SciMedCentral
Chemical Engineering & Process Techniques

Original Research

Biogas Production from Swine Manure and Energy Crops with Manual Intermittent Feeding or with Automated Fuzzy Logic Feedback Control

Paul Scherer[1], Sebastian Antonczyk[1], Anja Schreiber[2] and Vollmer GR[2]

[1]Research Center 'Biomass Utilization Hamburg', Hamburg University of Applied Sciences ('HAW'), Germany

[2]Department of Environmental Technology, University of Applied Sciences Nordhausen ("FHN"), Germany

*Corresponding author

Paul Scherer, Research Center 'Biomass Utilization Hamburg', Hamburg University of Applied Sciences ('HAW'), Ulmenliet 20, 21033 Hamburg, Germany, Tel: 49-163-724-6059; Email: paul.scherer@haw-hamburg.de

Submitted: 23 April 2020

Accepted: 02 May 2020

Published: 05 May 2020

ISSN: 2333-6633

Copyright

© 2020 Scherer P, et al.

doi: https://dx.doi.org/10.47739/Chemicalengineering.1057

OPEN ACCESS

Keywords

- Anaerobic digestion; Fuzzy; Process control; Biogas
- Biomass; Energy crops; Manure

Abstract

Anaerobic digestion of swine manure was performed with cereals as mono-input either by manual intermittent feeding or by feeding under the direction of a Fuzzy logic feedback control (FLC). The biogas process was conducted in semi-technical scale (1 m³ biogas reactor, 2.5 m³ dosage and 2.5 m³ digestate tank) by a process computer in the technical hall of the University of Applied Sciences in Nordhausen, 300 km away from Hamburg. But the process data of Nordhausen were supervised and internet based edited by FLC on the host computer in Hamburg. Only three control parameters were used: pH, methane content (% of the biogas) and specific gas production rate GPR. Specific GPR (GPR/ OLR/ d) or m³ biogas/ kgVS implied that the volumetric GPR (m³ biogas/ (m³d) was related to the organic loading rate OLR in kgVS/(m3 d), VS = volatile solids. The implemented FLC-system worked as a real feedback control system as the microbes itself directed the speed of substrate feeding by the dynamics of their substrate turnover. In test period I with manual intermittent feeding only a process-safe OLR of 4 kgVS/(m3 d) was possible, followed by an overloading and reactor disturbance at ≤ 6.3 kgVS/(m3 d). However, operation with an automated FLC system in test period II (585 trial days) enabled a safe OLR of 9 kgVS/(m3 d) with a concomitant hydraulic residence time (HRT) of only 10 days. The applied FLC-system increased the OLR by more than 5 kgVS / (m3 d), doubled the process space-time yield and enabled a degradation rate of nearly 100% without jeopardizing the safe biogas process. Therefore, usage of an FLC-system should open the door for a remote controlled biogas production with an autopilot function.

INTRODUCTION

Renewable energies in Germany and the whole European Union are of a great importance, because fossil and nuclear energy shall be complety replaced by renewables. In the year 2018/2019 39.7% of the total electricity demand in Germany was already produced by wind energy, 8.3% by biogas plants, 7.6% by photovoltaics. Around 9,500 biogas plants exist at present in Germany with an installed electrical output of 5.6 GW and a heat production of around 2.6 GW supplying more than 9 million inhabitants with electricity (State Agency for Renewable Energies, AEE, website, and [1]. Most of the biogas plants in Germany use 20-90% manure as input and get an additional bonus to the energy feed-in tariff by the government. Germany has a more centralized energy system and wind energy as well as photovoltaics is not always available. Therefore, several years ago a novel bonus for flexible electricity production on demand was introduced for biogas plant owners in Germany. As Lauer et al. pointed out [2], the combined electricity production on demand together with wind energy and photovoltaics is even cheaper and produces less greenhouse gas emissions as by base load capable electricity production of biogas plants alone. Several concepts for flexible electric power generation by demand-driven biogas supply are described [3]. They use easily degradable energy crops like sugar beet silage [4] to follow the demand promptly, but a Fuzzy logic control (FLC) concept [5,6] to stabilize the biogas production was not included.

One main parameter of biogas production is the right pH for the methanogenic microbes which desire a range between pH 7-8.5. Otherwise acidification occurs, which leads to severe disturbance of the biogas process. One suitable approach for buffering and stabilizing a microbial biogas process is using a nitrogen-rich co-substrate with a high buffering capacity like manure from cows or pigs and chicken. That circumvents an extra pH control-system like in other industrial fermenter processes with pure microbial cultures. Another simple approach is to use a recirculation of the effluent, but this can lead to a concentration of salts [7]. Biogas plants without manure still need additionally calcium oxide (lime) as a buffering agent for continuous operation [8].

The FLC technique has been applied in several studies as supervision and modelling strategy for anaerobic treatment of industrial wastewaters [9-15]. However, there exists only few information about the applications of FLC to operate an anaerobic digestion plant with particulate organic waste and/or energy crops [16,17].

