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EFFECT OF MIXING REGIMES AND IMPELLER GEOMETRY ON BIOGAS YIELD IN AN ANAEROBIC DIGESTER

Booklet of PhD Thesis

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Nomenclature

ρ	Density [kg m^{-3}]	P	Power [W]
γ_a'	Average shear rate [s^{-1}]	τ	Shear stress [Pa]
R_e	Reynolds number	μ_a	Apparent viscosity [Pa s^{-1}]
K	Consistency index	n	Power number
k_s	Otto-Metzner constant	N	Revolution per min [rpm]
N_P	Power number	C	Inter impeller spacing
D	Diameter of impeller	T	Diameter of tank
l	Litre		

AD	Anaerobic digestion	RT	Rushton impeller
TS	Total solids	COD	Chemical oxygen demand
OTS	Organic total solids	BPR	Biogas production rate
SS	Suspended solids	VFA	Volatile fatty acids
TVS	Total volatile solids	HRT	Hydraulic retention time
C/N	Carbon nitrogen ratio	OLR	Organic loading rate

1 INTRODUCTION

Energy recovery from biomass through anaerobic digestion (AD) is one of the most trending sources of renewable energy due to its very low carbon footprint. The AD process is a series of biological processes aided by a variety of microorganisms, which converts complex organic matter to biogas. Biogas, essentially a 40-70% CH_4 and 60-30% CO_2 flammable gas mixture, can be directly used for various purposes, such as cooking, power generation, and heating or as vehicle fuel following additional purification. The efficiency of the AD process depends on several external and internal factors, such as physical and chemical properties of the substrate, C/N ratio, temperature, pH, OLR, HRT, mixing and hydrodynamics of the digester. From all the above, mixing is one of the most prominent factors that determines the efficiency of an anaerobic digester. Studies reveal that nearly 44% of biogas plant failures are caused due to flaws in mixing[1]. Adequate mixing refers to the movement of particles between various parts of a whole mass. It is interesting to note that the optimization of mixing in anaerobic digesters is quite challenging because the AD process involves solid-gas-liquid phases along with microbes, which are highly sensitive to hydrodynamic shear and mixing conditions. The detrimental impacts of inadequate mixing in an anaerobic digester are observed as abortive methane yield, defective stabilization, sedimentation, and floating layers, whereas, adequate mixing helps the uniform distribution of nutrients to the microorganisms, avoids pH and temperature gradients, avoids the formation of scum, floating layers and dead zones. It should also provide favourable shear conditions necessary to disperse the bubbles, and droplets and also prevent disruption of microbial flocs [2]. Effect of mixing is highly significant when the digester is operated at higher solid content (>10%) and lower HRT (15-20 days) [3].

Mixing in an anaerobic digester can be performed by various modes, such as mechanical mixing, slurry recirculation, and biogas circulation. Mechanical mixing is preferred due to lower power consumption and higher biogas production as compared to others. An extensive number of previous studies were devoted to studying the effects of mixing intensity, mixing time, shear stresses, and design of digester and mixing equipment on biogas production[4–6]. Factors directly affecting the mixing efficiency in the digester include impeller design, bottom clearance, inter impeller clearance, impeller eccentricity, and rheology of the slurry. Previous studies established that an increase in the rotational speed of impellers can help in avoiding the development of dead zones, nutrient segregations, and non-uniformity of the dispersed phase, but, on the other hand, high mixing speeds can degrade the productivity of bacteria in the digestion process because these microorganisms are very sensitive to high shear stresses and also increase the overall operational cost[7]. It is a considerable challenge to achieve homogeneity for highly viscous slurry at minimum mixing intensity shear stresses.

Various impeller geometries and digester designs have been studied [3][8]. For instance, Lebranchu et al. [9] demonstrated that mixing with HR impeller produced 50% more biogas relative to a single RT impeller due to better distribution of shear and viscosity in the entire 2-liter digester during laminar flow. In another study [10] Marine impeller, rushton turbine and anchor impellers were compared to analyse the effectiveness of mixing of olive mill waste water in a lab-scale digester. The results demonstrated that the MI impeller provided good homogenization in the digester due to both axial and radial movement of slurry. The standard single impeller for mixing the slurry in an anaerobic digester is criticized due to the uneven distribution of hydrodynamic shear, high shear stresses near the blades, and the formation of dead zones near the walls. Trad et al.[11] have found that the flow patterns of the slurry were highly affected by varying the inter impeller and off bottom clearances. It is a great challenge to draw a general consensus about the optimum range of mixing intensity and time due to variation in various other physical factors such as rheological properties of slurry, geometry of the digester and impeller and feeding rates. Laminar flow paddle impellers with a high D/T ratio can generate better results[12]. The slurry broth shows properties of pseudo plastic fluid, which is generally characterized by shear thinning behaviour[13].

Furthermore, apart from the geometrical aspect, the mixing intensity (impeller rotational speed) and mixing time (continuous or intermittent) are also very crucial factors, which determine the performance of an anaerobic digester. There is no benefit from the continuously mixed digester at higher intensities. Hoffman et al.[5] reported that a negative effect was observed on biogas production rate in a 4.5 liter unbaffled digester because microbial flocs were destroyed at 1500 rpm. Similar results were demonstrated by Fei Shen et al. [14] as high flow velocities above 0.5 m s^{-1} lowered the digester performance due to destruction of sludge structure and granules.

Studying the effects of mixing in an anaerobic digester requires a multidisciplinary approach because both digester hydrodynamics and the behaviour of micro-organisms need to be understood under varying shear stresses. According a study [3], the uniform distribution of the shear rate at low mixing intensity inside the active volume of digester is very crucial to enhance the efficiency of the digester and energy dissipation. Effective mixing relies on the appropriate level of shear rate being applied to the substrate for the time necessary to achieve a required level of homogeneity throughout the digester. Accordingly, the optimum design of an anaerobic digester must limit the intensity of shear while still providing adequate mixing and mass transfer. The most important aspect of the impeller mixing does not only rest on the average shear rate in the digester but on how uniformly it is distributed within the active volume of the digester. The scale-up of a lab-scale digester requires similarity between the systems, which refers to geometric, kinematics, and dynamic similarities[15]. Related publications proclaim controversies and uncertainties about the effect of mixing in the anaerobic digestion process. Therefore, further studies on this subject can provide more insight in better understanding on the mixing parameters in the anaerobic digester. Due to its high mixing efficiency and the unique feature of producing axial flow, the helical ribbon impeller is mostly used for mixing high viscosity fluids at industrial scale [16].

The aim of this study was to identify the miscellaneous effects of mixing at various mixing intensities on biogas production rates, ammonia and total volatile acids in an anaerobic digestion process by modelling a lab-scale digester using sewage sludge and pig manure as substrate. The work included the evaluation of lab scale digester under different shear rates and minimal intermittent mixing and enhances knowledge of the influence of mixing operation on the AD process. The study is undertaken for following objective:

- To perceive the optimum mixing intensity and mixing time for slurry in anaerobic digester to biogas production.
- Optimize the impeller geometry for mixing in an anaerobic digester.
- To analyse the effect of impeller geometry on the entire active volume of digester.
- To optimize the mixing in large scale anaerobic digesters to decrease the energy consumption for agitation and enhance overall efficiency.

2 MATERIALS AND METHODS

2.1 EXPERIMENTAL SETUP AND PROCEDURES

The experiments were carried out in 3 parallel single-stage continuously fed 5-liter lab-scale digesters with a head space of 1 litre, custom-made from stainless steel[17]. The digesters were run under identical operating conditions of temperature and mixing speeds for each set of experiments. The schematic 2-D diagram of the experimental setup is shown in Fig 1. The reactors are equipped with helical ribbon impellers on a single vertical shaft driven by a variable speed engine to achieve mixing. Table 1. presents the geometrical dimensions of the impeller. The key parameters (temperature, mixing speed, and pH) were automatically controlled by computer software. The digesters were named B1F1, B1F2 and B1F3 for reference. All impellers were operated by a single electric motor in order to maintain identical mixing conditions. Fig. 2 illustrates the geometry and location of the impeller. The digester is equipped with a 12 DC motor with all the controls to adjust the rpm of the agitator and power consumption. The temperature in the reactor was maintained by the circulation of hot water through stainless steel pipes inside the vessel from an electrically heated thermostatic water bath with an accuracy of ±0.5 °C. Three sets of parallel experiments were conducted to recognize the effect of varying shear rates on biogas production rates and methane content. The experiments lasted for 60 days, including two weeks of pre-run phase. The agitation rate was 10, 30, and 67 rpm and the impellers were turned on for a period of 5 min every hour.

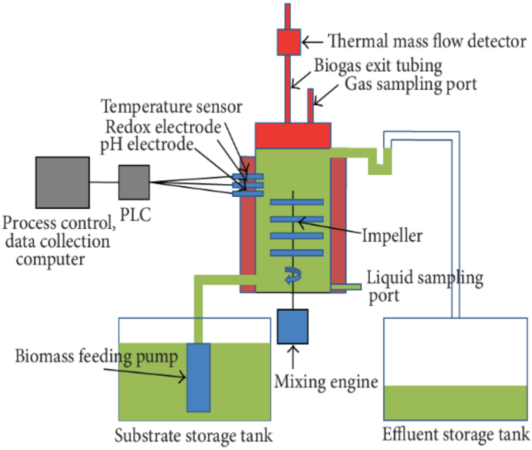


Figure 1. Schematic diagram of experimental setup.

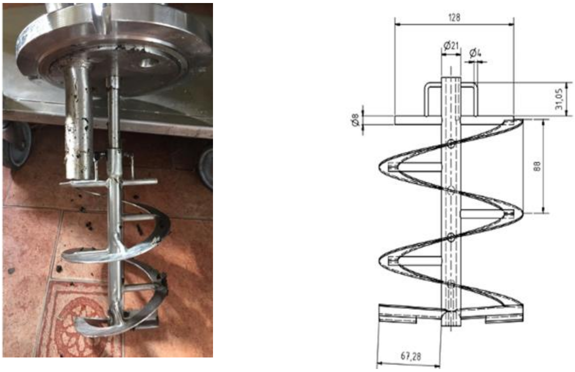


Figure 2. Representation of the geometry of the mixers inside the digesters

Table 1. Geometrical specifications of experimental setup.

