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# Doubling the Space-Time Yield of a Pilot Biogas Reactor with Swine Manure and Cereal Residues by a Closed Loop Feedback Control Based on an Automated Fuzzy Logic Control System

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**Abstract:** The anaerobic digestion of swine manure was performed for more than 2 years in a biogas pilot plant with cereal residues as a mono-input, either by a simple intermittent substrate feeding or by feeding with an automated "autopilot" system under the direction of a Fuzzy logic control (FLC) system, working with a closed-loop feedback control. The pilot plant of the University of Applied Sciences in Nordhausen consisted of a 2.5 $m^3$ dosage tank, a 2.5 $m^3$ digestate tank, and a 1 $m^3$ biogas reactor. Only three control parameters were used for FLC: pH, methane %, and the specific gas production rate (GPR) related to the organic loading rate (OLR), that is GPR/OLR $m^3$ biogas/($kg_{VS}$ d), vs = volatile solids. The specific GPR was referred to the OLR of the last feeding every 8 h in terms of $kg_{VS}/(m^3$ d). In test period I without an FLC system, a safe process with just an OLR of 4 $kg_{VS}/(m^3$ d) was reached, followed by an overloading and reactor disturbance at $\leq$6.3 $kg_{VS}/(m^3$ d) as indicated by acidification with volatile fatty acids up to 25,000 mg/L. However, test period II (585 trial days) with an integrated FLC system allowed a safe OLR up to 11 $kg_{VS}/(m^3$ d). Apparently, the microbes themselves directed the speed of substrate feeding by the dynamics of their substrate turnover and by the closed loop feedback control, while the three FLC parameters prevented acidification. Therefore, the application of FLC enabled a doubling of the throughput for a biogas reactor in the same time with a 'turbo speed'. The concomitant hydraulic residence time (HRT) of only 10 days reduced the stirring and heating costs. The usage of an FLC system should open the door for networked biogas production to enable flexible biogas production on demand.

**Keywords:** anaerobic digestion; Fuzzy; process control; biogas; biomass; energy crops; manure



**Citation:** Scherer, P.; Schreiber, A.; Arthur, R.; Antonczyk, S.; Vollmer, G.-R. Doubling the Space-Time Yield of a Pilot Biogas Reactor with Swine Manure and Cereal Residues by a Closed Loop Feedback Control Based on an Automated Fuzzy Logic Control System. *Processes* **2022**, *10*, 2511. https://doi.org/10.3390/pr10122511

Academic Editor: Ali Mohammadi

Received: 5 September 2022
Accepted: 8 November 2022
Published: 25 November 2022



## 1. Introduction

Renewable energies are of great importance in Germany and the whole European Union, because fossil and nuclear energy shall be completely replaced by renewables. In the year 2018/2019, 8.3% of the electricity demand in Germany was already produced by biogas plants. Currently, there are about 9500 biogas plants in Germany with an installed electrical output of 5.6 GW and a heat production level of around 2.6 GW, supplying more than 9 million inhabitants with electricity (Agency for Renewable Energies Germany resp. Agentur für Erneuerbare Energien AEE, website www.unendlich-viel-energie.de (accessed on 10 July 2022), and [1]). However, in the future, it will be worthwhile to purify biogas to biomethane, which will be directly fed into the German and European gas grids. Manure plus biomass forms 20–90% of the input for most of the biogas plants in Germany and attracts an additional bonus from the government by the energy feed-in tariff [2].

For the most part, Germany has a centralized electrical energy system, and more than 50% of its electricity is already generated from renewable energies such as wind power and photovoltaic energy. Renewable energies are not always available because they are weather-dependent. In contrast, the electricity and biomethane produced from biogas plants would be a powerful and reliable baseload source independent from weather conditions. 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 [3], the combined electricity production on demand, together with wind energy and photovoltaics, is even more economical and produces fewer greenhouse gas emissions as a baseload compared with the electrical production of biogas plants alone. Therefore, considerations were made to only operate biogas plants with reduced annual hours but a higher level of power generation. The future could be flexible with demand-driven biogas plants. Several concepts for flexible, demand-driven electric power generation strategies based on biogas supply have already been described [2,4]. For example, such biogas plants use easily degradable food leftovers or, in contrast, uniform energy crops such as sugar beet silage to promptly meet the demand [5]. However, energy crops could instigate a controversy regarding their usage as fuels or as food. Nevertheless, there is a need for local gas storage systems and a safe control system as given in the excellent review about 'Feed controls of anaerobic processes for renewable energy production' by Gaida et al. [6]. One aim is to maximize the economic yield, thereby minimizing process failures. This entails a maximum amount of biogas related to the input as expressed by the specific gas production related to the input via the OLR (GPR/OLR) in $m^3$ ($kg_{VS}$ d). In the past, feed controls were developed, but most of these systems were engineered for wastewater treatment. Full-scale biogas plants are generally manually directed or equipped, still with a simple remote system, but without a closed-loop control system or Fuzzy logic control (FLC) [7,8], which has not yet been established for this purpose. Such an FLC-driven feeding system uses empirically developed expert rules or algorithms in a computer program and stabilizes the biogas production like an "autopilot". FLC techniques have been applied in several studies as a modelling and supervision strategy for the anaerobic treatment of industrial wastewaters [9–15]. However, only few references about the application of FLC to feed an anaerobic digester with particulate organic waste and/or energy crops as an input exist in the literature [16–20], as reviewed by Gaida et al. [6]. Accordingly, we present herein the first example of an FLC or closed-loop control system in a semi-industrial-pilot-scale plant with a solid substrate.

One main parameter of biogas production is the right pH for the methanogenic microbes, which generally desire a range between pH 7–8.5. Otherwise, acidification by intermediates such as volatile fatty acids (VFA) generally leads to severe disturbance of the biogas production process. Thus, one suitable approach for buffering and stabilizing a microbial biogas production process is using a nitrogen-rich co-substrate with a high buffering capacity such as the manure from cows, pigs, and chickens. This approach circumvents the use of an extra pH control-system as in other industrial fermentation processes with pure microbial cultures. Therefore, low-cost, agro-based biogas plants are simply fed with a fixed pump velocity and interval time. However, biogas plants without manure still need, in practice, additional calcium oxide (lime) or carbonate as a buffering agent for their continuous operation, which strongly increases the risk of high levels of sediments [21]. Another approach to stabilize pH and biogas production is to increase HRT and decrease OLR by multiple sequential reactor stages, allowing for some substrates (e.g., food leftovers) even a separate acidic hydrolysis stage [4]. Also, the use of effluent recirculation is common [22], but this could lead to an unfavorable concentration of salts.

An FLC technique was introduced at the Hamburg University of Applied Sciences to achieve a stable biogas process for readily degradable substrates with a high risk for VFA overproduction. It was developed on the basis of a fully automatic Fuzzy logic system with a closed-loop feedback control suitable for continuously stirred anaerobic digestion at feeding intervals of 8 h [18,19]. Three control parameters—pH, the methane content of the biogas, and the specific gas production rate (specific GPR)—were found to be most suitable, which operated as a real feedback control system in a closed loop to sustain the aim of the safe and optimum performance of the biogas reactors. Specific GPR is a new control parameter [23], which is different from the volumetric GPR. The specific GPR is the methane yield in litres or $m^3$ related to 1 g or kg $_{VS}$. the substrate input, and not to the biogas reactor volume. Accordingly, the new feeding rate and organic loading rate (OLR) (decrease or increase) must be calculated with respect to the OLR of the previous substrate's feeding interval. This can be achieved with a pre-programmed computer program and empirically estimated expert rules. As physiological parameters are involved, namely, pH and methane production, the microbes themselves direct the speed of the substrate-feeding process by the dynamics of their substrate turnover [23]. Such an added expert system is analogously incorporated in FLC tools of ABS (automatic brake system for motor cars) as the most prominent example [6–8]. The triumph of this technology was made possible primarily by inexpensive, exchangeable pressure sensors networked with a computer on-board.

A high OLR of an easily degradable substrate is especially difficult to establish with manual feeding as the VFA-level can rapidly increase as in general the slow methanization process is rate limiting. An example of such a substrate is the acidic, pre-digested silage of sugar beets from Beta vulgaris (pH 3.0–3.5). Additionally, this silage is extremely low-buffered, as the mineral content of Beta vulgaris was continuously decreased by breeding down to around 1%, whereas the sugar content was concomitantly increased to 30–35% dry matter. The maximum alkalinity found for sugar beet silage was only about 2500 mg/L $CaCO_3$ [19,20], whereas Speece postulated 6000 mg/L $CaCO_3$ as minimum for a pH-neutral process during anaerobic digestion [24]. Therefore, the FLC technique successfully accomplished the stable performance of the anaerobic digestion of acidic beet silage as a mono-input without the use of chemicals or manure as a buffer source [19,20]. FLC seems to allow also stable fermentation with a high OLR using easily degradable food waste as a substrate (unpublished results). The developed FLC technique can master almost all situations, such as a careful start-up process and a gentle recovery strategy after a severe reactor failure, and it can accomplish a safe process with a high OLR and a short hydraulic retention time (HRT). In the case of fodder beet silage, this means that it is possible to operate an anaerobic digester with an extremely reduced HRT of 5.45 days and an unusually high OLR of up to 16.5 $kg_{VS}/(m^3\ d)$ as maximum [19,20]. The volumetric gas production rate (GPR) of 9–24 $m^3/(m^3\ d)$ achieved in such a process [19,20] allowed an outstandingly high throughput process with a highly economic space-time yield. We think that this is the maximum one can achieve with a mixed biogas production process. It should be a good precondition to flexibly produce biogas on-request in order to diminish electrical peak loads in an electric network by enhancing the intervals of the OLR of a biogas plant on demand or by transferring the bio-methane into a gas storage dome [3–5].