A FLC-technique was introduced at the Hamburg University of Applied Sciences on the base of a fully automatic Fuzzy logic feedback system for anaerobic digestion of beet silage [18,19]. Continuous, stirred biogas reactors in the laboratory scale were used with the three control parameters pH, methane content, specific gas production rate, which worked as real feedback control system. The microbes itself directed by the dynamics of their substrate turnover the speed of substrate feeding [18,19]. Especially sugar beet silage without leafs and manure (pH 3.0-3.5) .is extremely low buffered as the mineral content was decreased by breeding down to around 1% whereas the sugar content increased up to 30-35% dry matter. The maximum alkalinity for sugar beets was about 2,500 mg/L $CaCO_3$ whereas Speece postulated 6,000 mg/L $CaCO_3$ as minimum for a pH-neutral process [20,21]. Therefore, high organic loading rates (OLR) are difficult to establish with such an easily degradable biomass. The FLC-technique accomplished successfully the performance of anaerobic digestion of acidic beet silage without the use of chemicals or manure. The developed FLC can cover most of all applications, such as it provided a careful start-up process and a gentle recovery strategy after a severe reactor failure, also enabling a safe process with a high OLR and a low hydraulic retention time (HRT). That means in the case of fodder beet silage a stable HRT down to 6.0 days with an extreme OLR up to 15 $kg_{VS}/(m^3\ d)$. The volumetric gas production rate (GPR) of 9 $m^3/(m^3\ d)$ allowed an outstanding high throughput process with a high space-time yield [19]. That should be a good precondition to produce flexibly biogas on request to diminish electrical peak loads in an electrical network by enhancing in intervals the OLR of a biogas plant on demand or by transferring the bio-methane into a gas storage dome [3].

Now, the previously described FLC system should be tested with cereals as energy crops in a long term operation at the University of Applied Sciences Nordhausen, 300 km way from Hamburg, in a biogas reactor of semi-technical scale. This should be the first operation with alkaline, highly buffered swine manure and cereals as mono-input. It also should enable an internet based FLC-system including the headquarter computer in Hamburg and the process computer in Nordhausen. Secondly, it should demonstrate the feasibility to supervise and direct automatically biogas plants via an internet based remote and autopilot function.

MATERIALS AND METHODS

Principle of the used Fuzzy logic feedback controller

First, an overview of the remote monitoring and internet based Fuzzy logic feedback control system will be given. Process data of the biogas plant of the University of Appled Sciences in Nordhausen (Thuringia) were collected with the help of remote monitoring, saved and transferred online to the HAW in Hamburg, district Bergedorf. A rapid response and process adaptation should be guaranteed by a separate internet account (Figure 1).

The process computer in the technical hall in Nordhausen included a SIMATIC S7-300-interface and transferred the data to the HAW in Hamburg by a programmable Fuzzy logic controller. It could be a laptop, but it needs for continuous operation permanent air ventilation. By the FLC equipment and by the help of a commercial Labview® software with self-programmed user interface program, the parameters pH, methane (CH_4) content, carbon dioxide (CO_2), redox (oxidation reduction potential resp. ORP), temperature and biogas amount (litres) were recorded online and supervised in Hamburg. The measuring devices were checked daily and calibrated weekly to guarantee a stable operation during online recording. The process computer controlled the pump and the other electronic feeding equipment. The feeding amount was calculated by a liquid level measurement of the storage tank and the biogas reactor, Figure 4. In order to send and receive the parameters, file transfer programs (FTP) were written in Labview® for HAW and for Nordhausen. The master computer at the HAW read the process data from a FTP-server and calculated the new added FLC-driven OLR with respect to substrate supply in the previous control period (generally averaged by 8 hours). The calculated new OLR was sent by the FTP server in Hamburg to Nordhausen and their process computer recorded and converted it in a numerical signal for the process control-system and pump. According to this external command the feeding of substrate was performed by a Fuzzy logic feedback control.

Fuzzy control parameters

a) FLC uses exactly measured values as input parameters such as methane (in % of produced biogas) and pH as input parameters, but transfers them into imprecise or "Fuzzy" linguistic terms and connects them by the self-programmed Fuzzy rule base of the Simatic Fuzzy [5,6]. The specific GPR has been integrated as a genuine feedback parameter [20]. The developed FLC was based only on three measuring parameterspH: Especially useful in the case of easily degradable substrates and danger of biogas reactor acidification.

b) Specific GPR (volumetric GPR related to volume / OLR/ d): The resulting specific gas production rate GPR ($m^3/(kg_{VS}$ d) is important to observe the general activity, based on substrate

c) Specific GPR (GPR/ OLR/ d) or m^3 biogas/ kg_{VS} implied that the volumetric GPR (m^3 biogas/(m^3d) was related to the organic loading rate OLR in $kg_{VS}/(m^3\ d)$

d) CH_4: to evaluate the methanogenic performance and by the way for the detection of invaded yeasts. They produce only CO_2 as a 'biogas' reducing thereby the methane yield. This could be a problem in sugar-rich substrates like fresh beets.

The following Fuzzy control parameters indicate a high turnover: high CH_4-content, high spec.GPR, pH in the right, neutral range. They enhance the FLC-command below for

