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Enhancing Efficiency of Anaerobic Digestion by Optimization of Mixing Regimes Using Helical Ribbon Impeller

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Abstract: The appropriate mixing system and approach to effective management can provide favorable conditions for the highly sensitive microbial community, which can ensure process stability and efficiency in an anaerobic digester. In this study, the effect of mixing intensity on biogas production in a lab-scale anaerobic digester has been investigated experimentally and via modeling. Considering high mixing efficiency and unique feature of producing axial flow, helical ribbon (HR) impeller is used for mixing the slurry in this experiment under various conditions. Three parallel digesters were analyzed under identical operating conditions for comparative study and high accuracy. Effects of different mixing speeds (10, 30, and 67 rpm for 5 min h^{-1}) on biogas production rate were determined in 5-L lab-scale digesters. The results demonstrated 15–18% higher biogas production at higher mixing speed (67 rpm) as compared to 10 rpm and 30 rpm and the results proved statistically significant ($p < 0.05$). Biogas production at 10, 30, and 67 rpm were 45.6, 48.6, and 52.5 L, respectively. Higher VFA concentrations (7.67 g L^{-1}) were recorded at lower mixing intensity but there was no significant difference in pH and ammonia at different speeds whereas the better mixing efficiency at higher speeds was also the main reason for increase in biogas production. Furthermore, model simulation calculations revealed the reduction of dead zones and better homogeneous mixing at higher mixing speeds. Reduction of dead zones from 18% at 10 rpm to 2% at 67 rpm was observed, which can be the major factor in significant difference in biogas production rates at various mixing intensities. Optimization of digester and impeller geometry should be a prime focus to scale-up digesters and to optimize mixing in full-scale digesters.

Keywords: anaerobic digestion; methane production; mixing intensity; optimization

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1. Introduction

Modern society produces enormous volumes of biodegradable waste, posing a grave threat to both human and animal health, as well as the environment. Various waste treatment and disposal technologies are employed to help avoid and manage this problem. Anaerobic digestion is one of most trending non-conventional energy sources to produce energy from biomass due to its very low carbon footprint [1]. 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 used for various purposes, such as cooking, power generation, and heating or as vehicle fuel after upgradation to biomethane and removal of corrosive substances such as H_2S [2]. 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 of 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 [3]. 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 favorable shear conditions necessary to disperse the bubbles, and droplets and also prevent disruption of microbial flocs [4]. Effect of mixing is highly significant when the digester is operated at higher solid content (>10%) and lower HRT (15–20 days) [5].

Mixing in an anaerobic digester can be performed by various modes, such as mechanical mixing, slurry recirculation, and biogas circulation. From the above-mentioned modes of mixing, mechanical mixing is preferred due to lower power consumption and higher biogas production as compared to others [6,7]. Volumetric biogas productivity is a major economic indicator for a biogas plant. An extensive amount 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 [8–10]. 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; however, 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 [11]. 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 [5,12]. For instance, Lebranchu et al. [13] demonstrated that mixing with helical ribbon (HR) impeller produced 50% more biogas relative to a single RT impeller due to better distribution of shear and viscosity in the entire 2-L digester during laminar flow. In another study [14], marine impeller (MI), rhuston impeller (RT), and anchor impeller (AI) were compared to analyze 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. For instance, the multi-impeller generates lower shear rates and promotes uniform power dissipation in the bioreactor. Trad et al. [15] have found that the flow patterns of the slurry were highly affected by varying the inter impeller and off bottom clearances. Different combinations of MI, four-blade RT, six-blade RT, and elephant ear turbines were also analyzed. Due to the spatial variation in shear intensity in the stirred reactors, the precise shear conditions favorable for the microorganisms are poorly defined. However, 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/D* (impeller diameter to tank diameter) ratio can generate better results [16]. The slurry broth shows properties of pseudo plastic fluid, which is generally characterized by shear thinning behavior [17]. According to literature, at TS > 2.5% the slurry possesses non-Newtonian shear thinning behaviour and thixotropic characteristics in the laminar regime (approximately <10–100) [18]. According to Capua et al., high solid anaerobic digestion (HSAD) (TS >6%) results improves energy balance and quality of digestate [19,20]. To perform HSAD efficiently, appropriate technologies for mixing, transportation, pretreatment, and process control should be applied.

