), volatile solids (VS) and total ammonia nitrogen (TAN) of all samples were determined using standard methods. Total inorganic carbon (TIC) and volatile fatty acids (VFAs) were analysed by titration with 0.1 NH_2SO_4 to endpoints of pH 5.0 and 4.4, following the procedure of Zhang et al. 2014 [19]. The sludge viscosity was determined using a rotational viscometer at a shear rate of 60 min^{-1} as described by Chang et al. 2007. Cellulose and hemicellulose were determined using the sequential analysis method developed by Soest et al. 1985. All the above parameters were collected from each sample every 1–2 days for routine analyses in the present study. Additionally, the concentrations of heavy metal elements, including lead (Pb), manganese (Mn), copper (Cu) and zinc (Zn), in both liquid and solid fraction of the effluent were determined using inductively coupled plasma mass spectrometry (ICP–MS, Elan 9000, Perkin Elmer, USA). The stable isotopic enrichments of CH_4 and CO_2 were carried out as described by Nikolausz et al. 2013. In order to investigate the microbial difference between reactors, 16S rDNA characterization was carried out to analyse the microbial communities at the end of the experiment.

It was demonstrated that the recirculation operation improved methane production and system fermentation stability, particularly for organic loading rates below 5 g VS L^{-1} d^{-1}. The inhibition of methane production was found under an OLR of 6 VS L^{-1} d^{-1}, which was caused by significantly increased viscosity from 30 to 1,000 mPa·s and decreased mass transfer characteristics. The previously reported negative effects of accumulated ammonia and VFA on anaerobic digestion under digestate recirculation were not found in the investigation of pig manure treatment. However, the heavy metals Pb, Mn, Cu and Zn accumulated in both liquid and solid fractions of the generated digestate in the digestate recycled reactor. The stable carbon isotope analysis of $\delta^{13}C_{CO2}$ and $\delta^{13}C_{CH4}$ produced the biogas indicated different methanogenic pathways between the anaerobic reactors with and without digestate recirculation.

The dynamics of ammonium accumulation and mitigation control in anaerobic digestion of chicken manure under the recycled utilization of liquid digested slurry were investigated.
In the reactor with direct recycled utilization of the anaerobic digested liquid slurry, total volatilized fatty acids (in CH_3COOH) and NH_4+-N increased from 1,600 mg/L to 8,000 mg /L and from 2,600 mg/L to 5,000 mg/L, respectively. As well, the pH increased from 7.7 to 8.1, and the effluent viscosity significantly increased to 27 mPa.s from 13 mPa.s. Under this condition, the daily volumetric biogas production decreased from 1.4 ± 0.1 L/(L·d) to 0.8 ± 0.1 L/(L·d) with a reduction efficiency of 43±4 %. To avoid the negative effect of accumulated organic and inorganic compounds, air stripping was then integrated into our system for ammonium mitigation of recycled liquid digested slurry and ammonium control in the digester. This integration effectively reduced the ammonium concentration from 5,000 mg/L to 3,000 mg/L and maintained this level during the following 75 days (3 HRTs). Correspondingly, the biogas production performance was recovered as evidenced by the daily volumetric biogas production increasing back to 1.4 ± 0.1 L/(L·d). This indicated the potential of the integration of air stripping for ammonium mitigation and control in an anaerobic digestion process with liquid digested slurry recirculation.

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Flexible methane production using PI Controller with simulation based soft sensor

PI control, soft sensor, gain scheduling, flexible biogas production

Contribution of renewable energy sources to electricity production is increasing continuously. Considering the variable demand of electricity from consumers and the highly volatile electricity production from various power systems, a balancing approach which can provide flexible, demand-driven electricity production is beneficial. Since anaerobic digestion (AD) plants have the potential for producing biogas as needed, it can play a significant role in power balancing. In a demand-driven biogas production approach, more biogas should be generated at times of high electricity demand and less during times of lower demands. Alternatively, the surplus in biogas could be stored and fed to power system when there is a high demand. However, gas storage systems and their installation and maintenance always come with extra costs and can be very expensive. Therefore, it would be advantageous to develop flexible biogas production systems to minimize storage requirements. For this purpose, a flexible feeding rate can be used to provide biogas production responding to variations in demand.

The objective of this project is to develop a control system to produce biogas based on utilization demand while less storage capacity is required. As the anaerobic digestion process is highly nonlinear, in particular when it is operated over a wide range of biogas production, which increases the nonlinear behavior of these plants, its stable control is one of the biggest challenges. Standard PI controllers are an appropriate choice for a specific operating range for a system. However, due to the need for flexible biogas production, the system should be able to cope well with variable feeding rates from small to high values. Therefore, conventional PI controllers with fixed tuning parameters cannot compensate for the nonlinear behavior of the system for all operating ranges. In addition, high feeding rates can cause stability issues, which define a limit on the maximum safe feeding rate. Therefore, flexible gas production while maintaining the stability of the system is a challenging problem which requires an advanced control algorithm. In order to be able to evaluate the performance of the developed controller, a biogas utilization regime should be defined.

In Table 1, a utilization regime which is also used in the paper (Mauky 2016) is illustrated. It is assumed that the capacity of the combined heat and power unit (CHP) is larger than the average biogas production by the plant (Mauky 2016).

Table 1: Weekly biogas utilization scenario used for controller evaluation (Mauky 2016)

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Utilization times	7–15	7–14	7–15	7–14	7–14	9–12	11–12
	16–22	15–22	16–22	15–22	16–23	17–23	17–0
						0–1	

The proposed tuning method for the controller can compensate for the nonlinearity of the system over a wide range of operation, whilst guaranteeing system stability. The designed controller adjusts the input signal (substrate feed) to provide demanded biogas and keep the gas filling level inside the storage tank between 20 % and 50 % of its maximum value. In this paper, a novel PI tuning approach is proposed which is a function of the stability of the system state and feeding rate. This method consists of a two-step parameter tuning. In the first step to handle varying process nonlinear dynamics, a primary gain scheduling tuning method is used. Firstly, step changes are applied to different substrate feeding rates and dynamic characteristics of the output variable are captured. Secondly, based on main dynamic plant behavior at each operating point, primary tuning of the PI controller is done by gain scheduling. In the second step, a simulation based soft sensor is designed which estimates the stability degree of the plant at each moment. The utilized soft sensor, which has been proposed in (Irizar et al. 2018), can estimate the stability degree of the system which can be classified in three categories of strongly stable, moderately stable and unstable system by looking at the methane production profile for a pulse change in feeding rate. Based on the current stability state of the plant, a secondary tuning variable is defined which is applied on the tuning parameters of the PI controller to ensure plant stability.

In Figure 1, a general overview of the developed control algorithm is illustrated. As it can be seen, by means of feedback from current gas storage filling level, the controller is able to adjust the input to keep the storage level at a desired value. In addition to this, parameters of the PI controller are adjusted based on stability state and substrate flow rate.

