Iranica Journal of Energy & Environment 5 (2): 209-217, 2014
ISSN 2079-2115
IJEE an Official Peer Reviewed Journal of Babol Noshirvani University of Technology
DOI: 10.5829/idosi.ijee.2014.05.02.14

Application of Partial-Mixed Semi-Continuous Anaerobic Reactor for Treating Palm Oil Mill Effluent (POME) Under Mesophilic Condition

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Received: February 11, 2014; **Accepted** in Revised Form: June 11, 2014

Abstract: Partially mixed semi-continuous reactor was used to examine the effect of organic loading rate (OLR) and hydraulic retention time (HRT) on the mesophilic anaerobic digestion of palm oil mill effluent (POME). The performance of the reactor was evaluated with emphasis on biodegradability of POME, methane gas (CH_4) production rate and methane yield under different organic loading rates. The OLR of the anaerobic reactor increased stepwise from 1.0 to 6.0 g COD/L/day and HRT ranged from 13.3 to 80.0 days. The total chemical oxygen demand (TCOD) utilized was higher than 75% and the CH_4 percentage of the biogas was 62.00-63.00% for the OLRs studied. The methane yield coefficient (Y_{CH4}) was inversely proportional to the OLR due to the loss of biomass with effluent. The experimental observations proved that partially mixed semi-continuous reactor could perform similar to complete-mixed reactors.

Key words: Anaerobic Digestion · Mesophilic · Semi-Continuous · Palm Oil Mill Effluent (POME) · Methane Yield.

INTRODUCTION

Palm oil extraction process generates a massive amount of non-toxic but high organic strength liquid effluents, such as palm oil mill effluent (POME). Under proper operation, approximately 2.5 m^3 of POME is generated per ton of crude palm oil produced. POME is mainly contributed by a sterilization (0.9 m^3) and clarification process (1.5 m^3), in which a large amount of steam and hot water are used, along with washing water from hydrocyclone (1.0 m^3) [1]. It is a hundred times more polluted compared to domestic sewage. Anaerobic digestion is considered an effective treatment method for POME. This biological process disintegrates organic matter while generating green energy, specifically, methane gas (CH_4). The recovery of this renewable energy not only conserves cost by fuel displacement, it also represents a more acceptable alternative under the Kyoto Protocol, which aims to reduce greenhouse gas (GHG) emissions. Previous lab-scale anaerobic reactors were operated in continuous mixing mode [2-4]. The contents of most anaerobic reactors are completely mixed to ensure intimate contact between microorganisms and organic matter; prevent precipitation of dense particles and release biogas bubbles trapped in the medium. These results may enhance the anaerobic digestion process.

However, continuous mixing is not necessary in terms of attaining optimum performance; inhibitory factors are observed at higher organic loading rates (OLRs) [5]. Kim *et al*. [6] reported that non-mixed anaerobic reactors show higher gas production, given that non-mixing reactor configurations have closer microbial consortia proximity than others do. Sulaiman *et al*. [7], who conducted anaerobic digestion of POME in a semi-commercial closed digester tank, reported that vigorous mixing inhibits CH_4 production and causes a high concentration of total volatile fatty acids (TVFAs) in the system.

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Please cite this article as: Weng, C.K., N. Ismail and A. Ahmad, 2014. Application of Partial-Mixed Semi-Continuous Anaerobic Reactor for Treating Palm Oil Mill Effluent (POME) Under Mesophilic Condition. Iranica Journal of Energy and Environment, 5(2):209-217.

Seengenyoung *et al*. [8] have investigated the effect of alkaline and acid pretreatment on solubilization of solid organic matter in palm oil mill effluent (POME) and hydrogen production using enriched sludge; they have successfully converted the volatile organic compound of POME to hydrogen. Chelliapan *et al*. [9] have converted paper mill effluent to methane in anaerobic digester at OLR of 1.56 kg COD/m^3.d. Stafford [10] reported no improvement in gas yield for mixing speed between 140 and 1000 rpm; a slight reduction in biogas production at high speeds was observed due possibly due to shear forces separating hydrolytic bacteria from their polymer substrates. Mixing appears to inhibit the syntrophic oxidation of volatile fatty acids, possibly by disrupting the spatial concurrence of syntrophic bacteria and their methanogenic partners [5]. In addition, mixing systems not only affect the anaerobic efficiency, they are also often expensive to install, maintain and operate. Although many lab-scale investigations show the excellent performance of completely mixed anaerobic reactors at agitation speeds ranging from 70 to 260 rpm [2-4, 11, 12], high-speed, continuous mixing systems seem to be impractical in conventional digester tanks, since the operating volume may be up to a few thousand cubic meters, as stated by Tong and Jaafar [13]. Therefore, an efficient mixing system will be advantageous in terms of productivity and cost effectiveness [14].

