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Comparison of UASB and EGSB reactors performance, for treatment of raw and deoiled palm oil mill effluent (POME)

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ABSTRACT

Anaerobic digestion of palm oil mill effluent (POME) and deoiled POME was investigated both in batch assays and continuous reactor experiments using up-flow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) reactors. The methane potential determined from batch assays of POME and deoiled POME was 503 and 610 mL-CH_4/gVS-added, respectively. For the treatment of POME in continuously fed reactors, both in UASB and EGSB reactors more than 90% COD removal could be obtained, at HRT of 5 days, corresponding to OLR of 5.8 gVS/(L-reactor.d). Similar methane yields of 436–438 mL-CH_4/gVS-added were obtained for UASB and EGSB respectively. However, for treatment of deoiled POME, both UASB and EGSB reactors could operate at lower OLR of 2.6 gVS/(L-reactor.d), with the methane yield of 600 and 555 mL-CH_4/gVS-added for UASB and EGSB, respectively. The higher methane yield achieved from the deoiled POME was attributed to lower portion of biofibers which are more recalcitrant compared the rest of organic matter in POME. The UASB reactor was found to be more stable than EGSB reactor under the same OLR, as could be seen from lower VFA concentration, especially propionic acid, compared to the EGSB reactor.

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1. Introduction

The production of palm oil is increasing every year due to its application for biodiesel production. This leads to the increasing amount of palm oil mill effluent (POME); a by-products from the oil-palm extracting process [1]. Malaysia is the world's largest palm oil producer, with more than 40 million tons of POME produced every year [2]. 42.7 million tons of palm oil was produced globally in year 2008 [3]. For every ton of palm oil produced, 2.5 tons of POME is generated [4].

POME is a viscous brown liquid with fine suspended solids, pH ranging in between 3.5 and 4.2 with high content of COD (16–100 gCOD/L) and lipid (10–17 g/L) [5,6]. Deoiled POME is a thin brown liquid, obtained from a process step where POME is clarified by removing floating fats and settling organic particles in a de-oiling tank at HRT of 1.5 days. At this clarification process, most of particles and floating fats are removed from POME, and parts of the organic matter in POME are hydrolysed/fermented resulting in VFA production. Deoiled POME contains high content of VFA (6–8 g/L), but low lipid (2–3 g/L) and low suspended solids (5–7 g/L) [4]. Thong et al. [7] reported methane potential of POME around 45 m^3 methane/m^3 of POME, corresponding to a biogas energy potential of 18 GWh per year for utilization of the Malaysian POME.

Anaerobic digestion (AD) of POME is preferable compared to aerobic treatment due to the energy production from biogas [2]. The digested sludge from AD process could also be used as fertilizer for oil-palm plantation [8]. However, high-rate anaerobic digestion of POME has still not been widely applied. The main practice of treating POME is by storage/treatment in ponds and/or open facultative tank systems [9]. However, treatment of POME in ponds/open tanks requires long retention time and large treatment areas, causing odour genes and environmental load due to gas emissions and leachate contamination to groundwater [9,10]. In order to shorten the retention time, reduce the treatment area, and capture the biogas for energy utilization, high-rate anaerobic digestion has gained increased attention.

Anaerobic digestion is a multi-stage degradation of organic compounds through a variety of intermediates into methane and carbon dioxide, by the action of a consortium of microorganisms [11]. Since anaerobic bacteria have generally low growth rates, immobilised reactors systems give the possibility to operate with higher flows. Two widely used high-rate reactor types are upflow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) reactors, where biomass is immobilised in dense granular biomass associations. EGSB reactor is a variant of the UASB concept with the larger ratio of reactor height/surface area to obtain higher upflow velocity and thus improve the contact between substrate and biomass [12].

The potential of using UASB reactor for treating POME has previously been demonstrated [13]. POME treatment has been tested

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Table 1
Characteristics of POME and deoiled POME.