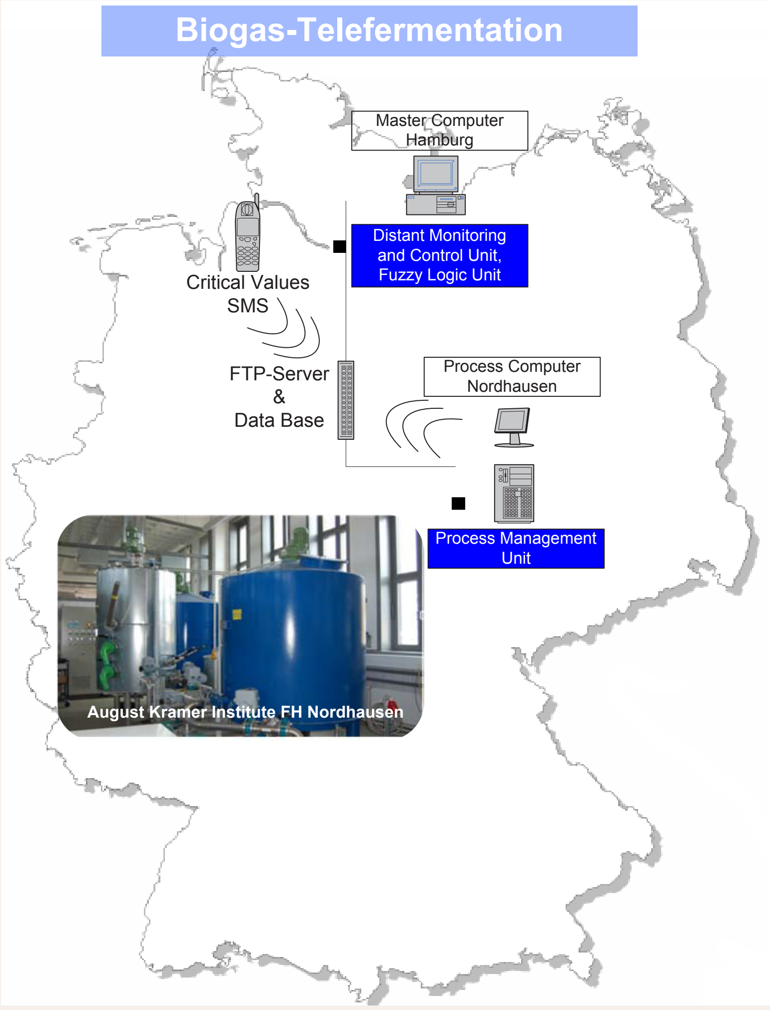

Figure 1 Scheme of the used internet based distant monitoring and autopilot system between the University of Applied Sciences in Hamburg and in Nordhausen, 300 km separated from each other. It was directed by a unique Fuzzy Logic feedback control system (FLC) for anaerobic digestion established in Hamburg. The process management unit in Nordhausen included a SIMATIC S7 interface and a file transfer program (FTP). The master computer at the HAW owned a similar user interface program and monitored and directed automatically the feeding of the biogas reactor in Nordhausen by calculating the new organic loading rate OLR with respect to the OLR of the previous substrate feeding interval.

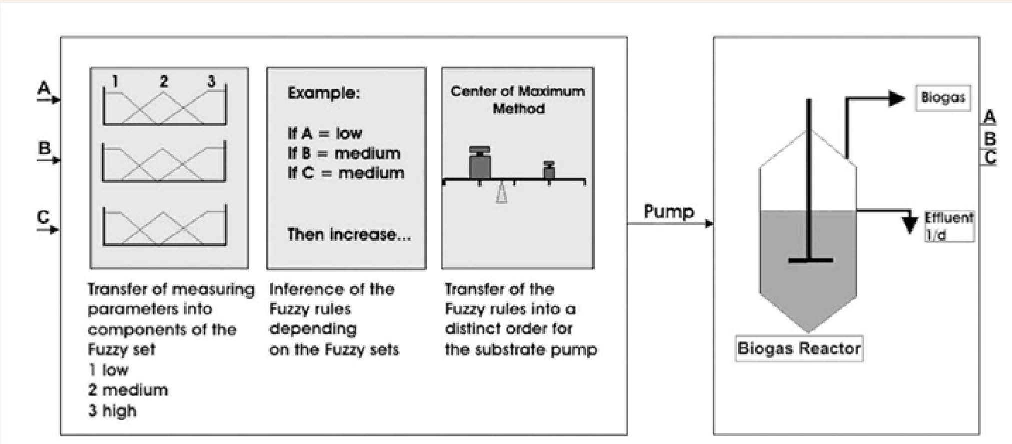

Figure 2 Scheme explaining the principle of the of the used Fuzzy Logic feedback control system (FLC) to feed automatically and in safe manner a biogas reactor. A, B and C are the three selected control parameters, representing the methane content (CH4), pH and the specific GPR. The programmable Fuzzy tool of LabView® was used to create the Fuzzy rules. The Fuzzy tool generated the new OLRadded into relative percentage 10 – 120 % of the last feeding by the center of maximum method [5, 6].The value had to be converted into a precise numerical command of the pump.

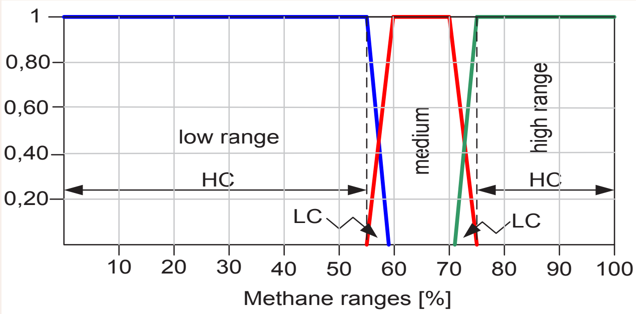

Figure 3 Scheme of the developed and implemented Fuzzy rules on the Fuzzy tool of the used LABVIEW ® software demonstrating the adjustment of control ranges for the FLC directed substrate feeding. The measured methane (CH4) percentage in the produced biogas was related as shown to the three ranges of low, medium and high (HC, LC = high or low concentration). The medium control range (MR) for CH4 percentage was 60–70%. The HC range was found experimentally to be above 75% and below 60% of methane. The LC range is a transient status between HC and MR. In the case of methane content, the HC value is not experimentally achievable, e.g. it means a high content above 75%.