However, most of the German biogas plants use manure to stabilize the pH. Therefore, it was very questionable whether a closed-loop feedback control system with pH as a control parameter would work in the case of such a stabilized biogas reactor. Now, the previously described FLC system [19,20] was tested for the first time [6] in a long term project (almost 2 years) with a pilot biogas plant at pilot scale and employing a solid substrate. However, instead of acidic beat silage (pH 3.0–3.5), defective batches of cereals were used as a solid substrate supplemented with swine manure as a base substrate. Supplementing manure with such a substrate provides enough energy to enable electricity production and enough heat energy to heat the biogas reactor through a combined power and heating energy station (CHP). Therefore, the pilot plant of the University of Applied Sciences Nordhausen could function as a model for large scale biogas plants in rural areas. It worked independently through an automated FLC-driven "autopilot" system.

## 2. Materials and Methods

### *2.1. Software: Data Transfer for Process Control between Hamburg and Nordhausen*

First, an overview of the remote-monitoring process and internet-based Fuzzy logic feedback control system shall be presented. Process data of the pilot biogas plant at the University of Applied Sciences in Nordhausen (Thuringia) were collected with the help of remote monitoring. They were saved and transferred online to the Hamburg University of Applied Sciences (HAW) in Hamburg, Bergedorf district. The monitoring scheme and control system between the two campuses is shown in Figure 1.

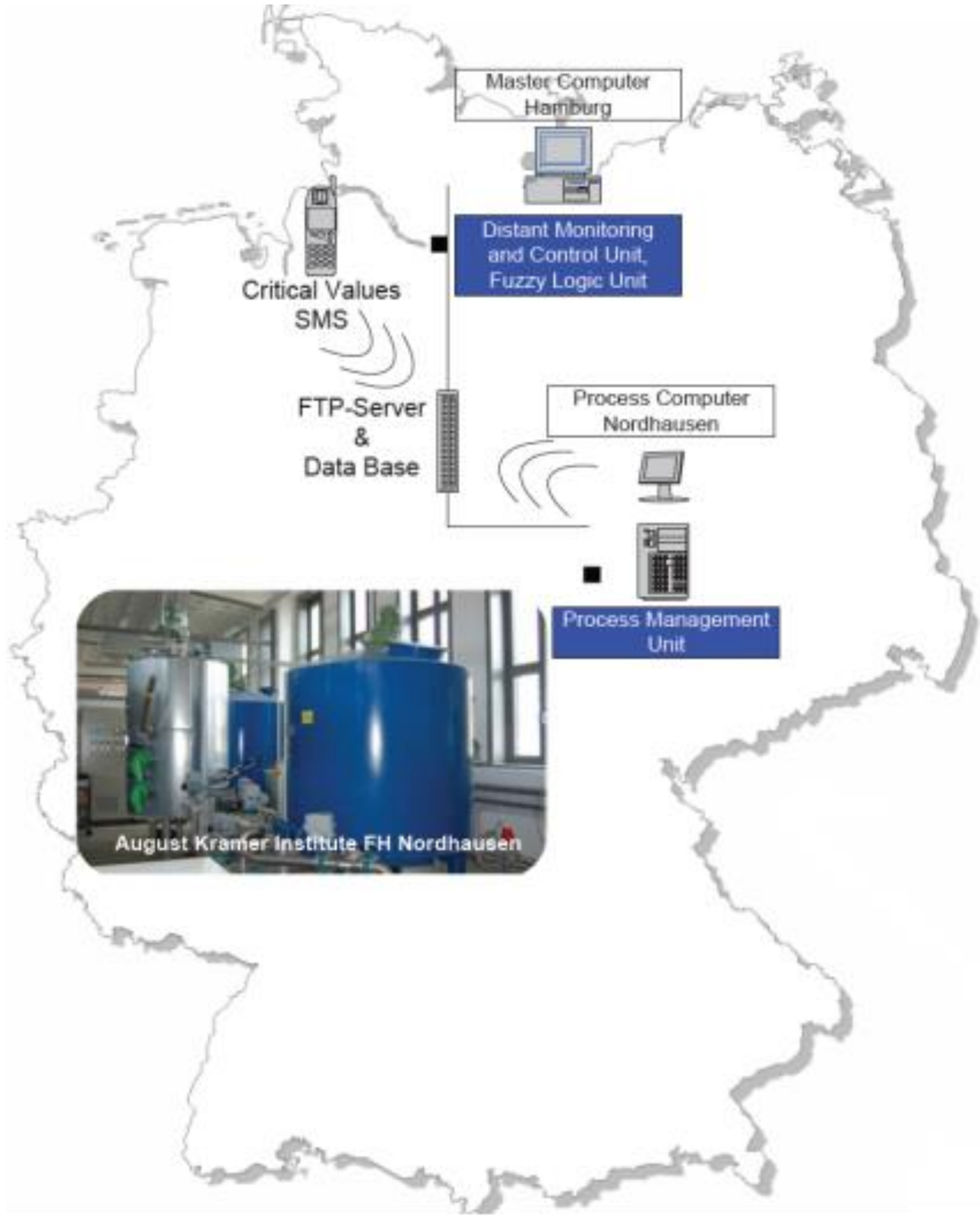



**Figure 1.** Scheme of the monitoring and control system used between the Hamburg University of Applied Sciences (HAW) and the August Kramer Institute of the University of Applied Sciences in Nordhausen (HSN). Process computer (server) with file transfer protocol (FTP) and data management were based in Nordhausen, which handled the data transfer and remote control of the substrate-feeding pump. The "master" computer at the HAW, being 300 km away, possessed a similar user interface program and supervised the FLC system by calculating new feeding rates every 8 h. Critical values were corresponded and additionally discussed with a short message system (SMS).

The process computer of the technical hall in Nordhausen included a SIMATIC® S7-300 interface and transferred the data to the "master" PC of the HAW in Hamburg, which was equipped with a programmable Fuzzy logic controller. It was a simple fifteen-inch laptop computer, but for continuous operation, it required permanent air ventilation. The process computer also hosted the self-programmed Fuzzy rule base (Figures 2 and 3A,B) developed with the commercial Labview® software (Version 6.1) to operate the developed FLC system as shown in the literature [18–20]. The parameters—pH, methane ($CH_4$) content, carbon dioxide ($CO_2$), redox (oxidation reduction potential, that is ORP), temperature, and biogas amount (liters)—were continuously recorded online in Nordhausen and supervised by the HAW with the same commercial Labview® software (free for universities) and a self-programmed user interface program. ORP measurements were only performed to check anaerobic conditions. According to Drosg, they should be below an ORP of −300 mV, but the values depend on the pH and salt concentration. Therefore, they are only of a restricted value for process control [25].