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. [9] reported that a negative effect was observed on biogas production rate in a 4.5 L unbaffled digester because microbial flocs were destroyed at 1,500 rpm. Similar results were demonstrated by Fei Shen et al. [21] 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 behavior of microorganisms need to be understood under varying shear stresses. According to our previous study [5], 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, kinematic, and dynamic similarities [22]. 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 an industrial scale [23]. Our current research aim is to study the effect of mixing by helical ribbon impeller in a 5 L lab-scale anaerobic digester. There is no incentive to apply a continuous mixing strategy in an anaerobic digester because it leads to both excess power usage and declining biogas output.

In this study, the main goal is to analyze digestion kinetics and biogas production under various mixing conditions. 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 modeling a lab-scale digester using sewage sludge, pig manure, and ensilaged sweet sorghum as substrate. The novelty of this work lies in both the method of experiments and the results obtained. Here, the effect of mixing in digester is analyzed both experimentally and numerically. The experimental results significantly comply with the numerical results. 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.

2. Materials and Methods

2.1. Experimental Setup and Procedures

The experiments were carried out in three parallel single-stage continuously fed 5 L lab-scale digesters with a head space of 1 L, custom-made from stainless steel [24]. The digesters were run under identical operating conditions of temperature (37 °C) and mixing speeds (10, 30, and 67) for each set of experiments. The schematic 2-D diagram of the experimental setup is shown in Figure 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. Figure 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. 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 analyzed that were operated at identical parameters to attain accuracy in overall process. 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.

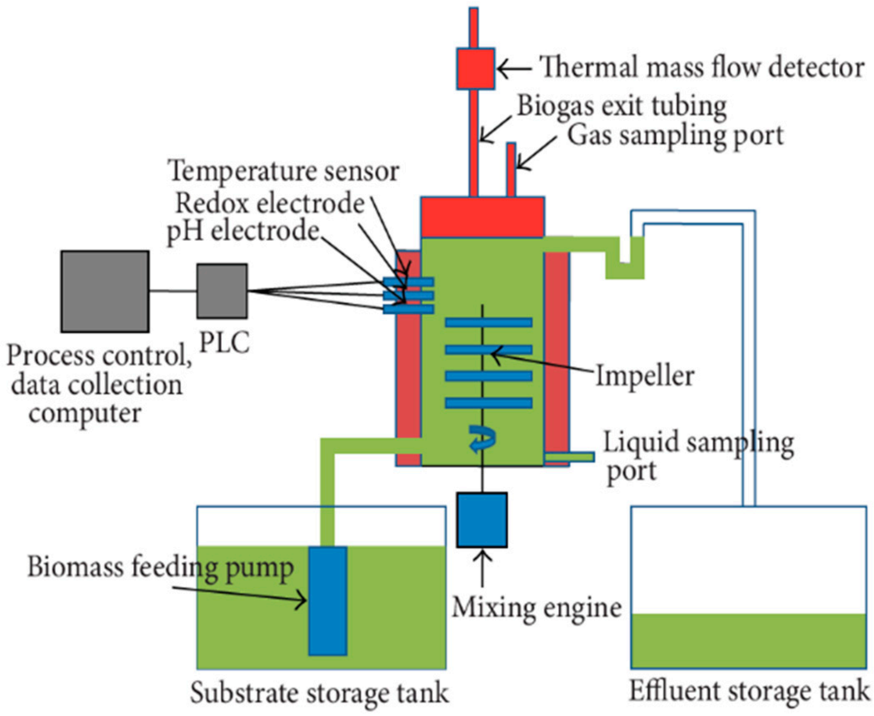


Figure 1. Schematic diagram of experimental setup.