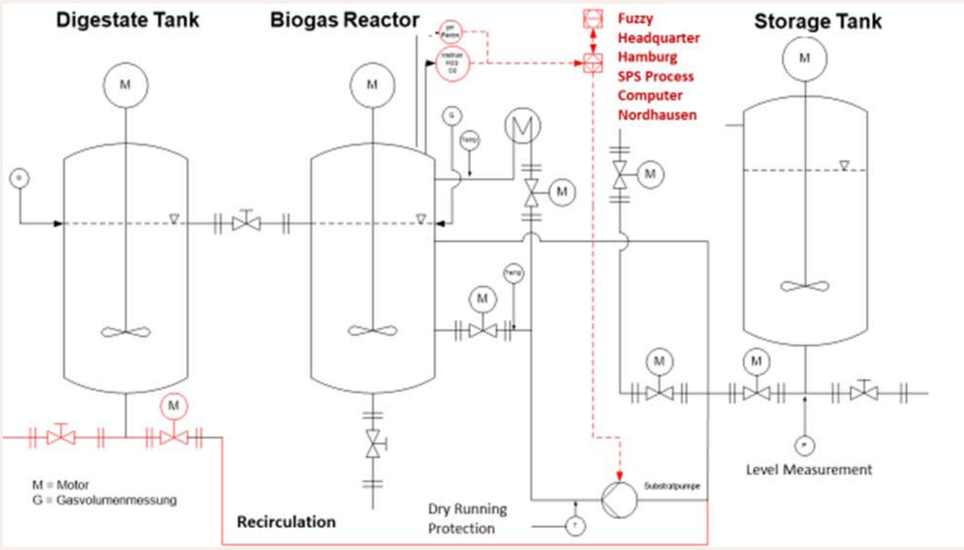

Figure 4 The operating biogas reactor system in Nordhausen. Dosage substrate tank 2.5 m^3, not heated. Biogas reactor with 1 m^3 working volume, permanently stirred with 100 rpm and heated at 38 °C. The 1m3 reactor was inoculated by the content of a biogas plant digesting swine manure with cereals as energy crops. The pH was 7.6 on start, with an alkalinity of 14,500 – 15,000 mg/L CaCO3 and a ammonium content of 4,500 mg/L.

OLR increase of substrate. Inconvenient values decreased the substrate dosage. Therefore, feeding was impacted indirectly by the metabolic performance of the microbial population. The general principle of the used FLC-system is shown in Figure 2.

The finally tuned Fuzzy rules are presented in detail in Figure 3. The specific OLR was individually computed by the FLC program every 8 hours per day, created by the Fuzzy rules. The preprogrammed Fuzzy tool of LabView® was used to create the Fuzzy rules. The Fuzzy tool generated the new OLR_{added} into relative percentage, individually after each feeding cycle. The percentage of substrate addition was compared by the FLC with the substrate addition of the last cycle. The new addition was called the new OLR and was adjusted in a selected frame, e.g., 10 – 120 % of the last feeding. The value had to be converted into a precise numerical command of the pump. This could be done by the center of maximum [5,6]. The steepness of dosage was adjusted by additional rules before. They influenced the velocity of adaptation to a feeding situation e.g., the start-up period should be performed with another adjustment than the recovery after a reactor failure (Figure 3).

The mode of the given rules enabled a reproducible feedback control being not provided by a neural learning system. A learning system leads to useful adaptions, but also to unknown changes. Based on the consideration, that a completely documented system is a precondition for application in technical scale, we forwent on an adaptive system. The advantage of FLC is that a programmable, commercial Fuzzy tool could be used and that it requires no complicated mathematical model with a variety of kinetic data to describe the dynamics of the anaerobic digestion process [22]. A disadvantage of FLC is the use of precise measuring data with the need of calibrating and cleaning the measuring probes continuously. That needs trained manpower being generally not available on a farm biogas plant. An industrial self-cleaning pH calibration system seems to be too expensive for a low cost biogas production. Simple one-way pH-sensors like for the pressure measurement of automatic