Parameter	Dimensions [mm]
Diameter of tank (D)	260
Height of liquid (H)	232
Diameter of impeller (*d*)	150
Height of blade (*h*)	15
Length of blade (L)	20
Off bottom clearance (C_1)	50
Inter impeller spacing (C_2)	88
C_1/d	0.9
C_2/d	1.2

2.2 INOCULUM FEEDING, SUBSTRATES AND SAMPLING

The digestate was collected from a commercial biogas plant in Szeged and stored at 4°C before the start of the experiment. The substrate consisted of a mixture of pig slurry (25% V/V) and ensilaged sweet sorghum (75% V/V). Fresh sweet sorghum was collected from plants and was chopped to a particle length of less than 5 mm and stored frozen at -20°C. The sorghum was stored at ambient temperature and mechanically pre-treated by a shredder pump. Sewage sludge for the lab-scale experiment was collected from a commercial biogas plant in Szeged to initiate the fermentation. The experiment was pre-run for at least 2 weeks to have a stable digestion process and constant biogas production.

Ultrapure nitrogen gas was used to replace the headspace at the beginning of the experiment. The digester was continuously fed with 5 gVS l^{-1} of cellulose every day. The digester was operated at a thermophilic temperature range (37°C) and HRT of 15 days. Various characteristics of sewage sludge are presented in Table 2. The TS content of the slurry was maintained at 4.28%. Digestate samples were collected from the bottom of the digester after mixing to achieve a homogenous sample.

Table 2. Characteristics of sewage sludge from wastewater treatment plant.

Parameter	Value range
TS (%)	4.28
SS (g l^{-1})	57.8±10.0
Total carbon (%)	46.2
TVS (g l^{-1})	87.6±3.4
COD (g l^{-1})	141±6.4
VFA (g l^{-1})	4.15±1.38
pH	8.6
ρ (kg m^{-3})	1068
HRT (d)	15

2.3 ANALYTICAL METHODS

Gas analysis

Gas volume was measured continuously by means of direct mass flow controllers (DMFC, Brooks Instruments) attached to each gas exit port. Biogas production was recorded every four hours by the software. Data collected from the digesters were stored in a computer system on line. Biogas composition was analyzed using gas chromatograph (6890N Net-work GC system, Agilent Technologies). A 250 µL gas sample was collected from the head space and injected into a gas chromatograph equipped with a 5 Å molecular sieve column (length 30 m, I.D. 0.53 megabore, film 23 µm) and a thermal conductivity detector.

Volatile fatty acids

Volatile acids were determined by HPLC (Hitachi Elite, equipped with an ICSep ICE-COREGEL 64H column and a refractive index detector L2490), under the following conditions: solvent 0.1 N H_2SO_4, flow rate of 0.8 mL min^{-1}, column temperature 50˚C, detector temperature 41˚C. 10 mL of sample was collected from each digester for analysis. The samples were centrifuged at 13,000 rpm for 10 min to separate the solid and liquid and then filtered through a 0.45 µm membrane. The samples were analysed every week.

TS and oTS content

The dry matter content was determined by drying the substrate at 105°C for 24 hours and measuring the residues. Further heating of this residue at 550°C in the oven until its weight did not alter gave the overall organic solid material.

Statistical analysis

Statistical analysis was performed in Microsoft Excel using Student's unpaired t-Test, with a two-tailed distribution and in PASS using a permutational multivariate analysis of variance (PERMANOVA). The t- test was performed in Microsoft excel to obtain *t* values. Tests were performed between the same digesters at different rpm, i.e, at F1R10, F1R30, F1R67. Further, the tests were also undertaken between all three digesters at one particular rpm, i.e F1R30, F2R30, F3R30 and so on.

3 MIXING OPERATION

3.1 MECHANICAL MIXING

Mechanical mixing is preferred for mixing operations in an anaerobic digester as it is the most effective mode according to the literature. During mixing the biomass is exposed to varying grades of hydrodynamic shear. In addition, granulation, which is the main technology for high rate reactors to maintain high cell density, is dependent on hydrodynamic shear. Many studies have been published dealing with the impact of mixing speed and impeller geometries on biogas production, focusing on the design, position, and configurations of the impellers[18–21]. In this study, a helical ribbon impeller of diameter 150 mm and height 232 mm; fitted, hermetically sealed and mounted inside a coupler shaft with a DC motor is used for mixing in digester.

3.2 RHEOLOGY

Rheological study of the slurry for an anaerobic digestion process is very important aspect in designing the digester, mixing and transport equipment. From the literature data (Table. 3) it is confirmed that if TS>2.5% then the slurry possesses non-Newtonian shear thinning behaviour and thixotropic characteristics in the laminar regime (approximately < 10-100). Fig 3. represents rheological behaviour of various fluids.

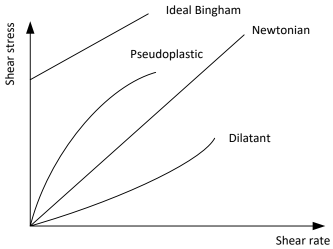


Figure 3. Different types of fluids and their behaviour with respect to shear rates.

Table 3. Rheological properties of substrate.

Temperature (^{o}C)	**K** (Pa s^{n})	*n*	*y* (s^{-1})	*η (Pa s)*	*ρ*
37	0.19	0.56	0.237	0.01-0.03	1000.78

For this instance, the power law model can be proposed to calculate the apparent viscosity and shear rate.

$$\mu_a = K \cdot \gamma_a^{\prime\,(n-1)} \tag{1}$$

For a non-Newtonian shear thinning the value of n is always less than 1. For this instance, the rheological data for the waste water sludge is taken from the literature presented in Table 3 [22]. The average shear rate inside the vessel can be calculated as per the equation

$$\gamma_a^{\prime} = k_s \cdot N \tag{2}$$

Here k_s is Otto-Metzer constant which is directly associated with the impeller geometry. From the experimental measurements by Zhang et al. [23] value of k_s for helical ribbon impeller was k_s=34.8.

$$\tau = K \cdot \gamma_a^{\prime(n)} \tag{3}$$

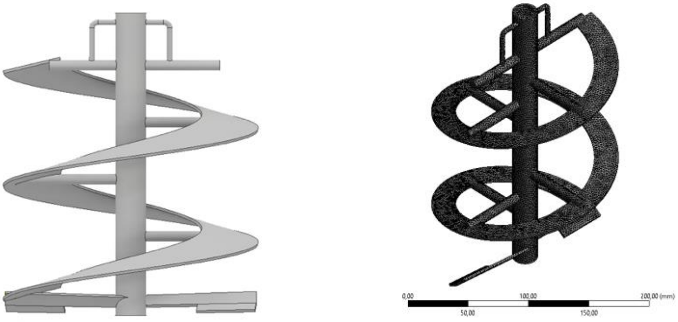
4 CFD ANALYSIS

Computational fluid dynamics (CFD) is the application of computer models to simulate flow patterns utilizing basic equations, boundary conditions, and flow rates in order to predict the outcomes of an experimental system. The CFD simulation in this study is performed using ANSYS 2021. For simulation, transient simulation is used to determine the velocity distribution in the fermenter. The isometric view of grid generated is shown in Fig 4. The turbulence model k-ω is used for the simulations. The time step was constant, the value was 10^{-5} s. FLUENT was setup to iterate until the convergence parameters were satisfied, to reach the convergence, in all step have maximum 50 inner iteration step per time step based on the 2945850 cells.

In this study a single-phase model is used to reduce the simulation time. In this model, the solid particle containing liquid was considered as a homogenous phase with the density and viscosity values of the liquid-solid mixture. It should be noted that single-phase models are reliable when the percentages of the solid and fluid volumes coexisting in the container are approximately equal. Also, as the solid particles be finer and the difference in the densities of the two phases be less, application of a single-phase model would be more logical. The reason is that the mixture will be more homogenous, and its behaviour will approach that of mono-phase systems, in this state. In the simulated systems, densities of the solid and liquid phases are 998 kg m^{-3} and 1000 kg m^{-3}, respectively, and their volumetric percentages are 50%. In the CFD simulation, the mixture of slurries (substrate) was assumed to be incompressible and pseudo-plastic fluid. The power law model was used to describe the slurry rheological properties as mentioned in the previous section. The velocity profile was viewed, and the flow patterns were compared at various mixing speeds. The hydrodynamics of each agitation condition used experimentally were numerically simulated.

The volume-averaged velocity magnitudes were obtained as:

$$<\parallel u \parallel> = \frac{1}{V_L} \iiint_{V_L}^{1} \parallel u \parallel (V) dV \tag{4}$$



(a)

(b)

Figure 4. 2D geometry(a) of impeller and Isometric view (b) of the tetrahedron elements of the impeller.

5 RESULTS AND DISCUSSION

5.1 START-UP PHASE

Effective mixing relies on the appropriate level of shear rate being applied to the substrate for the time necessary to achieve the required level of homogeneity throughout the digester. Three parallel digesters were analysed that were operated at identical parameters to attain accuracy in overall process. The digesters were pre-run to obtain a stable digestion process and constant biogas production. The OLRs were set at 1 g l^{-1} for the entire experiment. It was observed that till the end of first two weeks of pre-run the operation of digesters became stable with 0.24-0.25 ml day^{-1} gas production. After the pre-run period of 15 days, the biogas production was constant and the VFA and alkalinity (FOS/TAC) ratio was recorded as 0.35, which is considered normal as it indicates that the digestion process was stable.

5.2 EFFECT OF MIXING INTENSITY ON BIOGAS PRODUCTION RATE

The findings of the experiments show that the mean biogas generation rates in the digester are closely connected to the mean hydrodynamic shear rate. All three digesters were seeded with 5 l of incubated manure substrate solution. For the first 14 days, the digesters were fed with 5 g of cellulose until the digestion process became stable. The cumulative biogas production by all three digesters is given in Fig 4. The agitation rate values selected for each phase were chosen a priori to obtain comparable mean and maximum shear stress values for each configuration, enabling a more rigorous comparison of the three systems. Each of them had its own distinctive character. Fig 4. clearly states the difference in biogas production under various stirring rates. All digesters exhibited comparable biogas production rates as slow agitation improved system stability through 1) reduced VFA accumulation from 7.872 g HAc/*l* as compared to 4.634 g HAc/*l*, 2) lower propionate content of 0.456 g/*l*, and 3) enhanced VFA to alkalinity ratio (α) to 0.3. As a result, the start-up of the digestion process was quite even and stable. During the first week there was negligible difference between the biogas production at all intermittent mixing intensities. It is therefore postulated that slow mixing helps to improve the stability and loading capacity of thermophilic digesters that treat substrates in the absence of an acclimatized seed. Similarly, Lin and Pearce [24] demonstrated that methane production was higher during intermittent mixing when compared to an unmixed digester and on other hand, a study by Tian et al.[25] proved that continuous mixing resulted in declined biogas production rates[25,26]. From day 15 to 31 during the minimum mixing speed of 10 rpm, lower biogas production was observed due to higher VFA's concentration and instabilities in the AD process. The mean biogas production per day during these two weeks was recorded as 2.622 m*l* d^{-1} and overall cumulative volume of biogas produced during this period was 43.5 L. From day 32 to 48 the rotational speed of the mixer was increased to 30 rpm. Under these operating conditions, the mean BPR was recorded as 2.85 *l* d^{-1} and the total biogas production under these conditions was 45.2 *l*. At both loading rates and shock rates the biogas production was higher at 67 rpm as a raise in rotational speed up to certain level is beneficial for decreasing the mixing time and enhancing heat, mass, nutrient homogeneity [27], efficient dispersion of metabolic waste, reduction on particle size due to shear forces, and improvement in hydrolysis process. The mean BPR and total volume at higher mixing were noted as 3.2 *l* d^{-1} and 52.5 *l* respectively. The results demonstrated that there was 15-18 % higher biogas production at 67 rpm as compared to the slower mixing speeds. Fig 5. represents the mean biogas production per day by all three digesters at various rotational speeds.

