An integrated UMAS for POME treatment

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ABSTRACT

The direct discharge of palm oil mill effluent (POME) wastewater causes serious environmental hazards due to its high chemical oxygen demand (COD) and biochemical oxygen demand. This paper proposes a new approach for integrated technology of ultrasonic membrane for a POME treatment. The paper evaluated the economic viability based on the changes of the new design of ultrasonic membrane anaerobic system (UMAS) when a POME introduces this approach. Six steady states were attained as a part of a kinetic study that considered concentration ranges of 13,800–22,600 mg/L for mixed liquor suspended solids and 10,400–17,350 mg/L for mixed liquor volatile suspended solids. Kinetic equations from Monod, Contois and Chen and Hashimoto were employed to describe the kinetics of POME treatment at organic loading rates ranging from 1 to 15 kg COD/m^3/d. throughout the experiment, the removal efficiency of COD was from 92.8 to 98.3% with hydraulic retention time from 500.8 to 8.6 days. The growth yield coefficient, Y, was found to be 0.73 gVSS/g COD, the specific microorganism decay rate was 0.28 day^{-1} and the methane gas yield production rate was between 0.27 and 0.62 L/g COD/d.

Key words | COD, methane, POME, treatment, UMAS

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INTRODUCTION

The palm oil industry has grown tremendously in recent years and accounts for the largest percentage of oil and fat production in the world (Jundika *et al.* 2016). Over the last few decades, the palm oil industry has been growing rapidly. Palm oil has risen to become the most produced and consumed vegetable oil in the world, widely used in food, cosmetic and hygienic products due to its affordable price, efficient production and high oxidative stability (Jundika *et al.* 2016). Palm oil is the most produced vegetable oil in the world with a global production of almost 60 million tonnes and a global vegetable oil market share of more than 35% by weight in 2015 (Hansen *et al.* 2015; Malaysian Palm Oil Board MPOB 2015). The industry continues to generate huge revenues for the producing countries. Accordingly, it is not surprising that the oil palm industry is expected to grow further in the coming years, as shown in Figure 1.

The conventional methods for palm oil mill effluent (POME) treatment include aerobic, membrane, evaporation, fluidized bed, anaerobic filtration and continuous stirrer tank reactor. The main drawbacks of these methods are either large volume of digestion, long retention time, lower methane emission, clogging at high organic loading rates (OLR), high power requirement, high cost of carrier media, not suitable for high suspended solid wastewaters, and less efficient gas production at high treatment volume.

This study introduces ultrasonic membrane anaerobic system (UMAS) to overcome the above-mentioned drawbacks of the conventional methods because UMAS has the following advantages:

- treats high organic load wastewater efficiently and effectively;
- reduces the anaerobic treatment time;
- reduces the plant floor area;
- produces renewable energy efficiently;
- reduces biomass sludge discharge.

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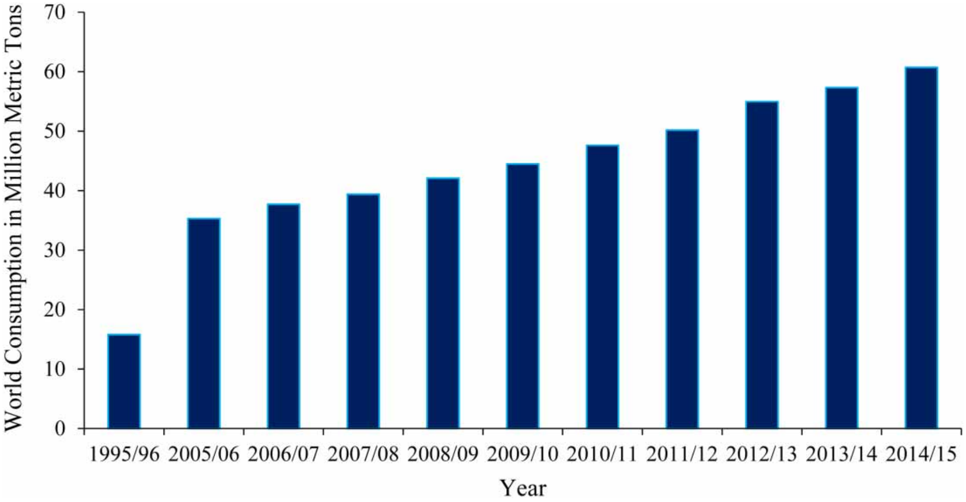

Figure 1 | Global consumption of palm oil from 1995/1996 to 2014/2015 (USDA 2016).

