The influence of different solid-liquid ratios on the thermophilic anaerobic digestion performance of palm oil mill effluent (POME)

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Abstract

An alternative method was proposed to optimize the treatment process of palm oil mill effluent (POME) in an effort to address the poor removal efficiencies in terms of the chemical and biological oxygen demand (COD and BOD), total suspended solids (TSS) as well as oil and grease (O&G) content in treated POME along with many environmental issues associated with the existing POME treatment process. The elimination of the cooling ponds and the insertion of a dewatering device in the treatment process were recommended. The dewatering device should enhance the anaerobic digestion process by conferring a means of control on the digesters' load. The objective of this study is to identify the optimum solid: liquid ratio (total solids (TS) content) that would generate the maximum amount of biogas with better methane purity consistently throughout the anaerobic digestion of POME, all while improving the treated effluent quality. It was established that a 40S:60L (4.02% TS) was the best performing solid loading in terms of biogas production and methane yield as well as COD, BOD, TSS, and O&G removal efficiencies. Meanwhile, at higher solid loadings, the biogas production is inhibited due to poor transport and mass transfer. It is also speculated that sulfate-reducing bacteria tended to inhibit the biogas production based on the significantly elevated H_2S concentration recorded for the 75S:25L and the 100S loadings.

Keywords: Palm oil mill effluent, Solid loadings, Thermophilic anaerobic digestion, Biogas production, Methane yield

Contents

1. Introduction

Being the second biggest palm oil producer worldwide, Malaysia faces a severe concern when it comes to the disposal and management issues of the waste associated with the production of palm oil, Palm Oil Mill Effluent (POME). POME is a thick brownish liquid of pH around 4.0-5.0, with a discharge temperature of 80-90°C. POME consists of organic materials such as lignin, carotene, phenolic compounds, and pectin, which are at concentrations 4700 ppm, 8 ppm, 5800 ppm, and 3400 ppm, respectively (Choong et al., 2018; Iskandar et al., 2018; Khadaroo et al., 2019b). The factors making POME detrimental to the environment are its high Chemical Oxygen Demand (COD) (15,000-100,000mg/L), Biological Oxygen Demand (BOD) (10,250-43,750 mg/L), and suspended solids (5,000-54,000mg/L) content which causes water pollution when discharged into watercourses. The existing treatment process has deficiencies due to ineffective residual oil removal from the waste stream and a large amount of greenhouse gas emission owing to the ponding system (Mansor et al., 2017). After the oil removal pit, otherwise known as the cooling ponds, POME is allowed to cool down to a suitable mesophilic temperature, after which it is sent directly to anaerobic digestion. However, often, the treated effluent quality is poor and does not conform to the stringent environmental standards (Chin et al., 2013; Ahmed et al., 2015).

Owing to excessive greenhouse gas emission, the Malaysian government introduced the National Key Economic Areas (NKEA) to enhance oil extraction efficiency and as an incentive for the mills to install biogas facilities to capture the biogas generated (Ministry of agriculture and agro-based industry, 2019). However, for mills to set up the biogas capture facilities as per the NKEA, the system has to be beneficial to the plants in terms of power generation and provide other potential uses such as use in package and/or high-pressure boiler as an alternative for diesel. Therefore, the amount of biogas produced during anaerobic digestion and the methane yield must be significantly enhanced to enable a stable generation of electricity downstream. Based on previous literature (Chin et al., 2013a; Lam Man & Lee, 2010; Yacob et al., 2006), it has been reported that the percentage of methane present in the biogas produced from the anaerobic digestion of raw POME ranges from 35% to 54.5%

which is too low for the required applications. Another disadvantage is the fluctuation in the physicochemical properties of POME from low crop season to high crop season (Poh et al., 2010).

Literature on other types of substrates, predicts that more biogas would be produced if a lower solid content was fed to the digester. The study by Angelonidi and Smith (2015) is in agreement with the statement; they observed that wet anaerobic digestion of municipal solid waste and food waste operating at low total solids (TS) (< 20% TS) proved more cost-effective with higher biogas productivity. On the other hand, dry anaerobic digestion operating at high total solids (> 40%TS) had shorter retention time, reduced the usage of water, and gave a more manageable end-product for which the primary use is agricultural fertilizers. Both dry and wet anaerobic digestion can be advantageous depending on the conditions that needed to be satisfied.

For dry anaerobic digestion systems, the high solids content has a significant impact on the rheological behavior of the digestates. High solids content suspensions are visco-elastic-plastic materials characterized by high yield stress. The compressibility of such materials is dependent upon the extent of dewatering and can be quantified by the compressive yield stress. The latter dictates the TS concentration, ϕ, to which a suspension will be dewatered at a known applied pressure (Khadaroo et al., 2019a). The yield stress was noted to increase significantly as the TS content increases (Abbassi-Guendouz et al., 2012). In a study using POME, Khadaroo *et al.*, (2019) concurred with this by establishing that at a TS content higher than a gel point, the compressive yield stress exponentially increases as the TS content increases. However, at TS concentration below the gel point, namely as solids volume fraction at which a network starts to form, the compressive yield stress is zero (De Kretser et al., 2001; Harbour et al., 2001). Controlling the solids fraction of a digestate thereby impacts on the rheology.

