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Optimizing Biowaste Material Mixing for Efficient Biogas Production via Airlift Pump-Equipped Digesters

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Abstract **-** In today’s world the use of energy is significantly increasing, so it is essential to develop and sustain other sources of renewable energy, including biogas which is derived from organic matter like food waste. This paper aims to develop a sustainable method for repurposing and recycling food waste through an anaerobic digestion process to generate biogas. The study evaluates the effectiveness of extracting biogas from food waste using a digester or bioreactor implemented with multiple airlift pumps, a deviation from using the less efficient traditional continuous stirred tank reactors (CSTRs). The evaluated digester has multiple airlift pumps implemented at equally spaced circumferential locations, that reinject biogas to circulate and blend the liquid sludge, thereby enhancing the mixing rate of the liquid sludge within the digester. Additionally, computational fluid dynamics (CFD) simulation was utilized to examine the mixing process within the digester when four standard riser airlift pumps were implemented within the digester. The analysis involved evaluating the velocity contours of air-water with those of biogas-liquid sludge. It also observes the differences in the average velocity of water and liquid sludge, examining the change in rheological property, Newtonian and/or non-Newtonian, behavior for liquid sludge at a different mass flow rate of biogas. The study revealed that despite the high viscosity and density of the liquid sludge, the average velocity of the liquid sludge follows the same trend of average velocity observed in water, concluding that the liquid sludge acts like a Newtonian fluid in terms of the average velocity and shear rates within the digester at low mass flow rates of both liquid and gas phases.

Keywords**:** Multiphase flow; Airlift pumps; CFD; Standard risers; Flow regimes; Liquid Sludge; Biogas

1. Introduction

1.1. Background

Biogas is produced via the anaerobic digestion process, in which organic matter decomposes in the absence of oxygen. The anaerobic digestion process undergoes four key phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [1]. In the hydrolysis phase, complex organic matter breaks down into simpler monomers. Acidogenic bacteria then convert these monomers into organic acids during the acidogenesis phase, thereby the acetogenic bacteria then transform the organic acids into acetate, carbon dioxide, and hydrogen in the acetogenesis phase [2, 3]. Methanogenic bacteria in the final methanogenesis phase convert acetate and hydrogen into methane gas, carbon dioxide, and impurities [1]. Methane is the primary component of biogas as it contributes 55 to 65% of biogas content, while carbon dioxide contributes to around 30 to 45% of the biogas produced, along with minor traces of other impurities like hydrogen sulfide (H_2S) [4]. Fig.1 represents the main phases of the anaerobic process which represents all of the four main phases of the anaerobic digestion process.