Over the long term, global palm oil demand shows an increasing trend as an expanding global population gives rise to increased consumption of palm-oil based products (Meryana *et al.* 2016). Sayer *et al.* (2012) stated that since POME is a major contributor to the economies of several developing countries, the global production and demand for palm oil is increasing rapidly and the plantations are spreading across Asia, Africa and Latin America. The five leading palm oil producing countries are Indonesia, Malaysia, Thailand, Colombia and Nigeria (Mba *et al.* 2015), as shown in Figure 2.

The development of palm oil industry in Malaysia has turned into a phenomenon in which the area of plantation expanded from year to year. The country is experiencing a robust development in new oil palm plantations and palm oil mills. This commodity plays a significant role in the Malaysian economic growth (Awalludin *et al.* 2015). Throughout the year, Malaysia is blessed with favorable weather conditions which are advantageous for palm oil cultivation (Yusoff 2006). Thus, it is not surprising that the highest yields have been obtained from palms grown in this region, which is far from its natural habitat. Moreover, the Malaysian palm oil industry has grown to become a very important agriculture-based industry, and the country is today one of the world's leading producers and exporters of palm oil.

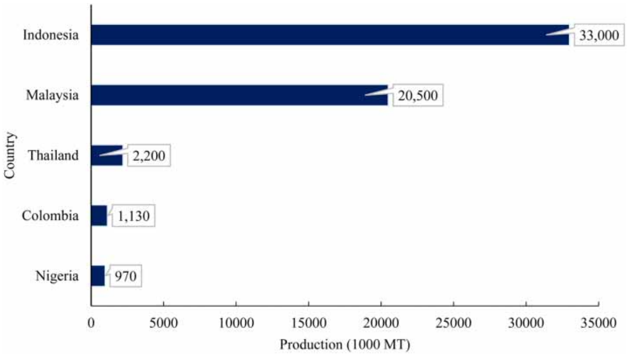

Figure 2 | Palm oil production by country (Barrientos & Soria 2016).

According to Yacob *et al.* (2006), 381 palm oil mills in Malaysia generated about 26.7 million tonnes of solid biomass and about 30 million tonnes of palm oil mill effluent (POME) in 2004. Discharging the effluents or by-products on the land may lead to pollution and might deteriorate the surrounding environment. There is a need for a sound and efficient management system in the treatment of these by-products in a way that will help to conserve the environment and check the deterioration of air and river water quality.

The main objective of this study was to evaluate the performance and kinetics of the new designed UMAS in treating POME based on three models: Monod (1949), Contois (1959) and Chen & Hashimoto (1980).

MATERIALS AND METHODS

Wastewater preparation

Raw POME was collected from a local palm oil mill in Lebah Hillier, Kuantan, Malaysia. In the first stage, raw POME was pre-settled using an ordinary sedimentation tank. In the second part of this study, raw POME was chemically pretreated to remove suspended solids and residual oil. The samples were then stored in a cold room at 4 °C. POME stored under such conditions has no observable effects on its composition. Table 1 shows mathematical expressions for specific substrate utilization rates (SSUR) for three kinetic models (Monod, Contois, and Chen and Hashimoto).