In fig 4. it can be clearly seen that all the three digesters (F1R67, F2R67, F3R67) at 67 rpm produced a higher amount of biogas as compared to 10 rpm and 30 rpm. This study therefore disagrees with the results demonstrated by Hoffmann et al. [5] where it was demonstrated that various mixing intensities (1500, 500, 250, 50 rpm) had no effect on the efficiency AD process. On the other hand, at higher mixing intensities, *Methanosarcina app*. and *M. concilii* were found abundant, which also supports the fact that mixing intensities provide a favourable environment for methanogens. Moreover, intermittent mixing did not destroy microbial flocs, which apparently gave positive results in long term performance of the digester. Shear rate was noted as 5.6, 17.4, 38 s^{-1} at 10, 30 and 67 rpm (Table 4) according to equation 2. The results show close proximity to the study by Jiankai et al. where proposed optimal values for shear rate were between 28 to 48 s^{-1}. Nevertheless, the same authors reported in another study that under a continuous mixing regime, the optimal shear rate should be 6.8 s^{-1} for maximum biogas production. We obtained quite similar results statically to the study by Lebranch et al.[9].

According to our study the hydrodynamic shear (γ_a') threshold is 39 s^{-1} which resulted in the highest biogas production without disruption of microbial flocs. Additionally, the small scale of the digester in a lab is insufficient to answer all the questions related to mass transfer and mixing efficiency that can be encountered in large scale biogas plants. For instance, for a large scale digester, the rotational speed of an impeller can be different to achieve homogenisation in terms of nutrient, temperature and distribution of fresh substrate [3]. Our results showed that the mean biogas production is strongly linked to the mean hydrodynamic shear rate in the CSTR. Within the examined range of shear rate, the mean biogas production rate reached a maximum. At low shear rate, the mass transfer mechanism limits biogas generation. Increased shear rate combined with increased stirring speed enhances flow convection around granules and, as a consequence, the effectiveness of external mass transfer, resulting in a greater biogas production rate. Finally, it can be concluded that the geometry of the impeller as well as the digester will determine the optimal rotational speed of the mixer along with consideration of the rheological behaviour of the slurry.

Table 4. Experimental results at various mixing speeds.

	N (rpm)	Mixing regime	Shear rate [$\gamma'_a(s^{-1})$]	Shear stress [τ (Pa)]	BPR (l)
F1	10	5 min/hour	5.6	5.14	43.5
F2	30	5 min/hour	17.4	9.54	45.2
F3	67	5 min/hour	39	14.99	52.5

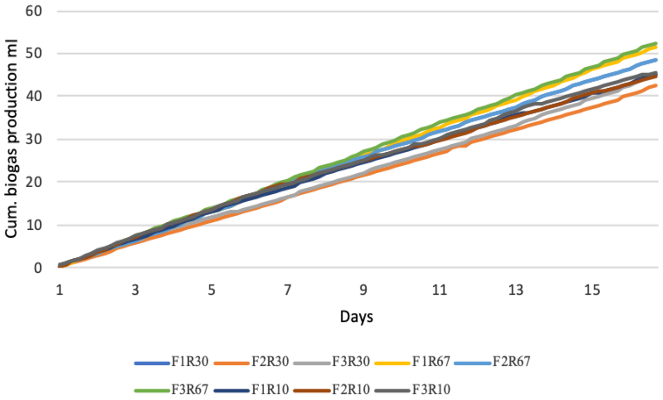


Figure 5. Cumulative biogas production rates in the three digesters.

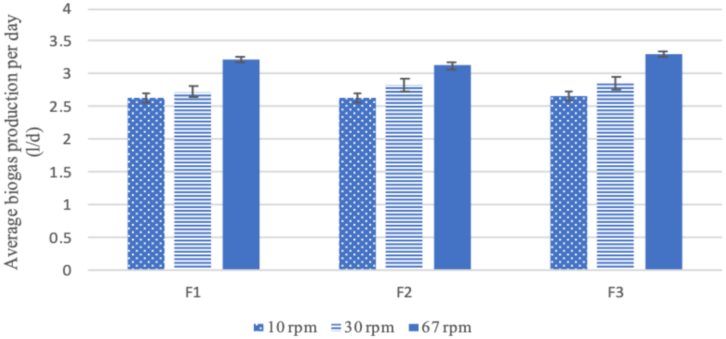


Figure 6. Average biogas production per day by the digesters at 10, 30 and 67 rpm.

Table 5. The analytical data measured during the experiment.

	Batch 1 (10 rpm) (Period 15-30 days)			Batch 2 (30 rpm) (Period 31-48 days)			Batch 3 (67 rpm) (Period 48-64 days)		
Fermenters →	F1	F2	F3	F1	F2	F3	F1	F2	F3
Total BP	45.1	44.2	43.5	48.6	42.6	45.2	51.5	48.6	52.5
VFA’s (g/l)	7.3	6.1	5.8	3.1	3.8	4.9	1.1	1.9	2.2
pH	7.4	7.1	7.9	8.2	8.1	7.9	8.3	8.1	8.0
NH_4^+-N (g/l)	0.95	0.93	1.15	0.78	0.81	0.75	0.62	0.71	0.59
FAS/TOC	0.35	0.69	0.40	0.25	0.54	0.59	0.19	0.34	0.41

5.3 STATISTICAL DATA ANALYSIS

Statistical analysis revealed that the methane production was consistently significant at $p<0.05$ by Student’s t-test. First, the t test was performed during the experiments on data from all three digesters at identical rotational speed. The results proved that the biogas production rates from all the digesters at identical speed were similar as the p-values are above 0.05. The p values at identical impeller speed lied between 0.08 to 0.66, whereas values at different mixing speeds were below $p<0.05$. Table 6. summarizes the statistical analysis results of biogas production at various mixing speeds. The biogas production rates had significant differences between various mixing speeds.

Table 6. The statistical analysis of biogas production at various mixing speeds.

	Data set			p values
10	F1	F2	F3	0.66454
30	F2	F3	F3	0.561287
67	F1	F3	F3	0.084101
F1	10	30		0.0032712
	30	67		1.0968E-12
	10	67		6.65976E-26
F2	10	30		0.00138614
	30	67		7.69224E-10
	10	67		0.001386142
F3	10	30		0.01789452
	30	67		2.47333E-12
	10	67		2.49809E-18

5.4 EFFECT OF MIXING REGIMES ON VFA ACCUMULATION AND AMMONIA

VFA concentrations were measured regularly during the digestion process and served as an indicator in terms of the stability/instability of the digesters routinely [28][5]. But this study did not support the idea that at higher mixing a destabilisation of the AD process would occur due to accumulation of VFAs. The main intermediate products are acetic acid, propionic acid and butyric acid during the AD process and the pH range for optimal anaerobic digestion is between 6.8 and 7.2 [29]. Apparently, the growth rate of methanogens is significantly reduced below pH 6.6 and an extreme decrease in pH will contribute to the disintegration of microbial granules and the breakdown of the mechanism. For a stable AD process the FOS/TAC should be in the range of 0.3-0.4 [30]. During the pre-run period the pH of F1, F2 and F3 was noted as 8.6, 8.1 and 8.1 respectively. FOS, TAC and ratio FOS/TAC was measured as 1.1, 0.2 and 0.15 respectively. Initially, VFAs concentration recorded was 6.8-7.2 g HAc l^{-1} during the start-up. Whereas, VFA concentration was stabilised at 1.5 -2.8 g HAc l^{-1} after one week of operation. At the minimum mixing of 10 rpm the average VFA levels were of 7.4 g l^{-1}. A similar trend was observed by Ghanimeh et al. [28] where slower mixing resulted in enhanced acetate levels at 15.6 g l^{-1} at minimum mixing. Furthermore, after increasing impeller rotational speed from 10 to 30 rpm a significant change in VFAs level was noted within range of 3.1 to 4.9 g l^{-1} (Table 5).

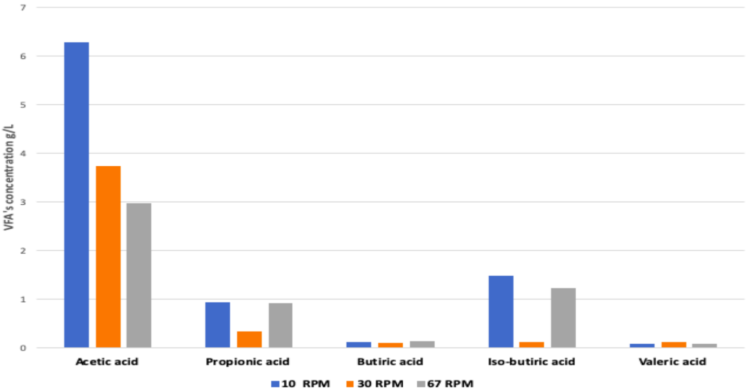


Figure 7. VFAs concentration at different mixing intensities.

The results indicated that VFAs degraded at higher rate at a higher mixing intensity (67 rpm). Elevated pH values were noted during higher VFA content during start-up up to 8.5 and later stabilised at 7.8. The results also demonstrate that either the VFAs degradation is rapid at 67 rpm or the production is slower after the overload and feeding. Methanogenic activity can be reduced by dispersion of VFAs at high mixing intensities as it can affect the establishment of methanogenic zones [31]. 67 rpm mixing intensity led to reduced production of VFA, which contributed to the high biogas production of the 10 and 30 rpm mixing speed. Increase in VFAs concentration lead to damage of microbial flocs along with reduction of removal efficiencies. The pH value remained in the range 7.8–8.2 throughout but fell gradually over the course of the experiment. The VFAs and pH values are summarised in Fig 7 and 8. Ammonia is produced by the biological degradation of the organic matter, mostly proteins and urea. Several pathways for inhibition of ammonia have been suggested, for example a change in intracellular pH, rise in energy demand for maintenance and the inhibition of a particular enzyme reaction[32]. The average ammonia concentration was recorded between 0.71-0.93 g l^{-1} during the whole experiment. The results suggest that mixing is compulsory when the VFA levels increase to disperse the localised inhibiting environments.