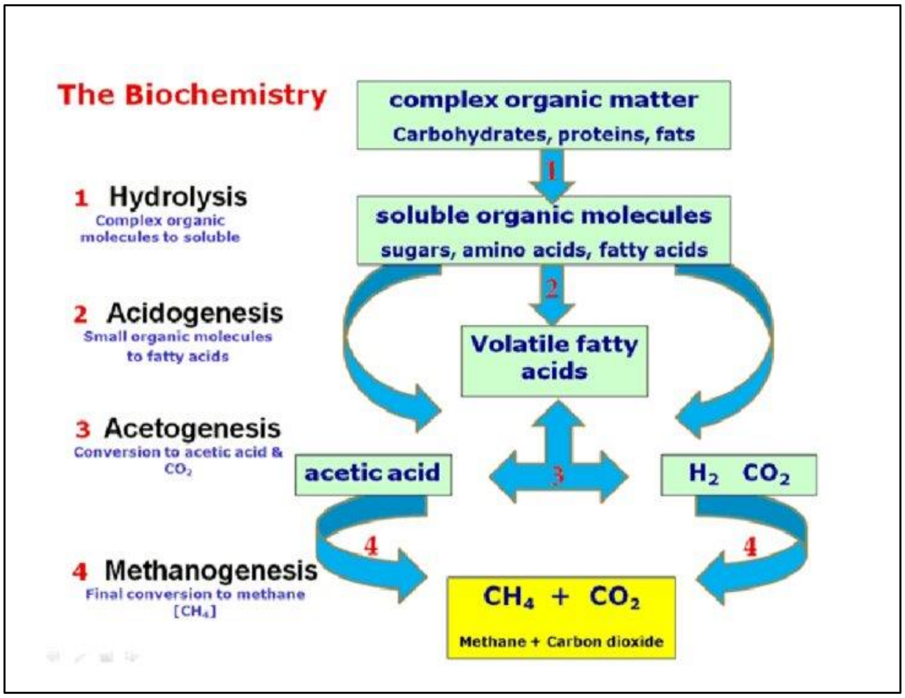

Fig. 1: Phases of the anaerobic digestion process [1].

1.2 Types of Reactors

The most known type of digester that is used in many industrial processes is the continuous stirred tank reactor (CSTR). This reactor consists of an industrial-scale tank where the reactants mostly consisting of liquid sludge are continuously fed, and the product consisting of biogas will be continuously collected from the top of the reactor [5]. The continuous stirring throughout the tank is accomplished via a mechanical impeller or other mechanical means which ensures homogeneity across the mixture (liquid sludge) [5]. Thus, the primary advantage of this type of reactor is its ability to maintain a uniform and continuous mixing throughout the digester, enhancing the yield product of biogas. Another positive aspect of this type of reactor is the ease of operation, as it requires minimal supervision because the control system will adjust and monitor the movement and speed of the impellers. However, CSTRs have one major drawback which is the fact that there is a low concentration gradient for the reactant at regions far from the impellers resulting in not forming an adequate or linear mixing in these regions [6]. This means that the liquid sludge will not be fully mixed, and this affects the rate of biogas production. Additionally, this type of reactor is expensive in terms of initial, running, and maintenance costs [7].

1.3 Objectives

This work's main aim is to evaluate the effectiveness of an airlift pump-equipped digester for extracting biogas from food waste. The examined digester will be integrated with four standard riser airlift pumps at equally spaced circumferential locations within the digester. Airlift pump is a type of pump that uses gas flow to circulate and mix the liquid sludge, which is the byproduct of food waste material consisting of a semi-solid mixture of organic and inorganic materials. The airlift pump aims to improve various parameters such as the mixing rate, mixing time, and low concentration gradient regions, and reduce the accommodation of residuals at the bottom of the digester. These improvements would enhance the efficiency of the digester and result in a higher yield of extracted biogas. Furthermore, the study aims to analyze the rheological properties of liquid sludge, including the average velocity of water versus liquid sludge. It also examines the velocity contours for liquid sludge versus biogas and water versus air within the digester. Thus, by that to conclude the behavior of liquid sludge at different mass flow rates within the digester. Liquid sludge that was used in this study had a density of 996 kg/m^3 and a viscosity of 1.757×10^{-1} Pa. s, while water had a density of 998 kg/m^3 and a viscosity of 1.003×10^{-3} Pa.s. However, both biogas and air had a viscosity and density of 1.789×10^{-5} Pa.s and 1.225 kg/m^3, respectively.