UMAS bioreactor operation and experimental set-up

Raw POME wastewater was treated by UMAS in a laboratory digester with an effective 200-L volume. Figure 3 presents a schematic representation of the UMAS which consists of a cross-flow ultra-filtration membrane apparatus, a centrifugal pump and an anaerobic reactor. Six multi-frequency ultrasonic transducers, operated at 25 KHz, are bonded to two-sides of the tank chamber and connected to a Crest Genesis Generator (250 W, 25 KHz; Crest Ultrasonic, Trenton, NJ, USA). The principle of ultrasonic treatment relies on cavitation to disintegrate cell walls. High density intensity ultrasound enhances the disintegration of particulate matter, as shown by a reduction in particle size and increase of the soluble matter fraction. The ultra-filtration membrane module had a molecular weight cut-off of 200,000, a tube diameter of 1.25 cm and an average pore size of 0.1 μm. There were four tubes, each 30 cm long, and the total effective area of the four membranes was 0.048 m^2, and the pH ranged from 2 to 12. The reactor was composed of a heavy duty reactor with an inner diameter of 25 cm and height of 250 cm. The operating pressure in the UMAS was maintained between 2 and 4 bars by manipulating the gate valve in the retentate line after the cross-flow ultra-filtration membrane unit.

Table 1 | Mathematical expressions of SSUR for known kinetic models

Kinetic model	Equation (1)	Equation (2)
Monod (1949)	$U = \frac{kS}{k_s + S}$	$\frac{1}{U} = \frac{K_s}{K}\left(\frac{1}{S}\right) + \frac{1}{k}$
Contois (1959)	$U = \frac{U_{\max} \times S}{Y(B \times X + S)}$	$\frac{1}{U} = \frac{a \times X}{\mu_{\max} \times S} + \frac{Y(1+a)}{\mu_{\max}}$
Chen & Hashimoto (1980)	$U = \frac{\mu_{\max} \times S}{YKS_o + (1-K)SY}$	$\frac{1}{U} = \frac{YKS_o}{\mu_{\max} S} + \frac{Y(1-K)}{\mu_{\max}}$

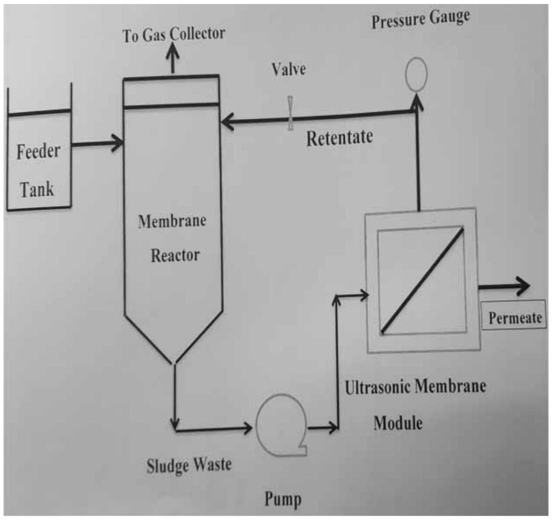

Figure 3 | Experimental set-up.

Analytical methods

Biogas volume was daily measured with water displacement, using a 20-L water displacement bottle, the methane (CH_4) and carbon dioxide (CO_2) content were analyzed by a J-Tube analyzer and a gas chromatograph (GC 2011, Shimadzu) equipped with a thermal conductivity detector and a 2 m × 3 mm stainless-steel column packed with Porapak Q (80/100 mesh). Total suspended solids (TSS), volatile suspended solids (VSS), volatile fatty acids (VFA) and alkalinity were determined according to *Standard Methods* (APHA 2005). The chemical oxygen demand (COD) was measured using a Hach colorimetric digestion method (Method #8000, Hach Company, and Loveland, CO, USA).