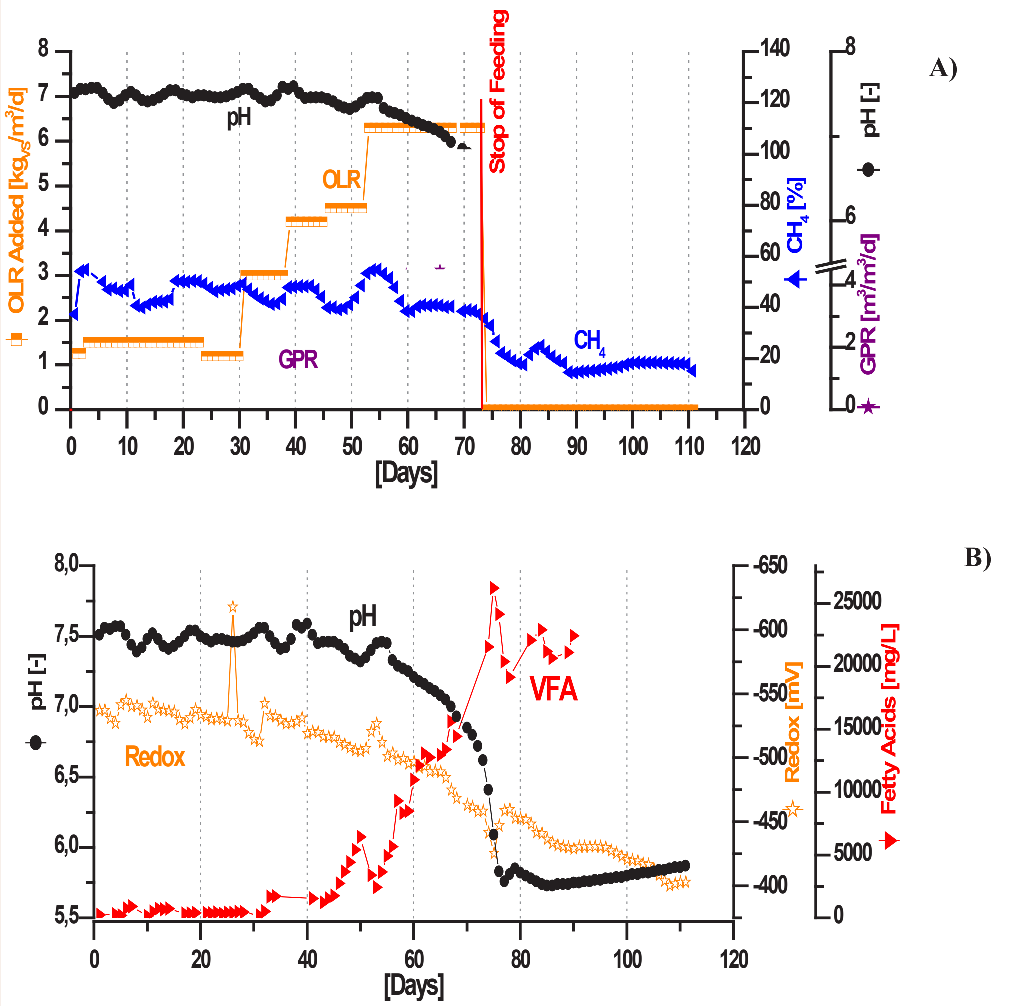

Figure 5 A) Test period I. Intermittent, successive feeding of the 1 m³ biogas reactor with bruised barley grains as substrate and mono-input. Recorded are the following control parameters: pH, added OLR, volumetric GPR [m3] and the methane content of the produced biogas. The provoked reactor overloading could be seen by the pH signal already on day 55-65. B) Test period I. The same reactor with intermittent, successive feeding of bruised barley grains as substrate and mono-input. Pictured are the parameters pH, redox resp. ORP and the volatile fatty acids (VFA). Increasing the OLR to 6.3 kgVS/(m3 d) led to a high increase of 25,000 mg/L VFA and decrease of pH. Feeding was stopped on day 74 to normalize the VFA level.

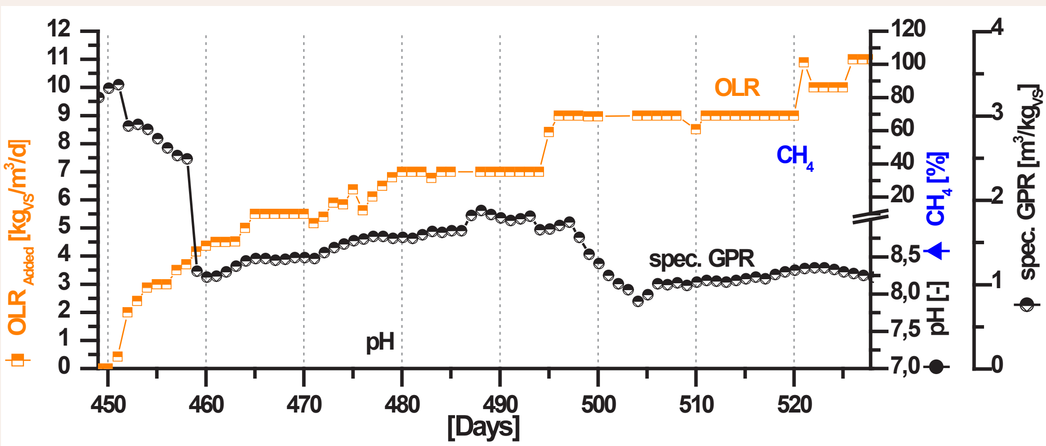

Figure 6 Test period II. The implemented, automatic Fuzzy logic feedback control was tested over a period of 736 trial days. Automatic substrate feeding of the 1 m3 fermenter 3x/d with a pump controlled by Fuzzy logics and the Fuzzy rules of Fig. 2, 3. Pictured are the days 449-528 with the control parameters pH, methane content [%] of the produced biogas, specific GPR [m3/kgVS] and the OLRAdded kgVS/(m3d). The diagram shows the given increase of OLR from 2 to 9 kgVS/(m3d) under the direction of automatic Fuzzy logic feedback control.

car brake systems (ABR) would be the solution for a wider application of FLC-systems in fermentation processes.

The biogas reactor system in operation

The substrate dosage tank had a volume of 2.5 m^3, but was originally constructed for waste water treatment, therefore the size for this application was somewhat too large, Fig. 4. The three reactors were located in the technical hall of the University of Applied Sciences in Nordhausen, called 'August Kramer Institute'. The methanogenic reactor, 1 m^3 working volume, had a heating system 38 °C and was permanently stirred with 100 rpm by a 1.1 KW engine. Dosage and digestate tank were not heated and worked at room temperature between 17°C and 24°C. The effluent of the digestate tank was used to mix it with the substrate 1:10. Thereby, a low indirect recirculation was obtained. The density was postulated to be 1.0 kg = 1 litre for calculation of the liquid level measurement and HRT. Substrate pump (Netzsch, Waldkraiburg), directed and automatically contolled by a Siemens Simatic S7-300 (Figure 4)

The 1m^3 biogas reactor was inoculated by filling it with the reactor medium of a biogas plant digesting swine manure with cereals or maize/triticale (1:3), sometimes titled 'energy crops'. But substrate of test period I was first bruised barley grain. At starting conditions (test period I) the pH was around 7.6, with an alkalinity of 14,500 – 15,000 mg/L $CaCO_3$, ammonium content 4,500 mg/L, phosphate content 625 mg/L, dry matter (DM) 4.16%, volatile solids (VS) 3.28 %. It resulted in a conductivity of about 25 mS/cm corresponding to about 15 g KCl/l. The FLC-system was originally developed for acidic beet silage with an alkalinity of only ≤ 2500 mg/L $CaCO_3$ [18-20]. As the biogas reactor was overloaded during manually driven test period I, the VFA level of 25,000 mg/L (Figure 5B) had to be decreased. This was accelerated by adding aqueous compost eluate according to Scherer and Neumann [23]. The compost was based on a mushroom substrate (straw + horse dung). The test period II had a slightly different DM- and VS-content at the beginning: 2.50 % DM resp. 1.67% VS. The volumetric GPR was measured by the instrument GMT 2.5 (**BONGAS** Deutschland GmbH, Oberkirch), 1 impulse corresponded to 10 L gas, the exact range lay between 0.025 - 4 m^3/h. The gas composition was online measured by a Biogas Controller BC20, CHEMEC GmbH, Bielefeld): CH_4 (0 - 100 vol. %), CO_2 (0 - 100 vol. %), O_2 (0 – 20.9 vol. %), H_2S (0 – 0.2 vol. %, H_2S verified by test tubes of the company Dräger, Lübeck).