In this work, we proposed a substitute treatment process for POME, which consists of eliminating the conventional cooling pond and introducing a dewatering device, for example, a thickener (Usher et al., 2009). The dewatering device will contribute to the solid-liquid separation, removal of microbes, and other impurities from the wastewater. The dewatering device will aid in making the anaerobic digesters used for the treatment of POME more effective by inferring a means of control on the digesters' load (Khadaroo et al., 2019a). POME will be sent from the dewatering device to the anaerobic digesters at a thermophilic temperature (55℃) to avoid heat loss. Nevertheless, to know at which solid loading to operate the digesters for optimal anaerobic digestion performance, it is fundamental to understand methodically how the solid loading affects the latter. However, there is no literature to the best of our knowledge on the study of the effect of different solid loadings on the anaerobic digestion of POME. This paper aims to find the optimum solid: liquid ratio (TS content) that would produce the highest amount of biogas at a consistent rate during the anaerobic digestion of POME as well as to provide a better insight into how the solid content of POME affects anaerobic digestion in terms of the stability of the reaction and methane yield.

2. Materials and Method

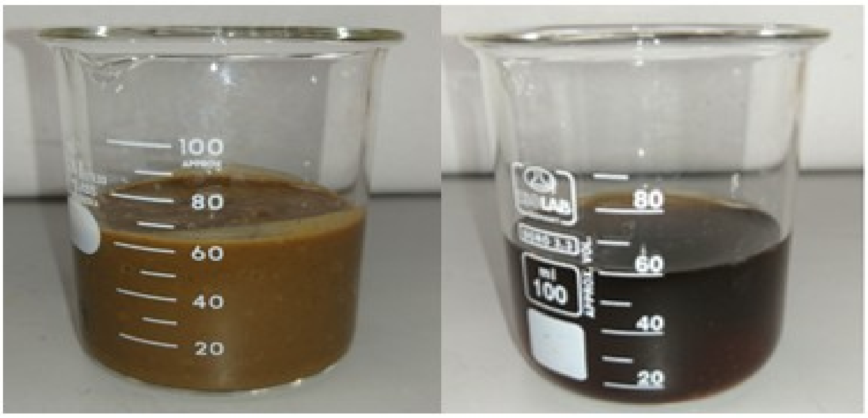
2.1 Materials

POME was sampled during low crop season at Sime Darby East Oil Mill, Malaysia. The sample site lies at coordinates 2.8843° N, 101.4369° E. The temperature of POME at the collection location was measured to be 65°C. From batch settling experiments, it was inferred that raw POME has varying solid concentrations in terms of suspension phase ranging from 55-85% by volume (Khadaroo et al., 2019a). Anaerobic seed sludge which was subsequently used as inoculum in the experiments was also collected at the Sime Darby East Oil Mill.

2.2 Experimental Set up

The chosen mode of anaerobic digestion was thermophilic batch anaerobic digestion. The temperature selected for thermophilic anaerobic digestion in this study was 55℃.

To separate the solid and the liquid phase, 5L of POME was placed in a settling column of height 0.7 m with multiple sampling points to enable the removal of each phase. The solid flocs in POME were allowed to settle for approximately 24 hours at room temperature. Samples of settled suspension and clear liquid (hereafter designated ``solid" and ``liquid") obtained are shown in Figures 1a and 1b.



(a) Solids Sample (b) Liquid Sample

Figure 1a and 1b: Dewatered Solids and Liquid samples used in this study

Having settled raw POME into solid and liquid phases, they were recombined to achieve the desired ratios by volume for this study. The solid: liquid ratios studied were 20:80, 40:60, 50:50, 75:25 and 100:0. These ratios were chosen to allow the study over the full range of solids ratios. The 0:100 ratio consisting of 100% liquid was not investigated as the COD of the latter was found to be 1500 mg/L while the average COD of raw POME is 50,000mg/L indicating that the solid portion of POME is primarily where the organic matter is found for anaerobes to thrive.

The selected solid: liquid ratio of POME was placed in a 250ml Schott bottle with two outlets. The working volume of the system was taken as 100mL. An inoculum (anaerobic seed sludge) volume of 20% of the working volume was used and maintained throughout the experiments. The inoculum was cultivated and acclimatized in a reactor heated at 55°C under anaerobic conditions to allow the bacteria to become accustomed to the conditions under which the anaerobic digestions experiments were undertaken. The digesters were placed on a heated magnetic stirrer for proper homogenization of the medium, as sketched in Figure 2. Each digester was connected to a water displacement column via a pipe to allow the measurement of the volume of biogas produced. The pH of the water in the displacement column was adjusted to 2.0 to ensure that carbon dioxide does not readily dissolve in the latter, which is in concurrence with ASTM D5511 (Müller et al., 2004). Since the pH of water in the displacement column is low, the solubility of CO_2 decreases, which makes measuring the total biogas volume with the water displacement method more accurate.

The pH of the digester system, however, was kept between 6.8 to 8.0 by dosing with 1M $NaHCO_3$ to ensure optimum conditions for the methanogenic bacteria to produce methane (Choong et al., 2018; Lindner et al., 2015). The composition of biogas was measured using the COMBIMASS Gas Analyzer.