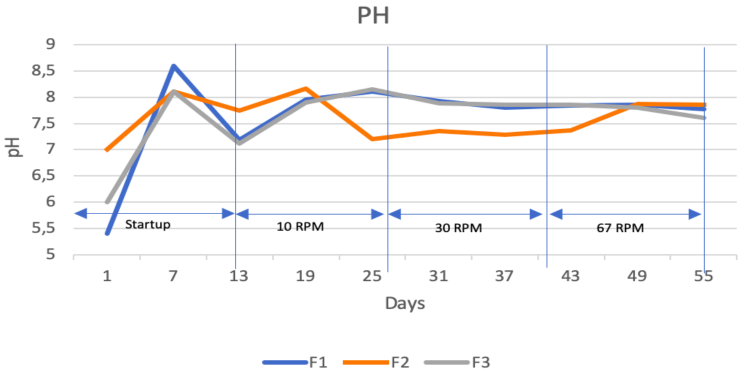
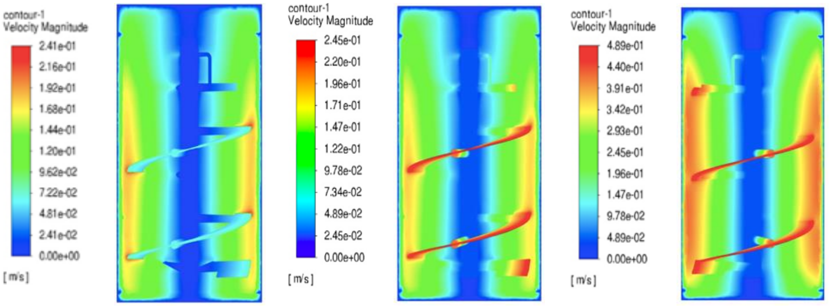


Figure 8. pH during the experiment under various mixing intensities.

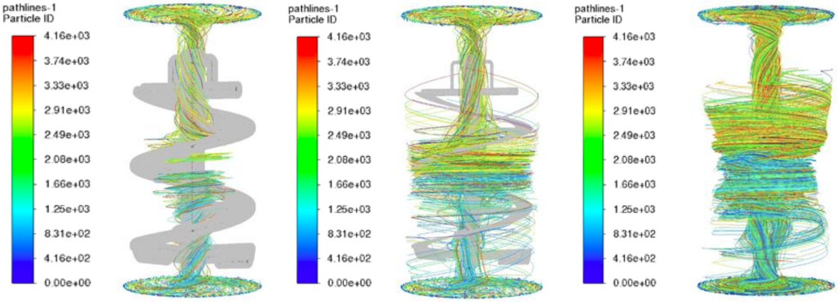
6 CFD SIMULATION OF DIGESTER

Simulations revealed the presence of higher unmixed zones at lower mixing speeds characterised by reaching near zero velocities (Figs. 9(a) & 9(d)). The colour intensity of contours and streamlines indicates the magnitude of velocity in each region. The liquid flows theoretically downwards between the blades and the tank wall, inwards along the bottom of the tank, upwards near the shaft, and radially outwards at the surface of the digester. The impeller drives the fluid towards the walls of digester where the shear rate is maximum. On the other hand, a little movement is observed in axial direction near to the shaft. The red colour near the walls of the digester (Fig. 9(b), 9(c)) indicates the higher velocities between the interference of the impeller blades and the walls of the digester. Furthermore, the larger magnitude of velocities is readily seen as the mixing speed increases.

It can be observed that increasing the impeller's rotating speed causes reduction of dead (Fig. 9(c), 9(f)) A higher rotational speed, on the other hand, necessitates more energy consumption, which directly results in increase of operating and maintenance expenses. The flow field outlines show that increasing the rotating speed from 10 to 30 rpm has no discernible effect on the elimination of stagnant areas, but the energy consumption skyrockets. Furthermore, exceeding a specific rotating speed might damage the microbial growth and seedling habitat. Despite the impeller's interference, the overall flow pattern is consistent with what has been described in the literature. The radial and axial flow, along with a dominating annular flow, is enough to suspend and shear the sludge granules in the reactor.

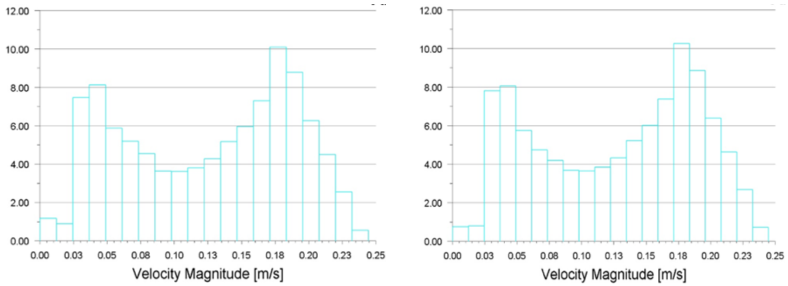


(a) 10 rpm (b) 30 rpm (c) 67 rpm

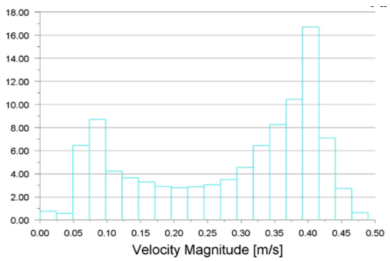


(d) 10 rpm (e) 30 rpm (f) 67 rpm

Figure 9. Velocity contours (a) 10 rpm; (b) 30 rpm; (c) 67 rpm; (d) 10 rpm; (e) 30 rpm; (f) 67 rpm



(a) 10 rpm (b) 30 rpm



(c) 67 rpm

Figure 10. Volume percentage in the function of velocity magnitude at 10, 30 and 67 rpm

According to this study, slurry homogeneity was attained at a speed of 67 rpm. In this situation, increasing the rotating speed of the mixer will have no effect on mixing performance. Previous experimental findings also show that raising the impeller speed to a particular optimal level might improve the mixing system's performance. Beyond that point, the power consumption skyrockets, with just a minor beneficial impact to mixing performance and reduction in biogas production rates.

Figure 10. represents the volume percentage in the function of velocity magnitude at 10, 30 and 67 rpm. It is observed that in fig 10(a) & 10(b) there is negligible difference in the velocity magnitudes and the volume percentage under the velocities is less than 0.05 ms^{-1}. The maximum velocity at 67 rpm was recorded as 0.5 ms^{-1} which is almost twice the velocities recorded at 10 and 30 rpm which are recorded as 0.25 and 0.24 ms^{-1} respectively (ref table 7). The mixing intensities can be easily evaluated in terms of dead zone volume. The parts of the reactor with no flow or very low velocities are known as dead zones or stagnant zones. Dead zones are undesirable because that volume of the reactor remains isolated from the rest of the reactor volume and get no mixing, resulting in a reduction in the effective reactor volume. The dead zone volume under lower mixing speeds was observed to be comparatively very high. Under minimal mixing speed of 10 & 30 the dead volume was recorded as 18% and 17 % respectively, whereas under higher mixing intensity it was reduced to just 2%. Inside a dead zone volume, the pH and temperature gradient occur, which results in decrease of the digester's effectiveness and apparently decline in biogas production and sometimes even digester failure.

It can be inferred that raising the impeller's rotating speed is not always beneficial in improving the mixing pattern. Vortices can develop in some places as the rotating speed increases which can lead to disruption of biomass activity, phase interaction, and heat and mass transport. As a result, based on its rheological properties, the ideal impeller speed and optimum mixing pattern for each non-Newtonian fluid should be investigated independently which directly depends on the total solid content and temperature.

Table 7. Comparison of maximal and average velocities under the different mixing conditions.

Rpm	Torque (Nm)	Maximum velocity (m s^{-1})	Average velocity (m s^{-1})	Dead volume
10	3.9×10^{-6}	0.5	0.28	18%
30	3.9×10^{-6}	0.24	0.10	17%
67	1.33×10^{-5}	0.25	0.12	2%

Effect of geometrical characteristics on flow patterns and mixing efficiency

Mixing is a physical operation which is highly dependent on the design and geometry of the vessel and the impeller. In the current study, impeller speed, geometry and slurry rheological are considered as the principal factors that determine the efficiency of mixing system in an anaerobic digester. According to Amiraftabi et al. [16] the helical ribbon impeller provides stronger radial flow movement as compared to axial flow under different mixing speeds. Due to the optimum geometrical design used in this experiment, the greater amount of the slurry is pushed towards the walls where the hydrodynamic shear is low and very little is drawn towards the shaft of the impeller. Due to larger diameter the maximum mixing happens near to the clearance between the walls of the digester and the ribbons of impeller. Moreover, due to low bottom clearance the mixing effect can observed in the entire active volume of the digester and efficiency of the impeller is significant[33]. Furthermore, the non-Newtonian characteristic of slurry results in decrease of viscosity near the high shear zones close to the blades which creates a low viscosity film between the blades and walls that is significantly influenced impeller geometry. The weakening of core network of shear-thinning fluid increases both the molecular and the mass diffusions leading to an effective method of mixing. The results in this study also indicate that the increase in impeller rotational speed reduces the mixing time and enhances the uniformity of nutrients, heat and mass.

7 EFFECT OF MIXING INTERVALS

7.1 START-UP PHASE

All digesters were pre-run until a stable biogas production rate was obtained. The OLRs by α-cellulose substrate were set at 5 g day^{-1}, i.e. 1 g l^{-1}, for the entire experiment and the reactors were fed once a day. During the start-up phase process instabilities were observed that might be caused by increased hydrogen concentrations, which result in a better breakdown to propionic acid rather than acetic acid, carbon dioxide, and hydrogen [34]. After the first two weeks of pre-run, the operation of digesters became stable with 0.23–0.26 ml day^{-1} gas production. After the pre-run period of 15 days, the biogas production was constant and the VFA and alkalinity (FOS/TAC) ratio was recorded as 0.39, which is considered normal as it indicates that the digestion process was stable. Different mixing intervals were started at day 15.