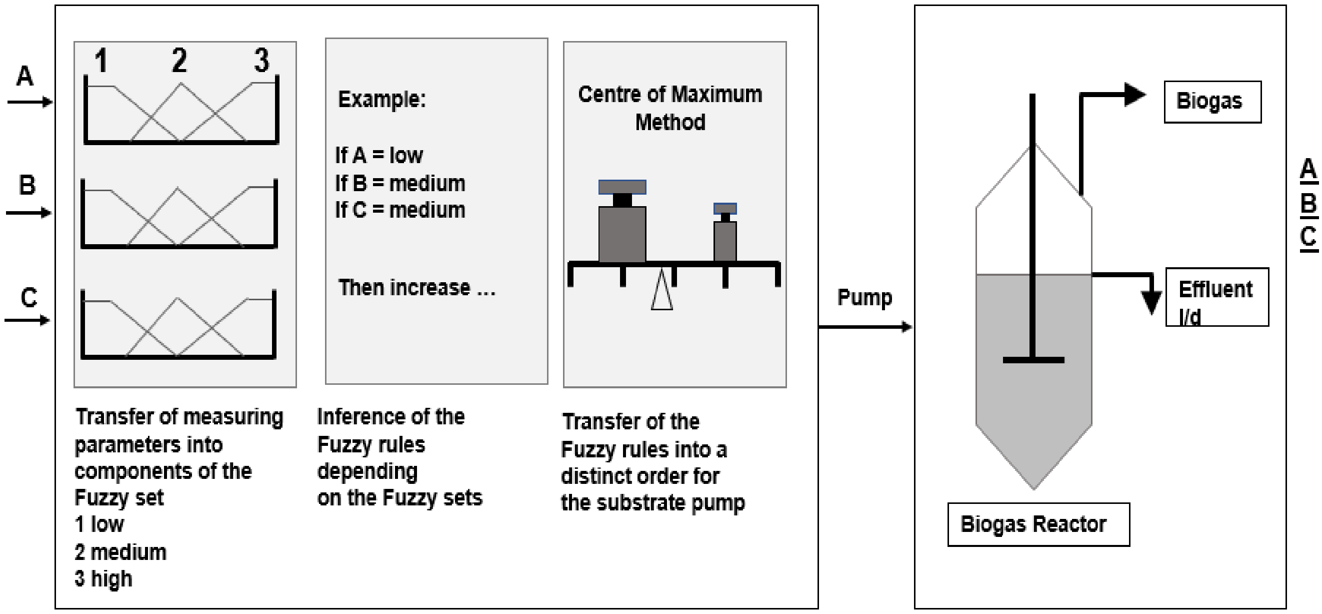
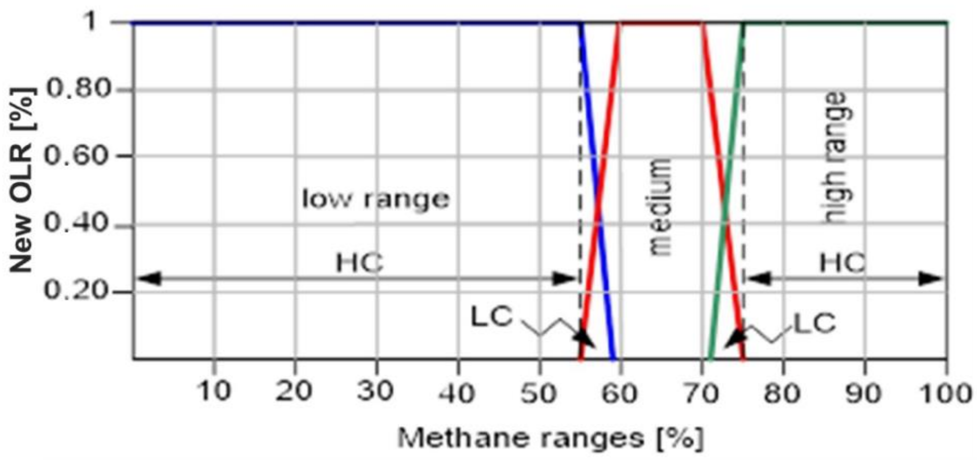
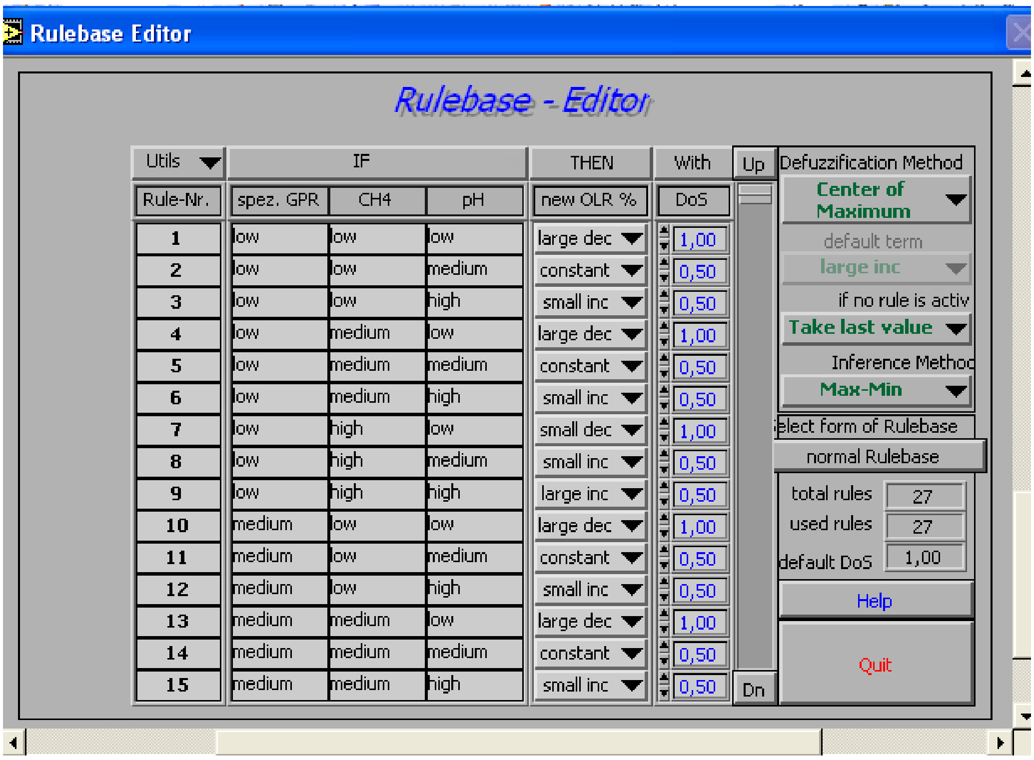



**Figure 2.** Scheme explaining the principle of the FLC system used for the performed biogas production process on a pilot-scale. A, B, and C are the three selected control parameters, representing the methane content ($CH_4$), pH, and the specific GPR (spec. GPR).

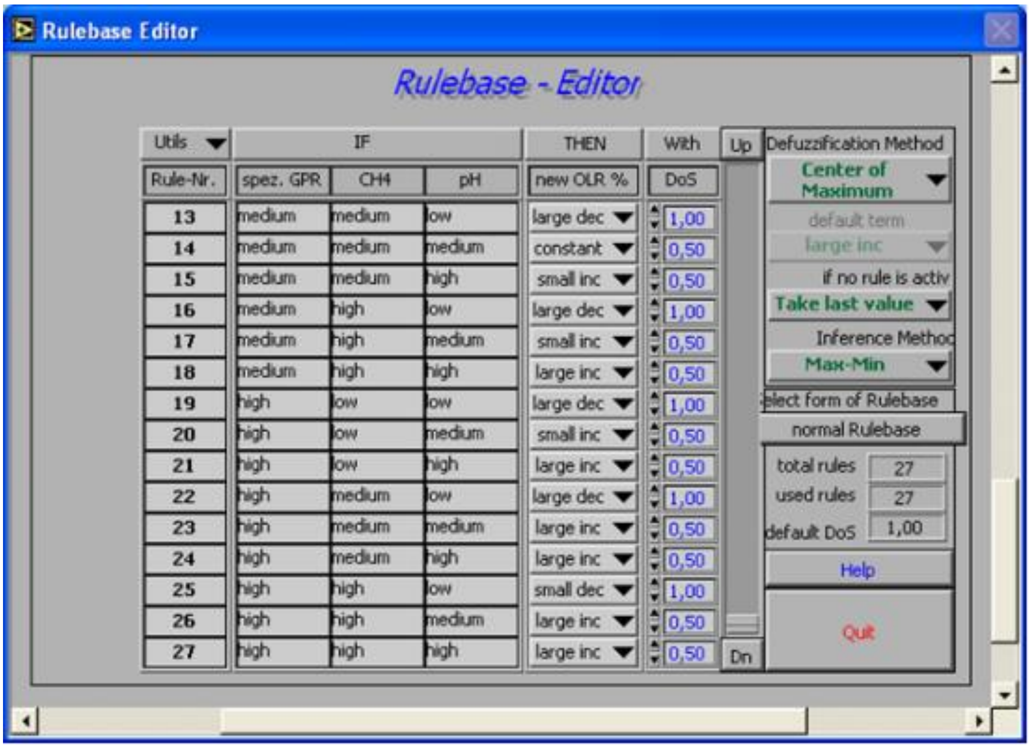



(**A**)

**Figure 3.** *Cont.*




(**B**)