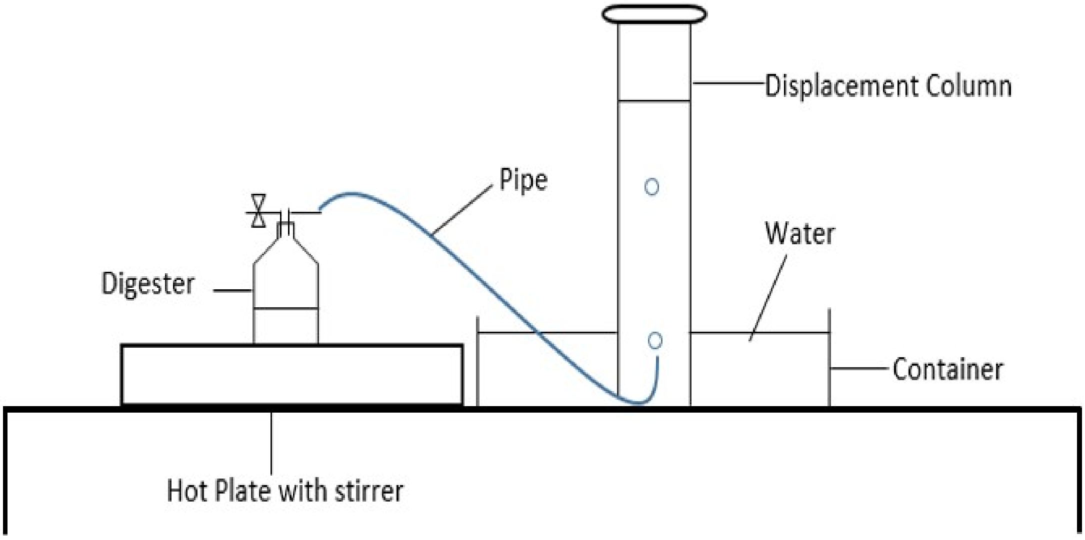


Figure 2: Thermophilic anaerobic digestion experimental set up

2.3 Physico-Chemical Analysis

Characterization tests such as the COD, BOD, TSS, and O&G experiments were conducted before and after anaerobic digestion to determine the quality of the discharged effluent from the anaerobic digesters. The COD, BOD, and TSS were undertaken as per the HACH Standard Methods 8000, 8043, and 8006, respectively, while the O&G test was done as per the ASTM method D7066-04. The most probable number (MPN), i.e., total anaerobes count, was performed as per ASTM STP695. Total solids (TS) test was undertaken as per the standard methods for the examination of water and wastewater (APHA, 1998). The methane yield was calculated based on the volume of methane produced and the mass of COD removed (Jingura and Kamusoko, 2017). For each condition (20S:80L, 40S:60L, 50S:50L, 75S:25L, and 100S) three runs were conducted. Each run consisted of 3 batch anaerobic digesters and triplicates were used for the physico-chemical analyses carried out. This set-up produced a total of 9 sets of data for each condition providing a good range of data to gain a better insight into how each tested ratio performed. The error bars in Figure 3 and 4 were calculated based on the standard deviations from the 9 sets of data obtained.

3. Results and Discussion

3.1 The effect of solids content on the anaerobic digestion of POME

This section describes the anaerobic digestion performance results obtained with varying solid loadings of POME. The effect of varying solids loading turned out quite significant. The findings for each ratio have been thoroughly discussed below.

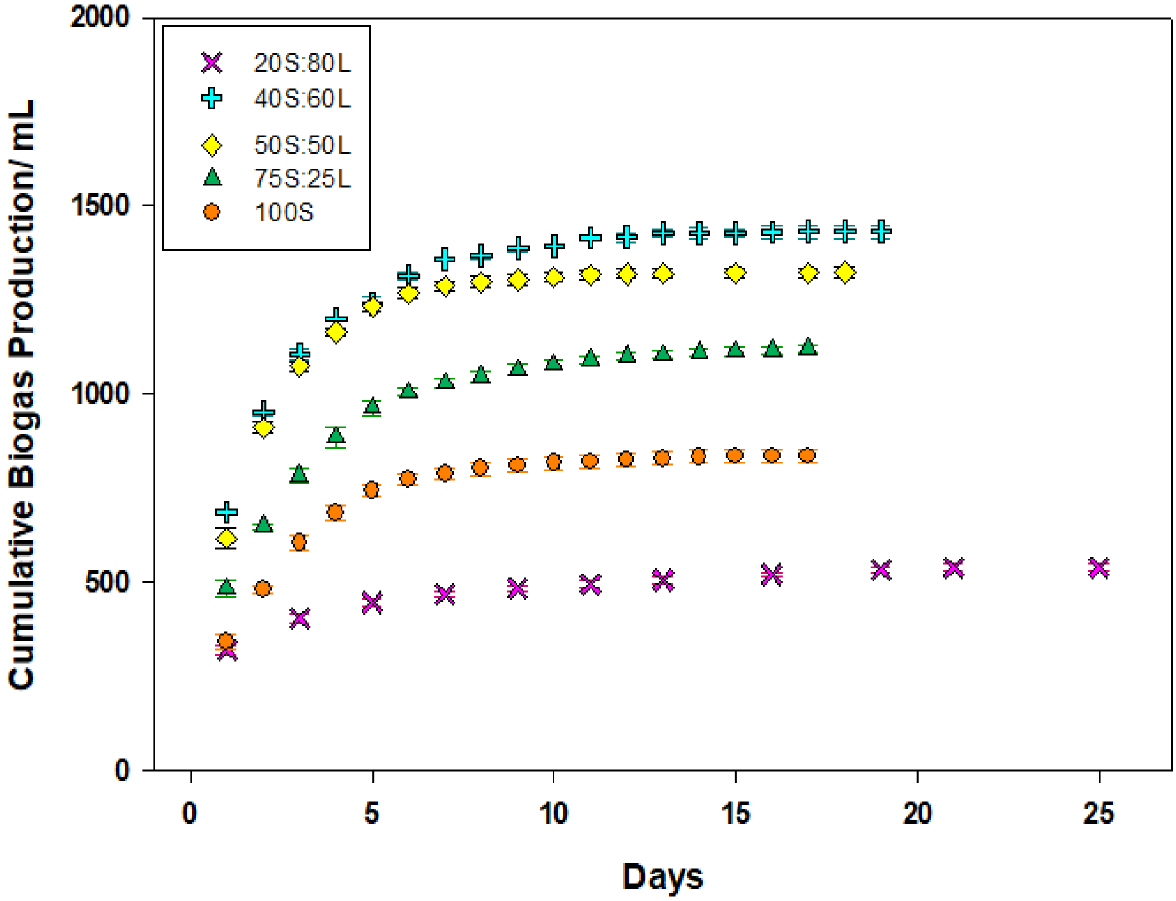


Figure 3: Combined cumulative biogas production graphs for different solid: liquid ratios

