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Article

How Efficient are Agitators in Biogas Digesters? Determination of the Efficiency of Submersible Motor Mixers and Incline Agitators by Measuring Nutrient Distribution in Full-Scale Agricultural Biogas Digesters

Andreas Lemmer *, Hans-Joachim Naegele and Jana Sondermann

State Institute of Agricultural Engineering and Bioenergy, University of Hohenheim, Garbenstraße 9, Stuttgart 70599, Germany; E-Mails: hajo.naegele@uni-hohenheim.de (H.-J.N.); jana.sondermann@live.de (J.S.)

* Author to whom correspondence should be addressed; E-Mail: andreas.lemmer@uni-hohenheim.de; Tel.: +49-711-459-22684; Fax: +49-711-459-22111.

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Abstract: The goal of this work was to evaluate the efficiency of two different agitation systems by measuring the nutrient distribution in a digester fed with renewable energy crops and animal manure. The study was carried out at the practical research biogas plant of Hohenheim University. A unique probe sampling system has been developed that allows probe sampling from the top of the concrete roof into different parts and heights of the digester. The samples were then analyzed in the laboratory for natural fatty acids concentrations. Three different agitation setups were chosen for evaluation at continuous stirring and feeding procedures. The results showed that the analysis approach for agitator optimization through direct measurement of the nutrients distribution in the digester is promising. The type of the agitators and the agitation regime showed significant differences on local concentrations of organic acids, which are not correlated to the dry matter content. Simultaneous measurements on electric energy consumption of the different agitator types verify that by using the slow-moving incline agitator with large propeller diameters in favor of the fast-moving submersible mixer with smaller propeller diameters, the savings potential rises up to 70% by maintaining the mixing quality.

Keywords: biogas; mixing; stirring; agitators; mixers; energy efficiency; nutrient distribution; incline agitator; submersible mixer; renewable energy crops; volatile fatty acids

1. Introduction

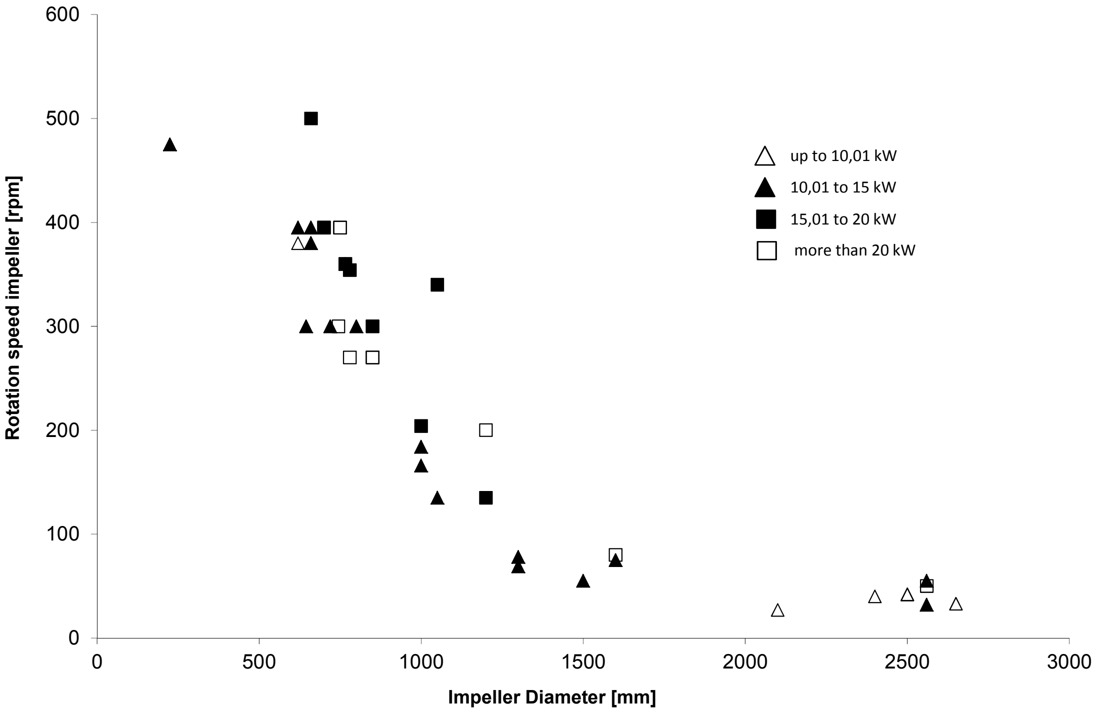
1.1. General Introduction

In most cases, continuous stirred tank reactors (CSTR) are used for producing biogas from energy crops or organic residues [1]. When using this type of biogas digester, the stirring of the substrate in the digesters is vital for the biogas formation process. The purpose of stirring is to distribute the nutrients in the biogas digester uniformly, to form a suspension of liquid and solid parts, to avoid sedimentation of particles, to ensure uniform heat distribution, to prevent foam formation and to enable gas lift from the fermentation substrate at high dry matter (DM) contents [2–8].

Almost all of the agricultural biogas stations based on CSTR use vertical digesters. In these vessels, the circular motion of material in a desired way is induced by agitation. For the agitation of the substrate, different types of agitators, stirrers or mixers are used. Mixing, a physical process carried out by agitators, stirrers or mixers, is physically defined as a random distribution of materials in different phases into another, forming a homogenous dispersion [9]. Mixing is described as one of the most common unit operations in process industries and many different types of mixers and impellers have been designed for varied operations [10].

Companies constructing agitators acknowledge that in agricultural biogas production, specially designed agitators, laid out according to digester volume and substrate properties, are used [11]. At present, there are several state-of-the-art agitation technologies that have been applied commercially. In general, they are known as mechanical, hydraulic or pneumatic mixing systems. In Germany, mechanical agitation is dominating the market for stirring fermenting substrates from agricultural origin [1]. A nationwide study in Germany in 2009 showed that 47% of all completely stirred anaerobic digesters are equipped with fast-rotating submersible mixers. It was found that by moving from substrates such as organic waste or animal manure to energy crops high in fiber, the DM content of the digestate increased significantly. Therefore, the requirements for agitators have changed and this has led to the dissemination of slow-rotating agitators. The authors report that in Germany, a share of 12.9% of the biogas plants (BGP) are equipped with incline shaft agitators, 7.4% with paddle agitators, 6.0% with central agitators and 0.8% with reel agitators. Furthermore, a combination of slow- and fast-rotating agitators is used in 16% of the BGP [1]. Similar results, with a trend towards low-velocity mixers with large agitation wings for continuous operation, were found by Hopfner-Sixt and Amon for BGP in Austria. Their survey showed that 36.6% of the BGP used paddle mixers. Submersible motor mixers were used in 34.7%, long-shaft mixers in 17.8% and paddle mixers in horizontal digesters in 8.9% of the cases [12]. An overview of agitators for biogas digesters is given in Figure 1 and shows that impeller diameters, rotation speed and the electric power requirement vary in a wide range. With increasing impeller diameter, the rotations speeds decline with a tendency towards lower power requirement.