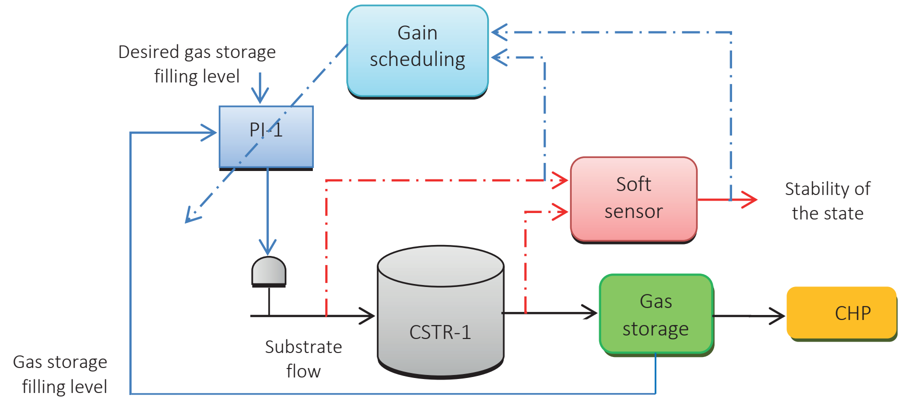

Figure 1 Flow chart of the biogas plant including PI controller and soft sensor

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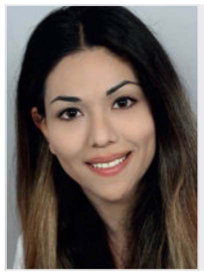

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POSTER PRESENTATIONs

Model-based Process Optimization of Biogas Plant Operation
Manuel Winkler, DBFZ Deutsches Biomasseforschungszentrum gGmbH

Software for measurement and prediction of methane potential
Sasha D. Hafner, Konrad Koch, Hélène Carrere, Sergi Astals, Sören Weinrich

Monitoring and optimizing nine UK biogas plants: laboratory and in-situ measurements, key process indicators and data analysis and interpretation
Denise Cysneiros

Increase of safety-related requirements for biogas plants following the example of the chemical industry – development of model P&ID-flow charts with all safety-related circuits
Gerhard Rettenberger

Monitoring of ammonia in biogas
Heike Wünscher, Thomas Frank, Andrea Cyriax, Ingo Tobehn-Steinhäuser, Thomas Ortlepp

Remote Monitoring of Biogas Plants: Brazilian Cases
William Carlos Marenda, Larissa Schmoeller Brandt, Juliana Gaio Somer, Breno Carneiro Pinheiro

POSTER EXHIBITION

Emil Brohus Lassen Agdal[1], René Casaretto[2], Jens Born[2], Jens Bo Holm-Nielsen[1]

Light cooking of lignocellulosic biomass as a cheap pre-treatment for Increased biogas production

Lignocellulosic Biomasses, Biogas production, Light Cooking, Low-cost pre-treatment

Background/motivation

As the biogas sector keeps developing across Europe, the need for increased biogas production from existing biogas plants becomes an important factor. The utilization of existing gas distribution infrastructure will highly enhance the ability to distribute biogas across Europe. Most modern biogas plant therefor includes upgrading-technology of biogas to biomethane that can be distributed via existing infrastructure. Hence, removing the local output/production constraints the biogas plants have been subject to in the past.

Lignocellulosic biomasses and grassland products, in general, shows great BioMethane Potentials (BMP) (Sawatdeenarunat et al. 2015), (Yousefi 2006), and thus should be of great interest to the biogas sector. Cereal production in Europe is estimated to yield between 70 to 135 Mt annually (Meyer et al. 2017). Problems, however, exists in order to ensure proper and timely digestion of straw and fiber-rich products in the biogas reactors. Due to their physical structure where cellulose and hemicellulose are encapsulated in a lignocellulosic matrix, straw is deemed to have a low degradability. Further, a layer of wax coats the outside of the straw lowering the accessibility to degradable cellulose and hemicellulose for the microbes. Studies have shown an increase in biogas yield if straw from a variety of cereal is treated with high-temperature water (Rajput et al. 2018).

Using high-temperature and high pressure for pre-treatment of straw is an energy-intensive operation, as the method Steam-Explosion and other high-cost investments and procedures shows.

Aim of the work

The aim of the work is to investigate and evaluate the potential for biogas plants to utilize excess heat from already existing processes, as the input energy for a new low-cost pre-treatment method for lignocellulosic biomasses. The ability to feed in more cheap carbon rich biomass will potentially greatly increase plant profitability. However, light cooking is yet to be fully investigated.

Key research topics, novelty, and Methods

The method, Light Cooking, has been investigated in order to evaluate the effect of a low-temperature and low-cost treatment of wheat straw. In the temperature range from room temperature – ambient temperature to 105 °C and a time range from 20 minutes to 60 minutes, the BMP of wheat straw has been evaluated.

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Results

Preliminary studies show an increase in methane yield of 11.2 % for light cooked straw. It indicates that light cooking potentially can increase the biogas yield from cereal straw but further investigation is needed and is currently in progress. The results and analysis will be finalized before the conference.

In general, it is well known that large amounts of residues from cereal production remains unused on a European level (Searle 2013; Scarlat et al. 2010). However, the key enabling technologies to the full-scale incorporation of large quantities of lignocellulosic biomass remains partially hidden. Light cooking may be one of the unlocking technologies to solve this important issue.

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Monitoring and optimizing nine UK biogas plants: laboratory and in-situ measurements, key process indicators and data analysis and interpretation

Process monitoring and optimization, laboratory and in-situ measurements and analyses, key process parameters, data analysis

Background

Over the last 2 decades, the biogas industry has grown significantly in Europe, particularly in Germany. More recently, following a less attractive incentives policy, optimization of existing plants is the main aim of operators. Although Anaerobic Digestion is not a new concept, optimization of commercial plants is complex as there are many variables affecting performance which are related to diverse disciplines such as farming, biology, engineering, sustainability, amongst others. Optimizing biogas production and yields from feedstocks is particularly important to operators and therefore, monitoring different aspects of the plants is essential to identify areas for improvement. The result of monitoring diverse parameters is a large database that, if used by an appropriate data analysis tool and correctly interpreted, can be a powerful means to suggest areas for plants optimization. This work presents the data obtained during 5 years of operation of 9 biogas plants in the UK.

Aim of the work

It is of interest of operators of anaerobic digestion plants to maximize biogas production and utilization. The aim of the work was to identify key process parameters and areas of optimization and tools and techniques for process monitoring. Furthermore, due to the large amount and variability of data obtained during monitoring operation of full-scale plants, the work aimed to investigate methods for data analysis and interpretation best suited for the purpose of optimizing the plants.

Key research topics and novelty

Optimization of full-scale biogas plants. Optimization of feedstock. Laboratory and in-situ analyses. Key process monitoring indicators. Data analysis and interpretation applied on full-scale plants database.

Methods

Feedstock characterization:
Laboratory chemical composition and Biomethane Potential Tests.