Figure 3 illustrates the graph of cumulative biogas volume produced daily. As shown in the latter, the duration for anaerobic digestion determined as the time taken for methane to stop being produced, varies from ratio to ratio. It can be seen that as the solid content increases, the final cumulative biogas attains a plateau more rapidly. This observation is in agreement with a study conducted by Angelonidi and Smith (2015). From the daily biogas production, it was observed that the rate of biogas production is at its maximum during the first 8-10 days, after which it steadily decreases until no biogas is produced exemplified by the plateaus in Figure 3. A possible explanation for the shortened anaerobic digestion duration of the higher solids content ratios may be owing to the transport restriction within the digester making part of the system inaccessible for digestion (Benbelkacem et al., 2015; Markis et al., 2014). This, in turn, prevents the bacteria from thriving; an indication of the reduced bacterial activity is made known by the anaerobes count undertaken using the most probable number (MPN) method presented in Table 1. As that table shows, as the solid loading increased, the total number of anaerobes decreased, resulting in a deficit in active microorganisms present in the medium, thereby causing the biogas production to subside until it ceased altogether.

It was observed that 20S:80L ratio generated the least amount of biogas compared to the other ratios; an explanation for this incidence is due to the restricted amount of solids available for the bacteria to hydrolyze the substrate effectively to produce biogas (Cappai et al., 2015; Mishra et al., 2019). Conversely, the 40S:60L solid loading exhibited the maximum biogas volume produced compared to all the other conditions demonstrating that the solid content in the anaerobic digester is an essential parameter to be taken into consideration. The biogas production volume decreases from the 50S:50L to 100S as the solid content increases. The formation of a thick layer of scum was observed in the 75S:25L and 100S digesters; this occurs owing to a high oil content present in these ratios (Long et al., 2012). The maximum rates of biogas production for the 40S:60L and 50S:50L solid loadings were evaluated to be 194.00 and 183.97 mL/d, respectively. Despite the 50S:50L solid loading having a comparable biogas production rate as the 40S:60L solid loading, the latter had a more sustained biogas production as depicted by the slopes in the graph in Figure 3 whereby beyond day 6, the 40S:60L solid loading was still producing biogas consistently whereas the production of biogas for the 50S:50L solid loading started to decline gradually.