Few studies evaluate the anaerobic digestion of POME using reactors with minimal mixing. To fill this information gap, this study aims to i) develop a partially mixed semi-continuous mesophilic anaerobic reactor that provides minimal disturbance (mixing) on the anaerobic process; and ii) evaluate the performance of the anaerobic reactor in treating POME. For this purpose, an intermittently mixed lab-scale reactor is used and operated at different OLRs.

MATERIALS AND METHODS

Equipment: A 3 L glass flask with a working volume of 2 L was used as the mesophilic (35°C) anaerobic reactor. The reactor was placed in a water-bath to maintain a corresponding fixed temperature. The operation cycle was based on the draw and fill principle (fed-batch mode) via a peristaltic pump. The liquid in the anaerobic reactor was in mixing condition during the effluent withdrawal to obtain homogenous (mixed) effluent. An equal volume of POME was then immediately fed after effluent withdrawal and the reactor was mixed again to enhance the contact between the newly fed POME and anaerobic biomass. The reactor was mixed for 5 min twice per day, with the aid of manual shaking to guarantee complete mixing. In addition, manual shaking minimized the tendency of the substrate to stick to the reactor wall due to scum formation.

Table 1: The characteristics of inoculum and POME used in the experiment

Parameters	Inoculum	POMEa (mean)
pH	7.4	3.7
TCOD	1.650 x 10^4	8.000 x 10^4
SCOD	0.125 x 10^4	2.660 x 10^4
PCOD	1.525 x 10^4	5.340 x 10^4
TS	2.410 x 10^4	4.955 x 10^4
VS	1.255 x 10^4	4.228 x 10^4
TSS (MVSS)	1.525 x 10^4	2.518 x 10^4
VSS (MLVSS)	1.234 x 10^4	2.346 x 10^4
TDS	0.885 x 10^4	2.437 x 10^4
VDS	0.021 x 10^4	1.882 x 10^4
TVFA	0.12 x 10^3	1.98 x 10^3

* Unit for all parameter is mg/L except pH [a]n = 30

POME: POME was collected from Malpom Industries Sdn Bhd, located in Nibong Tebal, Penang, Malaysia; and was kept in a freezer at -20°C until further detailed analysis or experiments were conducted. POME was warmed to room temperature before chemical analysis and feeding. This storage had no noticeable effect on the composition during the experimental period. The POME used in experiment is characterized and shown in Table 1.

Inoculum: The inoculum for the mesophilic reactor, taken from a scum-sludge mixture of a facultative-anaerobic pond treating POME, was obtained from a laboratory-scale anaerobic reactor operated under mesophilic condition (35 °C). Table 1 summarizes the characteristics of the inoculum.

Experimental Operation: Prior to start an experiment, 2 L of mesophilic anaerobic sludge was loaded into the reactor and then purged with nitrogen gas for 5 min to achieve anaerobic condition. The inoculum sludge was incubated at 35 °C for two weeks before the start up of the experiment. The preliminary incubation step was followed by a series of semi-continuous flow experiments using stepwise increase OLR to minimize the organic shock in the reactor. The mesophilic reactor was operated at a hydraulic retention time (HRT) of 80.0, 40.0, 32.0, 26.7, 20.0, 16.0 and 13.3 days, which corresponded to OLRs of 1.0, 2.0, 2.5, 3.0, 4.0, 5.0 and 6.0 g COD/L/day, respectively. Decreased HRT was achieved by increasing the OLR, as well as by increasing the feed flow rate (Q). The reactor was fed and the effluents were chemically analyzed every two days. The volumetric feed applied was equivalent to 0.050, 0.100, 0.125, 0.150, 0.200, 0.250 and 0.300 L, respectively. Since the reactor was not equipped with a biomass separator or support medium, the OLR was gradually increased once a steady state was achieved, allowing for acclimatization of the microbial biomass. The steady-state value of a given parameter was defined as the mean of the consecutive measurements (n=3) for that parameter when the deviations between the observed values were less than 10% in all cases.