2 Results and Discussion

CFD simulations via the ANSYS software offer a range of models for multiphase flow simulation which would be essential in conducting and examining the multiphase flow phenomena in various applications. CFD simulation is used in numerical analysis of multiphase flow due to its exceptional capacity to handle complex interactions between various phases, such as gas-liquid or solid-liquid flows [8]. The process of conducting a CFD simulation using ANSYS software is divided into five main steps, consisting of geometry, meshing, fluent setup, solution, and results. The simulation will be carried out for water versus air and liquid sludge versus biogas the collected results from the simulation will be utilized to compare the average velocity of each liquid phase, along with comparing the velocity contours for both liquid and gas phases. Before running any calculation, it is a must to first analyze the parameters in terms of what remains constant and what will vary in the testing of water versus air and liquid sludge versus biogas. The parameter subject to variation includes the mass flow rate for each fluid (liquid and gas phase). Parameters, which are assumed to be constant, include the temperature of the liquid phase, the turbulence intensity, the backflow value of air and biogas, the rheological properties of fluids (assuming the fluid is initially defined as Newtonian fluid throughout the digester), viscosity, and density of both the liquid and gas phase. Upon analyzing the constant and varying parameters, the simulation results for the first case which is water versus air, and the second case which is biogas vs liquid sludge will rely on the specified input range of tests for the mass flow rates detailed in Table 1. Further investigations will be carried out to verify liquid sludge rheological properties, Newtonian and/or non-Newtonian, at high mass flow rates, with efforts aiming to optimize the anaerobic digestion process increasing the yield product of biogas within the digester.

For each of the cases, the measured parameters will include the average velocity of the liquid phase throughout the digester, the distribution of liquid and gas phases inside the digester, and the velocity contours of both liquid and gas phases across different cross-sectional planes. Figs. 2 and 3 illustrate the top and side views of velocity contours at 4000 timesteps for both water versus air and liquid sludge versus biogas. In both Figs. 2 and 3, section (a) represents the velocity contours of water versus air, while section (b) displays the velocity contours of liquid sludge versus biogas, For the carried-out tests where the mass flow rates for both liquid and gas phases are low, it is clear, from Figs.2 and 3, in both the top and side view of the velocity contours the dominance of yellow and red velocity contours is more observed in liquid sludge versus biogas compared to water versus air, particularly in regions close to the 4-inch riser. This discrepancy arises from the higher viscosity of liquid sludge compared to water, which causes liquid sludge to require more time to homogeneously mix within the digester. Accordingly, the liquid sludge tends to accumulate in these regions before initiating a larger-scale mixing throughout the entire digester. In addition, Figs. 2 and 3 for the top view showcase the presence of velocity contours for both liquid sludge and water at the bottom of the digester. The system's operational efficacy in preserving a well-mixed and residue-free environment, which is crucial for optimizing biogas generation, is tangibly represented by this type of visualization. Hence, the existence of these velocity contours at the digester's bottom validates the idea that utilizing airlift pumps will minimize the accumulation of residuals at the bottom of the digester over a long period, which will enhance the active volume capacity and mixing rate within the digester.

Table 1: The conducted tests and the corresponding liquid and gas mass flow rates.

Test	**Liquid phase**		**Gas phase**	
	(L/min)	**(kg/s)**	**(L/s)**	**(kg/s)**
1	60	0.998	0.50	0.000613
2	103	1.713	0.70	0.000858