7.2 EFFECT OF MIXING INTERVALS ON OVERALL BIOGAS YIELD (BY)

According to the results of our previous study [35], the mixing speed of 67 rpm was selected for further investigation of the effect of interval time, i.e. resting, non-mixing period in between the mixing operations, on biogas production rate. All three digesters were run with identical parameters such as TS content, temperature and mixing regimes. Mixing interval time of 1 hour was selected in initial stage (after start-up phase) of experiment from day 1 to day 20, which further increased to 2, 3 and 4 hours. The use of three parallel digesters is preferred to obtain more precise data on effect of varying parameters during the whole experiment. Accordingly, similar trends in all reactors were observed at particular defined mixing regime.

Results from this study indicated that BY was closely related to the mixing interval time. In Figure 11, F represents the digester, H represents the resting time (in hours) between mixing operations. In Figure 11(d) the green bars indicate the total biogas production in fermenter 1,2 and 3 at various resting times. The daily maximum biogas yields during resting time of 1, 2, 3 and 4 hours was noted as 3.84 *l*/d, 3.36 *l*/d, 3.12 *l*/d and 2.94 *l*/d, respectively (Figure 11 *(a)(b)(c)*). The average daily biogas yield during all the mixing regimes was noted as 3.3 *l*/d, 2.9 *l*/d, 2.8 *l*/d, 2.5 *l*/d as depicted in Table 8. Similar results were demonstrated by Latha et al.[36] where mixing regimes were 15 min/hr and 30 min/hr. Maximum biogas yield was observed at mixing rate of 15 min/hr between 50 rpm-200 rpm. The observed higher biogas yields at minimum resting time is attributed to have favoured better interaction among methanogenic and acetogenic granules and further enhanced bacterial contact between substrate and microbes.

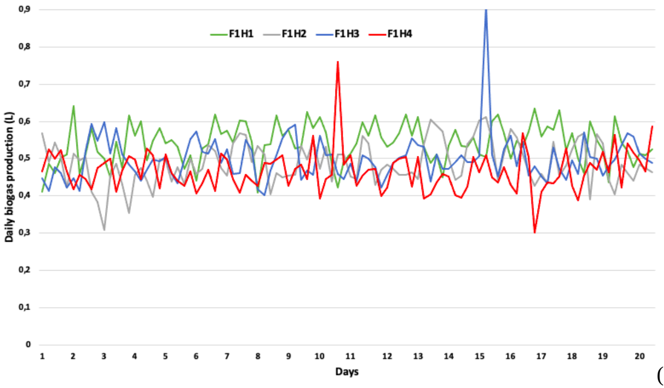
Table 8. Comparison of biogas production form all three digesters under similar working conditions.

	Batch 1 (1 hour resting time) (Period 15-35 days)			Batch 2 (2 hours resting time) (Period 35-55 days)			Batch 3 (3 hours resting time) (Period 55-75 days)			Batch 4 (4 hours resting time) (Period 75-95)		
Fermenters →	F1	F2	F3	F1	F2	F3	F1	F2	F3	F1	F2	F3
Total Biogas production (l/d)	54.1	52.24	55.5	48.9	48.6	51.2	49.9	49.8	49.6	46.6	33.4	47.3
Maximum BP (daily) (l/d)	3.84	3.24	3.71	3.36	3.20	2.91	2.98	3.12	2.34	2.94	2.82	2.35
Minimum BP (daily) (l/d)	2.50	2.44	2.43	2.36	2.39	2.42	2.34	2.53	2.77	2.31	2.22	2.43
Average (l/d)	2.70	2.61	2.77	2.44	2.43	2.55	2.49	2.82	2.48	2.33	2.51	2.36

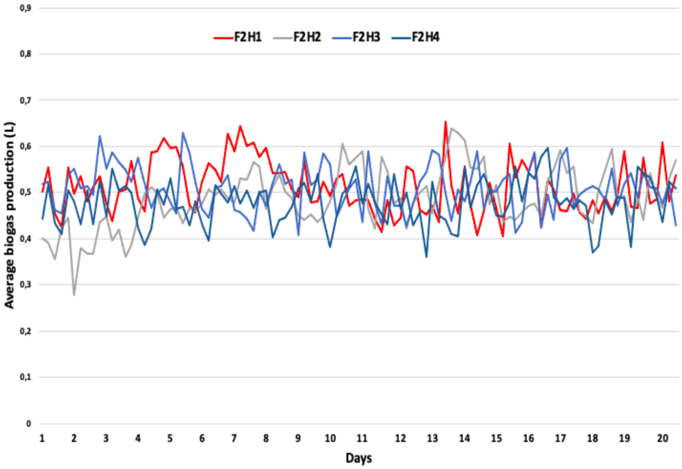
Similar trends can be recognized in all the three digesters in terms of biogas yields. Figure 11 demonstrates the biogas daily and cumulative biogas production in the digesters. The overall biogas production in fermenter 1 at resting time of 1, 2, 3 and 4 hours was 54.1 *l*, 48.8 *l*, 49.9 *l* and 46.6 *l* respectively. The higher yield of biogas at resting time of 1 hour is assumed to be due to the consequences of better chemical equilibrium along with better buffer action gained during the non-mixing time. The effect of increasing the interval between mixing periods was observed from day 35 when the resting time was reduced from 1 hour to 2 hours. The daily biogas

production dropped from 0.59 *l* to 0.41 *l* in F1, from 0.52 *l* to 0.41 *l* in F2 and from 0.61*l* to 0.55 *l* in F3. This variation at different mixing intervals might be attributed to the more frequent mixing, which allowed for more interaction between the substrate and the microorganisms.
The mixing interval of 4 hrs represented the adverse effect on BY as compared to other intervals. The BY was recorded as 46.6 *l*, 33.4 *l* and 47.3 *l* in all the three digesters respectively at this particular mixing interval. The main reason of lower BY was the settling of solid particles at the bottom of digester due to longer resting times. BY as low as 14-30% lower was recorded in all digesters in comparison with reduced mixing interval times. Formation of floating layers in digester is also one of the main factors responsible for deviation in BY at various mixing intervals [37]. Lowering the mixing interval time led to prevented floating layer formation, which was responsible for smooth discharge of biogas from the slurry. Floating layer is also directly associated with the OLR and TS content [38]. In our case the OLR was 1 gVS $l^{-1}d^{-1}$, which is within the optimum range where the reduction in pause between the mixing can led to reduction in formation of floating layer.

Figure displays the reduction of VS content in all digesters at different mixing-resting intervals. Similar trends can be recognized as in BY. The highest VS reduction rates (64.2% - 68.5%) were observed at lower mixing-resting intervals. Nevertheless, at mixing interval of 4 hrs the VS reduction was recorded as 58.3±1.4%, 53.6±2.8% and 56.7±2.5% for F1, F2 and F3 respectively. The average VS reduction at various mixing interval of 1, 2, 3 and 4 hours was estimated as 66.1%, 59.1%, 60.3% and 56.2% respectively (Table 9). According to recent study by Caillet et al [39], the variation in both TS and reduction in VS were also found when the different samples were taken from both top and bottom of a lab scale digester under various mixing speeds of 30, 40, and 50 rpm. The current study of TS and VS contents showed the effect of mixing on the displacement of solid matters. As a result, biogas production can be enhanced by appropriate mixer design, mixing speed and mixing-resting interval times. Furthermore, it is suggested that intermittent mixing is adequate for the anaerobic digestion process. Based on these findings, it can be concluded that biogas output could be increased with reactor design and that the operating parameters (intermittent mixing mode at lower mixing-resting intervals and OLR), can be favourable to the substrate and microorganisms.


F1H1
F1H2
F1H3
F1H4
Daily biogas production (L)
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Days

(a)


F2H1
F2H2
F2H3
F2H4
Average biogas production (L)
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Days

(b)

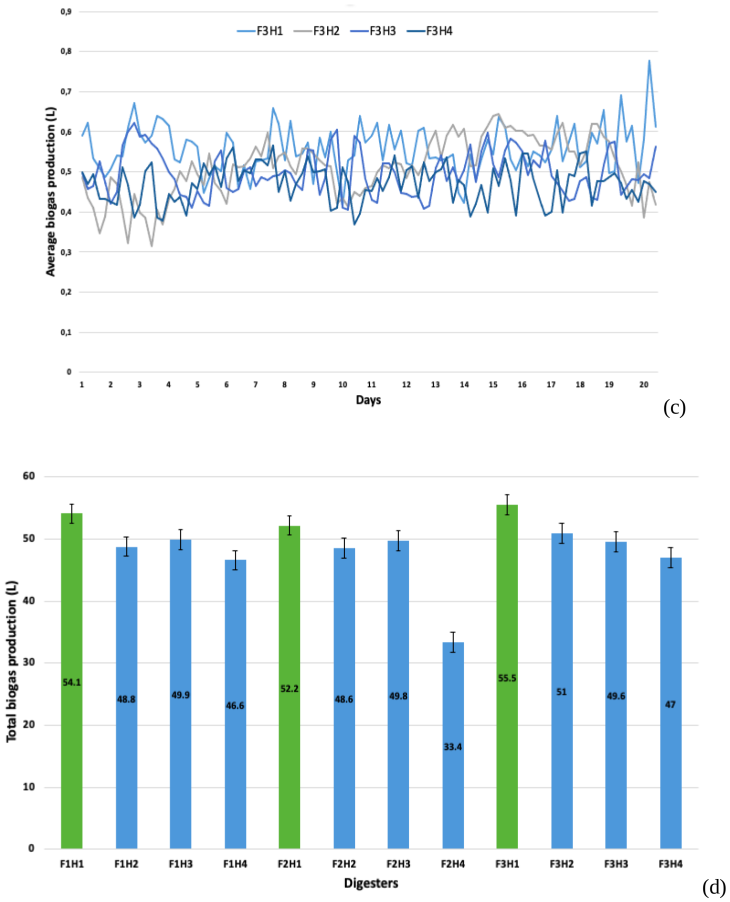


Figure 11. (a)(b)(c) represents the daliy biogas production for continuos 20 days at different mixing interavls for digester 1, 2 & 3 respectively. (d) represents the overall biogas production from all three digesters

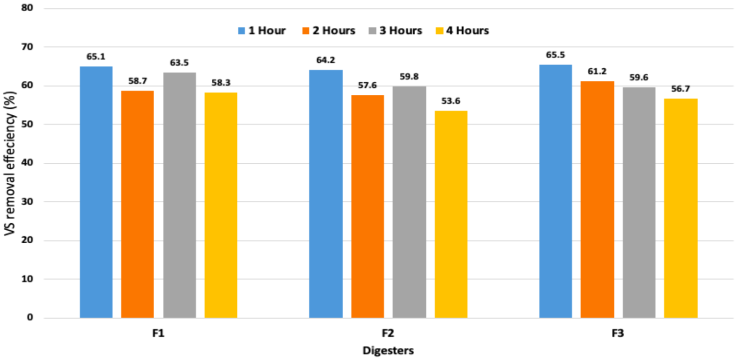


Figure 12. Performance of the all three anaerobic digesters for total volatile solids removal with different mixing intervals at 67 rpm.