Figure 1. Rotation speed of agitators in relation to the impeller diameter and its respective power requirements of agitation units available on the market (n = 46) (source: own survey in 2013).



There is little information on hand about the optimal choice of agitators and their setup in digesters, mixing intervals and the time required for optimal homogenization. Kissel *et al.* [13] presented data showing that operation hours in the first fermenting stage vary due to the agitator design. Reel agitators, central agitators and submersible motor agitators are continuously operated, while all other agitators are operated intermittently between 8 and 28 min per hour. If two stages are applied, the mixing time was reduced in the second step. Hopfner-Sixt found the average mixing time at 3–4 h per day in Austrian BGP [12]. In practice, the BGP operators set their agitator adjustment, its intervals and operating hours based on advice of manufacturers or consultants and after some time, on their own experience.

Weiland *et al.* [14] found that malfunctions in agitation technique accounted for ~15% of the workload on BGP as high wear and tear lead to failures after some years. Hopfner-Sixt [12] reported that 44% of the BGP dysfunctions are caused by agitators.

Up to now, the configuration of agitators in digesters, e.g., numbers, positioning, installation height and alignment in accordance to digester volume and substrate is, in most cases, based on the experience of manufacturers and operators and only in very rare cases based on scientific background. Hence, it is not an easy task for BGP operators to select the equipment, as many aspects have to be considered. The fermentation substrate characteristics, such as fiber content and rheology, as well as the digester design, have to be considered when choosing the agitators [8]. Despite first assumptions for agitator setups, the substrates may vary over the operation time. Furthermore, the capacity of agitators should be dimensioned in a way to react to changes in substrate composition or process failures. Easy access to agitators for maintenance during BGP operation will help to shorten service time [13]. In spite of its important role in performance, mixing quality in digesters has not been adequately quantified or characterized [3].

1.2. Economic Impact

Studies on electric energy consumption at the research BGP of Hohenheim University showed that mixing consumes up to 51% of total electric energy consumption for the biogas production process. The results show in detail that long-shaft agitators consumed up to 5.76 kW h 100 $m^{-3}\cdot d^{-1}$ while the submersible mixers used 11.29 kW h 100 $m^{-3}\cdot d^{-1}$ of electric energy for agitation in the first fermentation stage [15]. A field study showed electric energy consumption for agitation at 30%–50% [16]. Kissel *et al.* [13] reported that at ten pilot plants, the electric energy consumption for agitation accounted for 25% (in the first fermentation stage) of total electric energy consumption from agitation ranging from 6% to 58%.

This high electric energy demand is causing high costs and moreover lowering the CO_2 balance of this bioenergy source. By the end of 2012, approximately 7589 BGP with an installed electrical capacity of 3179 MW have been in operation in Germany [17]. Taking into account that approximately 8% [15] of the produced electricity is used for BGP operation and 50% [15] of this energy is used for agitation, calculations show that 1 billion kW h/a are used for agitation in German biogas stations. At an energy price of around 0.2 €/kW h, approximately 200 million €/a are spent on agitation. This calculation clearly shows the impact on the profitability of BGP operation.

In practice, however, the BGP operators usually evaluate their agitator performance based on visual monitoring of the fermentation substrate. The problem arising with this method is that only the condition and motion surface can be monitored. By doing so, no information can be obtained about the quality of mixing in other parts of the digester underneath the surface. Therefore the BGP operators tend to enhance both frequency and duration of agitation above the recommended intensity to assure the avoidance of technical problems and failures. In practice, it is almost impossible to run agitators at an energetic and qualitative optimum. The optimum of mixing can be defined as achieving homogeneity at the lowest energy input.

1.3. Research on Agitation in Biogas Digesters

Research on mixing quality in anaerobic digestion processes has been described by several authors (we refer to Monteith and Stephenson for older and Wu for latest sources) [6,18]. Early studies focused on the treatment of municipal sludge and later ones on agricultural residues. Research on high viscous fermenting substrate, resulting from the increased use of renewable energy crops, has been carried out in recent years and can be classified as two main research methods, such as intrusive (e.g., experimental research) and non-invasive [computational fluid dynamics (CFD), computed tomography (CT), as well as computer automated radioactive particle tracking (CARPT)]. It was found that researchers combine different methods.

Although "mixing" has been well researched for chemical and industrial applications, it was found challenging when applying those results to the biogas forming fermenting substrate. For engineering calculations, the rheological properties of substrates are required and liquid manure has been researched by many authors. Landry *et al.* [19] reported according to Chen [20] that beef cattle slurries were described as non-Newtonian pseudoplastic fluids, with an increasing deviation from Newtonian behavior by increasing total solid concentration. According to Vesvikar [3], it is more complicated to describe the rheologic properties of biogas substrates due to the fact that digester substrates are opaque and multiphase systems in which the physics are very complex and not fully understood. These multiphase systems contain liquids, solids, diluted minerals, fibrous material of different length, and biogas. Moreover the substrate temperatures vary from 40 °C to 53 °C. With increasing total solids concentration, the fermenting substrate shows non-Newtonian pseudoplastic behavior and viscosity, as well as shear stress, appear to increase exponentially [21]. Kissel [13] and Springer [22] described fermenting substrates as shear thinning. The shear viscosity is not consistently linear depended on the shear rate. As a defined value for viscosity cannot be given, the layout of agitators is hampered.

1.3.1. Effects of Mixing on Biogas Production

Due to the difficult multi-phase fermenting substrates, most of the mixing research in anaerobic fermentation systems is focusing on its effects on biogas yield. The effect of mixing in anaerobic digestion of animal manure was studied on a laboratory scale by Karim *et al.* [23], who showed that mechanical, hydraulic and pneumatic accounted for 29%, 22% and 15% higher biogas yields compared to the unmixed digester. With increasing DM content in the slurry, deposition of solids could be observed. They concluded that mixing is becoming prominent in digesters fed with thicker manure.

Laboratory scale research of anaerobic digestion of sewage water demonstrated that in continuous mixing systems, higher impeller speeds rising from 140 min^{-1} to 1000 min^{-1} did not improve total gas yields and even a slight reduction in gas production occurred [24,25]. By treating animal manure, similar effects on biogas production rates and yields at steady-state conditions of four different mixing intensities (50, 350, 500 and 1500 min^{-1}) could be determined in continuously stirred bioreactors [26]. Higher methane productions by 1.3% and 12.5% could be observed with intermittent and minimal mixing strategies of manure in anaerobic digestion compared to continuous mixing. An increase of 7% in biogas yields was found in pilot-scale studies comparing intermittent to continuous mixing [27]. Gentle and minimal mixing before feeding proved to be advantageous compared to vigorous mixing by high substrate to inoculum ratio in laboratory scale research. In accordance to Kaparaju *et al.* [27], it can be concluded that in biogas digesters fed with manure and solid substrates, mixing is indispensable. The mixing intensity had a small effect on biogas yield and mixing schemes proved to have an effect on anaerobic digestion of manures.