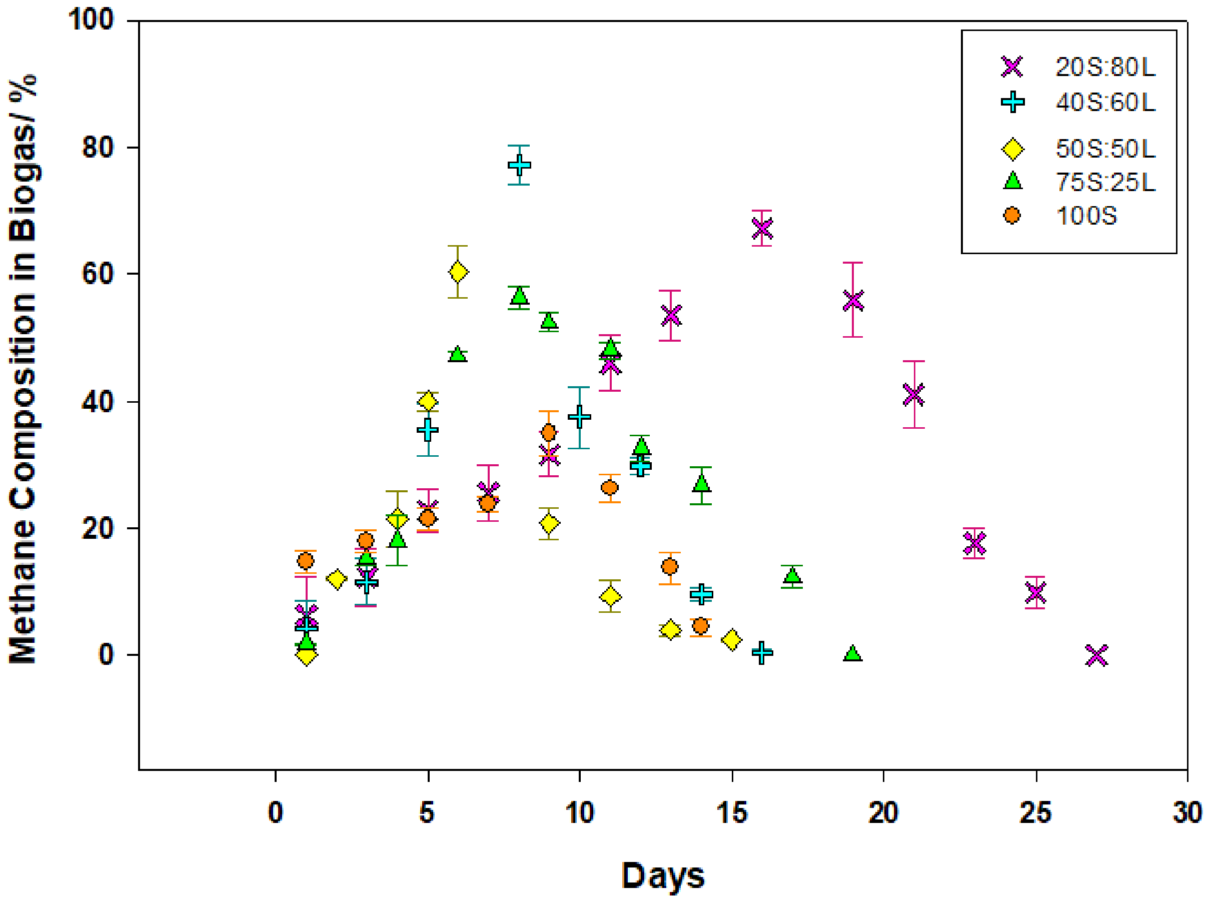


Figure 4: Combined daily methane composition as measured by the Combimass analyzer graphs for different solid: liquid ratios

Meanwhile, almost all the solid loadings produced less than 10% of methane in the biogas on the first day except 100S for which 15.3% of methane was recorded. It is important to note that the maximum methane purity tended to occur between day 5 and 8 for the 40S:60L, the 50S:50L, 75S:25L, and 100S, whereas for 20S:80L solid loading, it occurred much later at day 16.

The anaerobic digestion duration for the 20S:80L solid loading was found to be of approximately 25 days. Duration was measured via Figure 4 as the time for methane composition of the gas produced on any given day to fall to zero. The pH of the system ranged from the initial pH 7.23±0.05 to the final pH 7.52±0.03, indicating that the medium in which the inoculum was thriving was at the optimal pH and did not inhibit the biogas production as noted by the production of biogas over a long period. It can be observed that the maximum biogas production occurred between day 1 to day 15, after which the biogas production radically declined. The initial biogas production rate was evaluated to be 66.75 mL/d. The maximum biogas volume produced was found to be 539±10 mL. Figure 4 represents the daily methane composition; the latter shows that the maximum methane purity of the biogas produced was achieved from day 16-19. This is disadvantageous since it occurs during a period when the daily biogas production has already significantly decreased, there is a high proportion of methane but in a small daily volume of biogas. The methane yield calculated was 36.20 mL CH_4/g $COD_{removed}$ while the maximum methane purity in the biogas produced was 73.83±2.42% as indicated in Table 1 which is a significant increase in comparison to the methane production in the anaerobic digestion of raw POME which was reported to be around 35 to 54.4% methane (Chin et al., 2013b; Yacob et al., 2006). The initial chemical properties of the 20S:80L condition in terms of COD, BOD, TSS, and O&G were 37600±190, 16350±152, 9500±100, and 268±23 mg/L, respectively. Meanwhile, the COD, BOD, TSS, and O&G of the latter after anaerobic digestion were found to be 14088±430, 6855±287, 4233±328 and 197±1 mg/L. The findings resulted in a COD, BOD, TSS, and O&G removal of 62.53±1.45, 58.07±1.76, 55.44±3.46, and 26.20±0.46% correspondingly.

The results obtained for the 40S:60L solid loading proved to be the best performing amongst the tested conditions in terms of biogas production and methane yield. The anaerobic digestion duration for the 40S:60L solid loading was around 20 days compared to 25 days for the 20S:80L solid loading and shorter retention time is advantageous when it comes to anaerobic digestion. The pH of the system ranged from 7.21± 0.02 to 7.74± 0.09. This lies within the optimal pH range for sustained biogas production during anaerobic digestion is 6.8 to 8.0 (Iskandar et al. 2018; Choong et al. 2018). The pH of the system also corresponds to the condition under which methanogens will produce methane (Lindner et al., 2015). The maximum biogas volume was found to be 1431±17 mL, which was nearly three times more than that generated by 20S:80L solid loading, as shown in Figure 3 above. The methane yield was calculated to be 58.40 mL CH_4/g $COD_{removed}$, which is about 1.6-fold higher than the 20S:80L solid loading. It can be observed that the maximum methane purity yield occurred between day 5 to day 10. The initial COD, BOD, TSS, and O&G for the 40S:60L condition were 47700±120, 20740±138, 16200±113, and 279±13 mg/L, respectively. After anaerobic digestion, the COD, BOD, TSS, and O&G reduced to 24377±537, 13696±345, 9788±366 and 209±2 mg/L resulting in a removal of 48.89±1.12, 32.64±1.66, 39.57±2.26 and 25.05±0.62 % of COD, BOD, TSS, and O&G respectively.

For the 50S:50L solid loading, it was observed that the total biogas volume produced decreased compared to the 40S:60L solid loading. The anaerobic digestion duration was found to be around 18 days, which was also shorter than for the 40S:60L loading. However, although the shorter anaerobic digestion duration is preferred, the overall performance of the anaerobic digestion of the 50S:50L solid loading did not exceed that of the 40S:60L solid loading. The total volume of biogas produced was 1322±13 mL, which is approximately 107 mL less biogas than the 40S:60L solid loading while the methane yield was found to be 40.06 mL CH_4/g $COD_{removed}$. This indicates that on a full-scale application, this drop in the amount of biogas produced can be substantial, therefore favoring the use of the 40S:60L solid loading. The methane purity recorded was 64.26±2.7% of the biogas, which is also slightly less than the 40S:60L solid loading. The initial COD, BOD, TSS, and O&G for the 50S:50L ratio were 49500±210, 22098±195, 15800±115, and 294±25 mg/L, respectively. After anaerobic digestion, the recorded COD, BOD, TSS, and O&G were 33033±352, 16799±287, 11155±244 and 237±1 mg/L respectively. It is noted that as the amount of solid in the anaerobic digesters increases, the removal efficiency in terms of COD, BOD, TSS, and O&G decreased. The COD, BOD, TSS, and O&G percentage removal were calculated to be 33.26±0.71, 23.97±1.30, 29.40±1.55, and 19.24±0.45%.