Bioreactor operation

The UMAS performance was evaluated under six steady-states (Table 2) with influent COD concentrations ranging

Table 2 | Summary of results

Steady state (SS)	**1**	**2**	**3**	**4**	**5**	**6**
COD feed, mg/L	70,400	73,478	76,200	83,570	86,700	90,200
COD permeate, mg/L	1,197	1,617	3,048	3,343	4,508	6,494
Gas production (L/d)	290	310	340	400	480	540
Total gas yield, L/g COD/d	0.48	0.53	0.58	0.67	0.78	0.81
% Methane	81.0	78.5	75.6	73.8	68.6	64.6
CH_4 yield, L/g COD/d	0.39	0.54	0.57	0.60	0.64	0.70
MLSS, mg/L	13,800	12,400	13,400	14,800	17,648	22,600
MLVSS, mg/L	10,269	10,751	11,765	13,320	15,530	20,159
% VSS	74.41	86.70	87.80	90.00	88.00	89.20
HRT, d	500.8	60.6	22.6	14.7	11.20	8.6
Solid retention time (SRT), d	300	250	180	30.5	20.30	15.80
OLR, kg COD/m^3/d	1.0	3.5	6.0	8.5	11.0	15
SSUR, kg COD/kg VSS/d	0.164	0.195	0.252	0.263	0.294	0.314
SUR, kg COD/m^3/d	0.023	0.724	2.225	4.576	5.685	7.347
Percent COD removal (UMAS)	98.3	97.8	96.0	96.0	94.8	92.8

from 70,400 to 90,200 mg/L) and OLR between (1.5 and 9 kg COD/m^3/d). In this study, the system was considered to have achieved steady state when the operating and control parameters were within ±10% of the average value. A 20-L water displacement bottle was used to measure the daily gas volume. In anaerobic degrading of POME, biogas is formed when microorganisms, especially bacteria, degrade organic material in the absence of oxygen. Biogas consists of 50–75% methane (CH_4), 25–45% carbon dioxide (CO_2) and small amounts of other gases (Rahayu *et al.* 2015; Yunus *et al.* 2015). Therefore this paper assumed the produced biogas contained only CO_2 and CH_4, so the addition of sodium hydroxide solution (NaOH) to absorb CO_2 effectively isolated methane gas (CH_4). Table 2 depicts results of the application of three known substrate utilization models.

RESULTS AND DISCUSSION

The performance of UMAS

The performance of the UMAS was evaluated and is summarized in Table 2. The UMAS performance at six steady-states was established at different hydraulic retention times (HRTs) and influent COD concentrations. The kinetic coefficients of the selected models were derived from Equation (2) in Table 1 by using a linear relationship; the coefficients are summarized in Table 3. At steady-state conditions with influent COD concentrations of 70,400–90,200 mg/L, UMAS performed well and the pH in the reactor remained within the optimal working range for

Table 3 | Results of the application of three known substrate utilization models

Model	**Equation**	**R^2 (%)**
Monod	$U^{-1} = 2{,}025\ S^{-1} + 3.61$ $K_s = 498$ $K = 0.350$ $\mu_{max} = 0.284$	99.6
Contois	$U^{-1} = 0.306\ X\ S^{-1} + 2.78$ $B = 0.111$ $\mu_{max} = 0.344$ $a = 0.115$ $\mu_{max} = 0.377$ $K = 0.519$	99.1
Chen and Hashimoto	$U^{-1} = 0.0190\ S_o\ S^{-1} + 3.77$ $K = 0.006$ $a = 0.006$ $\mu_{max} = 0.291$ $K = 0.374$	99.5