Table 9. Represents the total VS reduction (%) in all the digesters at various mixing interval.

Digesters	Mixing intervals (hours)	VS removal efficiency (%)	Total biogas production (L)
F1	1	65.1 ± 3.4	54.1 ± .24
	2	58.7 ± 2.1	48.9 ± .31
	3	63.2 ± 3.6	49.7 ± .25
	4	58.3 ± 1.4	46.6 ± .14
F2	1	64.2 ± 2.5	52.2 ± .32
	2	57.6 ± 3.2	48.6 ± .13
	3	58.8 ± 5.2	49.8 ± .26
	4	53.6 ± 2.8	33.4 ± .27
F3	1	68.5 ± 2.7	55.5 ± .17
	2	61.2 ± 3.4	51.2 ± .30
	3	59.6 ± 3.2	49.6 ± .23
	4	56.7 ± 2.5	47.3 ± .21

7.3 IMPACT OF MIXING INTERVALS ON VFA CONCENTRATION, ALKALINITY, PH AND AMMONIA

The mixing intensity, mixing mode and frequency directly influences the AD bioprocess equilibrium and have major impact on overall biogas production yields. VFA such as acetic acid, propionic acid, butyric acid, iso-butyric acid and valeric acid are produced during acidogenesis reaction. The rise in VFA concentration has an effect on the efficiency with which substrates are converted to biogas. In this section the effect of mixing operation on VFA, pH, FAS/TOC ratio and free NH_3 is analyzed (Table 10). All parameters were measured twice a week after completion of mixing cycle to obtain the homogeneous sample. Rheology of substrate is one of major parameters, which have significant effect on performance during mixing. The digesters were operated at 4.2% TS content throughout the experiment therefore the rheological parameters of slurry could remain constant and more precise results can be obtained.

Table 10. Performance of the digesters at different mixing-resting intervals. Average values.

	Batch 1 (1 hour resting time) (Period 1-20 days)			Batch 2 (2 hours resting time) (Period 20-40 days)			Batch 3 (3 hours resting time) (Period 40-60 days)			Batch 4 (4 hours resting time) (Period 60-80)		
VFA's (g/l)	7.3	6.1	5.8	3.1	3.8	4.9	1.1	1.9	2.2	2.4	4.3	3.1
pH	7.2	7.0	7.7	7.1	8.0	7.7	8.5	7.9	8.1	7.6	8.0	7.9
NH_4^+-N (g/l)	0.94	0.89	9.15	0.88	0.82	0.85	0.66	0.75	0.58	0.78	0.82	0.99
FAS/TOC Ratio	0.34	0.49	0.45	0.35	0.44	0.60	0.29	0.24	0.42	0.24	0.35	0.44

The average pH of the reactor content remained between the optimal limits of 6.8-7.5 throughout the experiment. For one hour resting time the average pH recorded in all the digesters is 7.2, 7.0 and 7.7 in digesters 1, 2 and 3, respectively. At the maximum resting time of 4 hours, the pH values changed to 7.6, 8.0 and 7.9 in digesters 1, 2, and 3 respectively (Figure 13). Higher pH values at higher resting time is due to lower accumulation of VFAs during that period. The average VFA levels were noted as 5.8 g/l, 4.4 g/l, 5.3 g/l, 7.7 g/l for the resting time of 1, 2, 3 and 4 hours, respectively, followed by a concomitant increase in biogas production (Figure 14). According to Caillet et al. [39] the increase in VFA content had no detrimental impact on biogas generation. In terms of biogas production and changes in ammonium and VFA concentrations, no substantial fluctuation in these two concentrations was found to explain differences in biogas output. Higher VFA concentrations and lower ammonium concentrations resulted in greater biogas output. Whereas in our study the ammonia concentration was found to be in equilibrium during the whole experiment (Figure 15). Similarly, Franke et al. [40] found that the higher VFA levels (8-10 g l^{-1}) and pH values did not destabilize the anaerobic process.

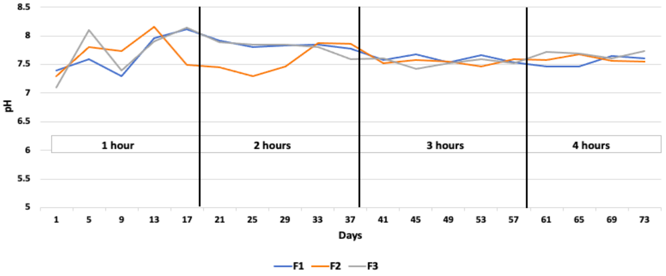


Figure 13. pH levels during the various mixing intervals throughout the experiment.

The concentrations of VFA and alkalinity, as well as the corresponding ratios of VFA-to-alkalinity (FAS/TOC) were used to assess the system's stability (Table 10). The average FAS/TOC was recorded as 0.39 which was reported below the threshold value of 0.5 for a stable process to avoid failure of digesters during transient conditions [41]. As a result, the startup with stable digesters was deemed successful prior to commencing varied mixing intervals to prevent the impact of shock loading. Greater alkalinity resulted in increased biogas generation. This outcome was predicted since the digestive environment alkalinity was more conducive to the AD process. Furthermore, a rise in VFA concentration resulted in an increase in pH. The average pH for VFA concentrations of 5.8 g l^{-1} was 7.6, whereas the average pH for VFA concentrations of 7.79 g l^{-1} was 7.9.

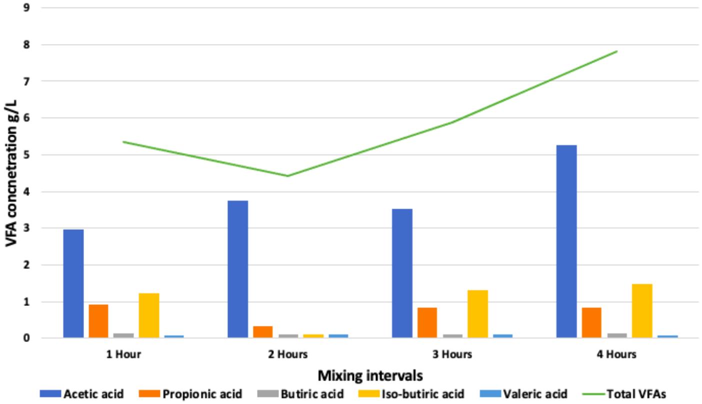


Figure 14. VFA concentration during different mixing regiemes..

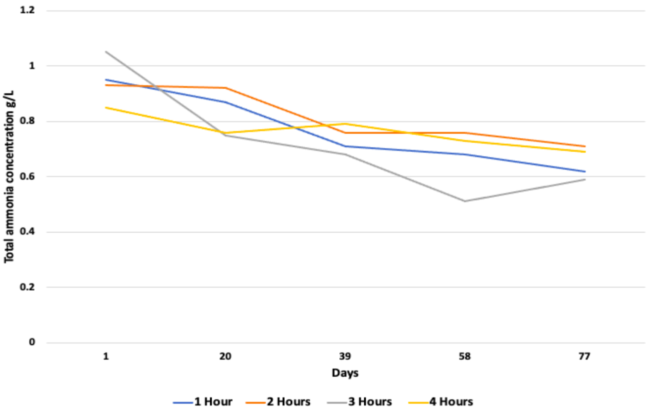


Figure 15. Total ammonia concentrations during the entire experiment.

7.4 SYSTEM MIXING INTENSITY FOR SEMI-CONTINUOUS MIXING MODE

The importance of efficient sludge mixing in anaerobic digesters has been recognized as a key design criterion for full-scale anaerobic digesters. For application in the design and operation of systems incorporating mechanical mixing devices, Camp and Stein[42] coined the term velocity gradient:

$$G = [\frac{P}{\mu V}]^{1/2} \tag{5}$$

Where G is the average velocity gradient, P the power dissipation, V the reactor volume, and μ the liquid viscosity. For this particular design and construction of setup the value of G is 10 S^{-1} as a slow mixing value was applied to the system by adjusting the mixing power to achieve this velocity gradient.

Due to biochemical process of anaerobic digestion which includes various microbes and formation of flocs the velocity gradient is not the only parameter which is determine the overall biogas production rates but also the mixing time and the interval between the mixing regimes. So, the parameter of velocity gradient mixing time integral in the case of semi-continuous mixing mode is calculated by the following equation:

$$mixing\ intensity\ no. = G \times T_m \tag{6}$$

Where T_m is the mixing time in seconds. The mixing intensity number can be accurately calculated and can be used to determine the appropriate mixing time of the impeller (Fig 16). In this case the mixing intensity number of 72000 is the found to be the optimum mixing intensity number which means mixing the slurry every hour for 5 min at 67 rpm can result in highest biogas production as compared to other mixing regimes (Table 11).

Table 11. Comparison between total biogas production and the mixing intensity number.

Resting time (hours)	Mixing time (seconds per day)	Mixing intensity no.	Total biogas production (*l*)
1	120	72000	54.1
2	60	36000	51.2
3	40	24000	49.9
4	30	18000	46.6

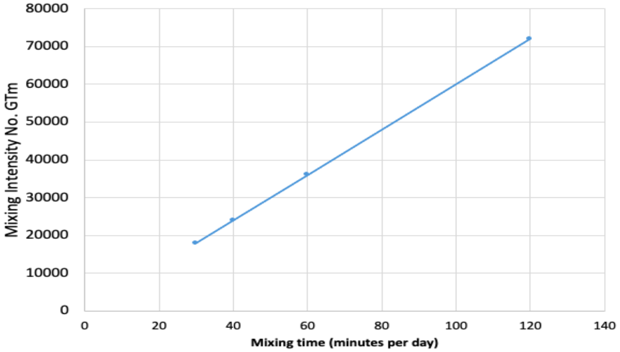


Figure 16. Relationship between mixing intensity number and mixing time.