1.3.2. New Approaches in Studying Mixing Efficiency

Monteith and Stephenson [18] analyzed the effects of mixing in full-scale anaerobic digesters (two water pollution and control plants) by tracer methods and found that dead zones accounted for as much as 77% of the volume theoretically available for active mixing, seriously reducing the hydraulic retention time. Deviations from ideal mixing were detected and attributed to short-circuiting.

Karim *et al.* [5] used noninvasive techniques combining computer-automated radioactive particle tracking with CT to identify the flow pattern caused by a mixing unit (gas recirculation) and to calculate various turbulence parameters quantitatively for a 20.32 cm diameter flat-bottom laboratory-scale digester. The results show that 27%–31% of the digester volume was found stagnant at gas flow rates of 28–84 L/h.

Research from Kjellstrand [28] was carried out combining tracer tests, hydraulic modeling and full-scale implementation to study hydraulic behavior in an activated sludge tank. Poor use of reactor volume was identified by using the invasive tracer method. Based on the results of the tracer tests, the hydraulic situation was quantified using a compartment model. The identified short circuiting stream was corrected with measures using CFD for virtual prototyping.

CFD was used by Maier to identify shortcomings of existing BGP and to develop proposals for new facilities by evaluating the flow field in the digester and the resulting mixing characteristics. Six slowly rotating mixing devices positioned in even distribution along the perimeter of a circumferential main digester proved to be the best setup [29].

Brehmer [8,30] combined CFD with experimental methods and showed on a laboratory scale with xanthan fluid that incorrect positioning of submersible mixers can lead to considerable stagnation zones and to a collapse of the bulk flow. In this respect, experimental setup numerical fluid flow simulations showed that a correspondence of agitators could not be achieved through an increase in jet range by raising the propeller speed. He found that the pseudoplastic flow patterns of fermenting substrates tend to build caverns around the mixers, leading to an expansion of the jet stream. For better correspondence between agitators and an increase of agitated volume, he suggested installing the submersible mixers towards the center of the digester to shorten the distance between the agitators. The positioning and geometry of the agitator, as well as the substrate composition and its rheology, influence the mixing characteristics and the mixed volume of the digester, as well as the jet width of the agitators. He concluded that based on the gained knowledge, no rules for mixing intervals and mixing duration can be derived yet, but a better understanding of the process could be achieved [30].

Process tomography was applied by Jobst [31] on a laboratory scale for procedural and energetic optimization of mixing and stirring processes in BGP. With this method, the mixing and flow processes of opaque and fibrous multi-phase systems, with consideration of the physical, chemical, granulometric and rheological characteristics, can be visualized. The results show that the active mixed reactor volume reaches from 60% to 85%. It can be concluded that in practice, the calculation of the dimensioning of the digesters by the loading rate is exceeded and that in digesters, great variations of the local distribution can be found. To obtain sufficient mixing, a minimum shear induced by the agitator is needed but an increase in shear does not necessarily lead to an improvement in mixing quality [32].

Biologically less-active or even dead zones in biogas digesters are also described by other authors. Vesvikar [3] studied visualization of flow pattern and hydrodynamic parameters of a mimic airlift loop anaerobic reactor with the help of CFD and evaluated these results with CARPT. In terms of flow pattern, location of dead zones and trends of velocity profiles, the CFD predations showed very good qualitative comparison with the experimental data, but the experimental velocity data could not be matched accurately with the CFD simulations. He found zones with no-flow or very low velocities in 11%–58.3% of the different digester configurations and classified them as dead or stagnant zones that reduce the effective reactor volume. A degradation of performance in the digester is described due to an increase in pH and temperature in non-mixed regions. Wu [21] explored non-Newtonian fluid flow of manure in anaerobic lab, scale-up and pilot-scale digesters with CFD simulations and described 14%–16% of the digester volume as dead zones.

1.4. Conclusions for This Study

Agitation accounts for approximately 50% of electric energy consumption in agricultural BGP fed with energy crops [15], but in practice, less is known about the selection of adequate mixing solutions. A lack of adequate mixing will lead to incomplete stabilization of raw sludge, inefficient methane yield and a system overdesign to compensate for the loss of digester volume and in the end, to excessive capital costs and increases in operating expenses [32].

Although much research is currently conducted in this field and new methods like CFD are used, it must be stated that all methods are still limited either in extent, e.g., on very short real-time simulation time of approximately 60 s [33], or incorrect assumptions regarding rheological properties, e.g., no varying viscosity, no different fiber length, lack of biogas or different temperature gradients of the fermenting substrate [8]. Furthermore, research is mostly based on laboratory scale work, which does not reflect the characteristics and large-scale effects of full-scale biogas production. Despite the rising numbers of published papers, there is a general lack of knowledge about the quality of stirring in full-scale biogas digesters.

Biogas production is a complex process resulting from incomplete anaerobic mineralization of biomass, carried out in four steps in single-phase BGP [34]. Organic acids formed in the hydrolysis and acidogenesis are intermediates of the biological process and can be described as nutrients for the microbes in the acetogenesis and methanogenesis.

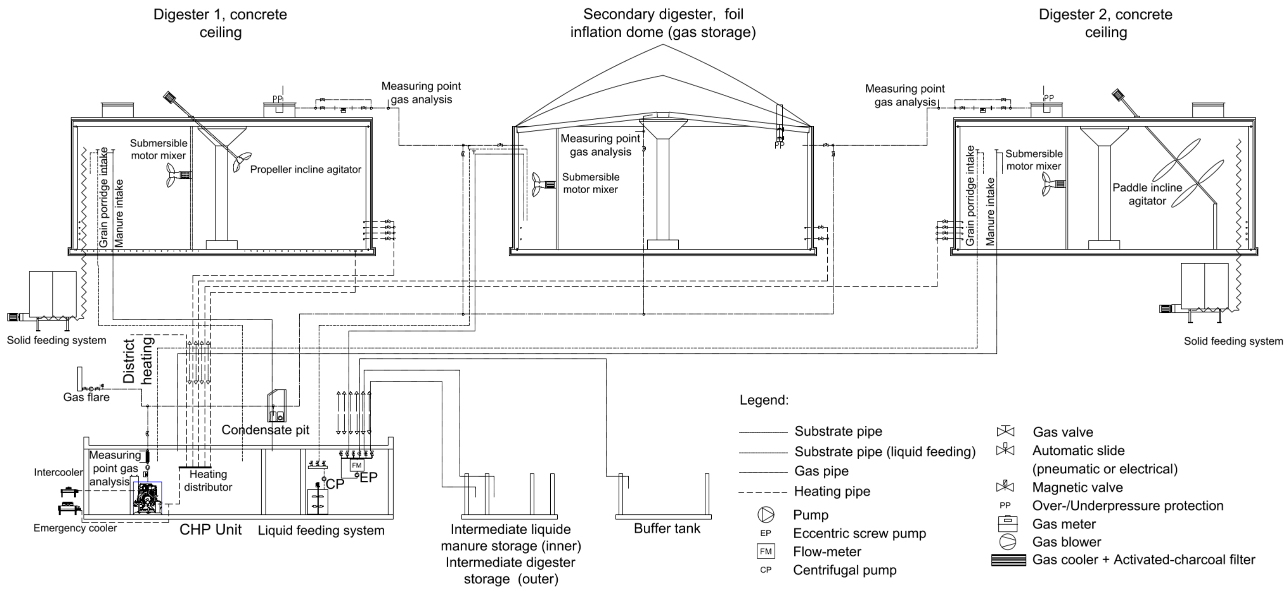
For this study, we conclude that in cases of biological inactive zones, caused by inadequate mixing layout, intermediates will be found unevenly distributed across the digester. An invasive method was chosen to prove the hypothesis that in full-scale research, the agitator type and setup influence the distribution of nutrients and DM in the fermenting substrate. Furthermore, the hypothesis is stated that at equal nutrient distribution, electric energy can be conserved by choosing the optimal equipment. These hypotheses were tested at the full-scale research BGP "Unterer Lindenhof" of Hohenheim University. The specific objectives of this study were:

