Optimizing mixing time to improve the performance of an anaerobic digestion waste-to-energy system for energy recovery from food waste

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ABSTRACT

Mixing in an anaerobic digester creates a homogeneous system enhancing mass transfer, and enables the solid wastes and microorganisms remain in suspension, but continuous mixing strategy is not cost-effective due to the demand of high electric energy. Optimizing mixing time to reduce energy consumption would create a more energy efficient anaerobic digestion (AD) process with higher biogas yield. This study particularly investigates the effect of different mixing strategies on anaerobic digestion of food waste in order to make the AD waste-to-energy process more energy efficient. Results showed that intermittent mixing is an alternative strategy to continuous mixing or unmixing for high efficient biogas production and energy saving. Through computational fluid dynamics modeling of fluid flow in anaerobic digesters, the mixing time was optimized to 2 mins/hr, at which point the reaction mixture is almost entirely homogeneous. The results of the CFD model was validated with the experimental data. At an organic loading rate of 2.4 g VS_{FW}/L/day, the semi-continuously mixed reactor maintains a higher specific methane yield of 437 ml CH_4/g VS_{FW} in comparison with the other controls. Based on the results of the bench scale experiment, the energy balance of the hybrid AD waste-to-energy system was simulated and evaluated. The energy balance investigated the electricity generated and the net heat output generated, in addition to self-sustaining and meeting the energy requirements of the various AD processes investigated. Based on the analysis, it was found the semi-continuous mixing is more energy efficient and sustainable to generate sufficient biogas output for the energy system to provide a net positive heat and electricity output.

Keywords: Anaerobic digestion; Food waste; Mixing; Computational fluid dynamics; Energy.

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1. Introduction

A major contemporary environmental concern faced by governments around the world is food waste management. One third of global food production, amounting to 1.3 billion tones, is currently wasted annually [1]. In addition urban centres around the world face an increasing demand for energy. In Singapore, import of energy products increased by 2% from 2015 to 2016, and electricity generation through combustion of imported natural gas peaked at 51.6 TWh in 2016 [2]. Given the combined challenges of food wastage and meeting ever-increasing energy demands, there is growing recognition that food waste management and the need for greener energy supply can be resolved together through a sustainable waste-to-energy solution. Anaerobic digestion (AD) is an ideal solution for converting food waste into energy because the methane-rich biogas generated by anaerobic microorganisms can be utilized for heat and power generation. Biogas is a highly desirable energy source because it produces low greenhouse emissions and is a cleaner alternative to fossil fuels, as well as the fact that it is produced from waste material.[3]. Compared to alternative disposal methods for waste food, such as landfills and incineration, anaerobic digestion poses minimal threats to the soil, water and air [4].

Effective production of biogas requires the development of a process that limits energy losses and has low input requirements, in addition to being energy efficient. Furthermore, the AD system must be self-sustainable by producing electricity and heat in excess of its normal operational requirements. Any excess energy produced can be used to power small appliances or diverted for other uses. In order to achieve a higher efficiency, the operating parameters and the energy balance of an AD waste-to-energy system need to be evaluated in detail and optimized

One critical parameter that can be optimized to reduce energy consumption in an AD system is the mixing speed and frequency. Generally, the energy consumption for mixing in a full-scale digester is varies from 14 to 54% of the total energy demand of the plant [5, 6]. Mixing results in the formation of a homogeneous substrate, eliminating stratification and ensuring the suspension of solid substrates for degradation [7]. In addition, mixing also facilitates the uniform distribution of heat within the digester and the transfer of gas from the inoculum [8, 9]. There are two main operational modes for mixing: Continuous, and semi-continuous mixing. Continuous mixing enhances the distribution of substrates, heat and microorganisms for the production of methane, but it also consumes a significant amount of energy [7]. Conversely, semi-continuous mixing requires significantly less energy input, but produces comparable quantities of the desired products[10]. The lack of consensus and continued contention regarding this specific AD operational parameter call for deeper investigation into and evaluation of the effects of mixing on the efficiency of AD systems.

During AD, bacteria and archaea facilitate the production of acetates and methane respectively; thus, efficient and continued growth of these microorganisms is instrumental in the production of biogas. Mixing is an essential step in AD as it influences the distribution of these microbial communities within the AD mixture. However, research has shown that mixing can affect the microbial structures; in particular, forceful and repeated mixing can disrupt the development and integrity of these structures[7]. However, an AD mixture with high solid content may require continuous mixing in order to inoculate fresh feed, distribute nutrition and homogenize the digestate. Furthermore, unmixed or poorly-mixed reaction mixtures can result in the formation of dead zones where the AD activity is severely restricted. Hence, the identification of optimal mixing conditions and mechanisms is important for AD processes.

Therefore, it can be concluded that the optimization of mixing conditions can facilitate efficient microbial growth and decrease energy input requirements in the AD system. This will yield a more energy efficient AD process with a higher production rate of biogas. Hitherto, most studies focus specifically on the effects of mixing on biogas yield [11-13], and little research has been conducted on the use of computational fluid dynamics (CFD) to study mixing conditions using AD system models. Thus, this study will consider the effect of mixing in an AD system for food waste to establish optimum conditions for AD waste-to-energy system and energy savings.