Bruised barley grain was intermittently fed in the investigation period I, manually one time per day as mono-input. In test period II the FLC was applied with Triticale as mono-input, which was fed automatically every 8 hours, i.e. three times a day as found for biogas production from beet silage as sufficient [18]. Shorter feeding intervals are of no problem. Biogas plants of industrial scale use often intervals of only ½ or 1 hour to minimize the electrical load of pumps. If the control parameters were in a convenient range, the OLR was set by the FLC to a higher value than before. The microbial population reached the higher OLR dynamically by their substrate turnover and the feedback control system. Otherwise the OLR stagnated or was reduced by the FLC-system. Online-sensors for measurement of the pH- and redox-value were used in the fermenter being protected by a sulphide lock for use in waste water treatment to enable downtimes of around 2 years (Mettler Toledo, Giessen). The following values were determined offline and weekly: dry matter DM (DIN 38 414, part 2), volatile solids VS (DIN 38 414, part 3), alkalinity [24,25], ammonium (NH_4-N) and phosphate (test kit by Merck, Darmstadt). The so called "FOS/TAC"-value to characterize the stability of the biogas fermentation was estimated also weekly, sometimes daily [24]. Most indicative for the instability of a biogas reactor is the occurrence of an increased level of free fatty acids (VFA, [26]). Below 500mg VFA /L means a very stable or smooth biogas process [24]. VFA were estimated by ion chromatography every week (Deutsche Metrohm, Stuttgart). The method allowed the determination of formic, acetic, propionic, iso-butyric, butyric and iso valerianic acid. Formic acid played only a small, but significant role during an acidification of the biogas reactor, Figure 5B. In Hamburg all graphics were plotted with the graphic software program Origin. Essential trace elements [27] were added prophylactically according to the microbial DMSZ medium 144 (www.dsmz.de) to exclude a deficiency (Peter Weiland, personal communication). Interestingly, Friedmann and Kube [28] used the trace element solution of the microbial DSMZ medium 141 (www.dsmz.de) for biogas production from maize.

RESULTS AND DISCUSSION

Part of the project plan was to find the limit of an overload or the highest applicable OLR during a stable biogas process. Therefore, a reactor disturbance by overloading was provoked deliberately in test period I. During start-up period I the OLR was increased with bruised barley grains from 1.5, 3.0, 4.2, 4.5 to 6.3 $kg_{VS}/(m^3\ d)$, but by daily intermittent feeding without operating the FLC, Figure 5A,B. For comparison: agricultural biogas plants are generally driven with an average OLR of 1.9 (1.1-3.3) $kg_{VS}/(m^3\ d)$ and an average HRT of 39 days (23-63 days) as evaluated with 27 full scale biogas plants in Sweden [29]. Such a conservative, low speed operation is also typical for German agricultural biogas plants. Therefore, the targeted OLR of 6.3 $kg_{VS}/(m^3\ d)$ was very sportive. Correspondingly, the level of volatile fatty acids (VFA) increased from around 500 mg/L to above 14,000 mg/L in 6 weeks or 50 days of test period I, Figure 5A. The pH decreased to 5.8 being out of the methanogenic range beingusually 7-8.5 [24], but the pH scale is a logarithmic one. During the 4th and 5th week of operation, the volumetric GPR of biogas ($m^3/(m^3\ d)$ stagnated, whereas the specific GPR ($m^3/(kg_{VS}\ d)$ decreased severely, as the OLR increased in this period between trial day 30d-70d from 3.0 to 6.3 $kg_{VS}/(m^3\ d)$, Figure 5A. After 80 days the methane content fell down to 20% only, Figure 5A. The biogas process became instable by the elevated OLR and feeding had to be stopped to prevent a complete disturbance and acidification. As in parallel the volumetric methane production GPR still increased with dangerous VFA accumulation, the experiments exhibited that only the specific GPR related to the amount of fed substrate was a reliable control parameter [20]. Normally, the pH value as process parameter plays not a dominant role in a well buffered biogas process with manure, but swine manure with barley as substrate was still decisive for the FLC as the pH decreased down to 5.8. In contrast to the previous non-buffered biogas fermentations with acidic beet silage [18,19], the process variable of the online recorded redox potential resp. ORP seemed to be a suitable, additional parameter, but the signal was not very pronounced, Figure 5B. Therefore, no reason was given to change the control parameters by implementation of the redox value Figure 5 A,B.

Parallel to the biogas process, the VFA spectrum was monitored continuously to give a more pronounced assessment about the process stability [24,26]. The maximum of VFA was reached on day 75 with about 25,000 mg/L VFA ((2700 mg/L formic acid, 9,100 mg/L acetic acid, 8,800 mg/L propionic acid, 750 mg/L iso-butyric acid, 1,500 mg/ butyric acid and 2,000 mg/L iso-valerianic acid). Already on day 50 at an OLR of 4.5 $kg_{VS}/(m^3\ d)$, a pH decrease of about 0.5 was detectable (Figure 4A). However, the volumetric gas production increased further on until day 65. Even when the VFA level had risen to 10,000 mg/l on day 60, the GPR still increased Figure 4 A,B. Accordingly, besides pH and methane content, only the specific GPR (GPR/ OLR/ d) should be used as control parameter.