- Development of an invasive system for spatial resolved sampling in a full-scale biogas digester;
- Studying the effect of stirring with different agitator units on nutrient distribution in the biogas digester.

2. Material and Methods

The research BGP of Hohenheim University is located at the "Lindenhof" agricultural research estate in Eningen unter Achalm (Germany). The substrates for the conversion process are solid and liquid manure from the 220 livestock units, as well as energy crops from 70 ha of arable land and grassland. The solid substrates are premixed in two different vertical mixer systems and fed in 48 equal batches a day into the digesters. Since all crops are harvested with a forage harvester and cut to a size of 10–65 mm, no additional pretreatment was applied. The BGP consists of two digesters, covered with insulated concrete, and a secondary digester, set up with a 227 m^3 foil inflation dome for gas storage. Every digester has a diameter of 14 m and a height of 6 m resulting in a maximum volume of 923 m^3 and is equipped with different heating systems (Figure 2).

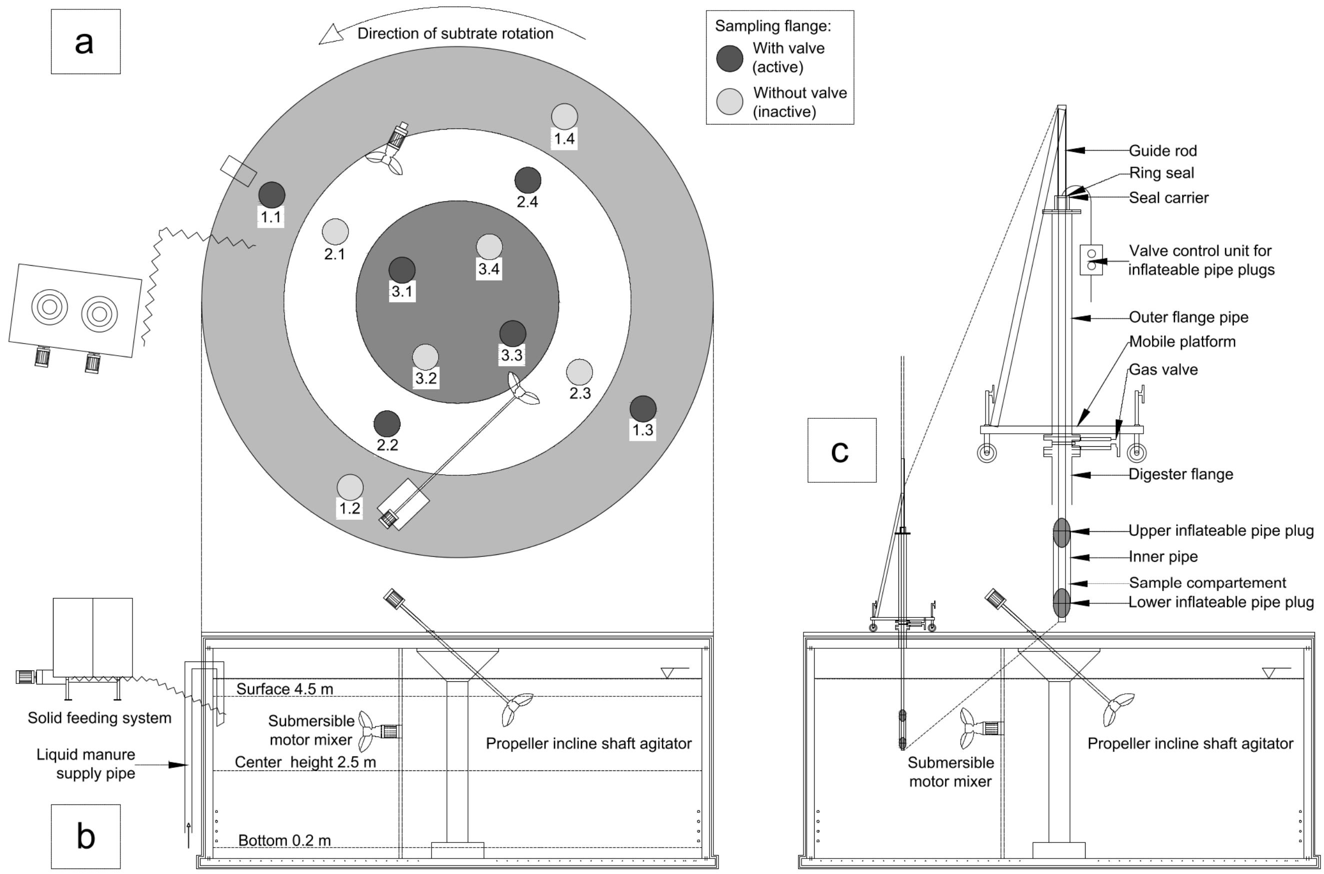
Figure 2. Flow scheme of the investigated research biogas plant (BGP).



All digesters are equipped with submersible motor mixers [35]. Furthermore, digester No. 1 is set up with a propeller incline shaft agitator, whereas digester No. 2 is fitted with a paddle incline agitator unit. Under mesophilic conditions, around 96 m^3/h [standard temperature and pressure (STP)] of biogas are produced, with a composition of approximately 52% CH_4, 48% CO_2 and 500 ppm hydrogen sulfide (H_2S). This allows operation of the combined heat and power (CHP)-unit (six cylinder gas engine MDE MB3066 L4, MTU onsite energy, Augsburg, Germany) at nominal 192 kW electrical and 214 kW thermal power as described by Naegele [36]. After transformation, the electrical power is fed into the local energy grid. The thermal power is primarily used for digester heating (40.5 °C) and the remaining energy is supplied to the thermal energy grid of the research station. The research BGP is equipped with a central plant control (CPC) unit for data collection, storage and evaluation. All substrates fed into the biogas process are weighed by the feeding systems or measured with a flow meter. The substrate temperatures in the fermenting substrate, gas quality and biogas temperature are measured continuously in every digester. Samples of input substrates and fermenting substrate were taken on a weekly basis and analyzed for DM, organic dry matter (oDM), pH, FOS/TAC, Ammonia (NH_4-N) and volatile fatty acids (VFA) content in the biogas laboratory of Hohenheim University. Furthermore, the electrical and thermal energy demand is measured for every key consumer unit [15]. The BGP is controlled and regulated via a programmable logic controller (PLC), which is joined to the CPC unit via a network. The CPC allows the operator to monitor and control the BGP over a graphic surface and automatically record, calculate, visualize and archive the data from all measuring units.