2. Materials and Methods

2.1. Inocula and substrates

Seed sludge was collected from a large-scale anaerobic digester from the Ulu Pandan Water Reclamation Plant (UPWRP) in Singapore. The anaerobic digester at UPWRP currently treats waste activated sludge from the secondary wastewater treatment plant for domestic sewage wastes. In this study, each reactor was inoculated with this seed sludge at approximately 80% (v/v). The ratio of volatile suspended sludge (VS) to total suspended sludge was 0.8 with initial TS of 15 g/L. Food Waste (FW) was obtained from a canteen at the National University of Singapore. Typical food waste from the canteen consisted of fruits, vegetables, noodles, meat, and white/brown rice. After removing any bones and non-biodegradable waste like plastic bags and utensils, the FW was homogenized by a blender and then stored in a freezer at -20 ^{o}C freezer for feeding the reactors. Detailed characteristics of FW are listed in Table. 1.

Table 1

Characteristics of food waste

Components	Unit	This Study	Other Studies	
			Zhang et al.[14]	Banks et al.[15]
Total Solids	wt %	31.70 ± 1.20	30.90	23.74
Volatile Solids	wt %	29.59 ± 2.37	26.35	21.71
VS/TS	wt %	93.34 ± 1.54	85.30	91.44
Non-Metals		This Study		Han et al.[16]
Carbon	wt %	47.08 ± 2.01	46.78	51.40
Hydrogen	wt %	7.04 ± 1.11	-	6.10
Nitrogen	wt %	3.02 ± 0.32	3.16	3.50
Sulphur	wt %	<0.5	-	1.00
C/N ratio	-	15.58 ± 1.87	14.80	14.69
Metals			Hamed et al.[17]	
Al	wt %	<0.01	0.054	
Ca	wt %	0.17 ± 0.10	-	
Cu	wt %	<0.01	0.001	
Fe	wt %	<0.01	0.072	
K	wt %	0.37 ± 0.06	0.795	
Mg	wt %	0.04 ± 0.01	0.161	
Mn	wt %	<0.01	0.005	
Na	wt %	0.86 ± 0.45	-	
Zn	wt %	<0.01	0.006	

2.2. Reactor specifications and operation

Three bench scale reactors with operating capacities of 5 L were used to investigate the effect of mixing conditions on mono-digestion of FW. The bench scale reactors were equipped with temperature control systems and controllable mixing systems. Reactors inoculated with seed sludge were incubated at 35℃. The reactors were labelled R1, R2 and R3. R1 was subjected to semi-continuous mixing, where the reactor mixture was mixed for 2 minutes at 80rpm between 1 hour intervals where no mixing took place. R2 was subjected to continuous mixing at 80rpm for the duration of the experiment. R3 was not subjected to any mixing. Organic loading rate (OLR) was increased from 0.9 g to 2.4-VS_{FW}/L/day.

2.3. Analytical methods

COD and ammonia were detected and quantified using HACH colorimeter (HACH DR900, USA) according to the manufacturer's instructions. The pH was recorded using a pH analyzer (Agilent 3200M, USA). TS and VS were determined based on the weighing method after being dried at 103-105 °C and burnt to ash at 550°C. Methane (CH_4) production was determined using a gas chromatograph (Clarus 580 Arnel, PerkinElmer, USA) equipped with a thermal conductivity detector. Elemental analyses in FW were determined using the vario MICRO cube (Elementar, Germany). The analysis of microbial communities was examined by IIlumina Hiseq 2000 pyrosequencing technology according to the method described by Zhang et al., (2017) [18].

2.4. Computational Fluid Dynamics modeling

The CFD model is single phase and the mixing in digesters is performed under turbulence flow conditions. The turbulence model used here is k-ε model, which is the most common model used in CFD to simulate flow characteristics for turbulent flow. To compute the flow field, the boundary conditions are specified as: (1) The fluid surface is set as a symmetry boundary; (2) No velocity slip exists at the solid wall; (3) at the moment of the injection, the mass fraction of tracer in the injected region is 1 while it equals 0 at all other regions.

The sludge and diluted food waste are Newtonian fluids. The viscosity and density of sludge are 0.0248 kg/m·s and 981.5 kg/m^3, respectively. The viscosity and density of diluted food waste are 0.0088 kg/m·s and 981.8 kg/m^3, respectively.

2.4.1 Mixing model

The Commercial CFD software, ANSYS 16.2 was used to solve the mathematical model. The geometry and mesh were generated using ANSYS ICEM in ANSYS Workbench 16.2 (ANSYS-Fluent, Inc, 2015). The impeller rotation was characterized using the Multiple Reference Frame method (MRF).