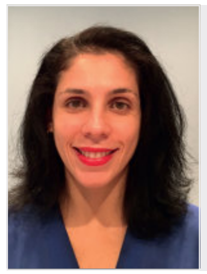
Process monitoring:
In-situ analyses: Feedstock: DM analyses every alternate day. Digesters: FOS/TAC, pH, gas composition (CH_4, CO_2, H_2S, O_2) analysed daily in-situ.

Laboratory analyses: digesters, post-digesters and digestate: Volatile fatty acids (speciation and concentration), macro and micro nutrients concentrations, ammonium, total Nitrogen, total and organic DM. Process data: (obtained from the sites Scada system): Feed rate, Retention time (level of tanks, volume pumped), stirrers (A and kW), biogas production (CHP and biomethane injection), temperature of tanks, downtime, amongst others
.

Data analysis and interpretation:
The different aspects of the process were initially analysed individually and manually to assess the importance of each variable. A Principal Component Analyses (PCA) was also performed to analyse the database set and identify clusters, similarities and differences between sites. The software used was JMP (SAS, IBM, version 14).

Results

Analysing and interpreting laboratory and in-situ analyses as well as process data in combination was shown important for monitoring the sites and ensuring the process was occurring as expected. Furthermore, the data analyses provided an insight of the process which allowed identification of important areas to be optimized during the operation of sites. During the 5 years this approach has been adopted, few examples of optimization can be given: feedstock mixtures, harvest time and varieties of crops for biogas production, increased retention time, improvement of stirring, use of additives, amongst others. These improvements improved plants performance, biogas yields, costs, amongst others. A more detailed analyses of results and quantification of benefits will be provided in the presentation.



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Software for measurement and prediction of methane potential

BMP test, data processing, stoichiometric model, software, web application

This contribution describes software aimed at improving the efficiency of biogas research and the biogas industry. With this free software users can process laboratory measurements to calculate biochemical methane potential (BMP), predict methane potential from substrate composition, and carry out simple conversions. In this contribution we will:

1. present a case for why standardized software is preferable to other approaches used for these tasks,
2. provide an overview of the functionality of the software, and
3. demonstrate the utility of the software through short case studies.

Calculation of BMP from laboratory measurements is done with a relatively simple sequence of calculations. Automated systems that return standardized cumulative volume of methane (CH_4) require the least data processing, while manometric or gravimetric methods require the most. Although these calculations are simple, assumptions and algorithms used in different labs are not identical and are seldom completely described in publications. The use of custom spreadsheet templates is the norm, contributing to non-reproducible research. Accurate, simple, and repeatable data processing with open-source software provide a better alternative, even if only to double-check the results of custom spreadsheets. The software described here can process volumetric, manometric, gravimetric, and gas chromatography measurements of biogas production using a flexible but consistent approach.

Maximum CH_4 potential of a substrate can be determined from measurement of chemical oxygen demand (COD), elemental composition, or even nutritional analysis results (carbohydrate, protein, and lipid content). The software described in this contribution provides an easy, transparent, and consistent way to make these calculations, based on the microbial stoichiometry approach presented by Rittmann & McCarty (2001). With additional information or assumptions on substrate degradability and partitioning between energy and cell synthesis, along with reactor pH and temperature, it is possible to predict CO_2 partitioning and estimate total biogas production and composition. Data processing and modelling possibilities are described in more detail in a recent publication (Hafner et al. 2018).

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The biogas software described here is available in two forms:

1. as an open-source add-on package for the R environment, called the "biogas" package (https://cran.r-project.org/package=biogas), and
2. a web application called OBA (from Online Biogas App) that runs in any browser (https://biotransformers.shinyapps.io/ oba1/).

Use of the package is limited to those who are familiar with the R programming language, but even so, has been downloaded more than 20,000 times since its release in 2015. Detailed usage for OBA is not available, but running time is > 150 hours per month, suggesting a user base of at least 100. OBA requires no programming skills as it is completely mouse-driven. The app relies on functions from the biogas package in the background. Several YouTube videos demonstrate how to use the web app:
https://www.youtube.com/channel/ UCxNGlwTnSkEa1GaFuAKM_3A

While our own experiences and user feedback indicates that the software has clearly made biogas research easier, its impact on the biogas industry is less clear. In its current form, OBA can improve both the accuracy and speed of BMP calculations, and the model can be used to estimate CH_4 yield and biogas composition from new substrates in a matter of seconds. Both features can be useful to biogas plant operators. But additional tools for extraction of kinetic information and improvements in the model would be useful. We anticipate that the software may serve as the base for a larger future platform that includes other functionality. Development is on-going, and new functionality is regularly added to both tools. Recent additions to OBA, for example, include new options for selecting BMP duration based on common rate criteria.

In conclusion, by providing access to transparent standardized algorithms for data processing and stoichiometric calculations, the software described in this contribution can contribute to more efficient and accurate biogas research and biogas plant operation.

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Robust VFA measurement in biogas

 # Online characterization of the biogas process, complex gas sensorics, data evaluation method for VFA levels, programmable in situ recalibrationn

The target of the investigation is a quantitative characterization of the digester process by sensor signal functions of volatile fatty acid (VFA) concentrations in the produced biogas. Electronic control of the sensors and an algorithm for in-situ calibration are applied for high operational stability.

The metal-oxide semiconductor (MOX) gas sensors with partial selectivity are operated in an electronic circuitry which stabilizes the thermodynamic response functions of the sensors. The continuous gas flow keeps the chemical activities of the gas mixtures during the measuring sequences constant. Before setting up the equipment, a first calibration is carried out in the laboratory using synthetic gas mixtures. When a certain parameter drift is achieved the required on-site recalibration is automatically activated.

Due to the partial selectivity of the sensors to the VFA constituents in the biogas the signal spectrum drifts with varying VFA concentrations. The diagnostics of the resul-ing transient functions consists in the following steps: (i) Evaluation of dynamic sensor signal functions by dimensionless representation of the complex data sets; (ii) approximation of the transient function parameters; (iii) calculation of an 1-dimensional array for quantitative recording the integral VFA constituent in the running biogas; (iv) fit of the heavy-tail experimental transients for asymptotic prediction. With this method the dynamic sensor signal functions from the VFA can be separated from the signal back-ground which is caused by varying biogas composition.