Analytical Methods: Different parameters of the samples were analyzed according to American Public Health and Association (APHA) standard methods for water and wastewater analysis [15]. The parameters studied were pH, total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD), total solids (TS), volatile solids (VS), total suspended solids (TSS), volatile suspended solids (VSS) and TVFA. TCOD and SCOD were analyzed according to the closed reflux, colorimetric method (5220 D). The particulate COD (PCOD), defined as non-soluble COD, was calculated by subtracting SCOD from TCOD. The samples were dried at 105 °C (methods 2540 B and 2540 D) to determine TS and TSS and ignited at 550 °C to measure VS and VSS (method 2540 E). TVFA (as acetic acid) was determined by distillation method (5560 C), which is a routine control test for the anaerobic digestion process. The biogas generated was collected in 5 L Tedlar gas sampling bags and the composition of CH_4 was analyzed using a portable gas analyzer (GA 2000, GEOTECH); the total volume of biogas was measured with a volumetric plastic syringe. The volumes of biogas and CH_4 were corrected to volume under standard temperature and pressure (STP).

Performance Parameters: Other than the aforementioned analytical parameters, other performance parameters were included to evaluate the start-up process, such as the fraction of organics utilized by microorganisms ($TCOD_{utilized}$) and methane yield (Y_{CH4} and B_{CH4}) of the anaerobic suspended growth reactors. $TCOD_{utilized}$, defined as the percentage of organic matter utilized by microorganisms for anaerobic metabolisms, was calculated by the following equation:

$$TCOD_{utilized} = \frac{(TCODi - TCODe)}{TCODi} x100\% \quad (1)$$

where $TCOD_i$ and $TCOD_e$ represent the TCOD concentration of raw POME and mixed effluent, respectively.

Methane yield, Y_{CH4}, was the methane conversion tool based on the organics utilized, while B_{CH4} is based on organic load:

$$Y_{CH4}\ (L\ CH_4/g\ COD_{utilized}) = \frac{Q_{CH4}}{Q*(TCOD_i - TCOD_e)} \quad (2)$$

$$B_{CH4}\ (L\ CH_4/g\ COD_{added}) = \frac{Q_{CH4}}{Q*TCOD_i} \quad (3)$$

where Q_{CH4} is the volume of methane generated per day (L CH_4/day) and Q is the volumetric feed rate of POME (L POME/day).

RESULTS AND DISCUSSION

Process Stability: The experimental results obtained at steady-state conditions for different analyzed parameters and performance parameters; calculations are summarized in Table 2. The mesophilic anaerobic digestion was carried out using progressive OLRs; the OLR of 1.0 g COD/L/day was the first and 6.0 g COD/L/day was performed at the end of this research. The influence of OLR on the pH and TVFA concentration in the mesophilic reactor were observed, as illustrated in Fig. 1. The pH remained practically constant, with values ranging between 7.3 and 7.4, which is near the inoculum pH. Previous investigations on different types of wastewater proved that the pH of a steady-state process ranged between 6.9 and 7.5 [16, 17]. The TVFA concentration was kept below 250 mg/L when OLR was increased stepwise from 1.0 to 5.0 g COD/L/day. The effective methane conversion did not allow for the accumulation of high TVFA concentration in the system. However, the pH value (4.3) significantly decreased when OLR reached the maximum value studied (6.0 g COD/L/day). For the lowest HRT studied (13.3 days), TVFA sharply increased to 8.2×10^3 mg/L. Low pH value and high TVFA concentration symbolized the destabilization and acidification of the anaerobic reactor, which may be due to the loss of biomass and sudden decrease in alkalinity. Rincon *et al.* [17] observed an appropriate buffering capacity (alkalinity) and high stability of the anaerobic digestion before the system was acidified due to high OLR. They have stated that the high buffering capacity reduced the possible acidification of the reactor by giving an

Table 2: Reactor performance at different OLR and HRT during steady state.

OLR (g COD/L/day)	1.0	2.0	2.5	3.0	4.0	5.0	6.0
HRT (days)	80.0	40.0	32.0	26.7	20.0	16.0	13.3
Process stability							
pH	7.4	7.4	7.4	7.4	7.3	7.3	4.3
TVFA, mg/L	140	170	190	200	220	250	8200
Digester effluent							
TCODe, mg/L	1.800×10^4	1.800×10^4	1.650×10^4	1.690×10^4	1.750×10^4	1.980×10^4	7.000×10^4
SCODe, mg/L	0.150×10^4	0.160×10^4	0.180×10^4	0.190×10^4	0.225×10^4	0.320×10^4	2.050×10^4
PCODe, mg/L	1.650×10^4	1.640×10^4	1.47×10^4	1.500×10^4	1.525×10^4	1.660×10^4	4.950×10^4
PCODe/TCODe, %	91.67	91.11	89.09	88.76	87.14	83.84	70.71
$TCOD_{utilized}$ (biodegradability) %	77.50	77.50	79.38	78.88	78.13	75.25	12.50
MLVSS, mg/L	1.220×10^4	1.259×10^4	1.037×10^4	0.936×10^4	0.905×10^4	$0.90^4 \times 10^4$	1.89×10^4
Biogas production & methane yield							
CH^4 composition, %	62.95	63.00	62.60	62.50	62.70	62.00	0
CH^4 production rate, L/L/day	0.348	0.673	0.799	0.936	1.187	1.267	0
Substrate utilization rate, g COD/L/day	0.775	1.550	1.984	2.366	3.125	3.763	0.750
Y CH^4, L CH^4/g COD removed	0.449	0.439	0.403	0.395	0.380	0.337	0
B CH^4, L CH^4/g COD added	0.348	0.337	0.320	0.312	0.297	0.253	0
Y/Y_o, %	95.25	92.13	85.38	83.88	80.55	71.41	-
B/B_o, %	98.35	95.13	90.29	88.14	83.84	71.59	-