2.4.2 Flow Model

The equations governing the mechanical mixing of anaerobic digesters are the well-known Navier-Stokes equations [19]. For low flow speeds (Mach < 0.3), the density of the fluid can be considered constant and the Navier-Stokes equations for incompressible Newtonian fluids can be simplified as:

$$\nabla \cdot \overrightarrow{u} = 0$$

$$\rho\left(\frac{\partial \overrightarrow{u}}{\partial t} + \overrightarrow{u} \cdot \nabla\overrightarrow{u}\right) = -\nabla p + \mu \nabla^2 \overrightarrow{u} + \overrightarrow{f}$$

where ρ is the liquid density, t the time, $\overrightarrow{u}$ the velocity, p the static pressure and μ the dynamic viscosity.

2.4.3 Mixing Time Model

Firstly, the normalized tracer concentration, C_n, is defined as:

$$C_n = \frac{C}{c_{ave}}$$

where C is the tracer concentration at any computational cell which will change with position and time, and c_{ave} is the average tracer concentration throughout the entire reactor. The mixing time was defined as the time required for normalized tracer concentrations at all monitoring locations to reach the range between 0.99 and 1.01 [20].

2.4.4 Model Validation

Fig. 1 shows that the model's predicted results fit well with the experimental results from Ihejirika and Ein-Mozaffari [20] who studied the mixing performance of xanthan gum solution in a mixing tank with helical ribbon impeller. It can be observed that the CFD results highlight features of the flow field of experiments and computed velocities. The small differences between the experimental and predicted date may be attributed to the difference between the blade widths of the impellers used in the model and the experiment, which in the latter was not mentioned in the paper, numerical errors and measurement inaccuracies arising from the experiments.

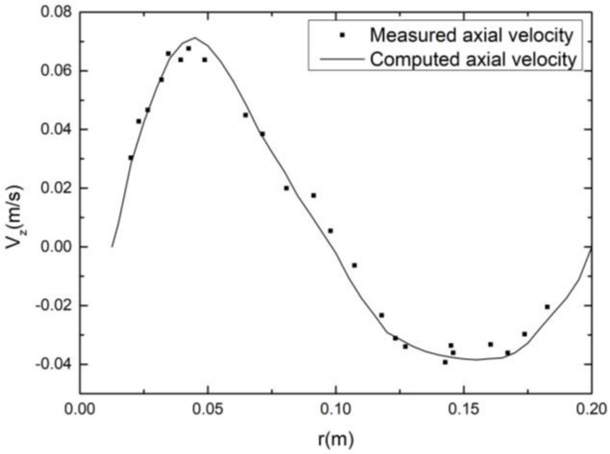


Fig. 1 Comparisons of computed and measured axial velocity at mid horizontal surface for xanthan gum solution

2.5. Energy Analysis

Fig. 2 shows the energy balance for the waste-to-energy anaerobic digestion system. The energy balance was scaled up to the size of a 1000 L reactor to obtain a more realistic understanding of the energy inputs and outputs.

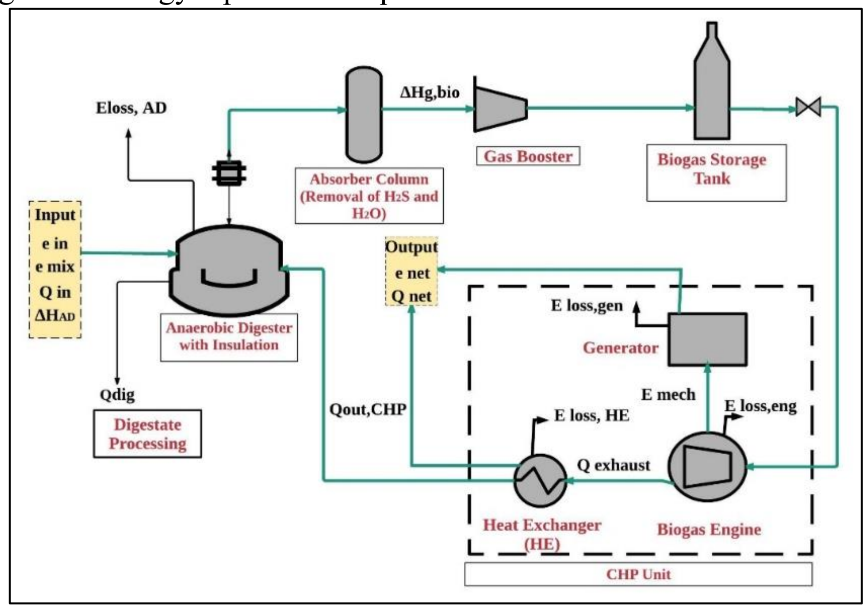


Fig. 2 Energy Flowchart for Hybrid AD – CHP System

The following equations were used to obtain the overall energy balance.