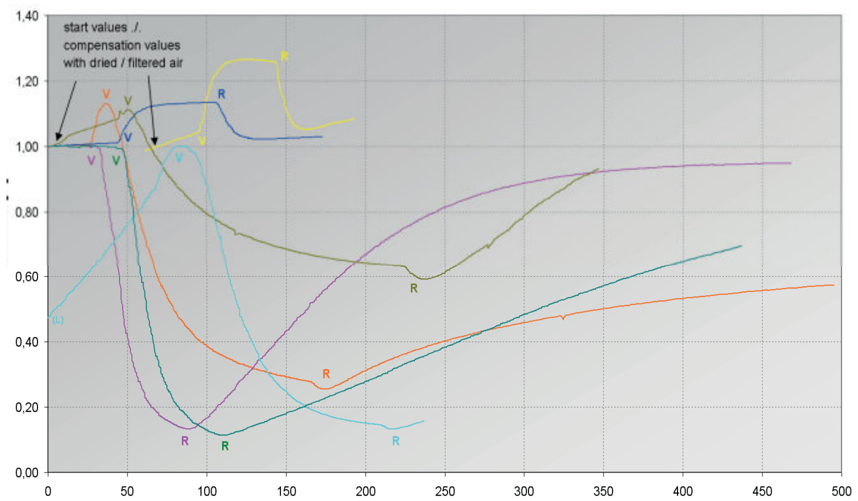

Figure 1 Representative sensor characteristics related to constant start values — the time intervals are divided into a phase of reoxidation (R) and a phase of VFA flow (V) with 100 ppm analytical pure acetic acid; 5 sensors exhibit amplitudes between -60 % and -89 %, 2 sensors +12 % and +22 %; the time constants between ~6.3 s and ~38 s yield spectra with high accuracy; in the laboratory calibration carbonate buffer solutions are adjusted with pH measurement

From a set of industrially available MOX sensors 7 sensors with sufficient selectivity for VFA concentrations in the range of ≤10–6 to ≥10–4 are chosen, see the fig. In the laboratory the calibration functions are measured using air and reducing gas mixtures as carrying gases. Background is the pH calibration of buffered aliphatic acid mixtures. A logarithmic addition rule is tested for the resulting transient parameters of the drift functions. The time constants increase as time increases, revealing a spectral distribution of time constants. From a derivative plot in log-time, the peak height, position, line width, and skewness are used to accurately predict the asymptotic values to within less than few percent. It is seen that the chemisorption and reoxidation kinetics of the sensors can be clearly separated. Artificial addition of different constituents of biogas like H_2, CH_4, CO, can be separated from the VFA single patterns.

The equipment with the adaptive software yields a cost-effective quantitative process control for biogas digester. No access to the sludge in the digester is required. The upcoming work deals with the further evaluation of the thermodynamic data of the biogas in the fluidic system. The online data evaluation makes possible to identify whether the measurement duration is long enough to extract the time constant spectra from one reduction interval. This method reduces the corrosion rate of the MOX sensors due to H_2S in the biogas.

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Residual gas potential difference between the summer and winter samples

Full-scale, residual potential, biogas, methane

Introduction

Renewable Energy Sources Act (2017) restricted new biogas plant in Germany, in the case of installations commissioned after 31 December 2016 and digestate facilities constructed after 31 December 2011, the hydraulic retention time (HRT) in the gas-tight system which is connected to a gas consumption device amounts to at least 150 days (BMU 2017). According to the VDI 3475, biogas plant built before 2012 needs to have a HRT of 110 days in heated system or 150 days in gas-tight system. Otherwise, a verification of less than 1.5 % residual methane potential of daily produced methane is necessary once a year.

The HRT differs strongly between winter and summer seasons as digestate is not allowed to be sprayed in fields in winter time (1 December – 10 January) (BMU 2017). A longer digestate storage time is needed compared to summer season, which will result in a different residual methane potential in biogas plants.

The goal of this work is to investigate residual methane potential among winter and summer seasons in full scale biogas plants, and investigate their differences if any.

Material and Methods

Residual gas potential test
Residual gas potential test was carried out with the Hohenheimer Biogas Yield Test (HBT), which follows the guidelines of the VDI 4630. The digestion of the homogenized samples took place in 100 mL glass syringes in a motor-driven rotor, which is located in an incubation chamber. Each HBT test was conducted with three replicates at 25 °C and 37 °C over a period of 60 days (Mittweg et al. 2012; Ruile et al. 2015).

Full-scale biogas plant and sampling
Sample collection of all full-scale plants was carried out both in winter and summer time. All samples were cooled down to 4 °C immediately after the sampling. Residual gas potential test were conducted for each sample.

In addition to the residual gas potential, actual plant operation data, such as power generation and consumption amount, substrate input and temperature, were recorded.
All samples were analysed for dry matter (DM), organic dry matter (ODM) for all samples were determined in accordance to DIN EN 12880 and DIN EN 12879. Content of volatile fatty acids (VFA) were determined by capillary gas chromatography (GC) (type CP3800 with a FID-detector, capillary column WCOT Fused Silica, Agilent Technologies Germany GmbH, Böblingen, Germany), as detailed in (Haag et al. 2015) and (Lindner et al. 2016).

Results

The difference of residual gas potential between summer and winter samples is strongly depend on the HRT of each individual biogas plant. However, there is no clear effect found due to low degradation of digestate samples, which is usually stored in an unheated tank in a full-scale biogas plant.
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Opportunities for optimisation and valorisation in real-time production & monitoring of anaerobic digestion (AD)

Anaerobic digestion, optimisation, microbial characteristics, additives, valorisation

Anaerobic digestion (AD) is a nature inspired technology converting organic waste to biogas and nutrient rich digestate. The implementation of AD can lead to generation of renewable energy and circular economy solutions to organic waste. However, uptake of industrial-scale AD in the developing world, and high standards of process control have been limited by monitoring equipment and the limited local research work done on locally available feedstock.

For the same reason, existing AD plants offer no rapid or detailed diagnosis of the biochemical balance of digesters, such as stress, build-up of inhibitors, scope for feedstock to be fed or reduced etc. As a result, most AD plants are not optimally operated, are oversized, and still run blind regarding the onset of inhibition or toxicity. No real-time metrics have been developed for use by industry to proactively optimise performance through new feedstock, nutrient supplementation, changes in organic loading rate, or temperature.

This project, in collaboration with Anaero Technology, aims to develop advanced metrics that can be used to develop and test control algorithms for real-time monitoring (an initial step for artificial intelligence control of biorefinery), and to acquire or develop dedicated Nano sensors for industrial control probes.

Currently results from a comprehensive literature study have highlighted the following research topics:

» Microbial characteristics
» Optimisation of methanogensis
» Impacts of chemical additives in nanoscale
» Alternatives products of AD

Research regarding the microbial communities of AD has focused on characterising those pertinent to each stage of AD, exploring the difference between microbial communities for mesophilic and thermophilic conditions, wet and dry conditions and the impact of inhibitory substances on microorganisms. Gaps in the research have been identified around the pre-treatment and the impact it has on microbial communities.

Focusing on the methanogensis stage, a number of key parameters are reported to have a significant impact on methane production; temperature, volatile fatty acid concentration, pH, carbon/nitrogen ratio, ammonia, long chain fatty acids and metal elements. Standard chromatographic methods are frequently used in studies for monitoring these parameters, however recent exploration into spectroscopic and electrochemical methods shows potential.