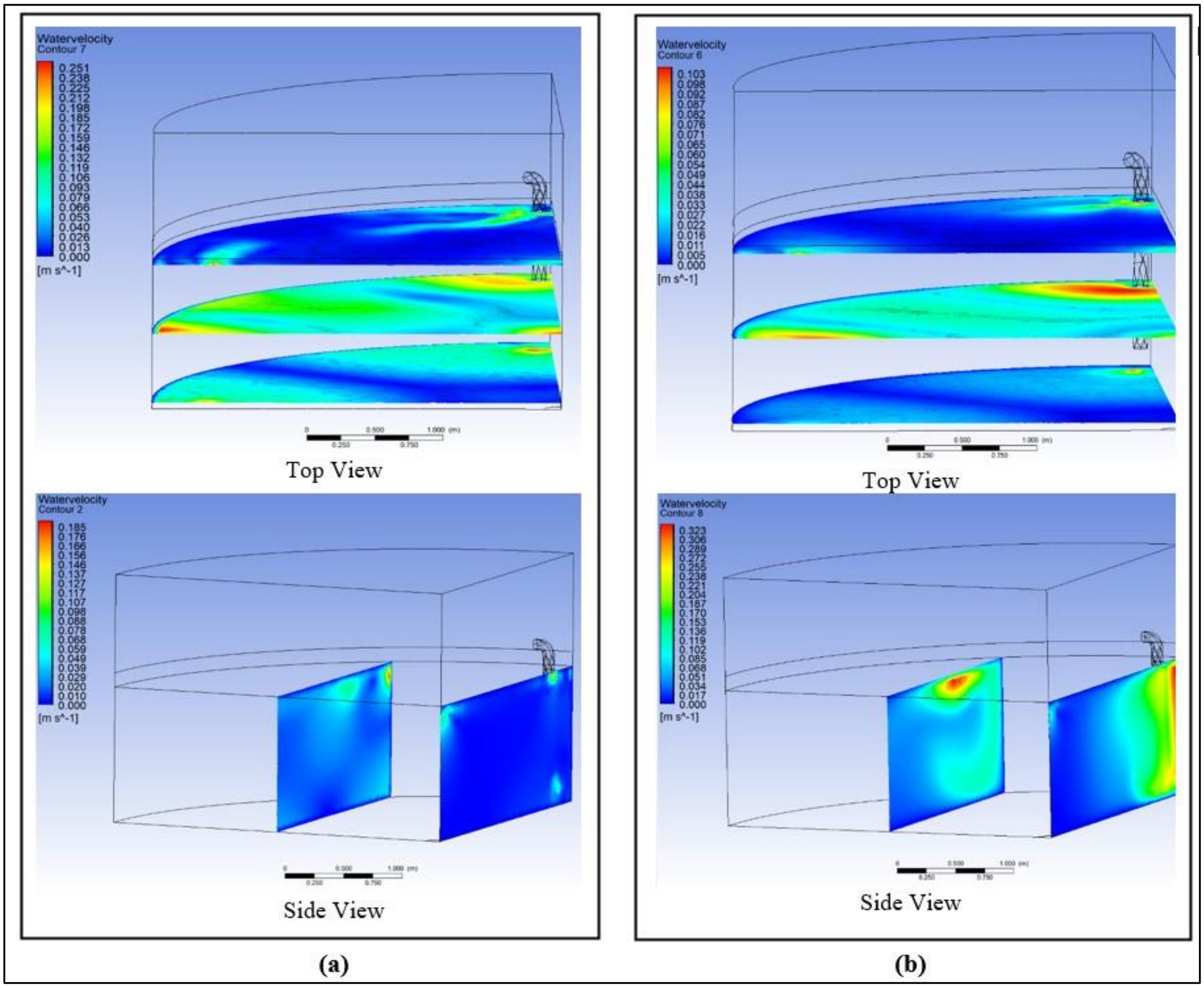

Fig. 2: Velocity contours of the top and side views at 4000 timesteps, for Test No.1: **(a)** water versus air **(b)** liquid sludge versus biogas.