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

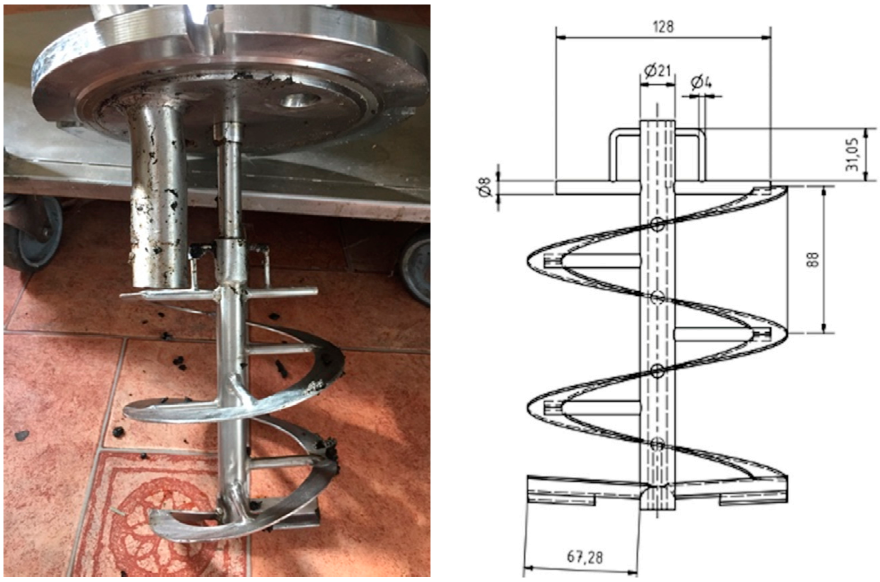


Figure 2. Representation of the geometry of the mixers inside the digesters.

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 sewage sludge, pig slurry, and ensilaged sweet sorghum. 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. 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 mesophilic temperature (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. 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.

Table 2. Characteristics of substrate used in the experiment.

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

2.3.1. Gas Analysis

Gas volume was measured continuously by means of direct mass flow controllers (DMFC, Brooks Instruments, Hatfield, PA, USA) 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 (6890 N Net-work GC system, Agilent Technologies, Glostrup, Denmark). 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.

2.3.2. Volatile Fatty Acids

Volatile acids were determined by HPLC 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 analyzed every week.

2.3.3. Total Solid (TS) and Organic TS Content

The dry matter content was determined by drying the substrate at 105 °C for 24 h 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.

2.3.4. 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. Furthermore, the tests were also undertaken between all three digesters at one particular rpm—i.e., F1R30, F2R30, F3R30, and so on.

2.4. Mixing Operation

2.4.1. 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 upon 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 [25–28]. 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.

2.4.2. 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, it is confirmed that if TS >2.5% then the slurry possesses non-Newtonian shear thinning behavior and thixotropic characteristics in the laminar regime (approximately <10–100) (Table 3). Figure 3 represents rheological behavior of various fluids.

Table 3. Rheological properties of substrate.

Temperature (°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

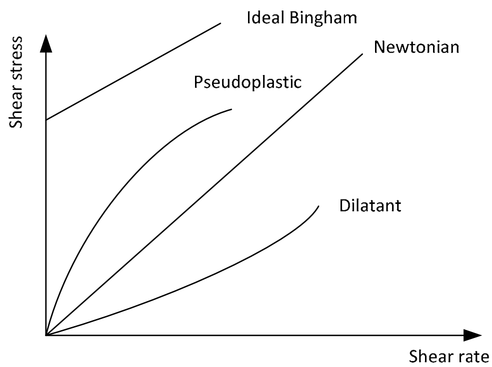


Figure 3. Different types of fluids and their behavior with respect to shear rates.

For this instance, the power law model can be proposed to calculate the apparent viscosity and shear rate (Equation (1)).