8 PRACTICAL IMPLICATION OF THIS STUDY

It is inferred from this study along with literature that the geometry characteristics of the impeller decide their efficiency in mixing and biogas output in slurry agitation. In most studies the turbine impellers were analysed to study the mixing effect of the slurry [43][44][44][45][24]. The concept of using paddle impellers can be encouraged by greater consistent distribution of viscosity at lower shear rates and mixing speed [24][46]. Slow moving propellers with longer agitating wings can do better in pilot scale digesters. It is reported that the impeller characteristics, such as pitch ratio, power number and axial flow number, are closely related to achieving homogeneity in the digester. These impellers can be adjusted in order to provide a consistent shear distribution such that the microorganisms remain unharmed and seek to reduce the energy consumption and increase the flow pattern of slurry in the digester [47]. Eventually, the impeller in an anaerobic digester can have almost constant pitch as it guarantees a consistent distribution of velocity at low shear speeds. As a consequence, the scaling-up of pilot scale mixing processes is a crucial feature for maximizing current mixing and flow processes by holding all measurements within a set ratio, known as a scale-up factor [48]. Minimum periodic mixing is observed to be favourable for a successful anaerobic digestion operation [49–51]. Intermittent mixing with longer resting periods may result in higher biogas output and, in most situations, increased mixing time cycles have not seen much impact on biogas production, but comparable results can be produced at lower power consumption [52]. The direct effect of the shear rate and the mixing speed is discussed in this study.

9 CONCLUSION

The mixing intensity (shear rate) and the length of time that shear rate is applied by an effective mixing system defines the degree of mixing achieved. The uniform shear rate can be considered as a tool to achieve stability of digestion biodegradation process. Higher mixing intensity of 67 rpm for 5 min h^{-1} produced 15-18 % higher biogas production as compared to 10 rpm and 30 rpm without creating any instability in terms of VFAs accumulation and dead zones. Furthermore, higher mixing speed can lead to reduction in dead zones to less than 2%. After analysing the results from the current study and literature it is concluded that mixing is a very important aspect, which significantly affects the biogas production rates but the impeller design is the principal factor. Large diameter impeller at medium mixing speed is best combination in direction of optimization of mixing in an anaerobic reactor.

Three digesters were operated under identical inoculation and operating parameters with various mixing-resting intervals. It is concluded that the efficiency of the mesophilic digester is directly associated with the mixing-resting time interval. The mixing regime has effect on the physicochemical properties of the substrate. The digester performance was best under the minimum resting time of 1 hour at 67 rpm impeller speed in this system. During the employed mixing regime, the biogas yield was 5-12% higher as compared to longer resting times. The FAS/TOC ratio was below 0.5 and the VS reductions was noted as 66.1 %. Drop in biogas yield can be due to VFA accumulation to some extent along with formation of floating layers and sedimentation at longer resting time between the mixing operations. The appropriate agitation interval might not only accomplish high biogas generation, but also boost the energy efficiency of the process. The findings can be used to run an anaerobic digester in an efficient and cost-effective manner.

NEW SCIENTIFIC RESULTS – THESES

T1. This research demonstrated that the higher mixing intensity of 67 rpm for 5 min h^{-1} produced 15-18 % higher biogas production as compared to 10 rpm and 30 rpm without creating any instability in terms of VFAs accumulation and dead zones. Furthermore, higher mixing speed lead to reduction in dead zones to less than 2%. Large diameter impeller at medium mixing speed is best combination in direction of optimization of mixing in an anaerobic reactor.

T2. It is concluded that the efficiency of the mesophilic digester is directly associated with the mixing time interval. The mixing regime also has effect on the physicochemical properties of the substrate. The digester performance was better under the minimum resting time of 1 hour at 67 rpm impeller speed as compared to resting time of 2, 4 and 6 hours. During this mixing regime the biogas yield was 5-12% higher as compared to longer resting times. The FAS/TOC Ratio was below 0.5 and the VS reductions was noted as 66.1 %. Drop in biogas yield can be due to VFA accumulations to some extent along with formation of floating layers and sedimentation at longer break time between the mixing operations.

T3. CFD results demonstrated that under minimal mixing speed of 10 and 30 the dead volume was recorded as 18% and 17%, respectively; whereas under higher mixing intensity (67 rpm) it was reduced to just 2%. Inside a dead zone volume, the pH and temperature gradient occur, which results in decrease of the digester’s effectiveness and apparently decline in biogas production and sometimes even digester failure

T4. Multidisciplinary approach including the hydrodynamics and biochemical process is very important to evaluate the effect of impeller and digester geometry on biogas production rates. Evaluation of mixing in digester without disclosing the geometry of digester and impeller is not valuable enough unless the amount of shear stresses produced and time to mix is known. Scale up of lab scale digester and scale down of full-scale digester should be focused to optimize the mixing intensity and time of operation.

T5. The intermittent mixing is strictly recommended as compared to continuous and un-mixing in terms of biogas yield and energy point of view. Geometrical similarity of lab-scale experiments and pilot scale biogas plants along with the rheological characteristics of slurry should be considered keeping the ratio of dimensions constant.

T6. Digesters operated at lower TS content and longer HRT were unaffected by mixing but at higher TS levels mixing have significant effect on biogas yields due to increase in viscosity of slurry. Reduction of dead zones is the primary motive during the mixing to obtain homogenous mixture. Design of impeller, speed of mixing should be optimized according to design of digester and rheological properties of slurry.

LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

1. Buta, Singh; Zoltán, Siménfalvi; Zoltán, Szamosi, Impact of mixing intensity and duration on biogas production in an anaerobic digester: a review Critical Reviews in Biotechnology 2020-03-30 | journal-article DOI: 10.1080/07388551.2020.1731413
2. Buta, Singh; Zoltán, Siménfalvi; Zoltán, Szamosi, State of the art on mixing in an anaerobic digester: A review Renewable Energy 2019-10 | journal-article DOI: 10.1016/j.renene.2019.04.072
3. Buta, Singh; Zoltán, Siménfalvi; Zoltán, Szamosi, M Rosas-Casals Decentralized biomass for biogas production. Evaluation and potential assessment in Punjab (India) November 2020 Energy Reports 6:1702-1714 DOI: 10.1016/j.egyr.2020.06.009
4. Buta, Singh; Zoltán, Siménfalvi; Zoltán, Szamosi, Critical Analysis of Methods Adopted for Evaluation of Mixing Efficiency in an Anaerobic Digester *Sustainability* 2021, *13*(12), 6668; https://doi.org/10.3390/su13126668
5. Buta Singh, Kornél L Kovács, Zoltán Bagi, József Nyári, Gábor L Szepesi, Máté Petrik, Zoltán Siménfalvi, Zoltán Szamosi, Enhancing Efficiency of Anaerobic Digestion by Optimization of Mixing Regimes Using Helical Ribbon Impeller *Fermentation* 2021, *7*(4), 251; https://doi.org/10.3390/fermentation7040251
6. Buta, Singh; Zoltán, Siménfalvi; Zoltán, Szamosi Techniques for evaluation of mixing efficiency in an anaerobic digester Solutions for Sustainable Development 2019-09-19 | book-chapter DOI: 10.1201/9780367824037-19 Part of ISBN: 9780367824037
7. Buta, Singh; Siménfalvi, Zoltán; Szamosi, Zoltán Comparison of mixing efficiency of different impellers for agitation of slurry in anaerobic digester November 2020 DOI: 10.1063/5.0024243
8. Buta, Singh; Siménfalvi, Zoltán; Szamosi, Zoltán Hydrodynamic factors in an Anaerobic Digester, Multiscience XXXII. MicroCAD International Multidisciplinary Scientific Conference Miskolc-Egyetemváros, Hungary: Miskolci Egyetem, (2018) pp. 1-9., 9 p. DOI: 10.26649/musci.2018.009 Publication:30418826
9. Buta, Singh; Zoltán, Siménfalvi; Zoltán, Szamosi Designing of Lab-scale anaerobic digester equipped with Maxblend impeller to evaluate effect of mixing on anaerobic digestion March 2019 International Journal of Engineering and Management Sciences 4(1):404-413 DOI: 10.21791/IJEMS.2019.1.50. (2018) pp. 1-8., 8 p. Publication:30418845

LITERATURE CITED IN THE THESES BOOKLET

[1] K. Hopfner-sixt, T. Amon, MONITORING OF AGRICULTURAL BIOGAS PLANTS IN AUSTRIA – MIXING TECHNOLOGY AND SPECIFIC VALUES OF ESSENTIAL PROCESS PARAMETERS, (n.d.).

[2] Michael H. Gerardi, The Microbiology of Anaerobic Digesters, John Wiley & Sons, 2003. https://books.google.hu/books?hl=en&lr=&id=kHRhlkmT0ggC&oi=fnd&pg=PR7&dq=Gerardi,+M.H.,+2003.+The+Microbiology+of+Anaerobic+Digesters.+John+Wiley+%26+Sons.+ISO-11734,+1995.+Water+Quality-Evaluation+of+the+%27ultimate%27+Anaerobic+Biodegradability+of+Organ.

[3] S. Buta, Singh; Zoltán, Szamosi; Zoltán, State of the art on mixing in an anaerobic digester: A review, Renew. Energy. 141 (2019) 922–936. doi:https://doi.org/10.1016/j.renene.2019.04.072.

[4] Y.& J.H.T. Liu, The essential role of hydrodynamics shear force in the formation of biofilm and granular sludge, Water Res. 36 (2002) 1635–1665. http://mechanics.

[5] R.A. Hoffmann, M.L. Garcia, M. Veskivar, K. Karim, M.H. Al-Dahhan, L.T. Angenent, Effect of shear on performance and microbial ecology of continuously stirred anaerobic digesters treating animal manure, Biotechnol. Bioeng. 100 (2007) 38–48. doi:https://doi.org/10.1002/bit.21730.

[6] J. Jiang, J. Wu, S. Poncin, H.Z. Li, Effect of hydrodynamic shear on biogas production and granule characteristics in a continuous stirred tank reactor, 51 (2016) 345–351. doi:http://dx.doi.org/10.1016/j.procbio.2015.12.014.

[7] H. Frey, Julian; Grüssing, Fabian; Nägele, Hans-Joachim and Oechsner, Cutting the Electric Power Consumption of Biogas Plants : the Impact of New Technologies, Landtechnik. 68 (2013) 58–63.

[8] B. Singh, Z. Szamosi, Z. Siménfalvi, Hydrodynamic factors in an anaerobic digester, Publ. MultiScience - XXXII. MicroCAD Int. Sci. Conf. (2018) 5–6. doi:10.26649/musci.2018.009.

[9] A. Lebranchu, S. Delaunay, P. Marchal, F. Blanchard, S. Pacaud, M. Fick, E. Olmos, Impact of shear stress and impeller design on the production of biogas in anaerobic digesters, Bioresour. Technol. 245 (2017) 1139–1147. doi:10.1016/j.biortech.2017.07.113.

[10] F. Battista, D. Fino, G. Mancini, B. Ruggeri, Mixing in digesters used to treat high viscosity substrates: The case of olive oil production wastes, J. Environ. Chem. Eng. 4 (2016) 915–923. doi:10.1016/j.jece.2015.12.032.