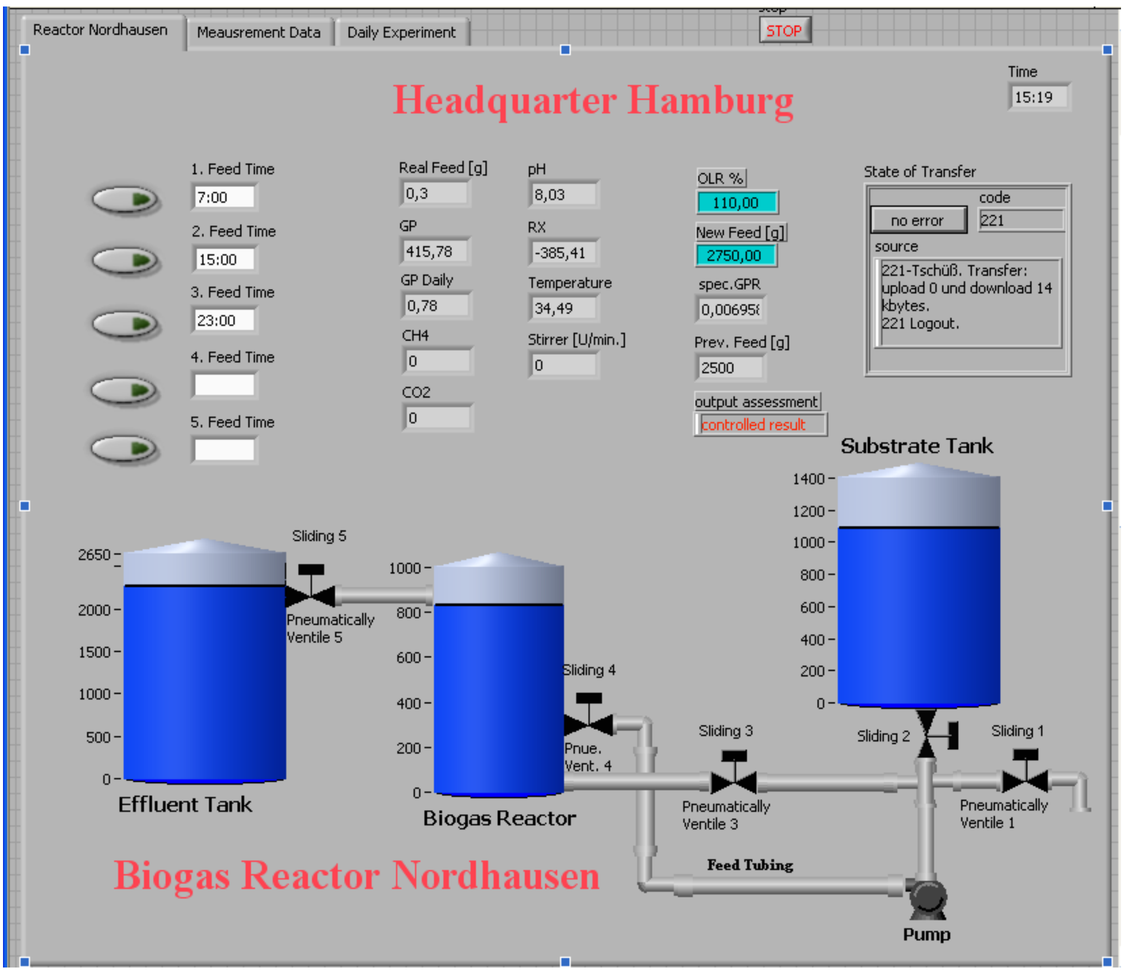



(**C**)

**Figure 3.** (**A**) Exemplary FLC scheme demonstrating the adjustment of control window ranges for substrate feeding according to the measured methane ($CH_4$) percentages in the produced fermenter biogas (HC—high control range; LC—low control range), with respect to the three ranges of low, medium, and high. The medium control range (MR) for $CH_4$ percentage was set at 60–70%. The HC range was defined to be above 75% and below 60% of methane. The LC range is a transient status

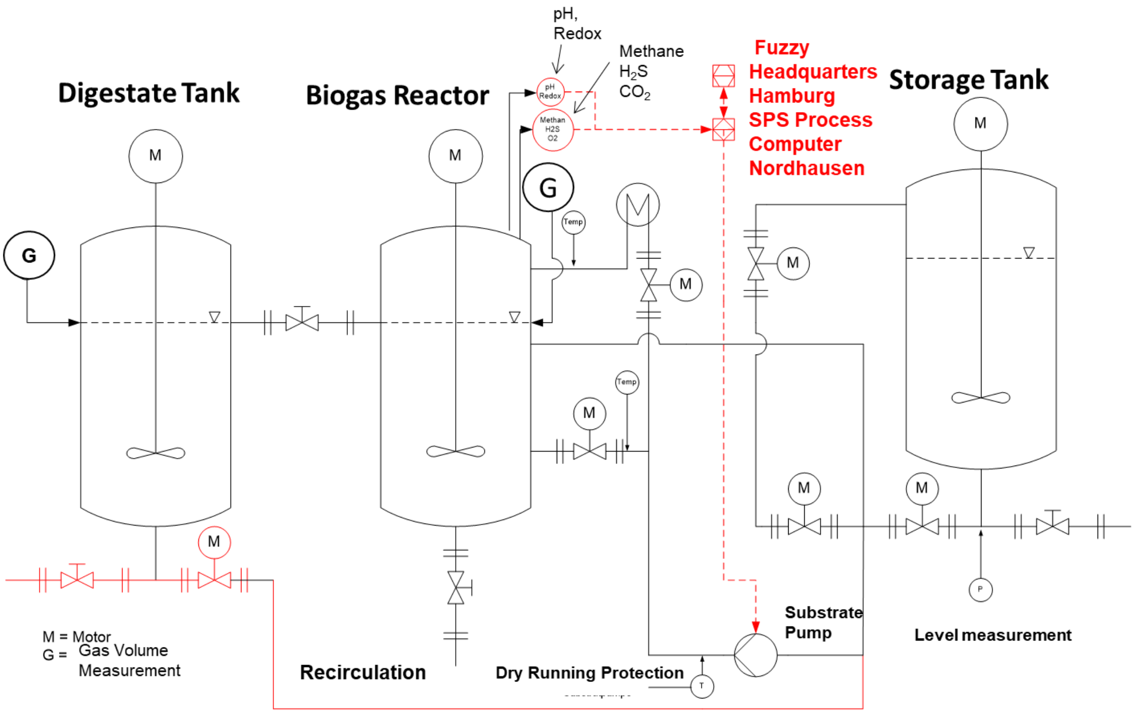
between an HC and an MR. In the case of methane content, an HC value above 75% is not achievable with a mixed substrate as it unable to generate a method content above this level. (**B**,**C**) The complete rule base editor with rules 1–13 and 13–27 for directing the feeding rate by the programmed Fuzzy tool of the used LABVIEW® software (Version 8). The primary target variable was the specific GPR (spec. GPR) with the linguistic categories low, medium, high. Increase and decrease in dosage are shown in columns 5 and 6. The Dosage of Substrate (DoS) could be modulated by a factor; in the given example, this was 0.50 or 1.00.

The measuring devices of the pilot biogas plant were checked on a daily basis and calibrated weekly to guarantee stable operation during online recording. The process computer also controlled the feeding pump and the other electronic feeding equipment. The feeding amount was calculated using a liquid level measurement of the storage tank and the biogas reactor, as shown in Figure 4. File transfer programs (FTP) were written in Labview® for HAW and for Nordhausen in order to send and receive the parameters. The 'master'-computer at the HAW read the process data from an FTP server and calculated the newly added FLC-driven OLR with respect to the GPR and substrate supply in the previous control period (GPR/OLR, generally averaged by 8 h). The calculated new OLR was sent by the FTP server of the 'master' computer in Hamburg to Nordhausen and the process computer recorded and converted it into a numerical signal for the remote control of the feeding pump. Generally, the process computer in Nordhausen worked independently, but in order to avoid any risks for this time-limited research project, the process was supervised in Hamburg. In addition, the graphs were plotted in Hamburg, primarily with Origin® software (Version 8), as shown in Figures 5 and 6.




(**A**)

**Figure 4.** *Cont.*




(**B**)

**Figure 4.** (**A**) Scheme of the constructed pilot biogas plant of the August Kramer Institute (AKI) at the University of Applied Sciences in Nordhausen. A self-programmed user interface of the control center at the University of Applied Sciences (HAW) controlled the 1.0 $m^3$ biogas reactor. Moving from right to left in Figure 4A: Substrate or storage tank (2.5 $m^3$), the 1.0 $m^3$ biogas reactor, and the effluent or digestate tank (1.5 $m^3$). In addition, the adjusted feeding interval of 8 h ('feed time') is indicated. (**B**) Scheme of the used pilot biogas plant as presented in Figure 4A but showing a technical circuit diagram with the control variables. From right to left: the storage or substrate tank (2.5 $m^3$), followed by the 1.0 $m^3$ biogas reactor and the digestate or effluent tank (2.5 $m^3$). Please note that commas have been used in Figure 4A for fidelity to the original. They have to be replaced by dots.

### *2.2. Features and Princples of the Used Fuzzy Logic Closed-Looped Control System*

FLC uses the exact measured values, such as methane (in % of produced biogas) and pH, as input parameters, but transfers them into imprecise or "fuzzy" linguistic terms [7,8] and links them to a self-programmed Fuzzy rule base like the Simatic®-Fuzzy device (Tokyo, Japan) [19,20]. The developed FLC was only based on three measuring parameters. Thereby, specific GPR has been integrated as a genuine feedback parameter, but the patent has expired and is, therefore, free [23].

pH: especially useful in the case of easily degradable substrates with the danger of biogas reactor's acidification. The pH value is of central importance for anaerobic, microbial biotechnologies [24]. A decrease is an indication of acidification or imbalance due to not converted VFA metabolites. VFA are routinely determined offline for process control of industrial biogas plants as online methods are not robust enough [25].