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

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 [29]. The average shear rate inside the vessel can be calculated as per the Equation (2):

$$\gamma_a' = k_s \cdot N \quad (2)$$

Here k_s is Otto-Metzer constant which is directly associated with the impeller geometry. From the experimental measurements by Zhang et al. [30] value of k_s for helical ribbon impeller was k_s = 34.8. (Equations (3) & (4)):

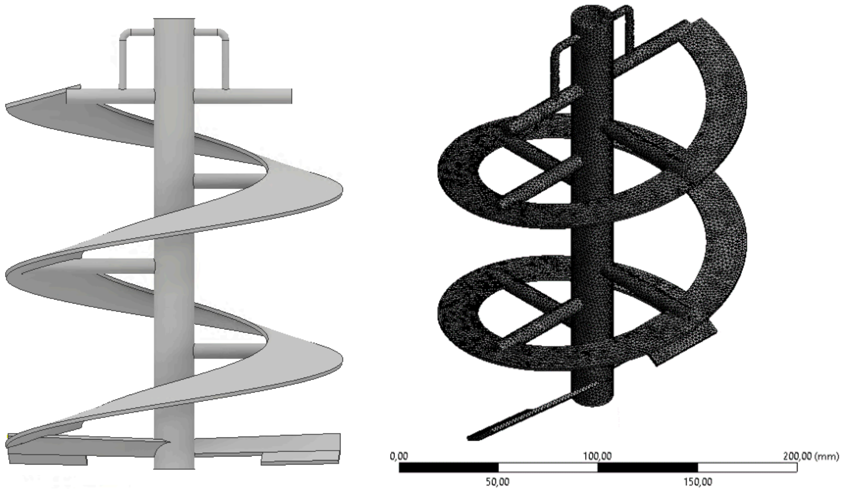
$$\tau = K \cdot \gamma_a'^{(n)} \quad (3)$$

$$\tau = K \cdot (k_s \cdot N) \quad (4)$$

2.5. 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 Figure 4. The turbulence model k-ω is used for the simulations. The time step was constant, the value was 10^{-5} s. FLUENT was set up to iterate until the convergence parameters were satisfied, to reach the convergence, in all steps having a maximum 50 inner iteration steps per time step based on the 2,945,850 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. Additionally, 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 behavior 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.



(**a**) (**b**)

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

The volume-averaged velocity magnitudes were obtained as (Equation (5)):

$$\langle \| u \| \rangle = \frac{1}{V_L} \iiint_{V_L}^{1} \| u \| (V) dV \tag{5}$$

3. Results and Discussion

3.1. Startup Phase

The digesters were pre-run to obtain a stable digestion process and constant biogas production. The OLRs were set at 5 g for the entire experiment. It was observed that, until 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.

3.2. 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. The cumulative biogas production by all three digesters is given in Figure 5. 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. Figure 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 [31] demonstrated that methane production was higher during intermittent mixing when compared to an unmixed digester and a study by Tian et al. [32] proved that continuous mixing resulted in declined biogas production rates [32,33]. From day 15 to 31 during the minimum mixing speed of 10 rpm, lower biogas production was observed due to higher VFAs concentration and instabilities in the AD process. The mean biogas production per day during these two weeks was recorded as 2.622 mL d^{-1} and overall cumulative volume of biogas produced during this period was 43.5 L. From day 32 to day 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 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 [34], efficient dispersion of metabolic products, 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. Figure 6 represents the mean biogas production per day by all three digesters at various rotational speeds.

In Figure 6, 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 of Hoffmann et al. [9] where it was demonstrated that various mixing intensities (1500, 500, 250, 50 rpm) had no effect on the efficiency of the AD process. At higher mixing intensities, *Methanosarcina app*. and *M. concilii* were found abundant, which also supported the fact that mixing intensities provided a favorable 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, respectively, 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. [13].