Component	Unit	Raw POME	Deoiled POME
pH		4.3	4.7
TS	g/L	67.3	19.7
VS	g/L	57.3	12.9
TSS	g/L	40.6	5.36
VSS	g/L	34.5	0.42
Total COD	g/L	97	45
Soluble COD	g/L	88	34
Lipid	g/L	8.4	2.67
Alkalinity	mg/L	148	85
Ethanol	mM	12.45	3.91
Acetic acid	mM	52.62	65.77
Propionic acid	mM	0.78	18.57
Butyric acid	mM	0.18	20.44
Total VFA	g/L	3.3	6.75
TKN	g/L	3.2	0.45

in a 10 L UASB reactor. COD removal of 96% was obtained at the OLR of 2.5 gCOD/(L-reactor.d) with influent COD concentration of 50 g/L and HRT 20 days. However, when the organic loading rate approached 17.5 gCOD/(L-reactor.d) with HRT 3 days, the process became unstable with an increasing of total VFA concentration from 0.007 to 3.55 g/L and COD removal rate dropped to 62.5% [14]. The anaerobic treatment of POME by a mesophilic EGSB reactor has also been applied [15]. A COD reduction of 91% was obtained at HRT of 2 days and OLR of 17.5 gCOD/(L-reactor.d), however only 46% organic matter was converted to methane. A survey of full-scale applications of UASB and EGSB by Franklin [16] reported that EGSB in average could operate at OLR of 20 gCOD/(L-reactor.d), while UASB could operate at lower OLR of 10 gCOD/(L-reactor.d), with COD removal approx. 85–90% for both types of the reactors.

Although POME treatment in either UASB or EGSB reactors has been previously reported, there is no report on direct comparison of these two types of reactor under controlled conditions. In this study, the methane potential of POME and deoiled POME were measured by batch assays, and the performance of UASB and EGSB reactors on continuous treatment of both POME and deoiled POME were compared in terms of methane production rate, methane yield, organic loading rate (OLR), process stability and COD removal efficiency.

2. Materials and methods

2.1. Palm oil mill effluent (POME) and deoiled POME

The palm oil mill effluent (POME) and deoiled POME used in this study were collected from palm oil mill plant, Malaysia. POME and deoiled POME were stored at the temperature of 4 °C before use. The characteristics of POME and deoiled POME are summarised in Table 1. The fresh POME newly released from the process has a temperature of 80–90 °C [17], thus it would be economical to apply thermophilic digestion due to less cooling requirement and faster bacterial growth rate.

2.2. Methane potential in batch experiments

Batch experiments were set up to determine methane potential of POME and deoiled POME at different concentrations. The batch assays were carried out in 540 mL glass bottles in triplicates. In each bottle 160 mL of inoculum and 40 mL of substrate/water mixture were added. The batch reactors had a pH of approx. 7. This was ensured by using cow manure as inoculum which has high buffering capacity, ensuring stability of the pH. The experimental setup for the batch assays is summarised in Table 2. The inoculum for the batch assays was obtained from full-scale biogas plant (55 °C). The inoculum contained 79 g/L total solids (TS), 61 g/L volatile solids (VS), and 53.5 g/L volatile suspended solids (VSS). After inoculation, the bottle headspace was flushed with a mixture of N_2:CO_2 gas (80:20) and then closed with rubber stopper, sealed with aluminium cap and placed in a 55 °C incubator. Methane content in the vial headspace was measured to register the methane production until the production has ceased.

2.3. Continuous reactor experiments

One 1.5 L UASB reactor with a working volume of 1.2 L and one 1.3 L EGSB reactor with a working volume of 1.0 L were used for the reactor experiment. Both reactors were operated at a thermophilic condition (55 °C) with an internal recirculation flow rate of 18 mL/h. The reactors were inoculated with thermophilic-adapted anaerobic granules by adding 240 and 200 mL of granules to the UASB and EGSB reactor, respectively, corresponding to 20% of the reactor working volume. The rest of the reactor active volume was filled up with BA medium [18,19]. To prepare the granules for the reactor experiment, mesophilic granules from Holland (diameter 0.25–0.5 mm) were adapted in a UASB reactor circulating with digested manure at 55 °C for 14 days to introduce the thermophilic bacteria to the granules. After inoculation, the reactors were started-up and fed with 2 g/L glucose for one week before changing to POME and deoiled POME respectively. During the reactor operation, alkalinity was introduced to the substrate by adding 5 g $NaHCO_3$ per L-substrate which was found to be enough to maintain the reactor pH above 6. Both reactors were first operated at an HRT of 10 days, and then decreased to HRT of 5 days with different substrate concentrations to vary the organic loading rate ranging from 1.3 to 10.4 gVS/(L-reactor.d) (Table 3). Biogas production was measured by an automated displacement gas metering system with 100 mL cycle of registration [20]. Biogas production was recorded daily, while pH and volatile fatty acids concentration were measured twice a week.