Specific GPR (GPR/OLR/d) or $m^3$ biogas/$kg_{VS}$ implied that the volumetric GPR ($m^3$ biogas/($m^3$ d) was related to the organic loading rate OLR in $kg_{VS}$/($m^3$ d). It is a unique control parameter for determining microbial performance based on the substrate used [23]. The volumetric GPR could be enhanced by increased substrate dosage. In contrast the specific GPR related to substrate dosage will concomitantly decrease [23]. Overdosage of substrate will lead to unmetabolized VFA and finally to acidification as indicated by a pH decrease.

$CH_4$: directly evaluates the methanogenic performance and should generally not be lower than 50%. Therefore, it also is a crucial control parameter and part of the developed

FLC expert system (Figure 3A–C). The percentage varies with the chemical composition. For example, carbohydrates such as cellulose reveal 50% methane, but with a constant substrate mix it does not change. Strong deviation indicates a severe process failure, whereby the feeding will be downsized by the closed loop with FLC feedback control.

*2.3. Function of FLC and the Created Fuzzy Rules*

The general principle of the FLC system used is shown in Figure 2. The FLC scheme can be explained by a scheme in 5 different stages (Figure 2). The first stage is used to record process measurement values, indicated as A, B, and C in Figure 2. The second stage is the fuzzification, which is employed to obtain a Fuzzy set of Fuzzy rules. Fuzzification entails that these online-monitored input values have to be converted by fuzzification into blurred linguistic terms, since the numerical input parameters are too precise for human logic. For example, the linguistic terms high, medium, and low for the methane content can be assumed. The rules of the FLC system are formulated as a Fuzzy rule set and this is the third stage after fuzzification (Figure 2). The numbers of the empirically created, distinct expert rules are presented in Figure 3B,C. As it has been defined above, fuzzy logic is based on logic rules found by experience (expert system). As mentioned, these expert rules were first formulated for the readily convertible, acidic-substrate-fodder beet silage as mono input with fully automated continuously stirred reactors (CSTR) at a lab-scale. This was done over several years by the biogas team of the HAW [21], as shown in Figure 1. The fourth stage is defuzzification, which is applied in order to achieve a final result. Since the FLC system provides the conclusion in linguistic terms (low, medium, and high), the result has to be converted to a number or a distinct signal of the substrate pump equipped with a remote control (Figure 2). The Centre of Maximum Method [6,7] was applied by the used Fuzzy tool of the LabVIEW® computer program and used in this stage as already tested [19,20]. However, there are also other Fuzzy tools on the market (e.g., Simatic® developed by the Siemens company, Tokyo, Japan). Finally, there is a numerical sum as a control output (Figure 2). Thus, the FLC system can determine the feeding time of a substrate pump and, consequently, the amount of substrate and OLR of a biogas reactor.

The following Fuzzy control rules (Figure 3A–C) indicate a high turnover and efficiency: high $CH_4$ content plus high specific GPR, with pH in the correct neutral range. Such properties enlarge the FLC command of Figures 2 and 3A–C for feeding with a pump; that is, the OLR increases via enhanced substrate feeding. Inconvenient values decrease the substrate dosage as closed-loop feedback. Such a feeding system using three cross-linked factors in a closed loop enables a direct feedback control of the metabolic performance and microbial turnover.

The finally tuned Fuzzy rules are presented in detail in the 'Rulebase Editor' of Figure 3A. The specific OLR was individually computed by the FLC program every 8 h per day. The 8 h period derived from previous, automated one-day feeding experiments with fodder beet silage based on an OLR of 4 $kg_{VS}/(m^3\ d)$ [19]. Since this method enabled methane production with the easily degradable substrate beet silage to be completed at 37 °C in 8 h, we have chosen these target values for further experiments [19,20], which were also successfully employed with maize silage and food leftovers (unpublished). The 27 Fuzzy rules with specific GPR, $CH_4$, and pH as implemented in the rule-base generator of the LabVIEW® Program are presented in Figure 3B. The programmed Fuzzy tool using LabView® generated the substrate dosage command every 8 h as new OLR or $OLR_{added}$, which represents the feeding rate as a relative percentage, and which was provided individually after each 8 h feeding cycle. The $OLR_{added}$ was adjusted in a selected frame, e.g., 10–120% of the last feeding cycle. The value was then converted into a precise numerical command for the pump's remote control. This was performed by the center of maximum method [6,7], as already mentioned and indicated in Figure 2. As an example, the FLC scheme for the control parameter $CH_4$ is given in detail in Figure 3A.

The substrate dosage was further changed by additional rules. They influenced the rapidity of the adaptation to a feeding situation; for example, a start-up period without acidification was performed with slower adjustments than the recovery after a reactor failure regarding acidification. This is indicated by the term DoS or Dosage Substrate in the rule base editor of Figure 3B.

*2.4. Conclusions Regarding the Fuzzy Logic Rules*

The mode of the given rules enabled a defined and reproducible feedback control. Such a traceable control scheme would not be provided by a neural-learning system [18]. A self-learning system leads to useful adaptations, but also to hidden changes. Based on the consideration that a completely documented system is a precondition for application and reproduction at a technical scale, we forwent selecting a system with empirically estimated preset rules. The advantages of the FLC system are that a programmable, commercial Fuzzy tool can 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.

*2.5. Hardware and Operation Mode of the Used Biogas Pilot—Chemical Parameters*

The three reactors were located in the technical hall of the University of Applied Sciences in Nordhausen, called 'August Kramer Institute'. The substrate or storage tank as well as the effluent tank of the biogas pilot plant were originally constructed for anaerobic wastewater treatment, employing a volume of 2.65 $m^3$ (working volume 2.5 $m^3$), as shown in Figure 4A,B. The methanogenic biogas reactor, with a 1.0 $m^3$ working volume, contained a heating system that enabled the interior to reach 38 °C and was permanently stirred at 100 rpm with a 1.1 KW engine. The dosage and digestate tanks were not heated and operated at room temperature between 17 and 24 °C. The effluent of the digestate tank was mixed with the substrate at a ratio of 1:10. Thus, a small degree of indirect recirculation was achieved. The density was postulated to be 1.0 kg = 1 L for calculation of the liquid level measurement and HRT. The substrate pump (Netzsch, Waldkraiburg, Germany) was automatically directed and remotely controlled by a Siemens Simatic S7-300 in test period II. The recorded process parameter values were transferred via an internet-based platform (Figure 1). The volumetric GPR was measured using a GMT 2.5 instrument (BONGAS Deutschland GmbH, Oberkirch, Germany) with 1 pulse corresponding to 10 L gas, and the exact range lay between 0.025–4 $m^3$/h. The gas composition was measured online with a Biogas Controller BC20 from CHEMEC GmbH, Bielefeld (www.chemec.de, accessed on 15 July 2022): $CH_4$ (0–100 vol. %), $CO_2$ (0–100 vol. %), $O_2$ (0–20.9 vol. %), and $H_2S$ (0–0.2 vol. %. $H_2S$ was additionally verified with test tubes from Dräger, Lübeck (www.draeger.com, accessed on 15 July 2022)).

The so-called "FOS/TAC" value (equivalent to VFA/TIC) was estimated weekly, but sometimes daily by titration according to [26,27], to characterize the stability of the biogas fermentation process. The occurrence of an increased level of free fatty acids (VFA) is a strong indication of the instability of a biogas reactor [28,29]. A VFA/L below 500 mg means a very stable or smooth biogas production process; >5000 mg VFA/L indicates an imbalanced, dangerous state [28].

VFA values were also more precisely estimated with ion chromatography (Deutsche Metrohm, Stuttgart, Germany, www.metrohm.com, assessed on 16 July 2022). This method allowed the determination of formic, acetic, propionic, iso-butyric, butyric, and iso-valerianic acid. Formic acid is a rare process parameter and accordingly played a small, but significant role during acidification of the biogas reactor (see results, Figure 5B).

*2.6. Test Periods I and II: Startup and Substrates for Fermentation*

The 1 $m^3$ biogas reactor was inoculated by filling it with reactor medium originally obtained from a biogas plant digesting swine manure with charges of maize/triticale (1:3), sometimes referred to as 'energy crops'. After inoculation, bruised barley grist was used as the fed substrate of test period I.