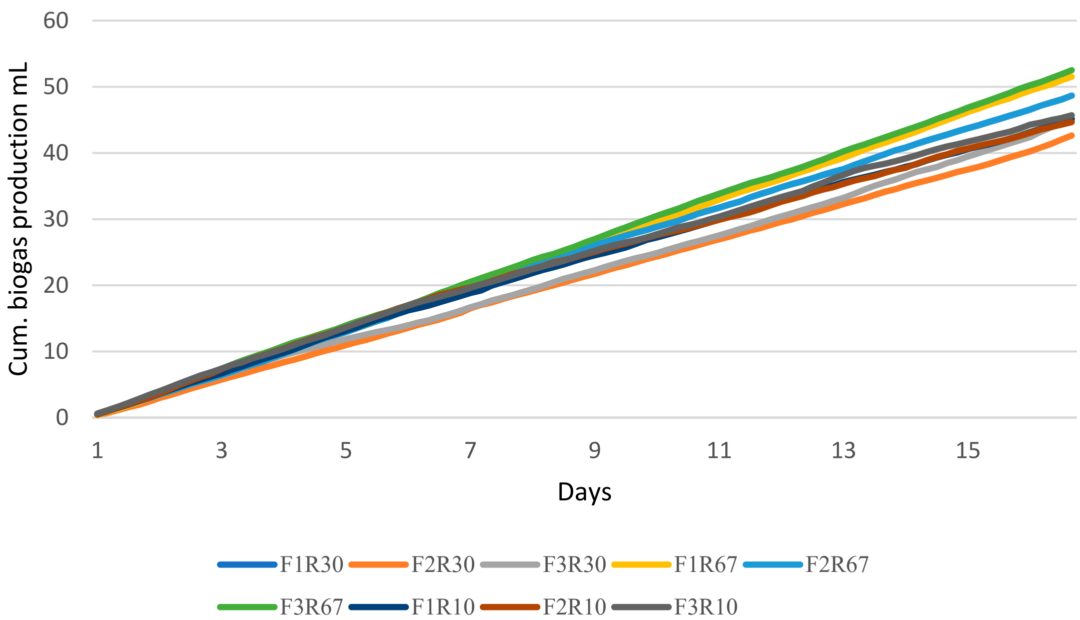


Figure 5. Cumulative biogas production rates in the three digesters.

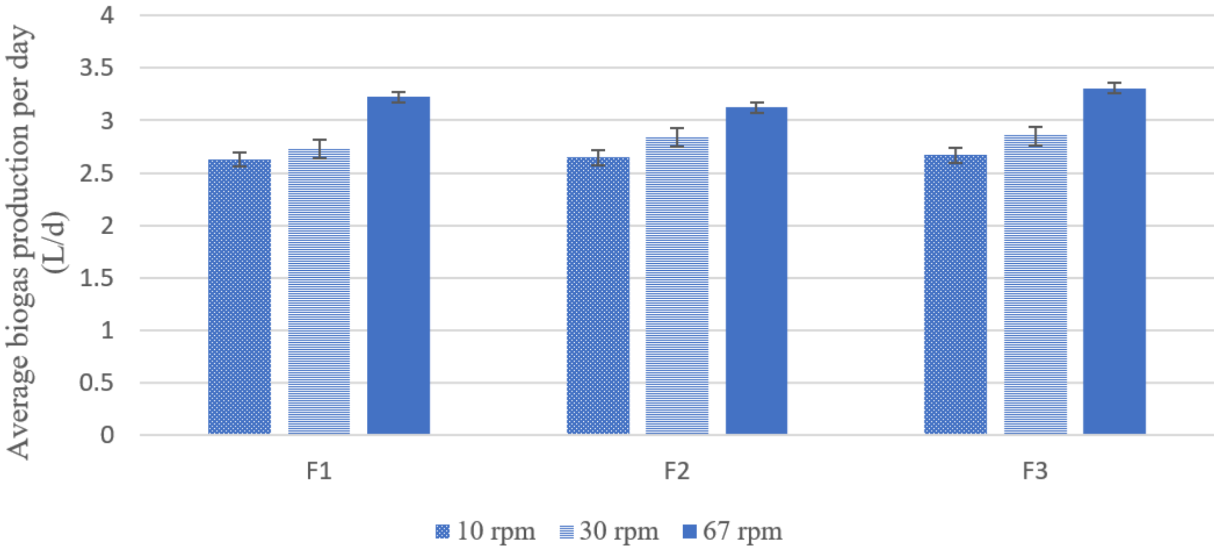


Figure 6. Average biogas production per day by the digesters at 10, 30, and 67 rpm.