Intensive measurements in the years 2010–2011 at the research BGP of Hohenheim University were conducted to evaluate the effect of agitation technology on nutrient distribution within the framework of the research project "Intensive Measuring Program." Hereto digester 1 was chosen for the experiment and set up with 12 probe sampling holes installed crosswise in the concrete roof with a distance of 1.75 m from the digester wall to the outer ring, 3.3 m to the center ring and 3.75 m to inner ring. Six of the sampling holes are fitted with gas valves. The position and numeration of the sampling holes are given in Figure 3a. Figure 3a,b shows furthermore the sampling holes chosen and fitted with gas valves, as well as the heights chosen for sampling. The samples are taken in three different heights (measured from the digester floor) named bottom (0.2 m), center height (2.5 m) and surface (4.5 m).

Figure 3. Plan view on digester one with probe: (**a**) sampling points and (**b**) sampling heights; (**c**) Represents the probe sampling system on the digester, enlarged and provided with additional technical information.



The samples were taken with a new probe sampling system. This innovative experimental apparatus (Figure 3c) for invasive sampling from the top of the digester is unique on a practical BGP. It is designed to take samples through the gas-phase right into the fermenting substrate. Therefore, special safety precautions were taken into consideration, to ensure overall safety of the personnel and to reduce emissions during sample collection. A mobile platform allows movement of the sampling system to different probe sampling holes. The sampler consists of a pipe-in-pipe system that can be moved with a six meter guide rod. For sample collection, the outer pipe is fitted on the gas valve of a probe hole and secured with a gas seal. The inner pipe contains two pipe plugs. Inflated with compressed air, these valves seal the sample compartment. After the gas valve is fitted, the digester flange is opened and the sealed sample compartment is inserted into the digestate. Reaching the desired height, the lower inflatable pipe plug is deflated via the valve control and the substrate enters the filling chamber. In a second step the upper inflatable pipe plug is opened to guarantee that the filling chamber is completely filled with digestate. To encase the sample, both inflatable pipe plugs are inflated again. Afterwards, the sample compartment is pulled out of the digester and the gas valve is closed. After unscrewing the outer pipe from the gas valve, the sample is released into a box.

The samples are cooled immediately in liquid nitrogen to a temperature below 10 °C. Then the samples are homogenized with an electric cutter (Robot Coupe, Vincennes Cedex, France) for a period of 1 min. The probe sampling system is rinsed with water after every sample collection. The samples are deep frozen until analysis of the VFA content with a gas chromatograph (Varian, Agilent Technologies Inc., South Taft, CO, USA) and DM according to VDI 4630 (The Association of German Engineers, Düsseldorf, Germany).

In the experimental period, two agitation systems, a submersible motor mixer and a propeller incline agitator were tested. The submersible motor mixer is directly driven by an electric motor and the incline propeller agitator is driven via a frequency converted electric motor for energetic speed control at 60% of its maximum power. Both systems can be run separately and simultaneously. During the experiment, a mixing time of one minute prior and two minutes post feeding was set. The substrate was supplied to the digester every 30 min. Permanent mixing during the feeding process was carried out. The agitator positions (Figure 3) stayed unchanged during the experimental period.

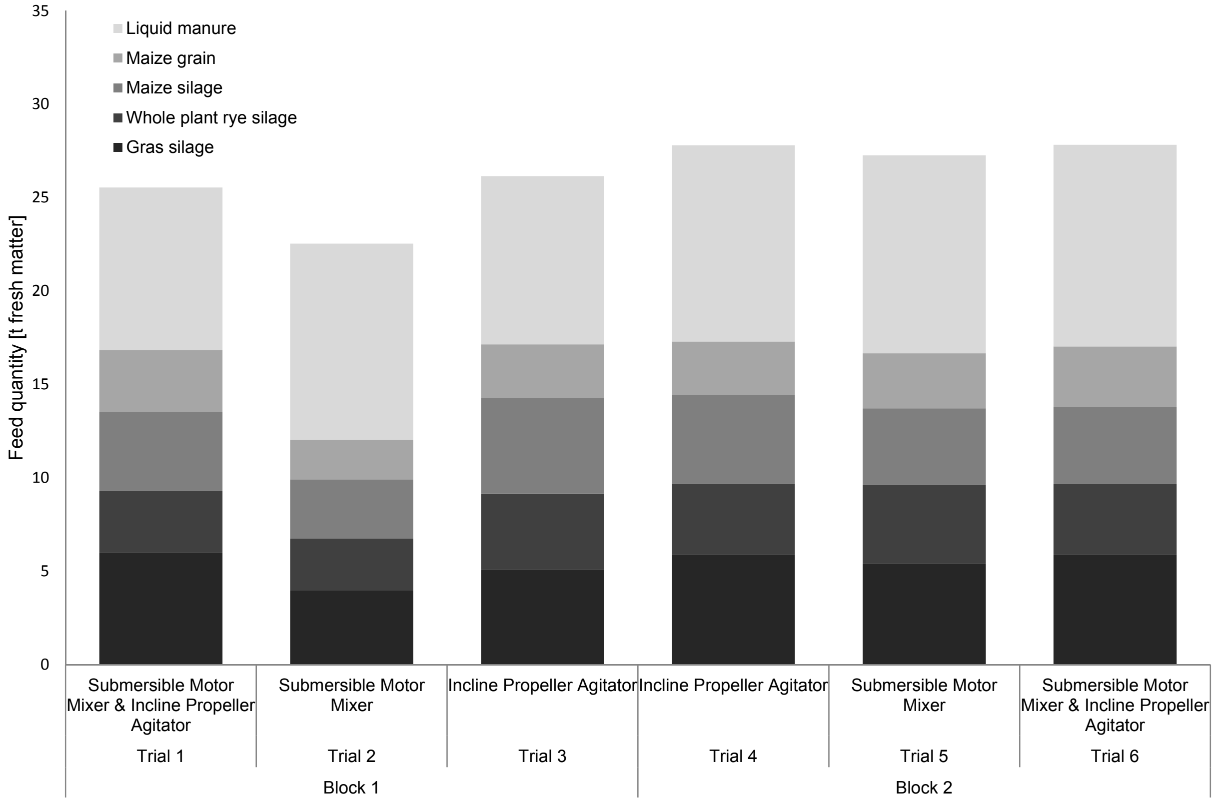
Extensive investigations were carried out prior to the experiments in order to determine the grade of homogenization, cooling, time requirement for probe sampling and handling of the sampling unit, confirming the robustness of the equipment and applicability. The experimental period began on 2 March 2011and lasted until 25 March 2011. It was chosen to test three different agitation setups with two block replications over six measurement periods with a total number of 90 samples. Every period started with an equalizing day on which both agitators were run for 6 h to ensure that the substrate was equally distributed. On the following two days, the agitators were run in the test regime every 30 min, along with the feeding of the digester. The third day was the sampling day on which samples from five sampling holes at three different heights each were taken randomly. The sampling day was followed again by an equalizing day and two days of agitating in the following setup. The samples were taken in between the feeding processes. The data received from the laboratory were processed with the statistical software SAS (SAS Institute Inc., Cary, NC, USA) using a variance analysis and comparison of the means.