The results obtained for 75S:25L solid loading confirmed that the higher the amount of solids in the digester, the lower the performance of the anaerobic digestion process, albeit the conditions of the experiments are still within the range of what is considered the optimal in terms of pH and temperature (Trisakti et al., 2017). The initial rate of biogas production for 75S:25L solid loading was recorded as 146.98 mL/d. The total biogas volume produced with the 75S:25L ratio was 1122.70±9.94 mL, which was approximately 309 mL less biogas than the 40S:60L solid loading. The methane yield was found to be 27.84 mL CH_4/g $COD_{removed}$; this indicated a decrease in methane yield of slightly more than twofold compared to that of the 40S:60L condition. Furthermore, the purity of methane for 75S:25L was noted to be 12.5% less than the 40S:60L loading, while the H_2S content was exceedingly elevated as shown in Table 1. The initial COD, BOD, TSS, and O&G for the 75S:25L condition were 52400±145, 24950±230, 22000±162, and 322±35 mg/L, respectively. After anaerobic digestion, the COD, BOD, TSS, and O&G reduced to 40289±212, 18959±129, 17433±126 and 236±1 mg/L resulting in a removal of 23.11±0.41, 24.10±0.52, 20.76±0.57 and 26.57±0.18 % of COD, BOD, TSS, and O&G respectively. These results corroborated that the higher the solids loading, the less efficient is the COD, BOD, and TSS removal. However, the O&G removal efficiency improved compare to the 40S:60L and the 50S:50L solid loadings. A possible explanation for this occurrence is that some of the O&G were lost in the layer of scum formed on top in the 75S:25L solid loading digesters while there was no scum formation observed in the 20S:80L, 40S:60L, and 50S:50L loadings (Soares et al., 2019).

The 100S solid loading (i.e. pure settled suspension with no liquid mixed back in) was amongst the worst performing condition of all those tested in terms of methane yield, COD, BOD, and TSS. Although the anaerobic digestion duration was similar to that obtained for 75S:25L solid loadings both around 17 days, the total biogas volume, the methane purity, and the removal of COD, BOD, and TSS were substantially less than for the 40S:60L solid loading except for the O&G removal. The cumulative biogas production was found to be 833±17 mL, while the methane yield was 16.69 mL CH_4/g $COD_{removed}$. The initial COD, BOD, TSS, and O&G for the 100S solid loading were 54000±250, 25975±125, 23100±190, and 649±32 mg/L, respectively. Post anaerobic digestion, the COD, BOD, TSS, and O&G decreased to 49856±568, 20315±478, 18711±658 and 446±4 mg/L resulting in a removal of 7.67±1.05, 21.78±1.84, 19.06±2.85 and 31.16±0.62 % of COD, BOD, TSS, and O&G respectively.

A similar trend to this study whereby the 20S:80L (3.29% TS) ratio generated less biogas in contrast to the 100S (7.86%TS) solid loading was in concurrence to another study by (Deepanraj et al., 2015) on food waste which is further discussed in section 3.2. The decline in biogas volume at higher TS content was explained by the limited microbial/enzymatic substrate contact with an increased amount of solids present in the reactor or owing to the competition for substrate between the methanogens and the sulfate-reducing bacteria (Yan et al., 2018). Meanwhile an explanation for lower biogas yield at exceedingly low TS may be due to the limitation in microbial biomass hydrolysis whereby given that there is insufficient solid in comparison to the number of bacteria found in the medium owing to the low solids content, the microorganisms cannot efficiently convert the solids to methane, hence, the biogas production lessens (Mishra et al., 2019).

Based on the calculated average percentage deviation in the full set of measured quantities listed in Table 1 below, it can be observed that 20S:80L and 100S solid loadings tend to have the least stable anaerobic digestion process with a calculated average percentage deviation of 2.10%. Meanwhile, the 50S:50L and 75S:25L solid loadings tend to exhibit the most stable anaerobic digestion indicated by a smaller percentage deviation of roughly around 1.00% across all the quantities tested. The stability of the 40S:60L solid loading lies between that of the least and the most stable ratios at a percentage deviation of 1.22%. Since the latter is the best performing ratio despite its slightly lower stability, it can be established that 40S:60L notably improved the anaerobic digestion performance with respect to the COD, BOD, TSS, and biogas production, methane yield along with a comparatively stable anaerobic digestion process for POME.

Table 1 presents a summary of the results obtained for all the tested conditions. It can be observed that the anaerobic digestion performance increases from the 20S:80L to 40S:60L solid loadings in terms of biogas production, methane yield as well as COD, BOD, and TSS removal after which the efficiency of these parameters decrease with increasing solid loading except for the O&G. The pH of the medium for each condition was determined to be within the optimal pH range for thermophilic anaerobic digestion to prevent the inhibition of methane conversion by the methanogens (Appels et al., 2008; Nayono, 2009). It can also be noted that the total anaerobes population at the end of anaerobic digestion decrease as the solid loading increases. This is in concurrence with the amount of biogas being produce.