2.4. Analytical methods

The methane content was analyzed by a gas chromatograph (GC) equipped with a flame ionization detector [21]. Chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), and ammonium nitrogen and alkalinity were measured according to standard methods for the examination of water and wastewater [22]. Due to the substrate low pH (3.5–4.2), TS and VS determination were made by adjusting the pH to 6 by $NaHCO_3$, and dried at 90 °C instead of 105 °C to minimise the loss of volatile fatty acids [19]. Lipid content was determined by Soxhlet extraction method [22]. Volatile fatty acids (VFA) concentrations were measured using a gas chromatograph (Shimadzu GC-2010AF, Kyoto, Japan), equipped with a flame ionization detector (FID) [19]. The protein content (g-protein/L) was calculated by multiplying the organic nitrogen content (g-N/L) with a factor of 6.25 [23]. The organic nitrogen content was found by subtracting the total nitrogen from ammonia nitrogen.

3. Results and discussion

3.1. Characteristics and methane potential of POME and deoiled POME

The analysis results of POME and deoiled POME in Table 1 show that POME was a concentrated substrate with high content of protein and lipid which could potentially inhibit or overload the process. In contrary, deoiled POME was a partially hydrolysed and diluted substrate with very low lipid and protein content, but

Table 2
Summary of batch experimental setup and results.

Substrates	Substrate concentration in water (%)	Initial organic load (gVS/L)	Methane yield (mL-CH_4/gVS-added)	Estimated theoretical methane yield (mL-CH_4/gVS-added)[a]
POME	2.3	13	503	525
	4.6	26	482	525
	6.9	39	370	525
Deoiled POME	2	2.6	610	612
	4	5.2	440	612
	6	7.8	251	612

[a] Based on substrate compositions from Table 1.

Table 3
Summary of UASB and EGSB performance on treating POME and deoiled POME.

HRT (d)	Substrate concentra-tions in water (%, v/v)	OLR (gVS/L-reactor.d)	Methane yield (mL-CH_4/gVS-added)	Methane production rate (mL-CH_4/L reactor.d)	CH_4 (%)	COD reduction (%)	NH_4^+–N (mg/L)	Lipid (g/L)
UASB-POME								
10	50	2	361	722	55	96.5	45	0.02
5	25	2.9	448	1285	66	95.5	50	2.1
5	50	5.8	438	2557	61	92.5	80	4.6
5	100	10.4	265	2756	58	65	450	12.3
UASB-deoiled POME								
5	50	1.3	484	630	72	94	40	0.07
5	100	2.6	600	1560	74	91.5	180	0.13
EGSB-POME								
10	50	2	372	744	51	97	20	0.01
5	25	2.9	417	1196	61	95	15	0.14
5	50	5.8	436	2546	60	91.6	50	2.3
5	100	10.4	339	3527	59	53	490	14.7
EGSB-deoiled POME								
5	50	1.3	409	531	70	94	20	0.02
5	100	2.6	555	1443	73	92.3	150	0.05