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In the field of nano-additives, reports of zerovalent metals alongside pure metals, metal oxides, metal chlorides and non-metal compounds have been explored. It has been reported that nanoparticles with trace elements can enhance the performance of AD, by promoting hydrolysis and methanogensis. A number of mechanisms have been theorised for these effects; impact of dissolved ions, impact due to enzymes or coenzymes, change of electron transfer pathways, damages on microbe cell membranes, release of oxygen species and disruption of intracellular homeostasis. Gaps identified in the research include a limited selection of nanoparticle types, variation in feedstock's and experimental methods.

Exploring the products and intermediates of AD shows potential for a number of opportunities for valorisation of the process. Use of AD for volatile fatty acid production is well documented and could have high economic potential. Similarly, the production of phenolic compounds is a relatively unexplored research area with applications within the food & beverage, nutraceutical and pharmaceutical sectors. Increased operational understanding of AD could lead to opportunities to use the technology to produce these novel, high value products.

The outlook of the project is to explore the key focus areas discussed. A combination of computational and experimental techniques will be used and data generated will be used in development of the advanced metrics discussed. Future results are expected to provide a holistic picture of anaerobic digester operation and therefore as a starting point for real time monitoring and control algorithm development.

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Hydrogen concentration as a possible control parameter for biogas plants

Process Control, hydrogen concentration, optimizing biogas yield

Background/motivation

Anaerobic digestion processes are used in biogas plants for producing methane as a source of energy. The biological metabolic processes in biogas plants are complex and difficult to understand for the operator. Many of the over 9,000 biogas plants in Germany are not operated in the optimal range. This results in incomplete substrate degradation, inefficient biogas yield, acidification, emission of methane, ammoniac, hydrogen sulphide, volatile organic acids and foam generation. All these effects reduce the yield of bioenergy. In order to optimize the fermentation process we investigated the anaerobic digestion process by using different model substrates (glucose, cellulose, starch and albumin). The obtained analytical data were compared to the results of a mathematical model.
There are no reliable and easy to detect parameters to identify disturbances of an anaerobic biological digestion processes at an early stage. Easy to detect parameters like the pH-value in the reactor or high concentrations of ammoniac or hydrogen sulphide in the biogas indicate disruptions of the process too late. Reduced biogas yields or even the breakdown of the degradation process cannot be prevented. The concentration of volatile acids or VOA-TAC-value (Ratio of volatile organic acids and total anorganic carbon i.e. the buffer capacity) are not capable for fast on-line-analysis due to the effort for sample preparation. To solve this dilemma we compared many analytical data with the biogas yield in different stages and different substrates of the process.

Aim of the work

Aim of the work was the development of a reliable and easy to use process control technology. Hence we addressed the following aspects:

- » Deeper understanding of the biological process and interactions with the reactor
- » Optimized sensor technology for online-monitoring and process-control
- » Analysis of the population of microorganisms in the reactor
- » Mathematical models to identify possible control parameters
- » Comparing the results of different fermentation processes on laboratory scale

Parameters should be derived, which can serve for a model-based process control. Also microorganisms should be identified, which can serve as a guide for a genome- or protein-based population analysis for process monitoring.

Key research topics and novelty

The analytical parameters of experiments were compared to the results of the model and to the biogas yield of the different reactors. Different plants in laboratory scale with different substrates were used to get these parameters like VOA-TAC-value, compositions and concentration of fatty acids, microbial community composition and also methane and carbon dioxide in the biogas. Also new sensors were tested like a sensor for hydrogen concentration in the gas phase and a miniaturized polarimeter to detect the angle of rotation of polarized light. All parameters were detected during different states of the digestion process.

Methods

The fed-batch experiments were performed in 2-L and 8-L bioreactors equipped with gas meters and sensors for methane and carbon dioxide. Total solids and total volatile solids, VOA-TAC, and pH were measured. VFAs (volatile fatty acids) and amino acids were analyzed with ion exclusion chromatography equipped with a conductivity detector or an amperometric detector, respectively. The microbial community composition was identified using Illumina Amplicon sequencing. The mathematical model based on the „Anaerobic Digestion Model No. 1“(ADM1, Batstone et al. 2002).

Results

The anaerobic digestion process has a high hydrogen sensitivity (table 1).

Table 1 Threshold H_2 partial pressure of different anaerobic digestion phases of the biogas building process (Thauer et al. 2008; Stams, A. J. M. (1994); Harper and Pohland (1986)).

Treshold H_2 partial pressure	
Acetoklastic methanogenesis	> 10 Pa
Hydrogenotrophic methanogenesis	< 10 Pa
Homo-acetogenesis	52–95 Pa
Propionat oxidation	> 10 Pa
Butyrat oxidation	> 100 Pa
Ethanol and lactat oxidation	105 Pa

Even relatively low hydrogen concentrations have a regulatory effect and may affect the metabolic pathways of the reactor. A low substrate load results in a low hydrogen pressure and acetate as the predominant volatile fatty acid. In contrast, high loads lead to a high hydrogen pressure (> 10–4 atm) and subsequently to an increased formation of propionate, butyrate and lactate. An accumulation of these fatty acids can lead to a significant impairment of methane production (Bischofsberger et al. 2005; Bauer et al. 2008, 2009; Schieder et al. 2010; Harper and Pohland 1986). Our experiments show that the hydrogen pressure can be used as a parameter for early identification of the reactor state.

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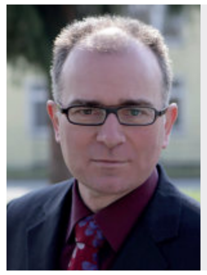

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Use of manganese oxide to oxidize hydrogen sulphide in biogas

 # Biogas, hydrogen sulphide removal, hydrated manganese

There are many methods for removing hydrogen sulphide from biogas. However, most of these methods are somewhat limited and new solutions are being looked for and investigated. In this paper new findings related to removal of hydrogen sulphide from biogas using catalytic MnO_2 are presented. The hydrated manganese (IV) oxide produced during manganese removal from drinking water is used as the H_2S sorbents and oxidation catalyst. Beechchips were coated with manganese (IV) oxide to form the sorbent/catalyst bed. A more efficient adsorption and faster regeneration of this bed in comparison to the iron-oxide bed was confirmed. The concentration of hydrogen sulphide in biogas produced from chicken manure dropped from about 1,650 to less than 5 ppmv after passing the filter. Similar effectiveness of the bed for biogas cleaning in the waste-water treatment plant was confirmed. Besides, it was found that effectiveness of hydrogen sulphide removal depends not only on the MnO_2 content but also on the size of particles. The smaller the particles, the larger biogas-flow resistance caused by the bed and more effective oxidation of hydrogen-sulphide molecules. The elementary sulphur produced during six-month filter-operation limited the access of hydrogen sulphide molecules to the catalyst and hydrogen sulphide concentration in the cleaned biogas increased to 45 ppmv.