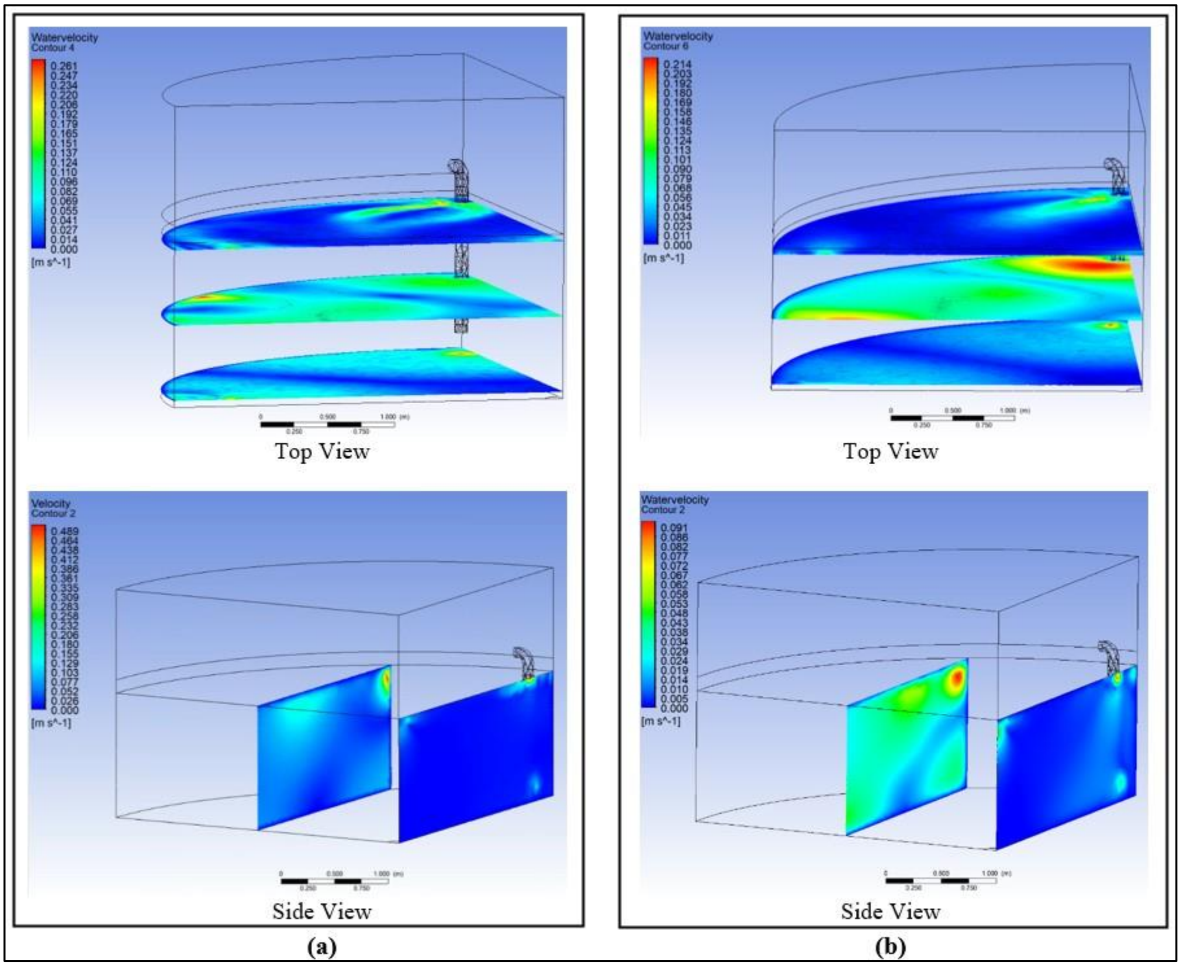

Fig. 3: Velocity contours of the top and side views at 4000 timesteps, for Test No.2: **(a)** water versus air **(b)** liquid sludge versus biogas.

After running the simulations for water versus air and for liquid sludge versus biogas, at different mass flow rates for both liquid and gas phases, the collected average velocity for both water and liquid sludge at each test is represented in Table 2. As seen, the average velocity of the water phase was much greater than that of the liquid sludge phase, for both tests No. 1 and 2, which can be attributed to the higher viscosity of liquid sludge in comparison to water. Additionally, Fig. 4 provides a visual representation of the average velocity of each liquid phase at its corresponding test. From Fig 4, the trend in average velocity for liquid sludge was almost identical to that of water with a slight decrease in values of average velocity. Therefore, it can be concluded that the liquid sludge acts like a Newtonian fluid in terms of the average velocity and shear rate of the fluid within the digester. This finding is in line with the research carried out by Hurtado et al. [9]. This implies that, since the liquid sludge acts like a Newtonian fluid the active volume and mixing rate will maintain a sufficient level for a certain period before dramatically decreasing [9]. This will enhance the mixing rate within the digester, thereby enhancing the yield product of biogas. Further investigations will be carried out to verify the rheological properties of liquid sludge, assessing whether it exhibits Newtonian or non-Newtonian behaviour, particularly at high mass flow rates.