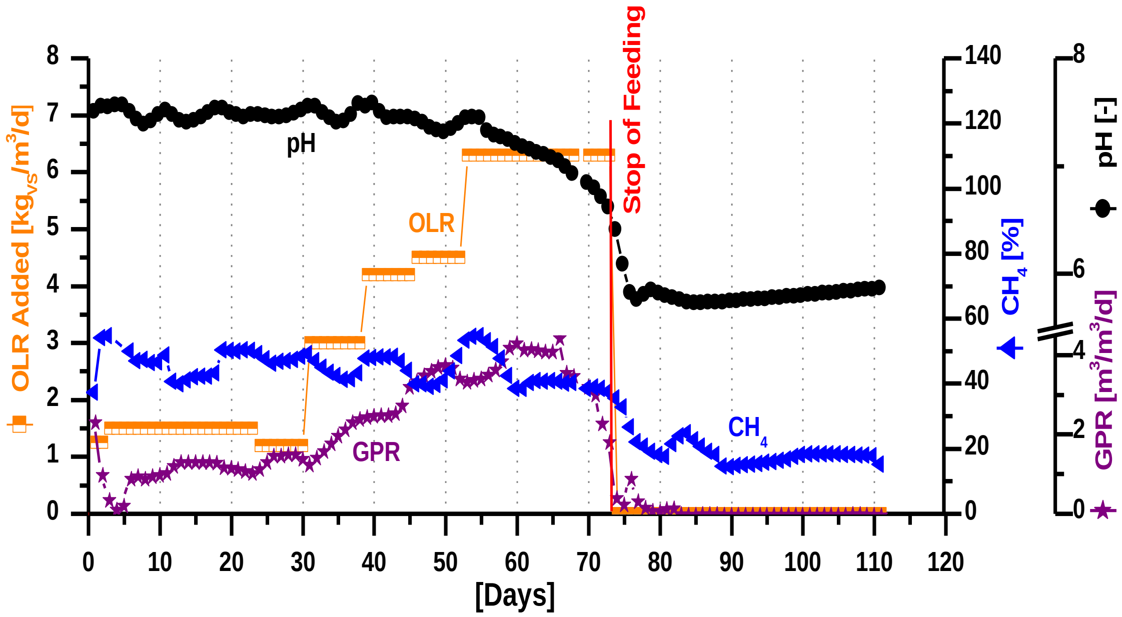
On the beginning of test period I, the pH was around 7.6, with an alkalinity of 14,500–15,000 mg/L $CaCO_3$, which represents a normal pH value with respect to agricultural biogas plants, but stabilized by a high alkalinity [28]. It should be mentioned that the FLC system was originally developed with pH (besides specific GPR and $CH_4$) as control parameter for lowly buffered, acidic beet silage with an alkalinity of only $\leq$2500 mg/L $CaCO_3$ [18,19]. Other process characteristics were as follows: ammonium content 4500 mg/L, phosphate content 625 mg/L, dry matter (DM) 4.16%, and volatile solids (VS) 3.28%. During the start of period I, the pump transferred 50 L of medium (substrate and water) from the storage tank into the reactor thrice a day at eight-hour intervals. The medium was again pumped back from the effluent tank and 20 L of the medium was drained on a daily basis in order for the process to remain stationary. Based on this feeding mode, the HRT could be assessed. Test period I was also used to explore the OLR limit for stable fermentation (see results). Therefore, the intention was to overload the biogas reactor during test period I, but the VFA level rose as high as 25,000 mg/L (see results, Figure 5B). This is an indication of strong acidification [25]. Therefore, to start the automated period II, the high VFA level first had to be decreased to achieve nearly equal starting conditions. The stabilization period was shortened by a new method: adding aqueous compost eluate according to Scherer and Neumann and Off et al. [30,31]. The hydrolytic anaerobic bacteria in compost were naturally enriched and based for practical reasons on a mushroom substrate (straw + horse dung). Accordingly, the automated test period II had at its beginning a DM and VS content of 2.50% DM and 1.67% VS, respectively.

In test period II, the FLC operation was performed with a similar energy crop, Triticale residues were used as mono-input (a bad batch of it), which was automatically fed every 8 h via the rule base editor, as shown in Figure 3B. If the control parameters featured a stable and convenient range, the $OLR_{new}$ was set manually via the FLC system to a higher value than before. Otherwise, the $OLR_{added}$ stagnated or was reduced automatically by the FLC system.

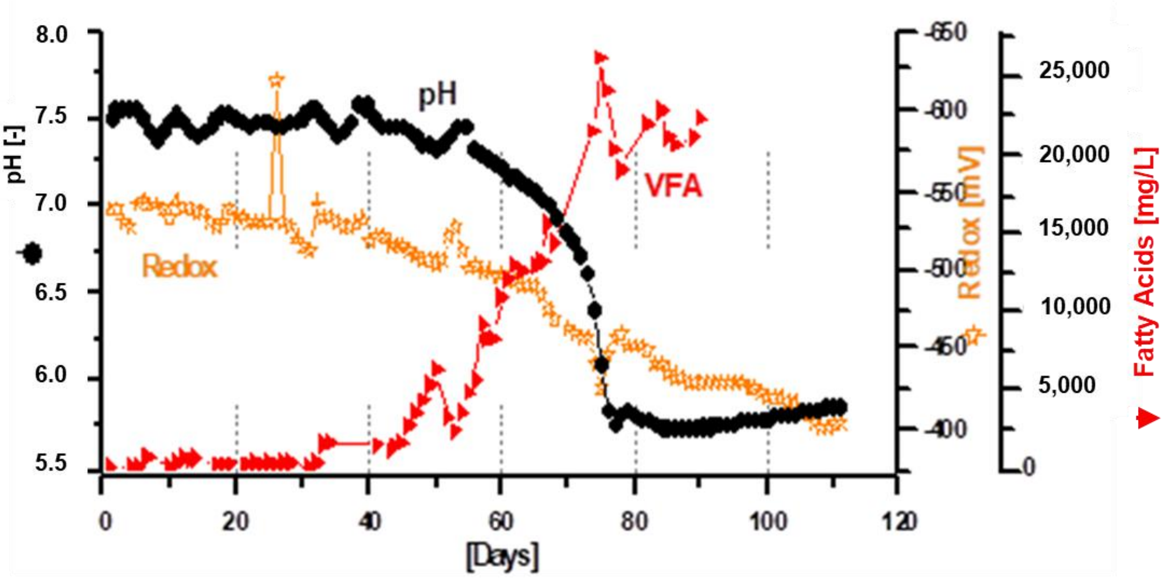
Trace elements were added only prophylactically added to exclude the possibility of a deficiency [32], as it was a large scale experiment with some risk. The trace element solution contained $H_3BO_3$, Fe, Mn, Mn, Zn, Cu, Mo, Co, Ni, and Se in the range of 0.1–1.8 mg/L as complexed by nitrile triacetic acid. Trace element solutions are commonly used for supplementation of agricultural biogas plants [32]. An example is published by Friedmann and Kube [33], which they used for biogas plants. Such trace element solutions are going back on trace elements used for the cultivation of pure microbial cultures like DSMZ medium 141 (www.dsmz.de, accessed on 15 July 2022).

## 3. Results and Discussion

Part of the project plan was to find the limit of overload or the highest applicable OLR for a stable biogas process under mesophilic conditions. Therefore, the disturbance of the reactor via overloading was provoked deliberately in test period I. During start-up period I, the OLR was increased from 1.5, 3.0, 4.2, and 4.5 to 6.3 $kg_{VS}/(m^3\ d)$, but without operating under the regime coordinated by FLC, only by manual and intermittent daily feeding (Figure 5A,B). For comparison: agricultural biogas plants are generally run 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 [34]. In our experience, such a conservative, low-speed operation is also typical for agricultural biogas plants in Germany. Therefore, the targeted OLR of 4.5 and finally 6.3 $kg_{VS}/(m^3\ d)$ was a sportive throughput. From trial days 30–60 of operation, the volumetric GPR of biogas increased from 1.0 to 3.0 $(m^3/(m^3\ d)$, whereas on trial day 52 the OLR was increased from 4.5 to 6.3 $kg_{VS}/(m^3\ d)$ (Figure 5A). As feared, the level of volatile fatty acids (VFA) increased from around 500 mg/L to above 7000 mg/L in 6 weeks or 50 days of test period I when the OLR increased from 1.0 to 3.0 and 4.2 to 4.5 $kg_{VS}/(m^3\ d)$ (Figure 5A). The pH had already decreased to 7.3, but was still in the safe methanogenic range, which is usually 7–8.5 [23].




(**A**)




(**B**)

**Figure 5.** (**A**) Test period I. Successive increases in the feeding rate and the added OLR, respectively. 1 $m^3$ biogas reactor with bruised barley grist as substrate and mono-input. OLR means organic loading rate. The procedure started with an OLR of 1.5 and finished, as shown here, with an OLR of 6.3 $kg_{VS}/(m^3\ d)$. The following control parameters were recorded: $OLR_{added}$, pH, volumetric GPR ($m^3$), and the methane content of the produced biogas. GPR = gas production rate. The provoked overloading of the reactor could already be seen by the pH signal on trial days 55–65. Manual feeding was stopped on day 74 to normalize the $CH_4$ level and pH for the subsequent test period II. (**B**) Test period I. Successive increases in the feeding rate of the 1 $m^3$ biogas reactor with bruised barley grist as substrate and mono-input as shown in Figure 5A. Plotted parameters are the pH; redox (that is the ORP) and the volatile fatty acids (VFA). Increasing the OLR from 4.5 to 6.3 kgVS/($m^3$ d) led to a dramatic increase up to 25,000 mg/L VFA and a decrease in pH to a value of 5.8. The feeding procedure was stopped on day 74 to normalize the VFA level and pH for the subsequent test period II.