[11] Z. Trad, C. Vial, J.P. Fontaine, C. Larroche, Mixing and liquid-to-gas mass transfer under digester operating conditions, Chem. Eng. Sci. 170 (2017) 606–627. doi:10.1016/j.ces.2017.01.056.

[12] J.B.G. VINCENT W. UHL, MIXING Theory and Practice, FIRST EDIT, Academic Press, NEW YORK, 1966.

[13] C. Aranowski, R., Hupka, J., Jungnickel, Changes in rheological properties during anaerobic digestion of activated sludge, Physicochem. Probl. Miner. Process. 44 (2010) 13–22.

[14] F. Shen, L. Tian, H. Yuan, Y. Pang, S. Chen, D. Zou, B. Zhu, Y. Liu, X. Li, Improving the mixing performances of rice straw anaerobic digestion for higher biogas production by computational fluid dynamics (CFD) simulation, Appl. Biochem. Biotechnol. 171

(2013) 626–642. doi:10.1007/s12010-013-0375-z.

[15] C.J. Rivard, B.D. Kay, D.H. Kerbaugh, N.J. Nagle, M.E. Himmel, Horsepower requirements for high-solids anaerobic digestion, Appl. Biochem. Biotechnol. 51–52 (1995) 155–162. doi:10.1007/BF02933420.

[16] M. Amiraftabi, M. Khiadani, H.A. Mohammed, Chemical Engineering & Processing : Process Intensification Performance of a dual helical ribbon impeller in a two-phase (gas-liquid) stirred tank reactor, Chem. Eng. Process. Process Intensif. 148 (2020) 107811. doi:10.1016/j.cep.2020.107811.

[17] E. Kovács, R. Wirth, G. Maróti, Z. Bagi, G. Rákhely, K.L. Kovács, Biogas production from protein-rich biomass: fed-batch anaerobic fermentation of casein and of pig blood and associated changes in microbial community composition, PLoS One. 8 (2013) e77265.

[18] B. Wu, CFD investigation of turbulence models for mechanical agitation of non-Newtonian fluids in anaerobic digesters, Water Res. 45 (2011) 2082–2094. doi:10.1016/j.watres.2010.12.020.

[19] B. Wu, Large eddy simulation of mechanical mixing in anaerobic digesters, Biotechnol. Bioeng. 109 (2012) 804–812. doi:10.1002/bit.24345.

[20] R. Mohammadrezaei, S. Zareei, N. Behroozi-Khazaei, Improving the performance of mechanical stirring in biogas plant by computational fluid dynamics (CFD), Agric. Eng. Int. CIGR J. 19 (2017) 91–97.

[21] E. Manea, D. Robescu, Simulation of mechanical mixing in anaerobic digesters, UPB Sci. Bull. Ser. D Mech. Eng. 74 (2012) 235–242.

[22] X. Cao, Rheological properties of municipal sewage sludge: dependency on solid concnetration and temperature, Procedia Environ. Sci. (2016) 113–121. doi:https://doi.org/10.1016/j.proenv.2016.02.016.

[23] M. ZHANG, L. ZHANG, B. JIANG, Y. YIN, X. LI, Calculation of Metzner Constant for Double Helical Ribbon Impeller by Computational Fluid Dynamic Method, Chinese J. Chem. Eng. 16 (2008) 686–692. doi:10.1016/S1004-9541(08)60141-X.

[24] M.E.J.P. K. C. Lin and, Effects of mixing on anaerobic treatment of potato-processing wastewater, Can. J. Civ. Eng. 18 (1991) 504–514. doi:10.1139/l91-061.

[25] Z. Tian, D. Chauliac, P. Pullammanappallil, Comparison of non-agitated and agitated batch, thermophilic anaerobic digestion of sugarbeet tailings, Bioresour. Technol. 129 (2013) 411–420. doi:10.1016/j.biortech.2012.11.056.

[26] Z. Tian, L. Cabrol, G. Ruiz-Filippi, P. Pullammanappallil, Microbial ecology in anaerobic digestion at agitated and non-agitated conditions, PLoS One. 9 (2014). doi:10.1371/journal.pone.0109769.

[27] X. Gómez, M.J. Cuetos, J. Cara, A. Morán, A.I. García, Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes. Conditions for mixing and evaluation of the organic loading rate, Renew. Energy. 31 (2006) 2017–2024. doi:10.1016/j.renene.2005.09.029.

[28] S.A. Ghanimeh, D.N. Al-Sanioura, P.E. Saikaly, M. El-Fadel, Correlation between system performance and bacterial composition under varied mixing intensity in thermophilic anaerobic digestion of food waste, J. Environ. Manage. 206 (2018) 472–481. doi:10.1016/j.jenvman.2017.10.062.

[29] L. Appels, J. Baeyens, J. Degrève, R. Dewil, Principles and potential of the anaerobic digestion of waste-activated sludge, Prog. Energy Combust. Sci. 34 (2008) 755–781. doi:10.1016/j.pecs.2008.06.002.

[30] S. Astals, V. Nolla-Ardèvol, J. Mata-Alvarez, Anaerobic co-digestion of pig manure and crude glycerol at mesophilic conditions: Biogas and digestate, Bioresour. Technol. 110 (2012) 63–70.

[31] V.. Vavilin, Anaerobic Digestion of Solid Material: Multidimensional Modeling of Continuous-Flow Reactor With Non-Uniform Influent Concentration Distributions, Biotechnol. Bioeng. 97 (2007) 354–366. doi:10.1002/bit.

[32] M. SandbergB. K. Ahring, Anaerobic treatment of fish meal process waste-water in a UASB reactor at high pH, Appl. Microbiol. Biotechnol. 36 (n.d.) 800–804.

[33] A.B.P. Parag R. Gogatea, Anthony A.C.M. Beenackersb, Multiple-impeller systems with a special emphasis on bioreactors:a critical review, Biochem. Eng. J. (2000).

[34] M.P. Bryant, Microbial methane production—theoretical aspects, J. Anim. Sci. 48 (1979) 193–201.

[35] B. Singh, K.L. Kovács, Z. Bagi, J. Nyári, G.L. Szepesi, M. Petrik, Z. Siménfalvi, Z. Szamosi, Enhancing Efficiency of Anaerobic Digestion by Optimization of Mixing Regimes Using Helical Ribbon Impeller, Fermentation. 7 (2021). doi:10.3390/fermentation7040251.

[36] K. Latha, R. Velraj, P. Shanmugam, S. Sivanesan, Mixing strategies of high solids anaerobic co-digestion using food waste with sewage sludge for enhanced biogas production, J. Clean. Prod. 210 (2019) 388–400. doi:10.1016/j.jclepro.2018.10.219.

[37] L. Tian, D. Zou, H. Yuan, L. Wang, X. Zhang, X. Li, Identifying proper agitation interval to prevent floating layers formation of corn stover and improve biogas production in anaerobic digestion, Bioresour. Technol. 186 (2015) 1–7. doi:10.1016/j.biortech.2015.03.018.

[38] P. Kaparaju, I. Buendia, L. Ellegaard, I. Angelidakia, Effects of mixing on methane production during thermophilic anaerobic digestion of manure: Lab-scale and pilot-scale studies, Bioresour. Technol. 99 (2008) 4919–4928. doi:10.1016/j.biortech.2007.09.015.

[39] H. Caillet, D.M. Madyira, L. Adelard, Study of the performances of a vinasse mesophilic anaerobic digester behavior submitted to intermittent mixing: Monitoring of the physicochemical properties of the digestate and local samples of the digester, Bioresour. Technol. Reports. 16 (2021). doi:10.1016/j.biteb.2021.100837.

[40] I.H. Franke-Whittle, A. Walter, C. Ebner, H. Insam, Investigation into the effect of high concentrations of volatile fatty acids in anaerobic digestion on methanogenic communities, Waste Manag. 34 (2014) 2080–2089. doi:https://doi.org/10.1016/j.wasman.2014.07.020.

[41] I. Ferrer, F. Vázquez, X. Font, Long term operation of a thermophilic anaerobic reactor: process stability and efficiency at decreasing sludge retention time, Bioresour. Technol. 101 (2010) 2972–2980.

[42] T.R. Camp, Velocity gradients and internal work in fluid motion, J. Bost. Soc. Civ. Eng. 30 (1943) 219–230.

[43] F. Shen, L. Tian, H. Yuan, Y. Pang, S. Chen, D. Zou, B. Zhu, Y. Liu, X. Li, Improving the mixing performances of rice straw anaerobic digestion for higher biogas production by computational fluid dynamics (CFD) simulation, Appl. Biochem. Biotechnol. 171 (2013) 626–642. doi:10.1007/s12010-013-0375-z.

[44] R. Sindall, J. Bridgeman, C. Carliell-Marquet, Velocity gradient as a tool to characterise the link between mixing and biogas production in anaerobic waste digesters, Water Sci. Technol. 67 (2013) 2800–2806. doi:10.2166/wst.2013.206.

[45] H.K. Ong, P.F. Greenfield, P.C. Pullammanappallil, Effect of mixing on biomethanation of cattle-manure slurry, Environ. Technol. (United Kingdom). 23 (2002) 1081–1090. doi:10.1080/09593332308618330.

[46] U. Bergamo, G. Viccione, S. Coppola, A. Landi, A. Meda, C. Gualtieri, Analysis of anaerobic digester mixing: comparison of long shafted paddle mixing vs gas mixing, Water Sci. Technol. 81 (2020) 1406–1419. doi:10.2166/wst.2020.248.

[47] J. Ding, X. Wang, X.-F. Zhou, N.-Q. Ren, W.-Q. Guo, CFD optimization of continuous stirred-tank (CSTR) reactor for biohydrogen production, Bioresour. Technol. 101 (2010) 7005–7013. doi:10.1016/J.BIORTECH.2010.03.146.

[48] A. Lemmer, H.J. Naegele, J. Sondermann, 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, Energies. 6 (2013) 6255–6273. doi:10.3390/en6126255.

[49] B. Singh, Z. Szamosi, Z. Siménfalvi, Impact of mixing intensity and duration on biogas production in an anaerobic digester: A review, Crit. Rev. Biotechnol. 40 (2020) 508–521. doi:10.1080/07388551.2020.1731413.

[50] Andrew G. Hashimoto, Effect of mixing duration and vacuum on methane production rate from beef cattle waste, Biotechnol. Bioeng. 24 (1982) 9–23. doi:10.1002/bit.260240103.

[51] K. Lewis, W. Hughes, Optimisation of Methane Production from Anaerobically Digested Cow Slurry Using Mixing Regime and Hydraulic Retention Time Submitted by, (2015).