<u>Higher Heating Value</u>

The equation proposed by Meraz et. al was used to obtain the value for the higher heating value (HHV) of the bio waste [21]:

$$\Delta H_{AD} = \frac{[m_s \times (\%TS_s) \times HHV_s]}{100} = \{m_s \times (\%TS_s) \times [370.8(\%C) + 1112.4(\%H) - 139.1(\%O) + 317.8(\%N) + 139.1(\%S)]\}/100 \quad \textbf{(1)}$$

$$\Delta H_{g,bio} = n_g HHV_g = n_g \frac{\sum HHV_k \times (vol\%gas_k)}{100} \quad \textbf{(2)}$$

where

$\Delta H_{g,bio}$ - standard enthalpy change of formation of the bio waste (produced gas); m_s - total mass of the biomass input; $\%TSs$ - percentage of the total solids of the biomass waste; HHV_s (HHV_g) - higher heating value of the input bio waste (produced gas) at standard state; n_g - total gas yield; %C, %H, %O, %N and %S - elemental mass percentage of the bio input on an oven dried basis; HHV_k - higher heating value of gas component k at standard state; $vol\%gas_k$ - volumetric percentage of gas component k;

Heat Loss

The reactor system is not perfectly insulated. Hence, heat lost from the digester system and the discharged digestate due to natural convection and conduction need to be accounted for in the calculations. The following equations were used for calculations [22], and it is assumed that the pilot scale reactor has a protective insulation cover that reduces the heat loss by about 50% [23].

$$Q_{dig} = m_{s,dig}(T - T_\infty)C_{dig} \quad \textbf{(3)}$$

$$E_{loss,AD} = \left[Nu_t \frac{k}{D} A_t + Nu_b \frac{k}{D} A_b + Nu_s \frac{k}{L} A_s\right](T - T_\infty) \quad \textbf{(4)}$$

$$Nu = \begin{cases} 0.54 Ra_L^{1/4} & , \quad top\ surface \\ 0.27\ Ra_L^{1/4} & , \quad bottom\ sueface \\ \left\{0.825 + \dfrac{0.387 Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right\}^2 & , \quad side\ surfacce \end{cases} \quad \textbf{(5)}$$

$$Q_{loss,total} = Q_{dig} + E_{loss,AD} \quad \textbf{(6)}$$

where

Q_{dig} - heat loss (digestate discharged); $m_{s,dig}$ - mass of the digestate; T (T_∞) - temperature of the AD reactor (atmosphere); C_{dig} - specific heat capacity of the digestate; $E_{loss,AD}$ - heat loss due to natural convection for the AD process; Nu_t, Nu_b and Nu_s - Nusselt numbers (top, bottom and side surface of the reactor); k - thermal conductivity of air; D - diameter of the AD reactor; A_t, A_b and A_s - Top, bottom and side surface areas of the reactor respectively; L - height of the reactor; Ra_L - Rayleigh number for reactor surfaces; Pr - Prandtl number for reactor surfaces; $Q_{loss,total}$ - total heat loss for the AD reactor.

Electricity for Mixing

The pilot scale reactor's energy requirements for mixing were used for the calculations [22]. The following equation was used for the various mixing times employed in the study:

$$e_{mix} = t_{mix} \times 564 \times 3600/1000 \quad \textbf{(7)}$$

where

e_{mix} = mixing energy requirements in kJ; t_{mix} = number of hours of mixing;

Power Generation – Combined heat and power (CHP) Unit

The CHP unit comprising the biogas engine, heat exchanger and generator produces heat and electricity using the biogas produced by the AD system. Equations proposed by Bacenetti et. al and Poeschl et. al were used for calculations [24, 25]:

$$e_{gen,CHP} = 0.38 * \Delta H_{g,bio} \quad \textbf{(8)}$$

$$Q_{out,CHP} = 0.48 * \Delta H_{g,bio} \quad \textbf{(9)}$$

Based on the proposed equations, the efficiencies for the generation of heat ($Q_{out,\ CHP}$) and electricity ($e_{gen, CHP}$) from the CHP unit were taken to be 38% and 48%, respectively. $\Delta H_{g,bio}$ is the standard enthalpy change of formation of the bio waste (produced gas).

<u>Overall Energy Balance</u>

The following equations were used for the energy balance of the pilot scale AD system:

$$e_{net} = e_{gen,CHP} - e_{mix} - e_{gas\ booster} \qquad \textbf{(10)}$$

$$Q_{net} = Q_{out,CHP} - Q_{dig} - E_{loss,AD} \qquad \textbf{(11)}$$

e_{net} and Q_{net} represent the electrical and heat energy, respectively, generated by the overall AD-CHP system in excess of the operational requirements of the AD system. These values can be negative or positive based on the efficiency of the system. The additional energy can be potentially harnessed and used to meet energy demands elsewhere.

Since the gas booster was operated semi-continuously to store the gas at high pressures, its energy requirements are ignored for this study's calculations.