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Remote monitoring of biogas plants: Brazilian cases

 # Monitoring system, Biogas Plant, Distributed Generation, Internet of Things

The increasing demand for electrical power and the concern with the environment impacts has boosted the biogas production sector in Brazil. According to the National Electric Power Agency (ANEEL), the brazilian installed power has increased by 14 % in the 2016–2017 biennium to a total of 163 GW. The 38 biogas plants registered at ANEEL add up to 149 MW installed power. The biogas potencial in Brazil has fomented new projects, of different dimentions, integrating the energy utilization of residual biomass, especially in the agricultural industry.

Biogas plants demand an automation and monitoring level that justifies the installation of online monitoring and control systems.The purpose of this paper is to exhibit the monitoring solutions developed by CIBiogás-ER and its partners for biogas production plants and eletrical power generation. Adopting the philosophy of internet of things, the systems allow the monitoring of several variables simultaneously.

The fisrt case introduced is the biomethane plant installed in ITAIPU, developed in partnership between CIBiogás-ER and Itaipu Binational Hydroeletric Power Plant, which have installed the plant to treat the organic waste produced in the restaurants of the Itaipu complex, generating biogas and biomethane for the continious supply of its fleet of vehicles. Aside of attend a susteinable plan which reduces the environment impacts resulting of the apropriate treatment, this plant fosters the economical, technological, social and environmental developing in the direct envolved areas, generating informations that allow the unfolding of analisys for the replicability of the project. Figure 1 shows the installed plant in Itaipu.

Figure 1 Biogas/Biomethan production plant installed in Itaipu Binational Hydroeletric Power Plant.

CIBiogás-ER also contributed to the installation of several other biogas plants throughout the western Paraná, southern Brazilian state. The biodigesters installed in rural properties of cattle and pigs transform environmental liabilities (organic waste) into energy assets (electric energy). Due to the geographic dispersion of these biogas plants, a remote monitoring system was developed that currently monitors biomass temperature, biogas flow and electrical energy data in five units (GALVAO et al). Figure 2 shows details of the developed solution.

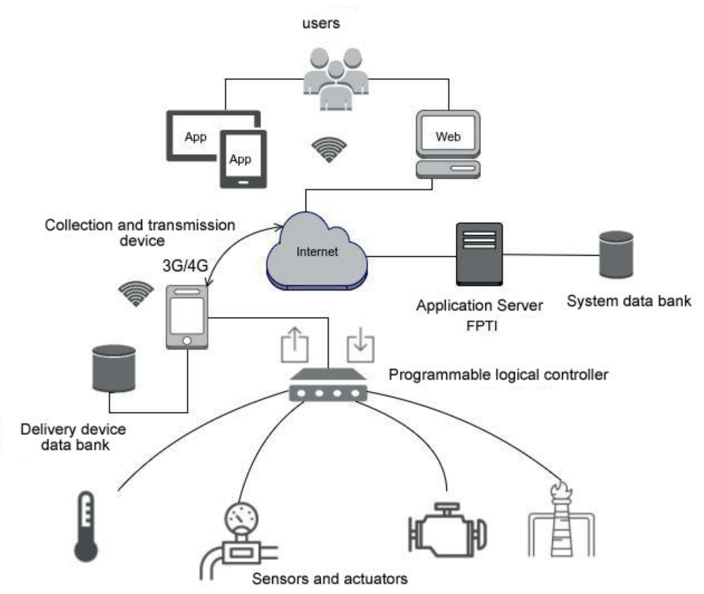

Figure 2 Details of the developed arquitecture for the monitoring system.

Additionally, CIBiogás-ER and the Laboratory of Automation and Simulation of Electronic Systems (LASSE), in partnership with Companhia Energética do Paraná (COPEL), develop a research project linked to ANEEL, which aims to install a grid of 23 km for the transport of biogas produced in 19 pig farms in the municipality of Entre Rios do Oeste in the state of Paraná. Biogas flows from the farms to a Thermoelectric Power Plant, where electricity is produced and used to compensate the energy consumed by the city's buildings. To monitor the entire plant, covering the farms, biogas grid and thermoelectric power station, a remote monitoring system, adapted for long distance data transmission using LoRa (Long Range), is under development. LoRa is a radiofrequency communication technology. The architecture of the projected solution is shown in Figure 3.

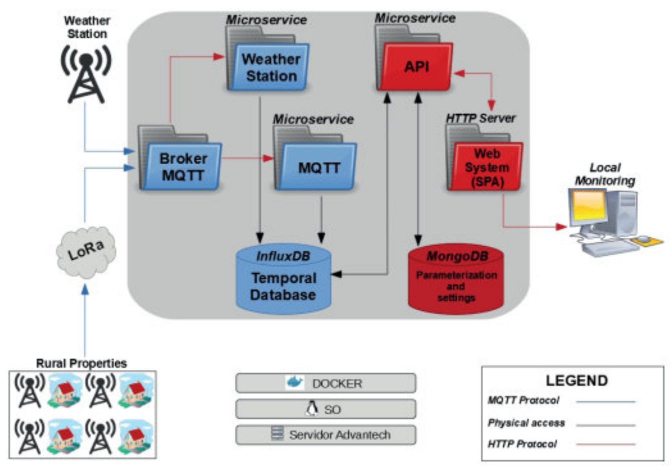

Figure 3 Arquitecture of monitoring system used in the Entre Rios do Oeste plant.

References

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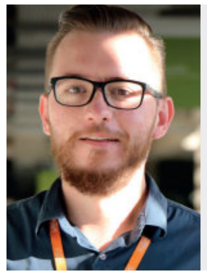

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Gerhard Rettenberger

Increase of safety-related requirements for biogas plants following the example of the chemical industry – development of model P&ID-flow charts with all safety-related circuits

 # Biogas plants, safety, measurement and control technology, P&ID-flow charts

In the present draft of the technical rule on installation safety "Safety requirements for biogas plants" – TRAS 120 – a concept for monitoring is required in which the operator must determine which conditions and processes have to be monitored to ensure the intended operating by technical provisions or organizational actions. In the technical rule different suggestions are mentioned and the working group "Biogas plants" of the commission on process safety prepared suggestions for configuration of a biogas generation plant with safety-relevant measurement and control technology. At present, on behalf of the Federal Environment Agency of Germany and in cooperation with the working group "Biogas plants" of the commission on process safety, Prof Rettenberger and his team work out models of process flowsheets and P&ID-flow charts separated for agricultural biogas plants and waste fermentation plants to relieve the implementation of the TRAS 120. The safety-relevant measurement and control technology is to be taken center. The models are initially valid for plants that are subject to the German major accident ordinance (Störfall-Verordnung). The flowsheets should be editable by potential users so that they can adapt them on technology and mode of their plants.

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Manuel Winkler, Sören Weinrich

Model-based process optimization of biogas plant operation

 # Flexibilization, Model-predictive control, Optimization

The European Union aims to reduce carbon dioxide emissions by 40 % of 1990 levels by 2030. While the two main technologies of renewable energy production, photovoltaics and wind power, can produce enormous amounts of carbon-neutral electricity at comparatively low cost, their performance depends directly on the weather and introduces instabilities into the power grid. Therefore, flexible storage and supply solutions are needed to guarantee a stable power supply. Biogas plants play a key role, since they can provide power on demand. The aim of this work is to present model-based process control strategies, which can be used to enable existing biogas plants for flexible operation.