A further pH decrease to pH 7.2 was first detected on day 65 as the VFA level rose to 10,000 mg/l on day 60 (Figure 5B). However, the level of volumetric gas production further increased until day 60 up to 3.0 and fell only slightly to 2.8 L per L on day 65. That indicated at first sight a stable process, but he specific GPR (GPR/OLR/d) ($m^3/(kg_{VS}$ d) decreased in this 30–70 d period from 3.0 down to 2.2, whereas after 80 days the methane content decreased even more to the very low value of 20%. Obviously, as a result of the elevated OLR, the biogas process became unstable. Later on, the dangerous VFA (volatile fatty acids ($C_1$–$C_6$)) level increased to the huge amount of 25,000 mg/L on day 75, as shown in Figure 5A,B.

Normally, the pH value will not play a dominant role as a process parameter in a well-pH-stabilized biogas process using cow manure, but the final pH value of swine manure with barley grist as an additional substrate decreased to 5.8, as seen by the dramatic increase in the VFA level in Figure 5B. Thus, feeding was stopped on day 7 to prevent acidification and disturbance, as indicated in Figure 5A. The obvious pH decline disclosed that the utilization of pig manure with cereal residues still proved to be in need of pH control if one wants to achieve a higher OLR than 4.5 $kg_{VS}/(m^3$ d). This opens a path for an universal FLC application using agricultural substrates mixed with manure, although the previously evaluated FLC system in lab scale was used for non-buffered biogas fermentation with acidic beet silage (pH 3.0–3.5) as an easily degradable mono-input [18,19].

Parallel to the biogas process, the VFA spectrum was continuously analysed to provide a more pronounced insight in the process [28,29]. The maximum level of VFA was reached on trial day 75 of test period I, which was about 25,000 mg/L VFA. The VFA consisted of 2700 mg/L formic acid, 9100 mg/L acetic acid, 8800 mg/L propionic acid, 750 mg/L iso-butyric acid, 1500 mg/butyric acid, and 2000 mg/L iso-valerianic acid, as shown in Figure 5B. These results show the dominance of acetic and propionic acid as the most common intermediates of the biogas process, but also show a remarkable amount of formic acid [24,29].

Figure 5B also shows the online-recorded redox potential, that is, the ORP, as a suitable, additional process variable, but the signal was not very pronounced. Therefore, there was no reason to prolong the following FLC control period II by the implementation of the redox value process parameter.

### 3.1. Conclusions from the Manually Driven Test Period I

The experiments of test period I clearly indicated that the specific GPR related to the amount of fed substrate should be a reliable control parameter [18–20], but not the volumetric GPR. The volumetric GPR could still imitate a safe situation, as shown in Figure 5A,B. Yet, it still needed the combination of the further online control parameters pH and methane % to guarantee a stable and safe performance of the biogas process. The VFA level would be an even more direct and sensitive indicator for an unstable biogas fermentation but is an offline lab method [25,28,29].

### 3.2. Results of Automated Test Series II with the Implemented Fuzzy Logic Closed-Loop Feedback Control

The biogas reactor's (1 $m^3$) starting conditions for test period II were as follows: Alkalinity—15.000 mg $CaCO_3$ equivalents/L; TS = 2.5% vs. = 1.67%; pH = 7.5. The FLC-directed experiments of test series II included a period of nearly 2 years; a section of 120 days between days 450 and 530 has been plotted, as shown in Figure 6.

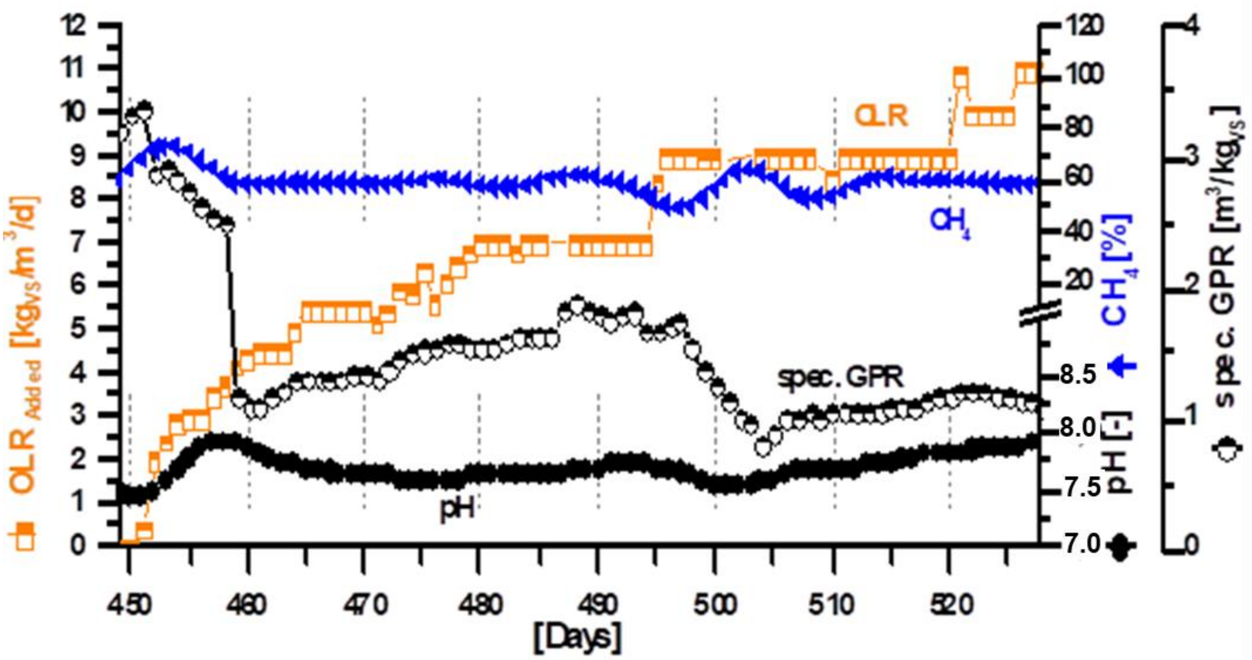



**Figure 6.** Test period II. Equal biogas reactor (1 m$^3$) as used in period I, but substrate feeding was managed by a pump with remote control device and controlled by Fuzzy logic and the Fuzzy rules from Figures 2 and 3A–C. Pictured are the trial days 449–528 with the control parameters pH, methane content (%) of the biogas produced, specific GPR (m$^3$/kgVS), and the FLC-calculated $OLR_{added}$ kgVS/(m$^3$ d). The diagram shows the automated OLR increase under the direction of the developed Fuzzy logic closed-loop feedback control from 3 to 11 kgVS/(m$^3$ d) via the selected and predefined steps of 4.5, 5.5, and 7 kgVS/(m$^3$ d).

Some unforeseen technical problems (the acidity of period I, pump problems, and the instability of measuring devices) and lastly, but not least, important foaming problems caused by the enormous degree of biogas production prevented a longer evaluation period of the fermentation of the cereal residues. As expected, the continuous FLC management worked as an "autopilot" system and allowed a much higher OLR and space-time yield than the test period I without FLC direction. Nevertheless, a safe fermentation was realized, as seen in Figure 6. The OLR values of 7, 9, and 11 kgVS/(m$^3$ d) were prefixed, but they were reached through the microbial activity reacting dynamically with respect to the Fuzzy feedback control parameters, as shown in Figures 2 and 3. The individually measured values of pH, $CH_4$, and the specific GPR were transferred into the Fuzzy rule base every 8 h (Figure 3B), directing the substrate pump to a higher or lower level than the last feeding level. Thus, the "master" computer in Hamburg was permanently connected via internet with the process computer in Nordhausen. A manual intervention through an SMS was always possible, but not necessary, as shown in Figure 1. The Fuzzy logic feedback control worked smoothly like an "autopilot" system.

With the support of the FLC system in test period II, a safe OLR increase from 6 to >9 kgVS/(m$^3$ d) was accomplished on trial day 500 d with a basic, short HRT of about only 10 days (for its assessment, see Sections 2.2 and 2.3), thereby doubling the OLR of the previous test period I without an FLC system, Figure 6. In addition, the pH remained stable between 7.6 and 8.0, providing a clear indication that the VFA level also remained stable. Even a very high OLR of 11 kgVS/(m$^3$ d) seems to be possible as shown at the end of the experimental period II (Figure 6), which is three- to ten-fold fold higher than the usually applied OLRs of 1.1–3.3 kgVS/(m$^3$ d) in agricultural biogas plants [34]. Anyway, there was no process risk, as the microbial population reached the higher OLR dynamically as a result of the rate of their substrate turnover and the feedback FLC control system potentiated by a closed loop.