Results of test series II with the implemented Fuzzy logic feedback control

Biogas reactor starting conditions of test period II were as follows: Alkalinity: 15000 mg/L ($CaCO_3$), TS = 2.5 %, VS = 1.67 %, pH = 7.5. The series II of FLC-directed experiments included a period of 2 years or overall 700 days, but plotted were only 530 days with a section of 120 days, Figure 6. Some unforeseen technical problems (acidity of period I, pump problems, instability of measuring devices) prevented a longer evaluation period. But by continuous FLC management a safe organic loading rate of 9 $kg_{VS}/m^3/d$ could be realized. OLR values of 7, 9 and 11 $kg_{VS}/(m^3\ d)$ were only prefixed, but they were reached by the microbial activity reacting dynamically on the Fuzzy feedback control parameters of Figure 2,3. The individually measured values of pH, CH4 and specific GPR were transferred every 8 hours into a Fuzzy rule base directing the substrate pump to a higher or lower level than the last feeding. Thereby, the master computer in Hamburg was permanently connected via internet with the process computer in Nordhausen. A manual intervention was always possible, but not necessary. The Fuzzy logic feedback control worked smoothly like an 'auto-pilot'- system.

With the support of the FLC system a safe substrate dosage of an OLR of 9 $kg_{VS}/\ (m^3\ d)$ was reached in period II on trial day 500d by at a residence time of only 10 days, Figure 6. The experiments demonstrated the dramatic influence of the Fuzzy control on increasing the OLR for cereals with swine manure as basic medium. By manual intermittent feeding in period I a safe process with an OLR of only 4 $kg_{VS}/(m^3\ d)$ was possible, followed by an overloading, acidification and reactor disturbance with an OLR ≤ 6.3 $kg_{VS}/\ (m^3\ d)$, Figure 4 A,B. The specific GPR was in period II during the FLC directed OLR of 9 $kg_{VS}/\ (m^3\ d)$ on average 0.72 m^3 biogas / (kg_{VS} d). Based on this gas yield and by comparison with the literature [30], a phantastic VS-degradation of nearly 100% of the fed Triticale has to be be assumed. During OLR 11 $kg_{VS}/\ (m^3\ d)$ the volumetric GPR reached on average a biogas production of 12.6 with a peak of 27 $m^3/\ (m^3 d)$, but the enormous gas production caused foam problems and prevented an exact level measurement of the input pump. Therefore, test series II had to be stopped (Figure 6).

With the FLC-system nearly a doubling of the OLR up to 9 $kg_{VS}/(m^3\ d)$ was possible. That meant a doubled space-time yield and a reduction of maintenance energy costs for heating, pumping and stirring. In another research project about anaerobic digestion of cereal grains, the same problems with overload could be observed. To overcome the problems of acidification, a separate first hydrolytic and acidic digester was connected in front of a pH-neutral biogas reactor as second stage. But also with this elaborate two stage reactor-system the manually directed OLR could be only increased from 4.0 $kg_{VS}/(m^3\ d)$ to an OLR of 4.5 $kg_{VS}/(m^3\ d)$ as final value [29]. Normally, two stage anaerobic digestion systems are more resistant to acidification of the biogas producing reactor as the separate hydrolytic reactor without methanogenesis can be driven sourly as a single, stable process [31-33].

CONCLUSION

As scheduled, the one stage biogas process of the semi-technical biogas plant in Nordhausen was controlled internet-based in Hamburg, 300 km away. Fuzzy calculations were performed in Hamburg on a host computer and sent for further process control via Internet and FTP-server to the process computer in Nordhausen, (Figure 1). The implemented FLC system worked with only three control parameter and enabled a real feedback control as the microbes itself directed the speed of substrate feeding by dynamics of their substrate turnover. FLC increased the organic loading rate by more than 5 $kg_{VS}/(m^3\ d)$ up to 9 $kg_{VS}/(m^3\ d)$, doubled the space-time yield and enabled a degradation rate of nearly 100% without jeopardizing the biogas process. Therefore, the used FLC-system passed successfully the endurance test with easily degradable cereals. That means also, that Fuzzy logic feedback control is suitable for biogas processes with slower degradable input biomass. Nevertheless, FLC systems for anaerobic digestion have become quiet in recent years. Perhaps one reason is that the measurement and control technology for agricultural biogas plants is in general on a low cost level. Therefore, inexpensive disposable sensors for pH measurement could lead to a greater acceptance of FLC systems in biogas plants, but also in general.

ACKNOWLEDGEMENTS

The management of the semi-technical biogas plant in Nordhausen by the FLC system in Hamburg was possible with financial support of the FNR, funding number FKZ 22 01 86 06 for Nordhausen, and for the HAW-Hamburg by FKZ 220 10405. FNR means Agency for Renewable Biomass in Guestrow which represents the research office of the ministry for agriculture, nutrition and protection of consumers. Both project reports (German) can be downloaded under www.fnr.de.

REFERENCES

1. Scarlat N, Dallemand JF, Fahl F. Biogas: Developments and perspectives in Europe. Renewable Energy. 2018; 129: 457-472.
2. Lauer M, Dotzauer M, Hennig C, Lehmann M, Nebel E, Postel J, Thrän D. Flexible power generation scenarios for biogas plants operated in Germany: impacts on economic viability and GHG emissions. Int J Energy Res. 2017; 41: 63-80.
3. Hahn H, Krautkremer B, Hartmann K, Wachendorf M. Review of concepts for a demand-driven biogas supply for flexible power

generation. Renewable and Sustainable Energy Rev. 2014; 29: 383-393.