high content of VFA which was a good substrate for biogas production. The methane potential of POME and deoiled POME at different concentrations are summarised in Table 2. The estimated theoretical yield of methane was calculated based on the characteristics of the substrate (i.e. carbohydrates, proteins, lipids, VFAs, alcohol, etc.). The high methane yield from both POME and deoiled POME indicated that they were good substrates for biogas production. However, raw POME has lower methane yield compared to deoiled POME, because the VS of POME consists of a higher portion of biofibers. During the deoiling process, a part of biofibers is removed. Biofibers are more recalcitrant compared the rest of organic matter in POME. Additionally as shown in Table 1, higher concentrations of hydrolysed oils and VFA in deoiled POME, are contributing to its higher methane potential. In Table 2, we also observed the low methane yields at high substrate concentration which indicated that they had potential to inhibit the process when overloaded. The degradation of POME and deoiled POME was faster than the controls containing cellulose and glucose as substrates. More than 90% of the methane production could be achieved within 14 days, indicating that they were very easily degradable. The methane yield from the cellulose control was 405 mL-CH_4/gVS-added, which was almost 98% of with the theoretical methane yield, thus ensuring of the validity of the assays. Due to the high lipid content in POME, the methane yield was higher than in the cellulose control. The maximum methane potential of POME was 503 mL-CH_4/gVS-added at 55 °C, corresponding to 28.8 m^3 methane/m^3 POME. The maximum methane potential of deoiled POME was 610 mL-CH_4/gVS-added at 55 °C, corresponding to 7.9 m^3 methane/m^3-deoiled POME. The digestion of deoiled POME at 0.26% VS gave the highest methane yield of 610 mL-CH_4/gVS-added. The deoiled POME had faster degradation and higher methane yield than the raw POME. This could be due to the fact that deoiled POME has been partially hydrolysed and fermented during the POME clarification process at 1.5 days HRT, which could be seen from the high VFA concentration in the deoiled POME compared to the POME. In contrary, when considered the organic composition of raw POME and deoiled POME, the calculated theoretical methane potential of the raw POME was higher than of the deoiled POME (Table 2). This implied that the POME might contain higher fraction of recalcitrant organics compared to the deoiled POME. Another explanation could be that the high content of long-chain fatty acid (LCFA) in the POME could also inhibit the degradation process. It has previously been reported that the lipid-rich waste contains long chain fatty acids; especially palmitate (higher than 50 mg/g dry weight) and oleate (higher than 200 mg/L) could inhibit bacterial growth and methane formation [24,25].

3.2. UASB and EGSB treatment of POME

The performance of UASB and EGSB reactors fed with POME is shown in Figs. 1 and 2, respectively, and the data is summarised in Table 3. Both reactors had similar methane yields at the same OLR (Table 3), and the methane production rate increased linearly with increasing of OLR. The maximum OLR resulting in stable operation of both reactors was 5.8 gVS/(L-reactor.d), with more than 90% COD removal and similar methane yield of 438 mL-CH_4/gVS, corresponding to 87% of the maximum methane potential determined from the batch assays. At OLR of 2–5.8 gVS/(L-reactor.d), both reactors had similar methane content of 60% in the reactor headspace. The methane content in both reactors gradually decreased with increasing OLR and sharply decreased when overloaded. At OLR below 5.8 gVS/(L-reactor.d), small VFA accumulation