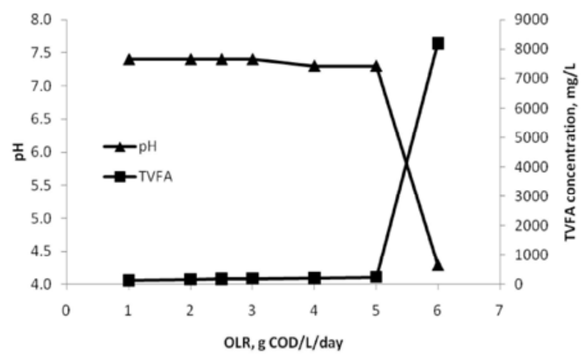

Fig. 1: Evolution of pH and TVFA with the OLR.

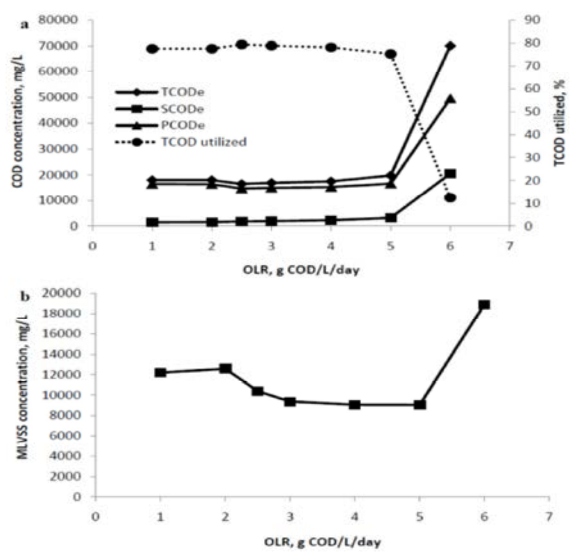

Fig. 2: Variation of the characteristics of the mixed effluent with OLR: a) $TCOD_e$, $SCOD_e$, $PCOD_e$ concentration and $TCOD_{utilized}$ and b) MLVSS

optimal pH for methanogens. The process with a TVFA/alkalinity ratio of less than 0.3-0.4 was considered one that operated favorably without acidification risk. Although the alkalinity and the TVFA/alkalinity ratio in this study were not measured, continuous monitoring on pH and TVFA was enough to examine the stability of the process.

Process Performance: As illustrated in Fig. 2a, $TCOD_e$, $PCOD_e$ and $SCOD_e$ were virtually steady when OLR increased from 1.0 to 5.0 g COD/L/day. However, $TCOD_e$ was 1.800×10^4 mg/L at an OLR of 1.0 g COD/L/day; then decreased to a minimum value of 1.650×10^4 mg/L at an OLR of 2.5 g COD/L/day; followed by a gradual increase with a further increase in OLR (Table 2). $PCOD_e$ displayed a similar development trend as $TCOD_e$. The unusual finding, high $TCOD_e$ and $PCOD_e$ observed at a low OLR, was probably due to the application of 100% inoculum to initiate anaerobic digestion. The undiluted inoculum had a high TCOD value of 1.650×10^4 mg/L, where 92.42% were in particulate form (Table 1). The excess sludge and refractory materials (PCOD) in the inoculum only washed out slowly by increasing OLR in the experiment. On the other hand, $SCOD_e$ showed a steady increase but remained at a low concentration, from 0.150×10^4 to 0.320×10^4 mg/L. All values showed a sharp increase at an OLR of 6.0 g COD/L/day. $TCOD_e$ increased from 1.980×10^4 to 7.000×10^4 mg/L; $PCOD_e$ increased from 1.660×10^4 to 4.950×10^4 mg/L; and $SCOD_e$ increased from 0.320×10^4 to 2.050×10^4 mg/L. $TCOD_{utilized}$ measured the total COD utilized by the mixed consortium of bacteria in anaerobic metabolisms, where organic load was equal to organic effluent plus organics converted to biogas. $TCOD_{utilized}$ generally remained steady (ranged from 75.25 to 79.38%) until OLR reached 5.0 g COD/L/day. Further increase in OLR caused a marked decrease in efficiency to a minimum level of 12.50%. Although CH_4 production ceased at OLR of 6.0 g COD/L/day, a small fraction of organic matter was utilized under acidic condition for the growth of hydrolytic and acidogenic bacteria. The performance of the anaerobic reactor became virtually independent on the OLR provided the OLR of the reactor was maintained below 5 g COD/L/day. Before the inhibition of methanogenesis, $PCOD_e/TCOD_e$ fractions ranged from 83.84 to 91.67% when HRT decreased from 80.0 to 16.0 days (see Table 2). Thus, major organic matter left in the effluent was in particulate form, mainly contributed by the undigested solids and small fraction of washed out biomass. Pretreatment may be required to solubilize solids in POME prior to feeding to anaerobic digestion.