4. Sarif A, Kazda M. Characteristics of on-demand biogas production by using sugar beet silage. Anaerobe. 2017; 46: 114-121.

5. Ross TJ. Fuzzy logic with engineering applications. 2nd edition. New York: Wiley, 2004.

6. Chen G, Pham TT. Introduction to Fuzzy systems. CRC Press. 2005.

7. Ni P, Lyu T, Sun H, Dong R, Wu S. Liquid digestate recycled utilization in anaerobic digestion of pig manure: Effect on methane production, system stability and heavy metal mobilization. Energy. 2017; 141: 1695-1704.

8. Barber NR. Lime/Sodium Bicarbonate treatment increases sludge digester efficiency. J Env Sci. 1978; 3: 28-30.

9. Estaben M, Polit M, Steyer JP. Fuzzy control of anaerobic digestor. Control Eng Pract. 1997; 5: 1303-1310.

10. Müller A, Marsili-Libelli S, Aivasidis A, Lloyd T, Kroner S, Wandrey C. Fuzzy control of disturbances in a wastewater treatment process. Wat Res. 1997; 31: 3157-3167.

11. Murnleitner E, Becker TM, Delgado A. State detection and control of overloads in the anaerobic wastewater treatment using Fuzzy logic. Wat Res. 2002; 36: 201–211.

12. Liu J, Olsson G, Mattiasson B. Control of an anaerobic reactor towards maximum biogas production. Wat Sci Tech. 2004; 50: 189-198.

13. Carrasco EF, Rodriguez J, Punal A, Roca E, Lema JM. Rule-based diagnosis and supervision of a pilot-scale wastewater treatment plant using Fuzzy logic techniques. Expert Syst Appl. 2002; 22: 11–20.

14. Pullammanappallil PC, Svoronos SA, Chynoweth DP, Lyberatos G. Expert system for control of anaerobic digesters. Biotechnol Bioeng. 1998; 58: 13-22.

15. Punal A, Rodriguez J, Franco A, Carrasco EF, Roca E, Lema JM. Advanced monitoring and control anaerobic wastewater treatment plants: Diagnosis and supervision by a Fuzzy-based expert system. Wat Sci Tech. 2001; 43: 191–198.

16. Boscolo A, Mangiavacchi C, Drius F, Rongione F, Pavan P, Cecchi F. Fuzzy control of an anaerobic digester for the treatment of the organic fraction of municipal solid waste (MSW). Wat Sci Tech. 1993; 272: 57–68.

17. Holubar ZL, Hager M, Froeschl W, Radak Z, Braun R. Start-up and recovery of a biogas-reactor using a hierarchical neural network-based control tool. J Chem Technol Biotechnol. 2003; 78: 847–854.

18. Scherer PA, Dobler S, Rohardt S, Loock R, Büttner B, Nöldeke P, et al. Continuous biogas production from fodder beet silage as sole substrate. Wat Sci Technol. 2003; 48: 229-233.

19. Scherer PA, Lehmann K, Schmidt O, Demirel B. Application of a Fuzzy logic control system for continuous anaerobic digestion of low buffered, acidic energy crops as mono- substrate. Biotechnol Bioeng. 2009; 3: 736-748.

20. Scherer PA. Process for the fermentation of biomass. European Patent. 2006.

21. Speece RE. Anaerobic biotechnology for industrial wastewaters. Nashville, Tennessee, USA: Archae Press. 1996.

22. Batstone D J, Keller J, Steyer J . A review of ADM1 extensions, applications, and analysis: 2002--2005. Wat Sci Tech. 2006; 54: 4.

23. Scherer P, Neumann L. 'Methano-compost', a booster and restoring agent for thermophilic anaerobic digestion of energy crops. Biomass and Bioenergy. 2013; 56: 471-478.

24. Scherer P. Operating analytics of biogas plants to improve efficiency and to ensure process stability. In: Progress in Biogas, IBBK Kirchberg ed. 2007; 77-84.

25. APHA. Standard methods for the examination of water and wastewater. 17th edn. Water Pollution Control Federation, Washington DC, 1989.

26. Pind PE, Angelidaki I, Ahring BK. Dynamics of the anaerobic process: Effects of volatile fatty acids. Biotechnol Bioeng. 2003; 82: 791-801.

27. Demirel B, Scherer P. Trace element requirements of agricultural biogas digesters during biological conversion of renewable biomass to methane. Biomass and bioenergy. 2011; 35: 992-998.

28. Friedmann H, Kube J. Trace element solution for biogas processes. German. 2009.

29. Ahlberg-Eliasson K, Nadeau E, Levén L, Schnürer A. Production efficiency of Swedish farm-scale biogas plants. Biomass and Bioenergy 2017; 97: 27-37.

30. Raposo F, De la Rubia MA, Fernández-Cegrí V, Borja R. Anaerobic digestion of solid organic substrates in batch mode: An overview relating to methane yields and experimental procedures. Renewable and Sustainable Energy Reviews. 2011; 16: 861-877.

31. Demirel, B, Yenigün, O. Two-phase anaerobic digestion processes: a review. J Chem Tech Biotech. 2002; 77: 743-755.

32. Griehl C, Vollmer GR. Process inhibition during anaerobic digestion of cereal grain – reasons and avoidance. Final research project report FKZ 220 20706 and FKZ 220 05407. 2010.

33. Lindner J, Zielonka S, Oechsner H, Lemmer A. Is the continuous two-stage anaerobic digestion process well suited for all substrates? Biores Technol. 2016; 200: 470-476.