Table 1: Results obtained for the thermophilic anaerobic digestion of POME for different solid loadings

	20S:80L	**40S:60L**	**50S:50L**	**75S:25L**	**100S**
Dry Solids Content/ %TS	3.29	4.02	5.25	6.40	7.86
Initial pH	7.23±0.05	7.21± 0.02	7.22±0.12	7.27±0.10	7.23±0.07
Final pH	7.52±0.03	7.74± 0.09	7.56±0.04	7.44±0.04	7.75±0.07

Cumulative Biogas Production/ mL	539±10	1431±17	1322±13	1122±10	833±17
Initial Biogas production rate/ mL/d	66.75	194.00	183.97	146.98	106.09
Maximum Methane Composition /%	73.83±2.42	77.33± 1.20	64.26±2.71	57.73±1.62	33.17±1.30
Minimum Methane Composition /%	50.36±2.07	57.80±2.67	54.13±0.87	40.67±0.58	20.87±3.04
Methane Yield/ mL CH_4/g $COD_{removed}$	36.20	58.40	40.06	27.84	16.69
H2S composition/ mg/L	204±4	341±16	560±21	1823±23	2968±52
MPN Total Anaerobes/ 100mL	$1.2x10^6$	$2.1x10^6$	$7.5x10^5$	$1.5x10^5$	$9.3x10^4$
Duration of Experiment /days	≈25	≈20	≈18	≈17	≈17
COD removal/%	62.53±1.14	48.89±1.12	33.26±0.71	23.11±0.41	7.67±1.05
BOD removal/%	58.07±1.76	32.64±1.66	23.97±1.30	24.10±0.52	21.78±1.84
TSS removal/%	55.44±3.46	39.57±2.26	29.40±1.55	20.76±0.57	19.06±2.85

O&G removal/%	26.20±0.46	25.05±0.62	19.24±0.45	26.57±0.18	31.16±0.62

3.2 Comparison between the effect of total solids on the anaerobic digestion of POME and other types of substrates

As the literature on the effect of different solid loading/ TS contents on digestion of POME is rather limited, a comparison was carried out between our results on POME and findings on different types of substrates to thoroughly understand the impact of TS content on the biogas production and the anaerobic digestion performance overall. Since the operational conditions and substrates were different, the comparisons were made relative by normalizing the cumulative biogas productions and the methane yields by their highest values in their corresponding data sets (Benbelkacem et al., 2015). A common observation from all the literature studied was that at a lower TS concentration, the biogas production and the methane yield tend to be more favorable. An explanation for this occurence may be attributable to the increase in water content and the associated more effective transport and mass transfer conditions whereby the microorganisms are better sustained with soluble substrates, thus making the anaerobic digestion process more efficient (Le Hyaric et al., 2012; Xu et al., 2014; Zhang et al., 2018).

In a study undertaken by Wang et al. (2016) on waste activated sludge (WAS) mixed with dewatered sludge collected in a domestic wastewater plant, it was observed that 4.00% TS produced the maximum methane recorded to be 181.7 mL CH_4/g Volatile Solids (VS) $_{added}$. This finding is in agreement with our study, whereby, POME at 4.02% TS (the 40S:60L solid loading) achieved the highest methane yield compared to the other TS concentration. Wang et al., (2016) also observed that at TS content higher than 6.00%, the biogas production decreased with increasing TS concentration. This observation also concurs with the present study in which it was observed that above 6.40% TS; the methane yield deteriorated significantly. Another comparable behavior for POME and WAS mixed with dewatered sludge was that both substrates produced the maximum amount of biogas between day 1 and day 10 across all the different TS contents, after which the biogas production declined progressively. Based on the results obtained, it was established that POME exhibited a similar trend as WAS mixed with dewatered sludge when it comes to the effect of TS content on anaerobic digestion performance.

In another study undertaken by Fernández et al. (2008) on the effect of substrate concentration in terms of TS content of organic fraction of municipal solid waste (OFMSW) during mesophilic anaerobic digestion, they noted that the methanogenic stage began at day 14 for 20% TS and on day 28 for 30% TS. For a working volume of 1.7 L, they observed that a total methane production of 7010 mL and 5530 mL for 20% TS and 30% TS correspondingly. The methane yield for 20% and 30% TS was evaluated to be 110 mL CH_4/g Volatile Solid $(VS)_{removed}$ and 70 mL CH_4/g $VS_{removed}$, respectively (Fernández et al., 2008). A noteworthy observation made was that at even lower TS concentration, a higher biogas production and methane yield was achieved. An example of the latter is the study of Dong et al. (2010), who investigated the mesophilic anaerobic digestion of water sorted OFMSW. They noticed that 11.0, 13.5, and 16.0% TS achieved a methane yield of 314, 283, and 273 mL/g VS, correspondingly with a working volume of 35L for each condition.

Abbassi-Guendouz et al. (2012) investigated the effect of total solids on the mesophilic anaerobic digestion of municipal solid waste (MSW) at concentrations ranging from 10% TS to 35% TS. They observed that as the TS concentration increased, the methane production decreased. They established that 10% TS yielded the highest methane, which was recorded at 149.00 mL CH_4/g COD, whereas POME achieved a maximum final methane yield of 58.40 mL CH_4/g COD at 4.02% TS. It is important to note that MSW is substantially inhomogeneous, which is a factor that can also affect its methane production (Ghanimeh et al., 2012). However, it was noted that the initial biogas production rates were similar across the different TS concentrations (Abbassi-Guendouz et al., 2012). Inhibition in the methane production was observed to occur at 35% TS in the mentioned study, whereas, for POME, it occurred even at 6.40% TS corresponding to 75S:25L solid loading. POME has a lower biogas production compared to the MSW; the latter may be explained by the lower working volume of 100 mL (compared to 1.7 L and 400 mL) or owing to the high lignin and phenolic compounds composition in the substrate (Abbassi-Guendouz et al., 2012; Veeresh et al., 2005). Veeresh et al. (2005) stated that phenolic compounds at a concentration higher than 750 ppm could inhibit anaerobic digestion owing to a reduced biodegradability.