The mixed liquor volatile suspended solids (MLVSS), determined by the same method as VSS, provided a crude measurement of the biomass within the reactors; since differentiating viable cells and inert materials are extremely difficult with the mixed culture of bacteria associated with hydrolyzed intermediates and undigested POME. As shown in Fig. 2b, MLVSS was slightly high at low OLR, gradually decreasing and achieving steady concentration of 0.904×10^4 mg/L at an OLR of 5.0 g COD/L/day. This implied that a significant fraction of biomass and inert materials, already present in the reactor during start-up, were gradually washed out with increased OLR. MLVSS concentrations at OLRs of 4.0 and 5.0 g COD/L/day were similar, indicating that the amount of biomass growth was the same as the amount of biomass flushed out. Higher OLRs would have resulted in excessive loss of biomass, but MLVSS was high (1.890×10^4 mg/L) due to the contamination of TSS from feeding POME.

CH_4 Production: As shown in Fig. 3, variations were observed in the CH_4 production and substrate utilization rates. The CH_4 production rates increased almost linearly, from 0.348 to 1.187 L CH_4/L/day, with OLR up to 4.0 g COD/L/day. Then, CH_4 production rates followed a slower increment, reaching 1.267 L CH_4/L/day at an OLR of 5.0 g COD/L/day; it ceased at a higher OLR. The decrease in CH_4 production might be due to the loss of methanogens that caused a sudden increase in effluent TVFA concentration (Fig. 1). Before the inhibition of methanogenesis, the detected CH_4 compositions varied between 62.00 and 63.00% (Table 2), similar to those reported by Tong and Jaafar [13]. A linear relationship

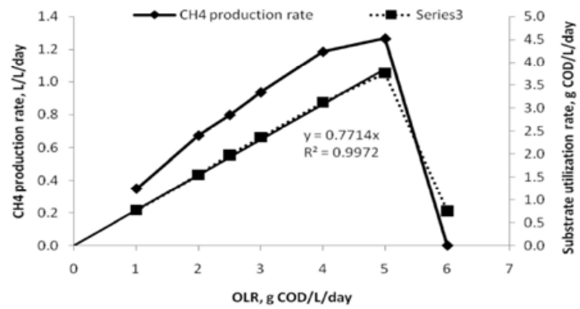

Fig. 3: Methane (CH_4) production rate and substrate utilization rate on different OLRs.

between the substrate utilization rate and OLR are presented in Fig. 3. A linear fit of all data points corresponding to OLRs in the range of 1.0 to 5.0 g COD/L/day gave a gradient of 0.7714, with a high correlation coefficient (R^2=0.9972). Thus, on average, 77.14% of input organics was biodegraded during the anaerobic digestion of POME at mesophilic temperature. However, at high OLR, a drastic decrease in efficiency was observed, coinciding with the deterioration of other parameters previously discussed.