anaerobic digesters (6.7–7.8). At the first steady-state, the mixed liquor suspended solids (MLSS) concentration was about 13,800 mg/L whereas the mixed liquor volatile suspended solids (MLVSS) concentration was 10,269 mg/L, equivalent to 74.41% of the MLSS. This low result can be attributed to the high suspended solids contents in the POME wastewater. At the sixth steady-state, however, the VSS fraction in the reactor increased to 89.20% of the MLSS. This indicates that the long SRT of UMAS facilitated the decomposition of the suspended solids and their subsequent conversion to methane (CH_4); this conclusion is supported by Abdurahman *et al.* (2011) and Nagano *et al.* (1992). The highest influent COD was recorded at the sixth steady-state (90,200 mg/L) and corresponded to an OLR of 15 kg COD/m^3/d. At this OLR, the UMAS achieved 92.8% COD removal and an effluent COD of 6,494 mg/L. This value is better than those reported in other studies on anaerobic POME wastewater digestion (Borja 1995). The three kinetic models demonstrated a good relationship ($R^2 > 99\%$) for the membrane anaerobic system treating POME wastewater, as shown in Figures 4–6. The Monod and Chen and Hashimoto models performed better, implying that digester performance should consider OLR. These two models suggested that the predicted permeate COD concentration (S) is a function of influent COD concentration (S_o). In the Contois model, however, S is independent of S_o. The excellent fit of these three models ($R^2 > 97.8\%$) in this study suggests that the UMAS process is capable of handling sustained organic loads between 1.0 and 15 kg m^3/d.

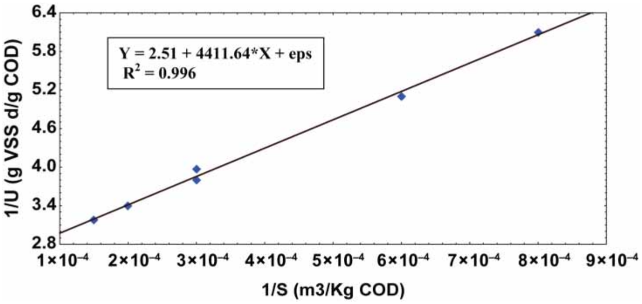

Figure 4 | The Monod model.

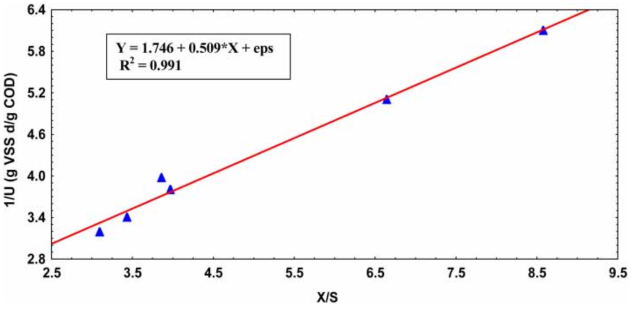

Figure 5 | The Contois model.

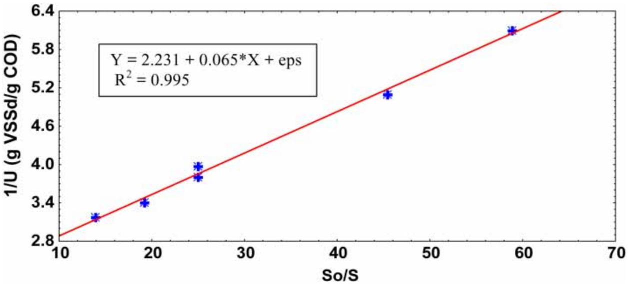

Figure 6 | The Chen and Hashimoto model.

Figure 7 shows the percentages of COD removed by UMAS at various HRTs. COD removal efficiency increased as HRT increased from 8.6 to 500.8 days and was in the range of 92.8–98.3%. This result was higher than the 85% COD removal observed for POME wastewater treatment using anaerobic fluidized bed reactors (Idris & Al-Mamun 1998) and the 91.7–94.2% removal observed for POME wastewater treatment using MAS (Fakhru'l-Razi *et al.* 1994), and the 93.6–97.5% removal observed for POME treatment using MAS (Abdurahman *et al.* 2011). It is observed that there are no COD values for the period between 100 and 500 days, this could be attributed to the