3. Results and Discussion

3.1. Feed Intake

As presented in Figure 4, Digester 1 was fed with 22.5–27.8 t of substrate per three days trial time. On average, 26.2 t of substrate were fed into the digester with a share of 38.43% of liquid manure, 20.38% grass silage, 16.22% maize silage, 13.96% whole plant rye silage and 11.09% ground maize grain. The feed supply resulted in a loading rate of 2.2 kg oDM/m^3 × day at an almost even feed supply. Due to a temporary breakdown of the solid feeding system during Trial 2 the feed supply was 3.7 t lower than the mean value for all experimental periods.

Figure 4. Feed supply and proportioning during the three days lasting trial periods.



3.2. Distribution of DM

The results show that the DM was equally distributed in the digester throughout the experimental period and did not show any significant difference. According to Tables 1 and 2, the variance is evenly distributed and no statistical outliers or aggregations could be detected. None of the fixed effects (Agitator type, Position and Height of the sample) had a significant influence on the distribution. The significant influence of the effect block cannot be precisely interpreted. It can be assumed that the blocks differ in loading rate due to a minimal increase in Block 2 affecting the DM content. The block effects are found as errors in the model for DM content and acetic acid. The DM content in the fermenting substrate over the measured period was 13.25% ± 0.5%.

Table 1. Type 3 tests of the fixed effects of dry matter (DM) content on the full model *alpha* = 5%.

Effect	Degrees of freedom numerator	Degrees of freedom denominator	*F*-Statistic	*Pr* > *F*
Block	1	9	28.18	0.0005 ***
Block × Agitator	2	9	1.65	0.2455 ns
Agitator	2	9	0.19	0.8271 ns
Position	5	9	1.29	0.3481 ns
Height	2	44	1.38	0.2611 ns
Position × Height	10	44	1.08	0.3969 ns
Agitator × Position	10	9	0.52	0.8406 ns
Agitator × Height	4	44	0.45	0.7711 ns

***: $p \leq 0.001$, highly significant.

Table 2. Type 3 tests of fixed effects of DM content on the reduced model.

Effect	Degrees of freedom numerator	Degrees of freedom denominator	*F*-Statistic	*Pr* > *F*
Block	1	19	44.05	<0.0001 ***
Block × Agitator	2	19	5.21	0.0157 *
Agitator	2	19	0.42	0.6600 ns
Position	5	19	1.70	0.1841 ns
Height	2	58	1.42	0.2489 ns

***: $p \leq 0.001$, highly significant; *: $0.01 < p \leq 0.05$, less significant.

The significance test showed that DM is evenly distributed in the digester. A reason for that may be the high frequency of mixing the substrate every 30 min while substrate was fed to the digester. This short time span in between mixing may prevent DM segregation. It can be concluded that at such high mixing frequencies, the agitator type does not have a statistically verifiable effect. A mixing frequency of every 30 min is a common procedure in agricultural BGP in Germany, therefore, this setup was chosen. However, we would like to recommend investigating the effects of lower mixing frequencies on intermediate distribution as the energy saving potential would be higher in this case. A segregation of DM could only be measured within a few hours after the agitation was stopped during additional tests. Kaparaju [27] reported that stratification of solids occurred within a 2 h mixer-blocking period ("non-stirring interval"). In our study, DM content was found to be lowest on the bottom with increasing values towards the surface. On the contrary, Kaparaju [27] found the highest volatile solid content in the upper and lower part of the digester and lowest solids content in the middle layer. The statistical analysis of the measured parameters showed that the distribution of DM in the digester is not affected by the type of the agitator at high agitation frequencies.

3.3. Distribution of Acetic Acid

Further investigations showed that the fatty acid concentrations did distribute independently from the DM content. In Tables 3 and 4, acetic acid is chosen in representation of all analyzed fatty acids as all others were measured below the limit of detection. A significant influence of the fixed effects agitator, position and height could be proved with the full and reduced model. It was found that the acetic acid concentrations differentiated depending on the measuring points, measuring height and agitation setup. A significant correlation of block and block × agitator was found.

The results of comparisons of means are presented in Table 5 regarding the distribution of acetic acid in position, height and agitator setup. The biological process showed high stability during the experimental period, hence the values for acetic acid did not exceed 1 g/kg. It was found that there was an uneven distribution of acetic acid in the digester. The highest acetic acid value was found at measuring Point 1.1 close to the solid substrate feeding system. Values measured close to the agitators, measuring Points 2.2 and 2.4 showed a significant difference to the measuring Point 1.1. The results show that on the opposite side of the solid substrate feeding system, lower acetic acid values were measured. These differences may be explained by the fact that close to the solid substrate feeding system, the degradation is higher and therefore more intermediates are found. The farther the measurement point is from the feeding system the more diluted the nutrients become. This fact can be interpreted by uneven distribution through the agitators. Regarding the heights, the distribution of fatty acids showed the highest concentration on the bottom (0.68 g/kg) of the digester. The lowest value (0.56 g/kg) was found at the center of the heights and a medium level (0.59 g/kg) underneath the surface. Such different quantitative distributions, with the lowest value in the middle and higher values in the upper and lower part of the digester were presented by Kaparaju [27] for volatile solids.

Table 3. Type 3 tests of the fixed effects of acetic acid content on the full model alpha = 5%.

Effect	**Degrees of freedom numerator**	**Degrees of freedom denominator**	***F*-Statistic**	***Pr* > *F***
Block	1	9	7.36	0.0239 *
Block × Agitator	2	9	4.56	0.0428 *
Agitator	2	11.5	10.90	0.0022 **
Position	5	11.5	4.08	0.0226 *
Height	2	19	5.25	0.0153 *
Position × Height	10	19.5	1.93	0.1030 ns
Agitator × Position	10	11.3	1.98	0.1366 ns
Agitator × Height	4	20.2	0.63	0.6434 ns

*: $0.01 < p \leq 0.05$, less significant; **: $0.001 < p \leq 0.01$, significant.

Table 4. Type 3 tests of fixed effects of acetic acid content on the reduced model.