<u>AD Efficiency</u>

The final AD efficiency was calculated based on the biogas output using the following equation:

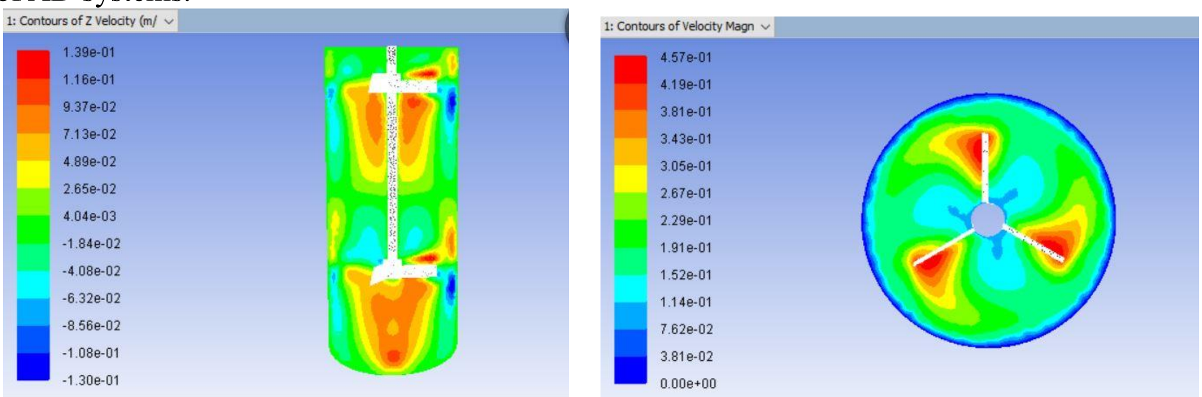
$$\eta_{AD}(\%) = \frac{\Delta H_{g,bio} - Q_{in}}{\Delta H_{AD}} \times 100(\%) \qquad \textbf{(12)}$$

3. Results and Discussion

3.1. Optimisation of mixing performance for high AD efficiency using CFD modelling

The simulation of a lab scale stirred tank with two HE-3 impellers was conducted to study the mixing performance of the digester. To study the flow pattern of the whole reactor, the axial velocity in the mid horizontal surface was analysed. As shown in Fig. 3, the two impellers generated eight small loops in the vessel. The flows split into two directions at the edge of the impellers in the outer region near the wall and change directions when they strike the top or bottom of the reactor, or the flow generated by the other impeller. It was also found that flows with high z velocity were concentrated in regions around the impellers, meaning that the flows were formed by the rotation of two impeller blades. Fig. 3 shows the velocity contours in the horizontal surface through the bottom impeller, demonstrating the rotating process of the impeller, as well as showing that the velocity of the flows around the wall is comparatively low due to the no-slip boundary condition.

It can be observed from Figure 4 that the mixing time for the reactor is 107s, at which point the reaction mixture is almost entirely homogeneous. Based on the simulated mixing shown in Figure 4, a mixing time of 120s is ideal for testing the effect of mixing time on the performance of AD systems.



(A) (B)

Fig. 3 (A) The contour of axial velocity at mid vertical surface and (B) The contour of velocity magnitude at horizontal surface through the bottom impeller

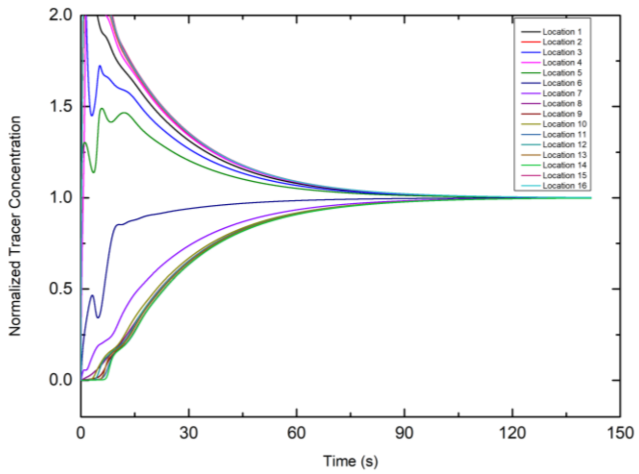


Fig. 4 Normalized tracer concentration versus time for 16 monitoring locations

3.2. Effects of mixing time on AD performance

Tab. 2 shows the methane production potential for mesophilic anaerobic mono-digestion reactors fed with food waste under different mixing time of 0, 2 mins/h and 60 mins/h. The mixing time of 2 mins/h was selected from the CFD modelling in Fig. 4 for semi-continuously mixed reactors. As the OLR is increased from 0.9 to 2.4 g-VS_{FW}/L/day, it can be concluded that the semi-continuously mixed reactor performs better than the unmixed and continuously mixed reactors.