Methane Yield Coefficient (Y_{CH4}): To understand further the relationship between substrate utilization rate and CH_4 production, the CH_4 yield coefficient (L CH_4/g $COD_{utilized}$), Y_{CH4} must be determined. The following typical equation was obtained by balancing TCOD around the anaerobic reactor:

$$Q * (TCOD_i) = Q * (TCOD_e) + Q_{CH4} * (1/Y_{CH4}) + m.V.X. \quad (4)$$

where m is the biomass maintenance coefficient (g $COD_{consumed}$/g MLVSS/d); V is the working volume of the mesophilic reactor (L); and X is the concentration of microorganisms, also known as MLVSS. Organic matter (TCOD) fed into the reactor was mostly utilized by microorganisms for CH_4 generation and cellular maintenance and a small portion will leave the reactor without any biotransformation. Thus, $TCOD_e$ also included biomass washed out from the reactor. Eq. (4) can be converted into the following equation:

$$Q * (TCOD_i - TCOD_e) = Q_{CH4} * (1/Y_{CH4}) + m.V.X. \quad (5)$$

Eq. (5) was applied by Rincon *et al*. [12] to determine the CH_4 yield coefficient and cellular maintenance coefficient for the methanogenic step of a two-stage anaerobic digestion process treating olive mill solid residue. The following assumptions were made.

- Constant volumetric flow (Q), which is the volume of POME fed into the reactor at every experimental day, was the same as the volume of effluent withdrawn.
- Constant biomass concentration, where the biomass from the feeding substrate, POME, was too low to be determined, can therefore be ignored.

However, a significant variation of MLVSS concentration was observed in this study; and it was inversely proportional to the increase in OLR. Therefore, applying Eq. (5), by assuming a constant biomass concentration for the calculation, would be inappropriate. As proof, Fig. 4a was plotted using Eq. (5), showing the relationship between daily substrate utilization and the corresponding CH_4 production. The data points were adjusted to a straight line and the correlation coefficient (R^2) obtained was 0.9780. The CH_4 yield coefficient, Y_{CH4}, determined by the reciprocal of the slope (3.1326), was 0.319 L CH_4/g $COD_{utilized}$. However, the interception point was a negative value (-0.9189), which contradicted Eq. (5) and was therefore unable to determine the biomass maintenance coefficient (*m*). To solve the problem, Fig. 4b was plotted to demonstrate the experimental Y_{CH4} corresponding to different OLRs. The Y_{CH4} was inversely proportional to the OLRs applied. It started at 0.449 L CH_4/g $COD_{utilized}$, before gradually decreasing to 0.337 L CH_4/g $COD_{utilized}$ when OLR increased from 1.0 to 5.0 g COD/L/day. The horizontal line (0.319) corresponds to the Y_{CH4} calculated by using Eq. (5) and the value is significantly lower than all experimental Y_{CH4}. The reduction of Y_{CH4} was due to losses of biomass with effluent, as well as reduced HRT and the different experimental system configurations of previous research [12]. Thus, Eq. (5) would not be appropriate to determine the Y_{CH4} of a partially mixed semi-continuous anaerobic system without support media of immobilized biomass or recycled sludge. A second-order polynomial regression curve was then plotted (Fig. 4a) and the fitted model expressed the experimental data (R^2=0.9910) better. The curve intercepted at the y axis had a value of 0.5046 g COD/day, which can indicate the daily consumption of organic matter by the microorganisms inside the reactor. The *m* value calculated was 0.0279 g $COD_{consumed}$/g MLVSS/day, on the assumption that the MLVSS concentration was 0.904×10^4 mg/L (lowest value obtained). The low calculated value showed the low

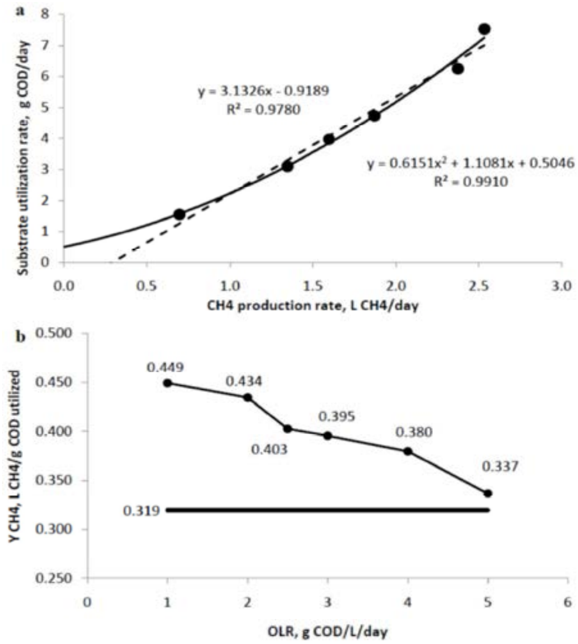

Fig. 4: Methane yield coefficient (Y_{CH4}): a) Application of typical liner regression, Eq. (10) and b) Variation of Y_{CH4} on different OLRs.

requirement of biomass for cellular maintenance. However, *m* is a combined coefficient of two distinct bacteria populations, the acidogenic and methanogenic populations. This value could be compared to the result from Rincon *et al*. [12], concluding the *m* value as 0.016 g $COD_{consumed}$/g MLVSS/day. They further pointed out that the actual value of *m* should be relatively higher than the calculated value because due to the *X* included both active biomass and non-biological solids in the reactor. The real biomass concentration, X_{real} is lower and can be determined only if the non-biological solids are removed from *X*.