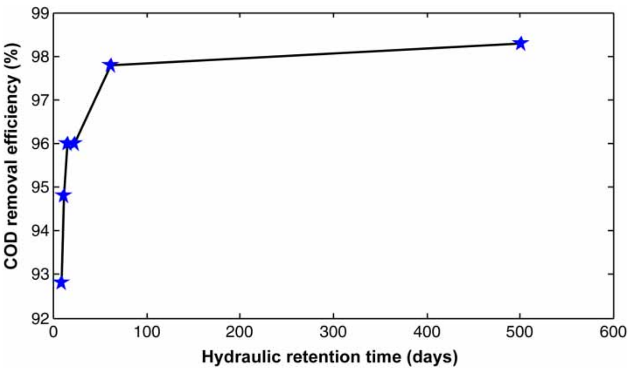

Figure 7 | COD removal efficiency of UMAS under steady-state conditions with various HRTs.

growth of VFA. The COD removal efficiency did not differ significantly between HRTs of 500.8 days (98.3%) and 14.7 days (96.0%). At HRT of 8.6 days, COD was reduced to 92.8%. As shown in Table 2, this was largely a result of the washout phase of the reactor because the biomass concentration increased in the system. This may be attributed to the fact that at low HRT with high OLR, the organic matter was degraded to VFA. The HRTs were mainly influenced by the ultra-filtration, UF membrane influx-rates which directly determined the volume of influent (POME) that can be fed to the reactor.

Determination of bio-kinetic coefficients

Experimental data for the six steady-state conditions in Table 2 were analyzed; kinetic coefficients were evaluated and are summarized in Table 3. Substrate utilization rates (SUR) and SSUR were plotted against OLRs and HRTs. Figure 8 shows the SSUR values for COD at steady-state conditions HRTs between 8.6 and 500.8 days. SSURs for COD generally increased with HRT decline, which indicated that the bacterial population in the UMAS multiplied (Abdullah *et al.* 2005). It observed that there are no SSUR values for period between 100 and 500 days, this may be attributed to the growth of VFA. The bio-kinetic coefficients of growth yield (Y) and specific micro-organic decay rate (b) and the K values were calculated from the slope and intercept as shown in Figures 9 and 10. Maximum specific biomass growth rates ($\mu_{\max}$) were in the range of 0.248–0.474 d^{-1}. All of the kinetic coefficients that were calculated from the three models are summarized in Table 3.

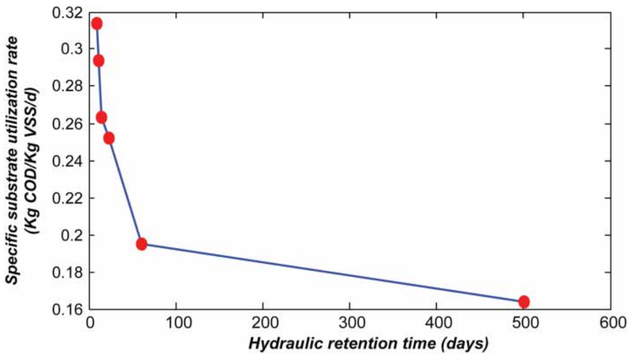

Figure 8 | Specific substrate utilization rate for COD under steady state conditions with various HRTs.

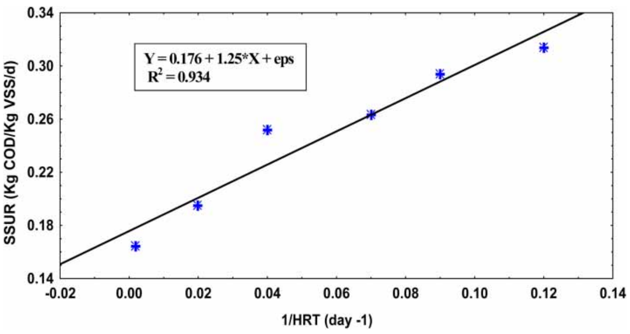

Figure 9 | Determination of the growth yield, Y and the specific biomass decay rate, b.