Table 2: Average velocity for water and liquid sludge phases obtained using ANSYS simulation.

Test	**Liquid phase average velocity (m/s)**	
	Water versus air simulation	**Liquid sludge versus biogas simulation**
1	0.0144	0.0052
2	0.0182	0.0114

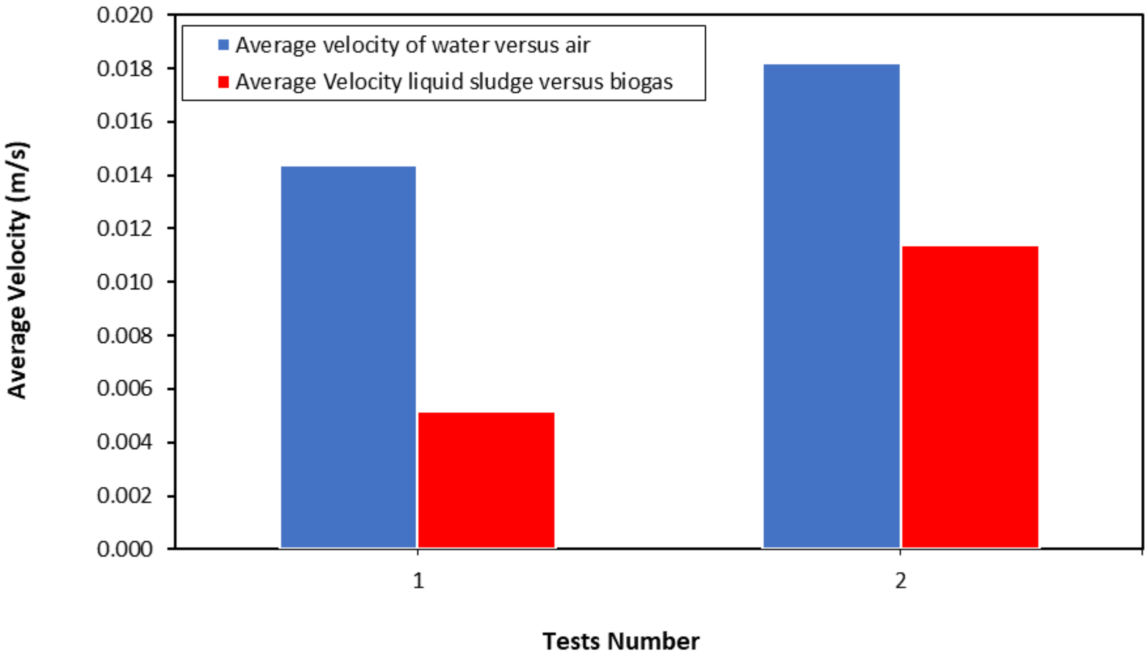

Fig. 4: Liquid phase average velocity for each test of water and liquid sludge obtained from ANSYS simulation.

3. Conclusion

This study uses a food waste digester that is effective and has many airlift pumps to produce biogas. At low mass flow rates, liquid sludge behaves like a Newtonian fluid despite its high viscosity, according to computational fluid dynamic models. However, it is crucial to acknowledge that with a further increase in the mass flow rates of liquid sludge, the Newtonian behavior of the fluid might become invalid. This indicates that at high mass flow rates, liquid sludge could exhibit non-Newtonian fluid properties. Furthermore, the findings demonstrate that employing airlift pumps minimizes residual accumulation at the digester's bed, promoting sustained active volume capacity and mixing rates within the digester. This contrasts with the limitations of CSTRs, where the digester bed is far from the impellers, resulting in low concentration gradient regions around the digester’s bed causing residual buildup, thereby decrementing the adequate mixing and reducing the biogas yield product. Further investigations will be carried out to verify liquid sludge rheological properties at high mass flow rates, with efforts aiming to optimize the anaerobic digestion process for increased biogas production within the digester.

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