Ultimate CH_4 Yield ($Y_{o\,CH4}$ and $B_{o\,CH4}$): The ultimate CH_4 yield, $Y_{o\,CH4}$, is defined as the maximum Y_{CH4} at infinite HRT, while $B_{o\,CH4}$ represents the maximum CH_4 yield at infinite HRT based on the organic loaded. Both values were determined by plotting a graph of the corresponding values versus the reciprocal of the HRT applied (Fig. 5a). The data points were fitted to a polynomial regression. By using the value of the intercepts, the $Y_{o\,CH4}$ and $B_{o\,CH4}$ determined were 0.4715 L CH_4/g $COD_{utilized}$ and 0.3539 L CH_4/g COD_{added}, respectively. The gap between the two curves implied the refractory portion of POME. Therefore, the biodegradability of POME can also be determined by the following formula:

Table 3: Performance comparison of anaerobic digestion treating different wastewater.

Wastewater	Reactor	HRT, days	OLR(g COD/L/day)	CH_4 production rate, L/L/day	TCO Dutilized, %	Reference
POME	Completely mixed, continuous flow, 35 °C	8.3	5.784	0.965	52.9	[2]
Condensation water	Completely mixed, continuous flow, 35 °C	2.7	2.088	0.573	86.7	[2]
TPOP	Stirred, daily fed, 35 °C	10.0	3.45	0.910	88.7	[17]
		12.5	6.49	1.545	88.5	[17]
		12.5	9.05	1.870	89.8	[17]
		12.5	12.02	2.120	88.4	[17]
TPOP	Completely mixed, daily fed, 35°C	20	9.5	0.9	46.8	[18]
OMSR	Stirred, daily fed, 35°C	17	9.2	1.700*	77	[15]
Acidified OMSR	Stirred, daily fed, 35°C	5	20	3.24	61.3	[16]
POME	Partial-mixed, fed per two days, 35°C	16.0	5.0	1.267*	75.25	This study

TPOP = two-phases olive pomace

OMSR = olive mill solid residue

* Values are corrected to STP conditions.

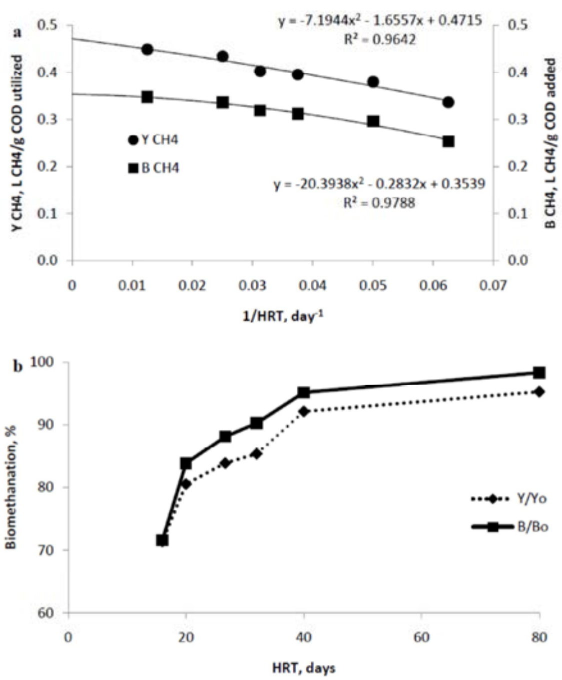

Fig. 5: Methane production efficiency: a) Determination of the ultimate methane yield coefficient based on organic utilized (Yo CH_4) and organic load (Bo CH_4) and b) Effect of HRT on biomethanation of POME.

$$\text{Biodegradability} = \frac{B}{Y} x100\% \quad (9)$$

where the calculated values are the same as those $TCOD_{utilized}$ declared previously and ranges from 75.25 to 79.38%. The biomethanation of POME based on substrate utilized (Y/Y_o) and substrate added (B/B_o) are shown and summarized in Fig. 5b. At HRT of 80.0 days (OLR=1.0 g COD/L/day), the Y/Y_o and B/B_o were very high, at 95.25 and 98.35%, respectively. The performance kept decreasing with shorter HRT, remaining at 71.51 and 71.59%, respectively, at day 16.0 of HRT. Thus, the partially mixed, semi-continuous anaerobic system only achieved good biomethanation (>70%) at HRT of 16.0 days or longer, when there was less biomass washed out.