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 (Table 4). 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 homogenization in terms of nutrients, temperature, and distribution of fresh substrate [5]. 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 a 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 higher biogas production rate (Table 5). 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 behavior of the slurry.

3.3. 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 were 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 4. Experimental results at various mixing speeds.

n (rpm)	Mixing Regime	Shear Rate [γ_a' (s^{-1})]	Shear Stress [τ (Pa)]	BPR (L)
10	5 min/h	5.6	5.14	43.5
30	5 min/h	17.4	9.54	45.2
67	5 min/h	39	14.99	52.5

Table 5. 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 biogas production	45.1	44.2	43.5	48.6	42.6	45.2	51.5	48.6	52.5
VFAs (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 ratio	0.35	0.69	0.40	0.25	0.54	0.59	0.19	0.34	0.41

Table 6. 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		1.0968×10^{-12}
	10	67		6.65976×10^{-26}
F2	10	30		0.00138614
	30	67		7.69224×10^{-10}
	10	67		0.001386142
F3	10	30		0.01789452
	30	67		2.47333×10^{-12}
	10	67		2.49809×10^{-18}

3.4. Effect of Mixing Regimes on VFA Accumulation

VFA concentrations were measured regularly during the digestion process and served as an indicator in terms of the stability/instability of the digesters routinely [9,35]. However, this study did not support the idea that at higher mixing a destabilization 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 [36]. 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 [37]. 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 stabilized 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. [35] 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}.

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 stabilized 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 accumulation of VFAs at high mixing intensities as it can affect the establishment of methanogenic zones [38]. A mixing intensity of 67 rpm led to reduced production of VFA, which contributed to the high biogas production of the 10 and 30 rpm mixing speed. Increase in VFA concentration led 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 summarized in Figures 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 [39]. 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 localized inhibiting environments.

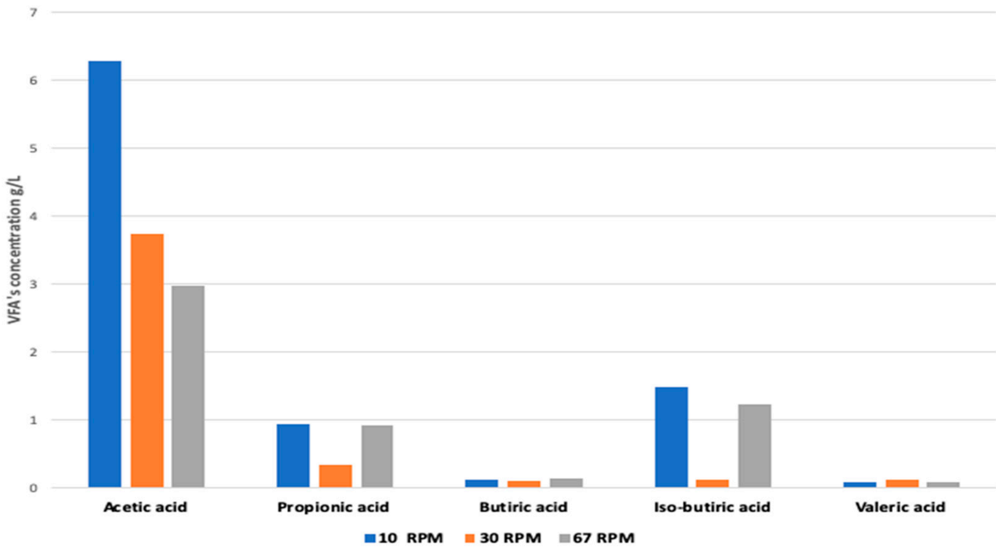


Figure 7. VFAs concentration at different mixing intensities.