From Tab. 2, it is evident that the continuously mixed reactor (R2) yields a higher SMP during start-up period with the lowest OLR of 0.9 g-VS_{FW}/L/day. Following the start-up period, the semi-continuously mixed reactor (R1) maintains a higher specific methane yield in comparison with the other reactors. Particularly, for the OLR 2.4 g-VS_{FW}/L/day, the SMP are 357, 326 and 89 ml CH_4/g-VS_{FW} for the semi-continuously mixed, continuously mixed and unmixed reactors, respectively. The specific methane yields of these reactors are in agreement with published studies conducted under mesophilic conditions [26]. The higher specific methane yield for the semi-continuously mixed reactor indicates that this reactor's performance is superior to that of the continuously mixed and unmixed reactors, demonstrating that semi-continuous mixing is sufficient to achieve optimum conditions for microbial growth and production of methane. For a given quantity of substrate (food waste), the semi-continuously mixed reactor can generate a higher volume of methane, thus allowing for a larger energy generation. Furthermore, less frequent mixing results in greater energy savings as the electrical energy input into the system is reduced, thereby increasing the energy efficiency of the AD system.

The higher performance of the semi-continuously mixed reactor can be attributed to the growth of microbial communities and effective mass transfer from the liquid to gas phase [7]. Firstly, these results corroborate existing studies on the effect of mixing conditions, which suggest that semi-continuous mixing is more beneficial than continuous mixing [27]. Continuous mixing can affect and break the syntrophic relationship between acetogens and methanogens. Furthermore, methanogens have a longer regeneration time (10-15 days), as opposed to acetogens (80-90 h), suggesting that lower mixing times and intensity may retain the syntrophic relationship between the microorganisms and enable the production of biogas with higher methane content [28]. In addition, mixing also affects the proper functioning of the microbes in the reaction mixture due to various cell morphologies. For example, *Methanosaeta concilii*, an archaeum responsible for methane production, has long filaments that can be easily damaged by continuous or strong mixing. Similarly, Ward et. al reported that continuous mixing increased the distance between microbial communities, reducing the strength of the syntrophic relationship [29, 30]. This could have resulted in significant differences in the methane yields between the reactors.

Secondly, gas transfer from the liquid phase of the inoculum is enhanced through sufficient mixing. Mixing enables the release of gases such as CH_4, CO_2, H_2S, H_2, etc, and allows for the production of a larger volume of biogas during the anaerobic digestion process. A study published by Stafford concluded that a gradual increase in mixing enabled better and faster separation of gas from the sludge, contributing to greater daily, cumulative and specific methane yields [31]. This explains the poor performance of the unmixed reactor, as gas release is severely restricted by the lack of agitation that facilitates gas separation.

For semi-continuously and continuously mixed reactors, the pH remained within the optimum range of 6.5 – 7.5 as the OLR increased due to the availability of more organic substrates for degradation and synthesis of methane gas. At the optimum OLR, the pH values for semi-continuously and continuously mixed reactors were 7.29 and 7.26, respectively. This suggests that semi-continuous mixing is sufficient to distribute organic substrates and microbes without any accumulation of VFAs, maximizing energy savings on a large scale, industrial level. Semi-continuously and continuously mixed reactors showed significant increases in the COD content. Since the pH did not fall below the optimum range, the COD content for semi-continuously and continuously mixed reactors was optimum, healthy and indicative of the presence of sufficient organic substrates to produce methane. The unmixed reactor is unsuitable for continuous and prolonged operation as the pH fell below the optimum range. As methanogens are sensitive to changes in pH, a decrease in pH will severely restrict their activity, resulting in an accumulation of VFAs, thus causing a further decrease in pH [32]. Given that the unmixed reactor had higher COD than the semi-continuously and continuously mixed reactors, it can be concluded that the unmixed reactor reached its maximum OLR at 2.4 g-VS_{FW}/L/day. The abundance of VFAs reduces the pH of a mixture and greatly affects the functioning of methanogenic microorganisms, curtailing the overall production of biogas.

Table. 2

Statistical analysis for specific methane potential of three anaerobic digesters in different OLRs.

Days	OLR (g VS/L/day)	N[a]	SMP[b] (ml CH_4/gVS/d)			pH		
			R1	R2	R3	R1	R2	R3
1-10	0.9	20	377 ± 36	387 ± 30	262 ± 27	7.3 ± 0.2	7.2 ± 0.1	7.1 ± 0.2
11-20	1.8	20	423 ± 40	398 ± 33	270 ± 26	7.3 ± 0.1	7.2 ± 0.2	6.2 ± 0.2
21-30	2.4	20	437 ± 26	396 ± 27	89 ± 12	7.1 ± 0.1	7.1 ± 0.2	5.6 ± 0.2

a. N is the number of data points.
b. Values are expressed as mean ± standard deviations from N data points.

3.3. Effects of mixing time on microbial communities

Figure 5 – Microbial Communities for Mono-Digestion (R1 represents the semi-continuously mixed sample and R0 represents the continuously mixed sample).

Fig. 5 represents the microbial communities that were obtained for the semi-continuous and continuous mixing of mono-digestion of food waste. It is evident that there exists a larger proportion of *Clostridium* bacteria in the semi-continuously mixed reactor. *Clostridiales* have an important function in the anaerobic digester because they enable the biological degradation of polysaccharides and other sugars into simpler substrates [33]. This crucial phase initiates any AD process. The higher proportion of these bacteria in the semi-continuously mixed reactor than in the continuously mixed reactor indicates that the rate of hydrolysis is higher in the former, thereby increasing the overall rate and efficiency of AD.