Currently, most of Germany's approximately 8,700 functioning biogas plants (Daniel-Gromke et al. 2018) are designed for continuous operation. However, to meet the abovementioned goals, process flexibilization both by hardware upgrades and targeted feeding modulation is indispensable (Hahn et al. 2014). In particular, substrate management demands an increased level of process monitoring and control to guarantee highly flexible, efficient and stable plant performance at all time.

From a modeling point of view, flexible operation of full-scale biogas plants presents several challenges. Data on biogas production rates and quality are rarely available and typically include great measurement uncertainty. Furthermore, it is complicated and costly to measure important state variables in the fermenter, e.g., concentrations and growth rates of the involved microorganisms. Profound substrate characterization data is scarce and subject to significant error.

If properly calibrated, the mass-based Anaerobic Digestion Model No. 1 (ADM1) and its reduced stages (ADM1-R1 to ADM1-R4) have shown their applicability for dynamic simulation of biogas production in individual fermenters (Weinrich 2017). Also, it has been demonstrated that the biogas process remains stable under frequently changing feeding strategies at full-scale conditions (Mauky et al. 2016). However, an overall concept of a control and optimization strategy for an entire plant concept is still unpublished.

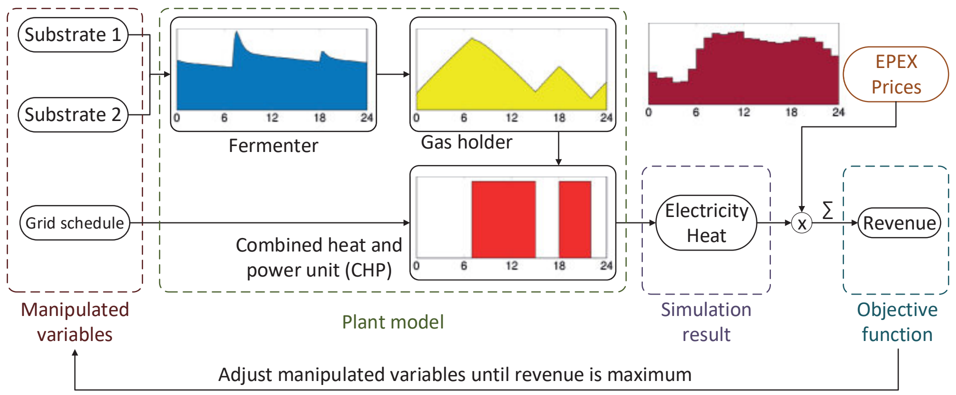

Figure 1 Scheme of model-based process optimization

The focus of the current study is to combine submodels of the fermenter, gasholder, and the combined heat and power plant (CHP) into an overall plant model. Considering several external inputs, including weather forecasts and daily electricity prices from the European Power Exchange (EPEX), economically optimal and technically feasible feeding and power generation schedules are ascertained to maximize plant owners' revenue (see also Figure 1). Biological process stability is implicitly regarded by the model.

Since CHPs are not operated under partial load in practice, and the dependency of feeding and biogas generation is nonlinear, the optimization problem assumes the form of a mixed-integer nonlinear program (MINLP) whose convergence is slow and whose results depend strongly on the initial values and employed solver. As a viable alternative, a decoupling of power generation and feeding schedule optimization has shown good preliminary results, as long as the outcome of each optimization can be neatly interchanged. Grid schedule is taken from price-rank method (PRM), given that the ratio of installed CHP capacity to rated power and thus, runtime per week, is fixed.

Feeding optimization accommodates times and amounts of feeding in such a way that oscillations in the gasholder, induced by flexible CHP operation, are minimized. Even though usage of detailed fermenter models like ADM1 would be preferable, computational runtime does only allow its usage for short-term optimization. Thus, for longer forecast periods, simplified fermenter models are employed because of their much faster convergence. Fermentation of organic dry matter (ODM) is modeled as first-order reaction, neglecting pH equilibria and inhibition, which allows for an analytic solution of the balance equations. These results can then be taken as initial values for short-term optimization with the detailed models.

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Monitoring of ammonia in biogas

Impedance, conductivity, resistance, condensate

In order to optimise the processes in a biogas plant it is necessary to determine continuously the control parameters during the fermentation process. Due to the interference of bacteria activity, the ammonia content is one of the important factors. However, ammonia cannot easily be determined by standard procedures. Usually a sampling process is necessary. Therefore, the aim of this work was the development of a system for the continuous monitoring of ammonia in the raw biogas.

As a result, a new measurement system has been constructed which is intended to be placed in the gas room above the fermenter. The measurement bases on the impedimetric principle, where a condensate is generated on the surface of an interdigital electrode (Fig. 1). The condensate fills the complete measurement surface and forms drops. For determining the conductivity of these drops impedance spectroscopy is performed. The ammonia of the biogas causes a decrease in the impedance due to a decreasing electrical resistivity of the drops in comparison to a pure aqueous condensate. The ammonia content in the gaseous and the condensed phase of the fermenter is related by Henry's law, so that the content in the condensate can be used to determine the concentration in the gas.

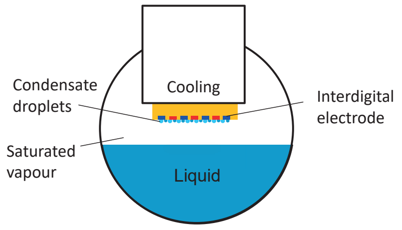

Figure 1 Measurement principle

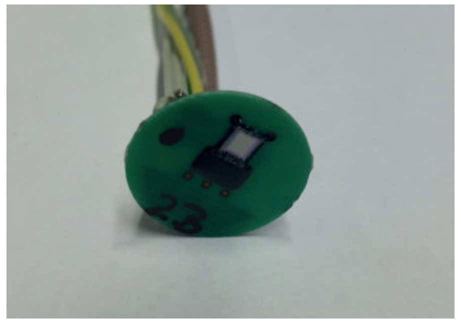

Figure 2 Interdigital electrode on a printed circuit board

In this system, the interdigital electrode is mounted on a thermoelectric element which is embedded in a printed circuit board (Fig. 2). The condensate is generated from the biogas by cooling down the interdigital electrode below the dew point. Using a PID controller a constant condensate temperature is achieved. After a period of equilibration, a stable measurement signal is obtained which can be used to determine continuously the ammonia. The impedance of the condensate is decreasing with a growing ammonia content of the gaseous phase. This is due to the extremely high solubility of ammonia in water and the formation of ions by the interaction with water molecules. However, the impedance is influenced by all other volatile and condensable components, especially by organic acids or hydrogen sulphide.

In this work, the measurement system is characterized by electrochemical impedance spectroscopy (EIS). Using artificial mixtures, the influence of the matrix composition on the impedance of the condensate is investigated. Calibration functions are given. Results regarding the life time of system components are shown.