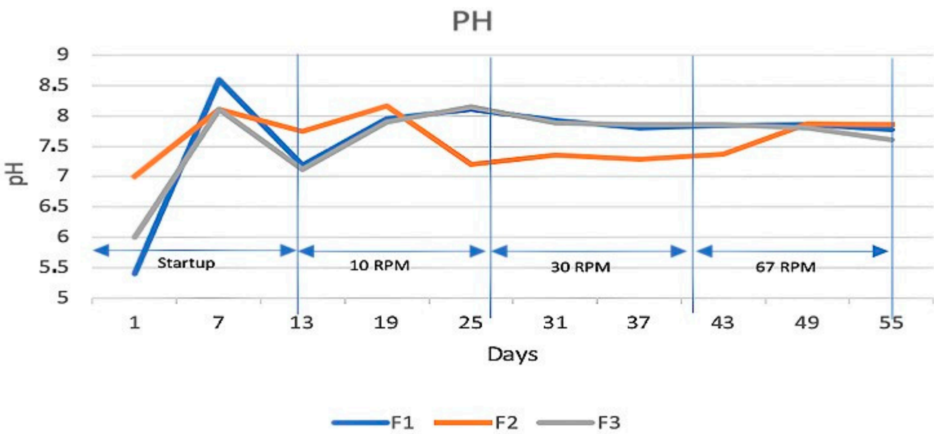


Figure 8. pH during the experiment under various mixing intensities.

4. Numerical Simulation of Digester Hydrodynamics

Simulations revealed the presence of higher unmixed zones at lower mixing speeds characterized by reaching near zero velocities (Figure 9a,d). The color 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 color near the walls of the digester (Figure 9b,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.

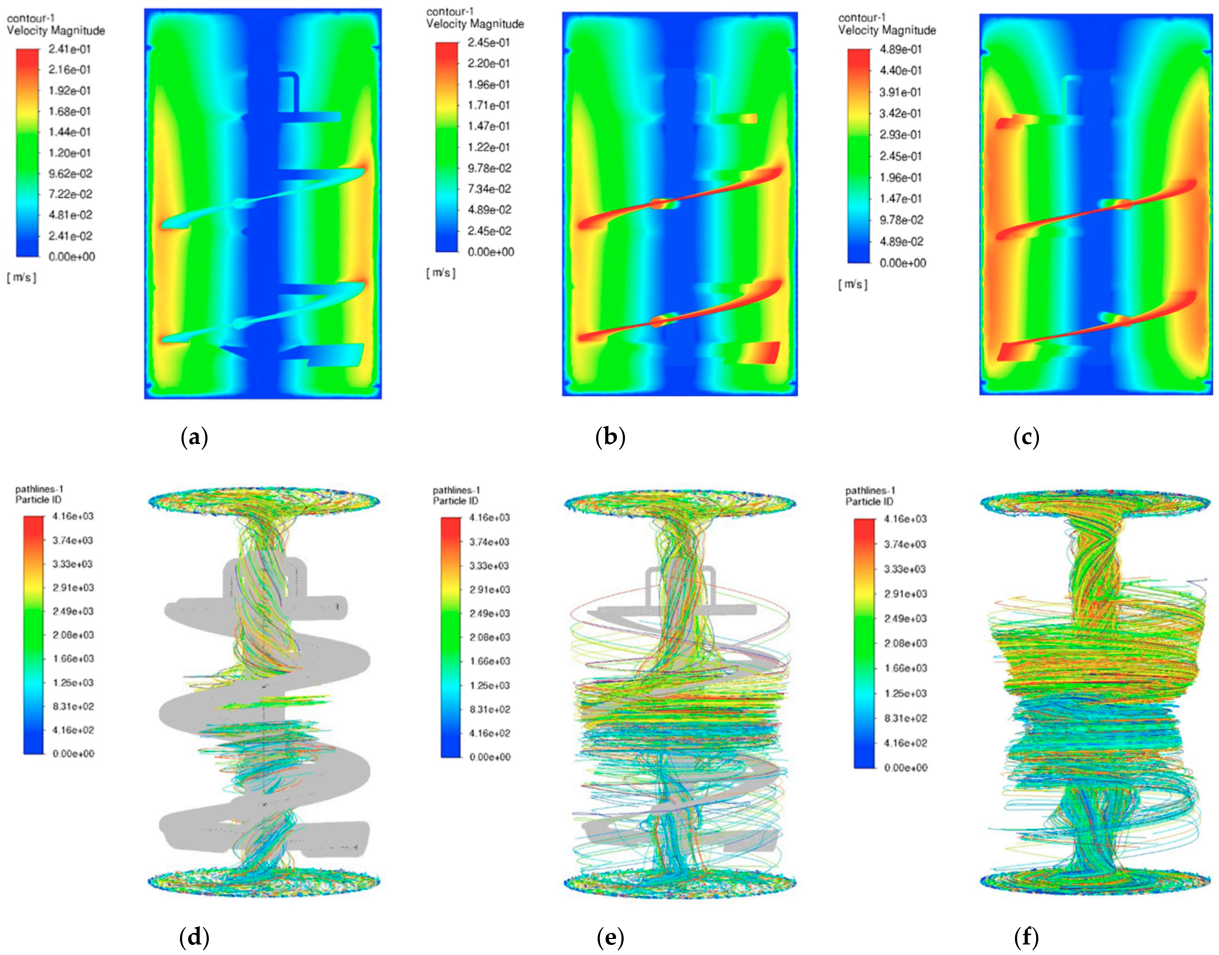
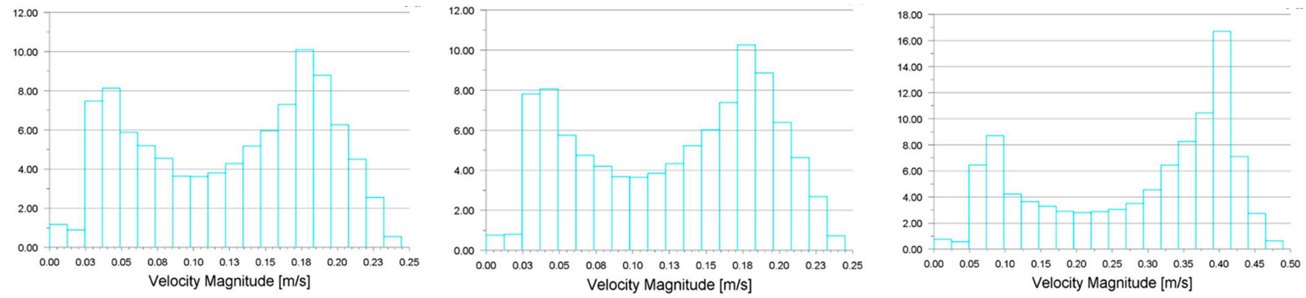