In addition, the semi-continuously mixed reactor has a larger proportion of *Bacteroides*. *Bacteroides* are a group of microorganisms that convert acetates and other simpler substrates to hydrogen, enabling hydrogenotrophic methanogenesis. The presence of these microbes in the semi-continuously mixed reactor ensures that methane is produced through multiple pathways (via acetates and carbon dioxide), resulting in a greater resultant biogas volume.

Furthermore, there is a significant difference between the types of methanogens present in both reactors. *Methanocuelles*, a group of methanogens specializing in hydrogenotrophic methanogenesis, is abundantly present in the semi-continuously mixed reactor. Coupled with the presence of more *Bacteroides*, *Methanocuelles* are able to reduce a greater volume of carbon dioxide to methane gas, facilitating the production of more biogas during the experimental period [33]. However, the continuously mixed reactor has a greater proportion of *Methanosarcina*, restricting the number of pathways through which methane gas can be generated. These results are in agreement with existing scientific literature [34].

3.4. Effects of mixing time on energy performance of the AD waste-to-energy system

This section evaluates the energy generation for the mesophilic mono-digestion. Continuously and semi-continuously mixed digesters were considered to determine the energy efficiencies of the AD processes in this study. Although the study was performed on a bench scale reactor, the energy analysis was done for a scaled up of 5 L to 1 m^3 reactor. The crucial assumptions made were the linear extrapolation for biogas produced based on the specific methane yield. The specific methane yields used for R1, R2, and R3 under mesophilic condition were 437 mL/g VS, 396 mL/g VS, and 89 L/kg VS (based on the above experiments on FW). These results were summarised in Tab. 2.

Fig. 1 shows a concept map the hybrid anaerobic digestion waste-to-energy system studied in this paper. The main components in the waste to energy model system: the anaerobic digester, gas compressor, gas storage tank, biogas absorber column and IC engine that produces electrical and heat energy. Mechanically pre-treated food waste is fed into the anaerobic digester for fermentation. From equation (1), the standard enthalpy of change of formation of FW (ΔH_{AD}) was obtained. This process produces the biogas fuel which is then compress and fed into a gas storage tank. To find the standard enthalpy of change of formation of biogas produced, using equation (2), it was noted that only methane contributed to the HHV of the biogas. The HHV of methane was found to be 39.7 kJ/L (NIST, n.d.) [35].

The biogas enters a combined heat and power (CHP) unit where heat and electrical power from the biogas is simultaneously produced to provide heat to the AD system and provide electricity for the mixing process.

3.4.1 Overall Heat Performance

The overall heat performance analysis aims to evaluate the heat generated by the overall AD-CHP system in excess of its operational requirements. The effect of mixing on the total biogas and net heat output will then be analysed to assess the efficiency of the AD process. Calculating heat losses about the AD reactor, equation (3) was used to determine the heat loss from digestate discharging (Q_{dig}). Subsequently, the heat loss from the reactor surfaces ($E_{loss,\ AD}$) can be determined using equation (4, 5, and 6). The ambient temperature was assumed to be the average temperature of 25 ºC. The value of $E_{loss,\ AD}$ has not accounted for the heat loss reduction from insulation. Fig. 6 details the energy distribution for food waste input, biogas output and the net heat output at the optimum OLR of 2.4 g-VS_{FW}/L over various mixing frequencies – 0, 2 and 60 mins/h. The energy distribution of the food waste input fed into each of the reactors was maintained at 7338 kJ/kg. Figure shows that the semi-continuously mixed reactor displayed the highest energy performance among all three reactors (2 min/hr/day ≈ 1 hr/day). The semi-continuously mixed reactor had a biogas energy output of 5460 kJ/kg at the organic loading rate of 2.4 g-VS_{FW}/L. In contrast, the continuously mixed and unmixed reactors only produced biogas energy outputs of 4913 kJ/kg and 1091 kJ/kg, respectively.

The significantly greater biogas output of the semi-continuously mixed reactor resulted in the generation of a higher amount of heat within the CHP unit. A portion of this energy can be routed back to the reactor to maintain its temperature at mesophilic conditions, eliminating the need for an external heat source. Furthermore, the semi-continuously mixed reactor had the highest net heat output of 1391 kJ/kg. The net heat output of the continuously mixed reactor was 1181 kJ/kg, which was lower than that of the semi-continuously mixed reactor. However, the unmixed reactor had a net negative heat output of -287 kJ/kg, suggesting that the lack of mixing resulted in an AD process with very poor heat/energy performance. Thus, this analysis proves that the semi-continuously mixed reactor yields a better heat performance, as the CHP unit is able to recover a larger amount of heat energy from the biogas, resulting in greater net heat output.