Overall Performance: The mesophilic anaerobic reactor was operated for 100 days until the production of CH_4 ceased. The activity of methanogenic microorganisms was not impaired up to OLR of 5.0 g COD/L/day because of appropriate stability. The corresponding operation conditions at higher OLRs produced a high TVFA concentration of $8.2{\times}10^3$ mg/L, which could be applied to develop a hydrolytic-acidogenic reactor in a two-stage anaerobic digestion system. The experimental results were comparable to those of Borja *et al*. [2], who reported on the maximum CH_4 production rate for anaerobic digestion of POME at OLR near 5.8 g COD/L/day. The digester performances of previous investigations are summarized in Table 3. The experimental observations proved that partially mixed semi-continuous reactor could perform similar to complete-mixed reactors. However, reactor performance may be affected by the mixing mode. The contact between microorganisms and POME was possibly reduced by the rapid formation of scum, since the reactor was only mixed twice per day. Therefore, frequent intermittent mixing (e.g. mixing every few hours) might be a better mixing mode to enhance the microorganism-substrate contact without significantly disturbing the microbial consortia proximity. Moreover, the feeding frequency was another factor that affects the anaerobic process. For example, in this study, the anaerobic reactor was fed every two days instead of daily, which was used in previous investigations [12, 17-20]. Given that the feeding interval was doubled, the volumetric feed rate doubled as well. The higher volumetric feed rate implied that more biomass will be washed out with the effluent and the reactor pH was affected by the higher feeding volume of acidic POME (pH=3.7). As the biomass inside the reactor was not immobilized, the slow growth of methanogenic bacteria was gradually flushed out as the volumetric feed rate, Q, increased with increased OLR. Nevertheless, the acidogenic bacteria seemed less sensitive to high OLRs. The oxygen consumption measurement in 20 hour biodegradation was a very good indicator of inhibitory effects. Inhibition started at an $OD_{20} > 17$ - 18g-O_2/kg [21].

Thus, the continuous decline in Y_{CH4} was affected by the considerable biomass loss with the effluent. In turn, the system became unable to support higher OLRs. A separation device for sludge recycling [4] or a support media for biomass immobilization [12] may be suitable to ensure sufficient and constant microorganism concentration inside the reactor.

CONCLUSIONS

The partially mixed semi-continuous mesophilic reactor prevailed at the methanogenic condition at OLR of =5.0 g COD/L/day (HRT=16.0), while the system shifted to acidogenic condition at higher OLRs and shorter HRT. CH_4 production stopped at an OLR of 6.0 g COD/L/day. The biodegradability of POME was previously more than 75%, with CH_4 compositions varying from 62.00 to 63.00%. The experimental results concurred with previous studies. In conclusion, continuously mixing in anaerobic digestion is not necessary; intermittent mixing is be preferable in continuous operation, in terms of cost saving. The application of typical linear regression to determine the Y_{CH} of present system is inappropriate, as well. The Y_{CH4} observed was inversely proportional to OLR, which may be linked to the loss of biomass with a higher OLR and lower HRT.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the research facilities by School of Industrial Technology and Universiti Sains Malaysia for granting RUI grant (1001/PTEKIND/814147) for the financial support of this study.

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Persian Abstract

DOI: 10.5829/idosi.ijee.2014.05.02.13

چکیده

راکتور نیمه پیوسته اختلاط جزیی برای ارزیابی تاثیر نرخ بار آلی (OLR) و زمان ماند هیدرولیکی (HRT) جهت تصفیه بیهوازی مزوفیلیک پساب کارخانه روغن نخل (POME) مورد استفاده قرار گرفت. کارایی راکتور توسط زیست تخریب پذیری POME، نرخ تولید گاز متان (CH_4)، و بازده تولید متان تحت نرخهای بار آلی متفاوت ارزیابی گردید. بار آلی راکتور بیهوازی از ۱ به ۲ g COD/L/day و HRT از ۱۳ به ۸۰ افزایش یافت. تمامیت اکسیژن مورد نیاز شیمیایی (TCOD) مورد استفاده از ۷۵٪ بیشتر شده و در صد متان بیوگاز ۶۳-۶۲٪ به دست آمد. ضریب بازده متان (Y_{CH4}) رابطه معکوس با OLR داشته که این به علت کاهش میزان بایومس با جریان پساب بوده است. مشاهدات آزمایش‌ها نشان می‌دهد که راکتور نیمه پیوسته اختلاط جزیی می‌تواند عملکردی مشابه با راکتورهای اختلاط کامل داشته باشد.