During the period of an OLR of 7 kgVS/($m^3$ d), the volumetric GPR reached on average volumetric biogas production of 5.5 $m^3$/per $m^3$ reactor volume and day, as presented in Figure 6. This is similar high as in case of the FLC-directed anaerobic digestion of beet silage with a volumetric gas production rate (GPR) of 9 $m^3$/($m^3$ d) and an OLR of up to 15 $kg_{VS}$/($m^3$ d) [19,20]. However, unfortunately, the extremely high volumetric gas production of the easily degradable cereal substrate caused foaming problems and prevented an exact level measurement of the input pump. Therefore, the FLC system-based test series II had to be stopped. However, with the FLC system a safe OLR of at least up to 9 kgVS/($m^3$ d) was possible. The reduction in the specific biogas GPR from 3.3 to 1.0–1.3 in Figure 6 is both a tribute to the high OLR, but also the concomitant short HRT of exceptional 10 days, if compared with an HRT of 39 days achieved on average by full-scale agro-biogas plants [34]. However, the achievable HRT also depends on the doubling time of the microbial population being individually different for each substrate [35].

### *3.3. Discussion of Results of Automated Test Series II with the Implemented Fuzzy Logic Closed-Loop Feedback Control*

Early experiments regarding the OLR of readily degradable agricultural energy crops concur with our results. These previous findings indicated the same, that by manual feeding only modest OLRs are possible in single-stage reactor systems [35]. With maize silage, fodder beet silage, and whole-crop rye silage added manually as a mono-substrate, only a stable OLR range of 1–4.0 kgVS/($m^3$ d) could be achieved in continuously stirred single-stage lab-reactors. Thereby, the specific methane yields decreased in parallel down to 50% at higher OLR [35]. Another feeding strategy for readily degradable substrates like pre-fermented silage or food leftovers is to increase the HRT by sequential reactor stages [4] or recirculation [22] as already mentioned in the introduction. In addition, results from the literature on the fermentation of wheat straw have shown that high OLRs and high specific methane production rates are possible without the aid of an FLC system. But this is particularly true for slowly degradable substrates in pH buffered media as the hydrolytic degradation of lignocellulose in straw is rate limiting and prevents an excessively high level of acidification. The straw digestion experiments additionally showed that the VFA could increase up to 6000 mg/L without a negative effect on the microbial cell counts if the pH was constant [36]. Furthermore, if automated intermittent 8 h feeding in CSTR reactors was compared with manual feeding once per day it turned out to be more favorable [36]. This was confirmed by Ahmed and Kazda for an easily degradable substrate mixture of sugar beet and grass silage at OLR of 1.5 and 2.5 kgVS/($m^3$ d) [5].

Studies regarding biogas fermenters with feeding control via an FLC system are rare, especially with solid substrates [6]. Holubar et al. [17,18] used a FLC-feeding system, as well. Their CSTR fermenter system was on laboratory scale and fed for a period of 64 days with a Fuzzy control system. A mixture of primary and surplus sludge from a local municipal waste water treatment plant was supplemented by wheat flour, vegetable oil, or sucrose as a substrate [17,18]. The manual-feeding scheme allowed a loading rate of 6 kg COD/($m^3$ d). However, the FLC-controlled feeding period made possible a doubling of the OLR, like in the present study with cereal residues. With their substrate [17,18], the OLR was higher than 12 kg COD/($m^3$ d) and did not destabilize the system. Simultaneously, a high level of methane content of about 70% was observed with mixed sludge and supplemented easily degradable carbon sources. Thus, the FLC control strategy resulted in a high volumetric biogas production of about 3 L per L and day [17,18]. The doubled space-time yield enables a drastic reduction in maintenance energy costs for heating, pumping, and stirring, because a much slimmer biogas reactor could be used.

A further rare example for a physiologically-based feeding control of an anaerobic digester is given by García-Diéguez et al. [37] in which methane production of an anaerobic upflow of sludge bed-reactor (UASB) for the anaerobic treatment of winery wastewater was maximized. In addition to the online measurement of methane production as control parameter, an offline-measured effluent VFA level was kept at a low prefixed concentration.

However, the applied PID cascade of two parameters' (one offline) were somewhat different to the presented completely online-directed FLC with a closed-loop feedback control, based on the control parameter pH, -besides the specific GPR and $CH_4$ content of produced biogas. But it led to a low VFA level and therefore a safe process performance.

## 4. Conclusions

The first control modes for feeding biogas plants were proposed in the 1970s; they were mainly on/off controls, which set the managed feeding pump to a binary value depending on a predefined threshold value based on empirical findings, as outlined in the review by the authors Gaida et al. [6]. PID controllers or three-term controllers (proportional–integral–derivative controllers) were used with a control loop mechanism employing simple feedback to maintain a constant measuring value. Such control modes of feeding are still in use in large-scale biogas plants because the operating staff or the owner(s) of the plants are present every day on the biogas plant. The facilities are driven often conservatively with a low OLR and using pH-buffering manure as co-substrate [34]. In such cases, the feeding is mainly determined indirectly by empirical observation of the methane content in the biogas stream and by indirect assessment of the performance based on a combined heat and power (CHP) plant connected to the biogas plant and the amount of electricity it generates [34]. However, a biogas process operated in such conservative manner with a low space-time yield will not correspond to ideal economic considerations.

Nevertheless, shorter feeding intervals than 8 h are also possible via an automated substrate dosage. Biogas plants of industrial scale often use intervals of only 1/2 or 1 h to minimize the electrical load of the pumps as the use of a high electrical load is expensive (own observation).

*Outlook*

The time seems to be ripe now to feed biogas plants by a FLC-driven, closed-loop feedback control system. The equipment is commonly available and therefore its use should be increased in biogas engineering [2]. Herein, such a system was successfully employed to control the feeding rate of a pilot-scale biogas plant with swine manure and cereal residues as energy crops. It required feeding pumps that were managed contemporarily by a remote control and a personal computer (server) with file transfer protocol (FTP) and data management. In our case, the FTP server with its Fuzzy rule base editor was supervised for safety and research reasons by a second 'master' computer allocating the calculated OLRs, Figure 1. But it proved to be unnecessary. Besides the specific GPR, only two further control parameters were sufficient to enable a safe feeding procedure and to prevent acidification [29]. The methane content of the biogas and the pH value of the fermentation process were additionally selected as physiological control parameters. Thus, the microbes themselves directed the speed of the substrate dosage by the dynamics of their substrate turnover. In the case of an easily degradable substrate such as cereal residues with swine manure, the integrated FLC system enabled a safe doubling of the fed OLR 4.5 $kg_{VS}/(m^3\ d)$ to up to 11 $kg_{VS}/(m^3\ d)$. It doubled the substrate throughput without jeopardizing the biogas production process and underscored the strong influence of Fuzzy control. Foaming was the only problem that prevented a higher OLR of the easily degradable cereal-based material. Therefore, the developed FLC system successfully passed the endurance test at the large pilot scale. Future users can already rely on the ready-to-use FLC rules, which are presented in Figure 3C. Moreover, flexible on-demand biogas production with an additional FLC system (in combination with a gas storage dome) seems to be in our opinion a perfect option for this application [3,4].

A fly in the ointment could be the absence of a cheap, exchangeable, and robust pH sensor. Feeding with a FLC system based only on the two parameters of specific gas production (GPR/OLR) and the well-established $CH_4$ online monitoring seems to be not safe enough. We employed pH electrodes used in wastewater treatment that were protected by a sulfide lock to enable downtimes of around 2 years. However, a remaining challenge is the need for continuous calibration and the cleaning of all the measuring probes. An industrial self-cleaning pH calibration system seems to be too expensive for agricultural, low-cost biogas plants. A simple and cheap one-way pH-sensor, which would be used analogously to pressure sensors for automatic car brake systems (ABS generally works with Fuzzy rules), would provide a breakthrough for the automated, safe feeding of anaerobic digesters by an FLC system. That is our predictive message and most important conclusion for this predestinated FLC system.

**Author Contributions:** Conceptualization: P.S. and G.-R.V. Methodology: P.S. and G.-R.V. Software: S.A. and R.A. Validation: S.A. and A.S. Investigations: S.A. and A.S. Resources: P.S., G.-R.V. and G.-R.V. constructed also the pilot biogas plant and made the facility turnkey ready. Data curation: S.A., A.S. and R.A. Original draft preparation: P.S. and G.-R.V. Writing: P.S., A.S. and R.A. Review and editing: P.S., R.A. and A.S. Visualization: P.S., A.S., S.A. and R.A. Supervision: P.S. and G.-R.V. Project administration: P.S., S.A., A.S. and G.-R.V. Funding acquisition: P.S. and G.-R.V. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by FNR Fachagentur für Nachwachsende Rohstoffe of the ministry for agriculture. FNR means the Agency for Renewable Biomass in Guestrow, which represents the research office of the German ministry for agriculture, nutrition, and protection of consumers in the capital Berlin. The funding number for Hamburg University of Applied Sciences was FKZ 220 10405, and funding number for University of Applied Sciences in Nordhausen in Thuringia, Germany, was FKZ 22 01 86 06. Both project reports (German) can be downloaded by the FKZ numbers from the FNR data bank under www.fnr.de (assessed on 15 February 2022).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

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