Figure 9. (**a**) 10 rpm; (**b**) 30 rpm; (**c**) 67 rpm; (**d**) 10 rpm; (**e**) 30 rpm; (**f**) 67 rpm.

It can be observed that increasing the impeller's rotating speed causes a reduction of dead zones. 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.

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 Figure 10a,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 (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 and 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.



(**a**) (**b**) (**c**)

Figure 10. Volume percentage in the function of velocity magnitude at 10, 30, and 67 rpm. (**a**) 10 rpm; (**b**) 30 rpm; (**c**) 67 rpm.

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}	0.25	0.12	17%
67	1.33×10^{-5}	0.24	0.10	2%

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.

5. 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. [23] 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 be observed in the entire active volume of the digester and efficiency of the impeller is significant [40]. 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 by impeller geometry. The weakening of core network of shear-thinning fluid increases both the molecular and 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.

6. 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 analyzed to study the mixing effect of the slurry [41–43]. The concept of using paddle impellers can be encouraged by greater consistent distribution of viscosity at lower shear rates and mixing speed [7,31]. 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 [44]. 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 [45]. Minimum periodic mixing is observed to be favorable for a successful anaerobic digestion operation [46–48]. 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 [49]. The direct effect of the shear rate and the mixing speed is discussed in this study.

7. Conclusions

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 VFA accumulation and dead zones. Furthermore, higher mixing speed can lead to reduction in dead zones to less than 2%. After analyzing 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. A large diameter impeller at medium mixing speed is the best combination in direction of optimization of mixing in an anaerobic reactor.

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