Effect	**Degrees of freedom numerator**	**Degrees of freedom denominator**	***F*-Statistic**	***Pr* > *F***
Block	1	12.7	5.73	0.0329*
Block × Agitator	2	12.7	5.92	0.0153*
Agitator	2	23.9	7.18	0.0036**
Position	5	24.1	3.30	0.0208*
Height	2	28.2	4.29	0.0236*

*: $0.01 < p \leq 0.05$, less significant; **: $0.001 < p \leq 0.01$, significant.

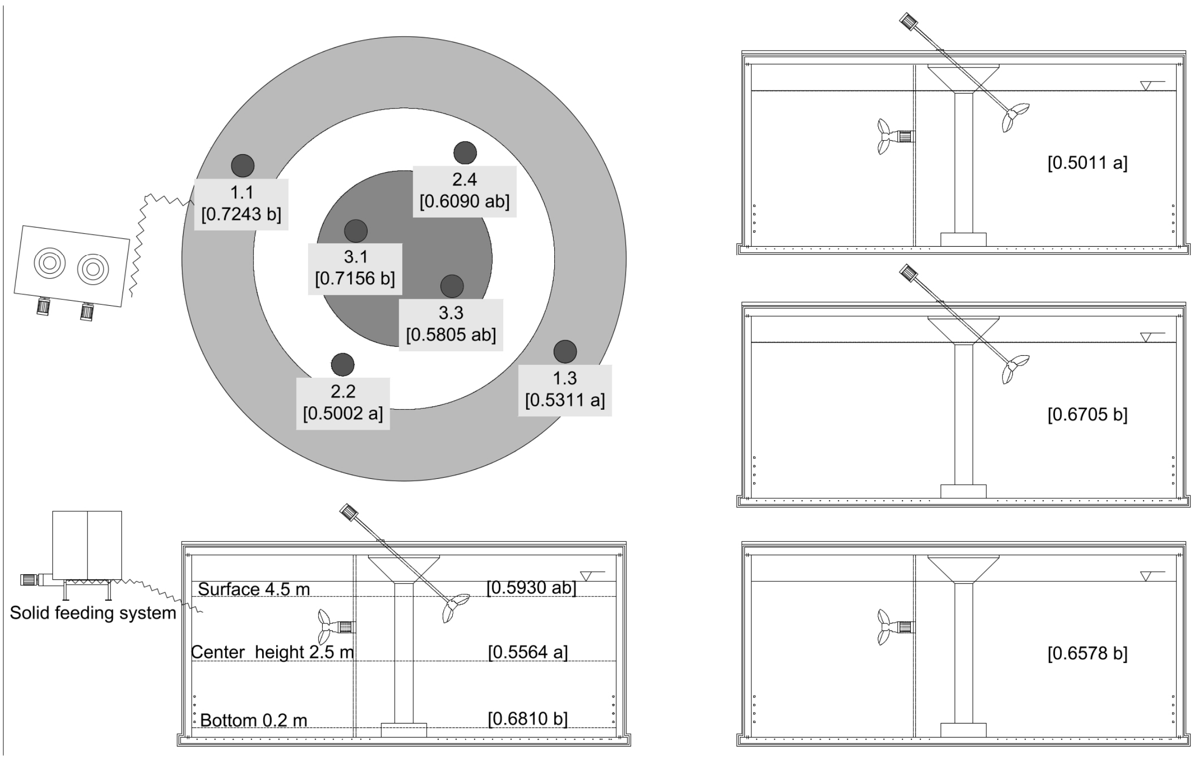
Regarding the influence of the agitator type and regime, the lowest acetic acid value (0.50 g/kg) was found by stirring with both agitators (Table 5). This value was significantly different from the higher values found by stirring with only the incline propeller shaft agitator (0.67 g/kg) or the submersible motor mixer (0.66 g/kg). No measurable correlation was found for gas production and the lower concentration of acetic acid, as this may indicate better degradation and therefore higher biogas production. It is not yet possible to measure the gas production of the digester with sufficient precision. Currently, there is a lack of adequate gas quantity measurement equipment for full-scale digesters, as the gas is wet, corrosive, has extremely low pressure and a flow rate ranging from almost 0 to 60 m^3 biogas per hour. Figure 5 highlights the results from Table 5. It shows a comparison of means of acetic acid concentration with different letters indicating the significant difference between the estimated values. The lower acetic acid value found by agitating with both devices may be a cause of a better nutrient distribution in the digester resulting in better degradation of VFA.

Table 5. Comparison of means of acetic acid with different letters showing the significant difference between the means of estimated values.

Effect	Agitator	Position	Height	Estimated means transformed	Mean raw data (g/kg)	Standard error	df	*t*-value
Height	-	-	Center	−0.2761 a	0.5564	0.02412	43.3	−11.45
Height	-	-	Surface	−0.2477 ab	0.5930	0.02412	43.3	−10.27
Height	-	-	Bottom	−0.1890 b	0.6810	0.02412	43.3	−7.84
Position	-	1.1	-	−0.1500 b	0.7243	0.04126	24.1	−3.63
Position	-	1.3	-	−0.3233 a	0.5311	0.04126	24.1	−7.84
Position	-	2.2	-	−0.3034 a	0.5002	0.04126	24.1	−7.35
Position	-	2.4	-	−0.2501 ab	0.6090	0.04126	24.1	−6.06
Position	-	3.1	-	−0.1446 b	0.7156	0.04126	24.1	−3.51
Position	-	3.3	-	−0.2544 ab	0.5805	0.04126	24.1	−6.17
Agitator	Incline propeller agitator	-	-	−0.1891 b	0.6705	0.02899	24	−6.52
Agitator	Submersible motor mixer	-	-	−0.1962 b	0.6578	0.02899	24	−6.77
Agitator	Submersible motor mixer & Incline propeller shaft agitator	-	-	−0.3276 a	0.5011	0.02899	24	−11.30

Different letters (a & b) indicate the effects with statistical difference (*alpha* = 5%).

Figure 5. Schematic drawing of the results of comparison of the significance test of acetic acid (values in g/kg).