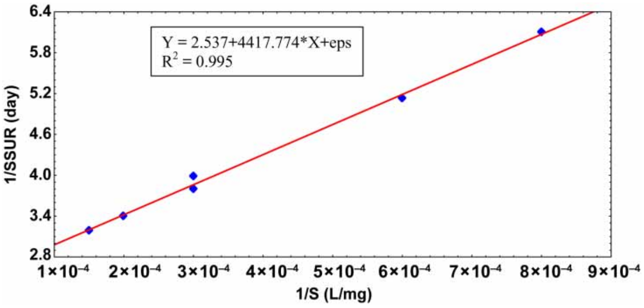

Figure 10 | Determination of the maximum specific substrate utilization and the saturation constant, K.

The small values of $\mu_{\max}$ are suggestive of relatively high amounts of biomass in the UMAS (Zinatizadeh *et al.* 2006). According to Grady & Lim (1980), the values of parameters $\mu_{\max}$ and K are highly dependent on both the organism and the substrate employed. If a given species of organism is grown on several substrates under fixed environmental conditions, the observed values of $\mu_{\max}$ and K will depend on the substrates.

PRODUCTION OF METHANE (CH_4) AND CARBON DIOXIDE (CO_2) GASES

To ensure the performance of anaerobic digesters and prevent failure, many parameters must be adequately controlled. For slaughterhouse wastewater treatment, these parameters include pH, mixing, operating temperature, nutrient availability and OLR into the digester. In this study, the microbial community in the anaerobic digester was sensitive to pH changes. Therefore, the pH was maintained in an optimum range (6.8–7) to minimize the effects on methanogens bacteria that might contribute to biogas production. Because methanogenesis is also strongly affected by pH, methanogenic activity will decrease when the pH in the digester deviates from the optimum value. Mixing provides good contact between microbes and substrates, reduces the resistance to mass transfer, minimizes the build-up of inhibitory intermediates and stabilizes environmental conditions. This study adopted the mechanical mixing and biogas recirculation. Figure 11 shows the gas production rate and the methane content of the biogas. The methane content generally declined with increasing OLRs. Methane gas content ranged from 64.6 to 81% and the methane yield ranged from 0.39 to 0.70 CH_4/g COD/d. Biogas production increased with increasing OLRs from 0.48 L/g COD/d at 1.0 kg COD/m^3/d to 0.81 L/g COD/d at 15 kg COD/m^3/d. The decline in methane gas content may be attributed to the higher OLR, which favors the growth of acid forming bacteria over methanogenic bacteria. Thus the methane conversion process was adversely affected with reducing methane content and this led to the formation of carbon dioxide (CO_2) at a higher rate. The gas production showed an increase from 290 to 540 L per day during the study. In this scenario, the higher rate of carbon dioxide (CO_2) formation reduces the methane content of the biogas.

CONCLUSIONS

POME is always regarded as a highly polluting wastewater generated from palm oil mills; however, reutilization of POME to generate renewable energies has great potential, especially when coupled with wastewater treatment technologies.

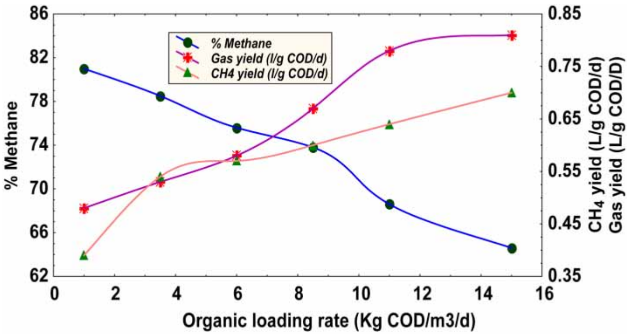

Figure 11 | Gas production and methane content.

This study proposed treating POME by-products through the integrated technology of ultrasonic and membrane production, UMAS at University Malaysia Pahang, UMP. This study evaluated the economic viability based on the changes of the new design of UMAS when a POME introduces this approach.

The integrated technology of UMAS is a more attractive solution compared to the case when the POME was treated individually using either ultrasonic or membrane technology. Moreover, the integrated technology, UMAS, showed improved economic viability, which is the most profitable approach compared to installing each technology alone.

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