Deepanraj et al. (2015) investigated the various TS contents ranging from 5 to 15% TS on the mesophilic anaerobic digestion of food waste (FW). They observed that from 5% to 10% TS, the biogas production increased after which it started to deteriorate steadily up to 15% TS. Subsequently, the 5% TS sample yielded less biogas than the 15% TS sample. They stated that the best performing condition was 7.5% TS at a pH of 7. In the latter condition, the maximum biogas produced was recorded to be 5673 mL from 1.6 L of substrate. The other reactors with 5, 10, 12.5, and 15% of total solids concentrations generated 3040, 3913, 3739, and 3582 ml of biogas, respectively. In another study on FW, Liotta et al. (2014) examined the influence of TS ranging from 4.5 to 19.2 % on the anaerobic digestion at mesophilic temperature; they stated that the methane yield attained was 350, 335, and 207 mL CH_4/ g $VS_{substrate}$ for 4.5, 12.9 and 19.2% TS respectively.

Liu and Lv (2016) studied the effect of TS content at different temperatures ranging from 31-43℃ on the anaerobic digestion of dairy manure. The investigated TS concentrations were 6, 8, and 10%. They observed that at temperatures higher than 37℃, as the TS content increased, the digestion period shortened; we also identified this occurrence in the digestion of POME at 55℃. Liu and Lv (2016) stated that the best performing condition was 8% TS at 40℃, where approximately 3800 mL biogas was attained at the end of 27 days. The maximum biogas was achieved around day 8 for 8% TS whereas the latter occurred after day 10 for 6 and 10% TS. The cumulative biogas production for 6% and 10% TS was 1750 mL and 2600 mL, respectively, at the most favorable temperature (40℃) (Liu and Lv, 2016).

To summarize the findings of this study, it was found that the biogas production increased from the 20S:80L (3.29% TS) to 40S:60L (4.02% TS) and decreased from 50S:50L (5.25% TS) to 100S (7.86% TS). In the study, we found that the best performing ratio (40S:60L) lies below the solid: liquid ratio of raw POME which ranges from 55S:45L to 85S:15L. Higher solid loadings produced an adverse effect on the biogas production, the methane yield as well as the methane purity in the biogas produced. The latter may occur owing to poor transport and mass transfer conditions and an elevated amount of hydrogen sulfide gas produced at the higher solid loadings due to the presence of sulfate-reducing bacteria (Yan et al., 2018). The removal efficiency of COD, BOD, and TSS deteriorated as the solid loading increased. An interesting observation was that the O&G removal efficiency decreased the 20S:80L to 50S:50L but steadily increases from the latter to 100S solid loadings. It was also observed from the cumulative biogas production volume graphs, based on the size of error bars that as the solid content increases the stability of the anaerobic digestion process increases.

This study demonstrates that with the ability to control the digesters' solid loading, specific desired outcomes can be achieved. For example, if the main aim of the anaerobic digestion process is to produce biogas with higher methane purity, then a lower solids loading is required whereas if the objective is to treat the effluent such that the end products are more manageable then higher solid contents may be more desirable i.e. to produce fertilizers. This study indicates significant potential in the customization of the anaerobic digesters’ load to enhance the anaerobic digestion process to cater for different industrial requirements. The implementation of a solid-liquid separation stage (e.g., a thickener) into the treatment process of POME should allow a consistent treatment process and a means of control on the characteristics of POME, although the latter fluctuates from high crop to low crop season (Poh et al., 2010).

4. Conclusion

A higher solid content may not necessarily signify a better anaerobic digestion process performance; contrariwise, this study indicated the opposite. It was observed that the methane yield per mass of COD removed, and the biogas production increased between the 20S:80L to 40S:60L loadings, after which it steadily decreased with higher solid loadings. It was observed that the COD, BOD, and TSS removal efficiencies progressively deteriorate as the solid loading increases. The O&G removal efficiency steadily decreases from 20S:80L to 50S:50L; however, it increases for 75S:25L and 100S solid loadings. It was established that the best performing solid loading is the 40S:60L which produced 1431±17 mL of biogas, having a methane yield of 58.40 mL CH_4/g COD and removal efficiencies of COD, BOD, TSS and O&G of 48.89±1.12, 32.64±1.66, 39.57±2.26 and 25.05±0.62 %, respectively. Based on this study, we now know that since the optimal ratio lies below the solid: liquid ratio of raw POME, the suggested way to operate the thickener is therefore to run a fraction of POME through the thickener and mix the clarified liquid from that thickener with the remainder of the raw POME to reach the targeted solids fraction. This study shows that the anaerobic digestion process for POME can be customized through the solid loading of the bioreactor to produce the desired outcome, whether it is in terms of enhanced biogas production or manageable end products. Implementing a solid-liquid separation step in the process to control the solid loading, thereby has tremendous potential for improving the process.

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Nomenclature

APHA	American Public Health Association
ASTM	American Society for Testing Material
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
FW	Food Waste
L	Liquid
MPN	Most Probable Number
MSW	Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
O&G	Oil and Grease
POME	Palm Oil Mill Effluent
S	Solid
TS	Total Solids
TSS	Total Suspended Solids
VS	Volatile Solids
WAS	Waste Activated Sludge

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