References

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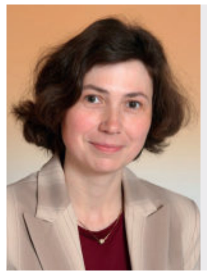
URL: http://www.renewable-energy-concepts.com/german/bioenergie/biogas-basiswissen/biogas-analytik-prozessanalyse/hemmtest-hemmung-bakterien.html (Status: 29.10.2018)



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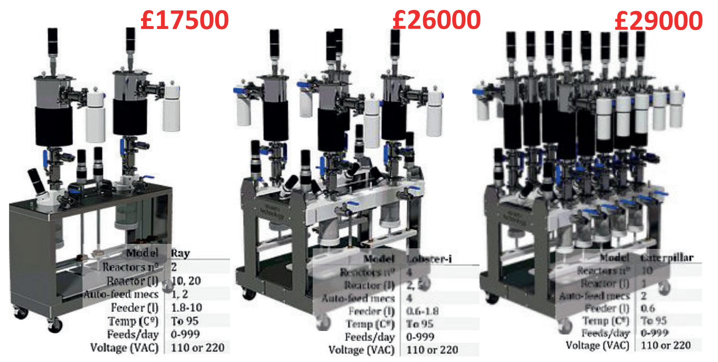

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References in the field of monitoring & process control of anaerobic digestion plants:

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Based on many years of experience in research and consulting Prof. Dr.-Ing. Frank Scholwin founded in 2012 the Institute for Biogas, Waste Management & Energy in Weimar. In close conjunction with a network of national and international experts independent scientific consulting services are provided.

The main targets are to implement biogas technology in order to contribute to the sustainable transition of the energy system from fossil fuels to renewables and to create sustainable material life-cycles.

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A large number of publications on biogas topics has been written during the last years. Prof. Scholwin is member of a number of scientific bodies and scientific boards/committees.

Besides other services, the Institute of Biogas Waste Management and Energy offers for example:
Biogas process control of medium and large-scale biogas plants

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Portfolio

References in the field of monitoring & process control of anaerobic digestion plants:

» Biogas from Algae – Project in Berlin
» Algaefacade in corporation with GASAG

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Fig. 1 Container-based dry fermentation plant (plug flow)

Fig. 2 Biogas Test Plant BTP2-control with automated gas analysis

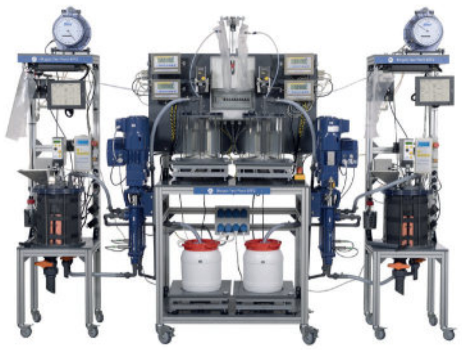

Fig. 3 Biogas Test Plant BTP2-control with automated feeding system

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As organizers we tried our best to keep CO_2 emissions connected to the conference as low as possible and chose an environmentally friendly venue, catering and promoted travelling by public transport.
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Info: www.govinda-leipzig.de

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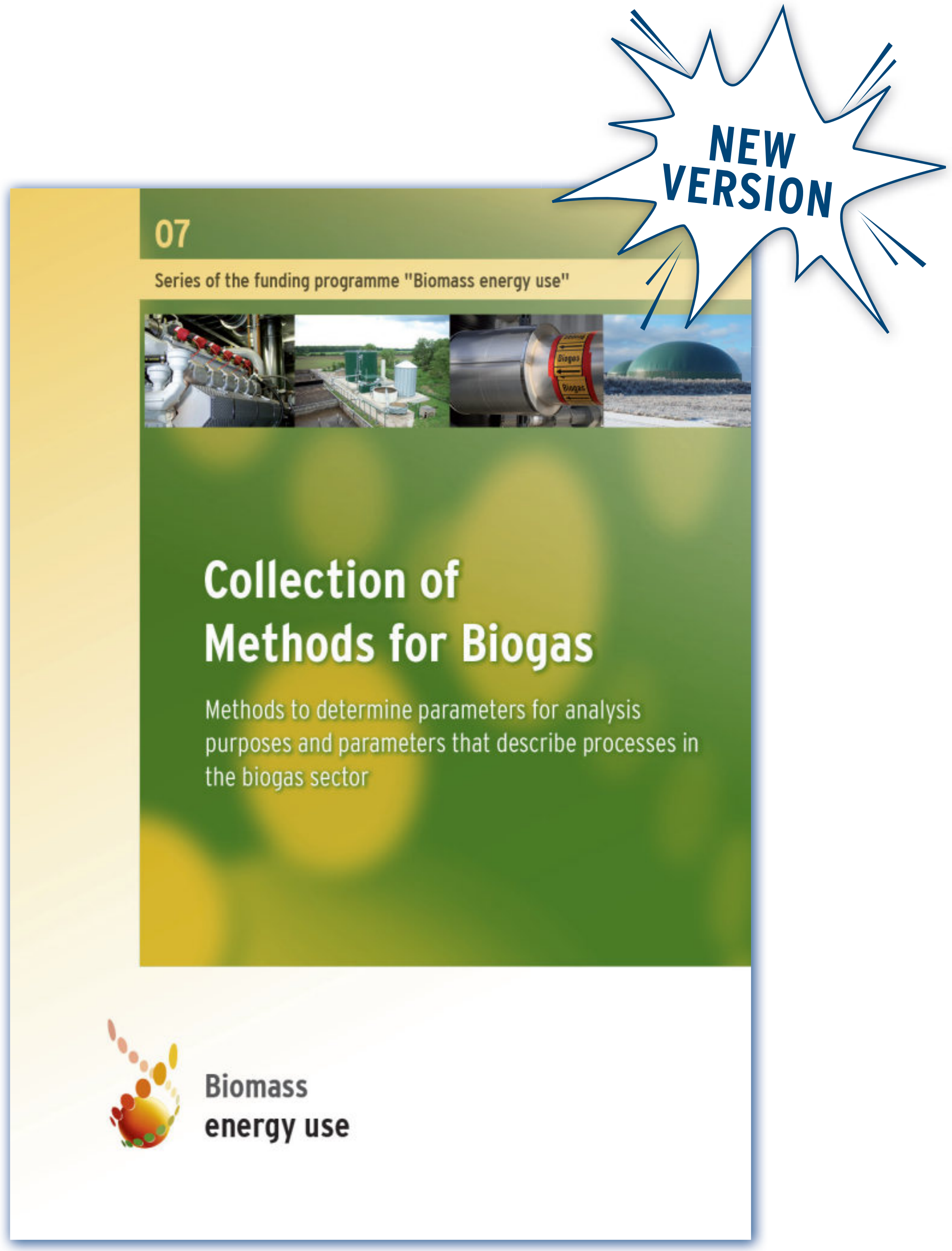

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