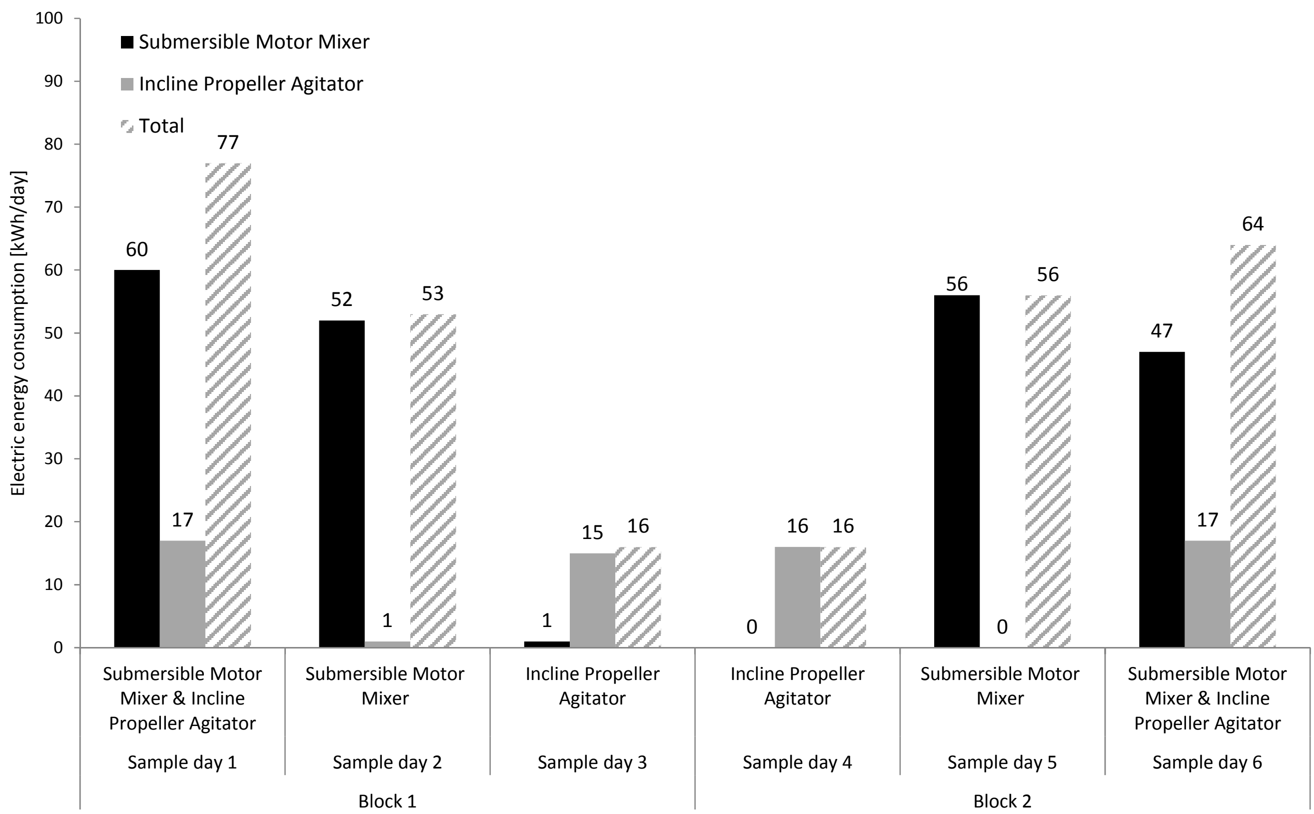


Laboratory scale research or simulation results from and Jobst, show that 15%–25% of the digester volume is not actively used [3,31]. Montheight and Stephenson found as much as 77% of the digester volume is dead zones [18]. In our study on a full-scale digester, no evidence was found that prove those results. Dead zones, as defined, are zones with no organic matter degradation leading to an accumulation of organic matter or zones with no supply of organic matter indicated by extremely low dry-matter contents. Furthermore, dead zones are areas with a limited degradation of organic matter by microorganisms so that no intermediary products can be detected. The results of our study show that DM and VFA were almost evenly distributed in height and position of the digester. Therefore, we conclude that there is no indication of a dead zone in the examined digester under our experimental layout. It seems that in practice, more digester volume is actively used than described by previous authors [3,31].

3.4. Electric Energy Consumption of Agitators and Mixing Quality

In addition to the biological parameters of the fermenting substrate, the electric energy consumption of the agitators was measured during the study. In Figure 6, the results for the days of sample taking are presented. Most of the energy was consumed when both agitators were used in combination as on sample day one and six ranging from 77 kW h/d to 64 kW h/d. The setup with the submersible motor mixer consumed 52 kW h/d at trial day two and 56 kW h/d at trial day five—an almost constant amount of electric energy. The incline propeller agitator setup used a constant amount of 15 kW h/d and 16 kW h/d at trial day three and five.

Figure 6. Electric energy consumption of the agitators according to the agitator setup for all sample days.



The results show that by using the submersible motor mixer alone, the electric energy demand could be reduced by 32.5% and 12.5% compared to the standard setup using both agitators. A reduction of 79% and 75% could be achieved by using the incline propeller mixer alone. By comparing the submersible motor mixer with the incline propeller agitator, the results show a consumption of 69% and 71% lower. The highest electric energy demand was measured using the combination of both agitators, but as a result, the lowest nutrients content in the fermenting substrate was observed. The submersible motor mixer and the incline agitator differed widely in their electric energy consumption but did not show a significant difference in mixing quality described by the nutrient distribution.

Taking into consideration that the mixing quality of the three setups is almost equal, but the energy demands differ widely, a savings of up to 70% of electric energy could be achieved by using the incline agitator in favor of the submersible motor mixer. For the experimental setup and the specific digestate characteristics, we conclude that the slow-moving incline shaft agitator fitted with large propellers is the most suitable and efficient technique. Applying those results to earlier measurements from Naegele [15] showing that up to 51% of the total electric energy consumption of a BGP accounts for agitation, the vast savings potential of those units becomes obvious. It can be highly recommended to adapt the mixing technique to the specific digestate characteristics to increase the mixing quality and to reduce the electric energy consumption of BGP.

4. Summary and Conclusions

An invasive sampling method was applied at a full-scale biogas research BGP to study the efficiency of different agitation systems by measuring the nutrient distribution and DM content in the fermenting substrate, consisting of renewable energy crops and animal manure. For the first time in biogas studies, samples were taken from a full-scale biogas digester and combined with technical process parameters e.g., electric energy consumption for evaluation. Unique and vital results were obtained showing significant differences to laboratory-scale studies and simulations.

The stirring intervals in this study were chosen as they are often found at full-scale BGP. No difference in distribution was found by measuring the DM. However there are differences found in nutrient distribution depending on the investigated agitation system, as well as position and height of the sample. Through all experiments, the highest acetic acid concentration was found on the bottom of the digester and the lowest was measured when both agitation systems were used. Samples taken closer to the solid substrate feeding system showed higher acetic acid values than samples taken on the opposite side. The quality of stirring with the provided agitators can be assumed as sufficient for this specific process. The data show that all three agitator setups differ significantly in their electric energy consumption. The optimum substrate metabolism is achieved with both agitators, due to the fact that the fatty acid concentrations were measured at the lowest level but a considerably higher electric energy input has to be accepted. In this study, an energy saving potential of up to 70% was measured by adapting the mixing system to the specific characteristics of the fermenting substrate.

Despite the first promising results gained with the developed innovative sampling method, it is necessary to conduct further measurements. In particular, a comparison of laboratory results from CFD or CT for the specific substrate and technical setup of the research BGP with the full-scale results from this study will provide a better understanding of the process. Hereto the research BGP offers a wide range of new approaches.

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Conflicts of Interest

The authors declare no conflict of interest.

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