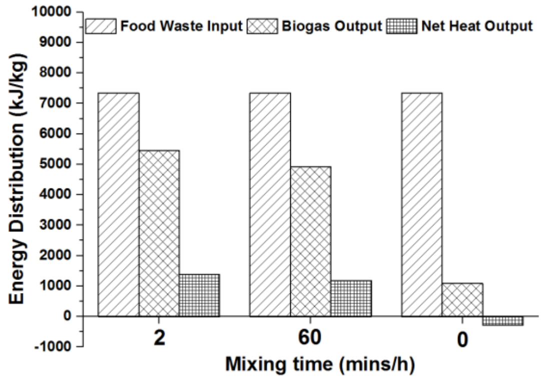


Figure 6 – Mesophilic Mono-Digestion Overall Heat Performance

3.4.2 Electricity Generation and AD Efficiency

The amount of biogas produced by the AD system affects the electricity generated by the CHP unit and the final AD efficiency. This section evaluates the biogas outputs at various mixing times and its impact on the amount of electricity generated and AD efficiency. The determination of the net electrical energy generated, using equation (7, 8, and 10) can be done. The AD efficiency to convert FW into biogas can be calculated based on equation (12), respectively. Fig. 7 shows the energy distribution of the biogas input into the CHP unit ($\Delta H_{g,bio}$), the electricity generated ($e_{gen,CHP}$) and the electricity required for mixing (e_{mix}) during the AD process at the optimum OLR of 2.4 g-VS_{FW}/L using various mixing frequencies – 0, 2 and 60 mins/h. As the mixing frequency increases, the electricity required by the digester system increases from 0 kJ to 48729 kJ (0 mins/h to 60 mins/h). The large energy requirement in the continuous mixing system renders the AD process energy inefficient, as the biogas produced by the system is insufficient to produce enough electricity to power the system. The electrical energy required for mixing in continuous mixing systems peaks at 48729 kJ. However, the biogas output of 39310 kJ only generates 14938 kJ of electrical energy, which is only 30% of the electrical energy required by the AD system. With insufficient biogas production, this AD process is energy inefficient and uneconomical for long-term and large-scale production.

However, it is evident that the semi-continuously mixed reactor (2 mins/h) yield a larger volume of biogas than the continuously mixed and unmixed reactors. At the aforementioned OLR, the highest biogas output of 43679 kJ is achieved by employing semi-continuous mixing at a frequency of 1hr/day. With greater biogas production by the digester system, the CHP unit is able to achieve a higher electrical energy generation of 16598 kJ. Since the electricity needed for mixing is only 2030 kJ, the electrical energy generated by the CHP unit is approximately 8 times greater than the amount input into the system. Therefore, it can be concluded that semi-continuous mixing results in a more efficient conversion of bio-waste to energy. This results in increased AD efficiency of the digester. The calculated AD efficiency of the semi-continuously mixed reactor is 74.4%, which is higher than the AD efficiencies of the continuously mixed (66.9%) and unmixed reactors (14.9%). Thus, it can be deemed that the semi-continuously mixing is more energy efficient and sustainable for long-term operation of a system undergoing low solid mono-digestion of food waste.

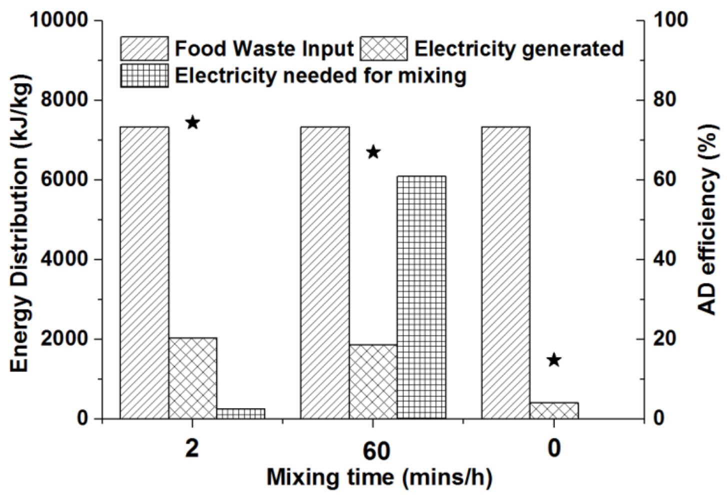


Figure 7 – Mesophilic Mono-Digestion AD Efficiency

4. Conclusions

This study considered the effect of mixing in an AD waste-to-energy system to establish optimum conditions for AD operation and energy savings. Through CFD modeling of anaerobic digesters with two impellers, the optimal mixing time was reduced to 2 mins/hr, at which point the reaction mixture is almost entirely homogeneous. The results of bench experiments showed that the semi-continuously mixed reactor with a mixing time of 2 mins/hr maintained a higher specific methane yield in comparison with the continuously mixed reactors and unmixed reactors. The experimental data validated the results of the CFD modelling. Based on these results, the energy performance of a hybrid AD waste-to-energy system was simulated and evaluated. It was found the lesser mixing time results in energy savings as the electrical energy input into the system is minimized, increasing the energy efficiency of the system.

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