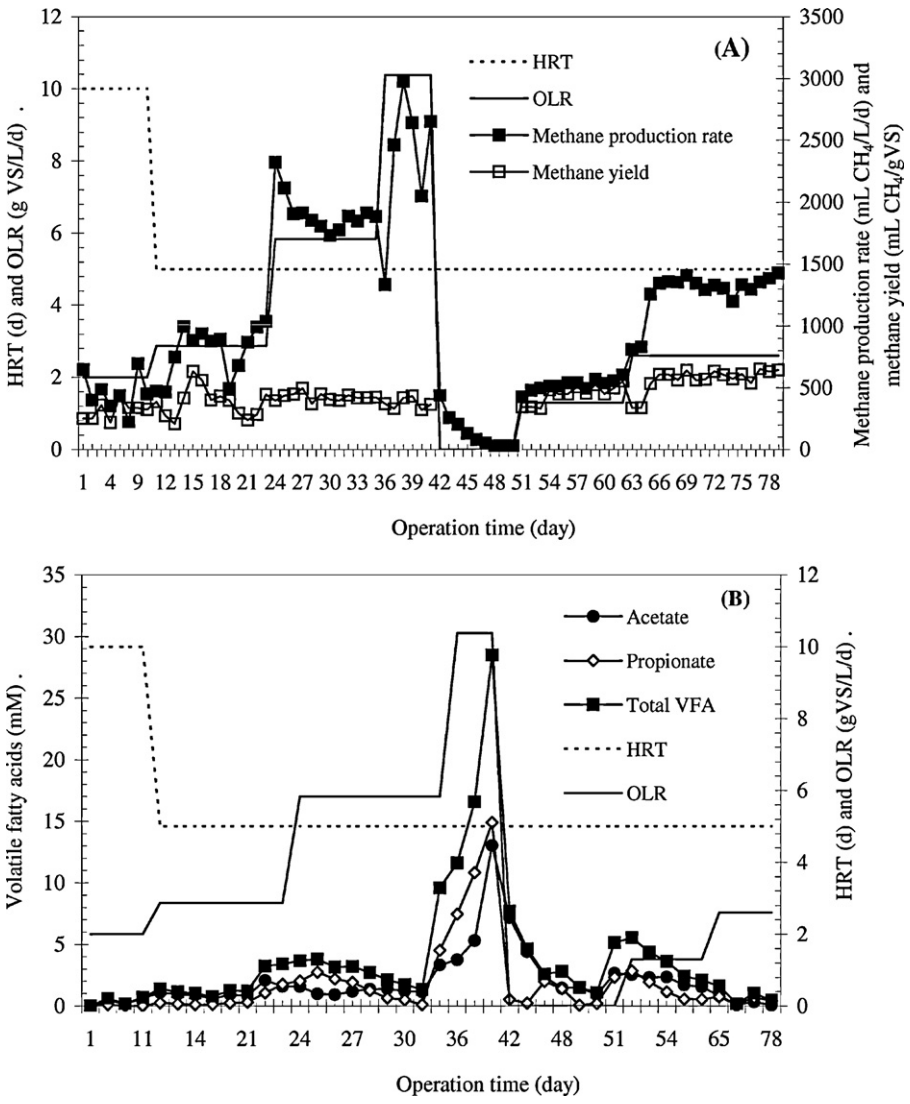

Fig. 1. UASB reactor performance of the anaerobic digestion process of POME and deoiled POME; (a) methane production rate, methane yield, HRT and OLR; and (b) VFA concentrations.

was observed when increasing OLR, however, the system was quickly recovered. Acetic acid was the main VFA detected at the lower levels of OLR and the absence of propionic acid and higher VFA reflected a stable digester operation. When the OLR was increased to 10.4 gVS/(L-reactor.d), both reactors became unstable due to organic overloading, and thus the feed had to be stopped. The concentrations of ammonium–nitrogen in both reactors were relatively low during the whole period of experiment, thus there should not be problem of ammonia inhibition. An obvious sign of reactor instability was a sharp increase of VFA concentration to very high levels, especially for propionic acid. The concentration of VFA has been recognized for a long-time as a good indicator for monitoring of the anaerobic process [26,27]. The VFA still continued to increase for a few days after stop feeding, with the same VFA accumulation pattern in the UASB reactor as in the EGSB reactor (Fig. 2). It has been reported that shock load and washout of methanogens were the cause of acidification [2]. In this study, the organic overload at high OLR resulted in the production of excess amount of acids with consequently inhibits methanogen activities [28]. This resulted in the decrease of methane yield. Moreover, foaming was also observed in the EGSB reactor under overloading and it could be seen that the poor-settled biomass began to be washed with the effluent. The EGSB reactor failed in 6 days after increasing the OLR from 5.8 to 10.4 gVS/(L-reactor.d). The foaming problem in EGSB reactor has also been reported by Kalyuzhnyi et al. [29] at OLR above 6.0 gCOD/(L-reactor.d). In this experiment, the OLR of POME at 10.4 gVS/(L-reactor.d) corresponded to 17.7 gCOD/(L-reactor.d) which was about 3 times of the OLR applied in the reference above. Moreover, the high suspended solids content in POME could also cause problem at high OLR (10.4 gVS/L-reactor.d). Suspended and colloidal components of wastewaters in the form of fat, protein, and cellulose have adverse impact on both UASB and EGSB reactors' performance and can cause deterioration of microbial activities and washout of active biomass [30]. In this case, an extra hydrolysis compartment might be necessary before the UASB treatment [31].

Although the UASB reactor was also overloaded at OLR of 10.4 gVS/(L-reactor.d), no foaming or biomass washed out was observed, which indicated that the UASB reactor was more robust than the EGSB reactor. The UASB reactor also showed more stable process than the EGSB reactor, as seen from the lower % variation in methane production in the UASB reactor (5.4–6.4%) compared to the EGSB reactor (8.9–104%). The VFA and propionic acid were substantially higher in the EGSB reactor compared to UASB reactor. From the results above, it is suggested that the UASB reactor would be simpler to operate and require less extensive monitoring and

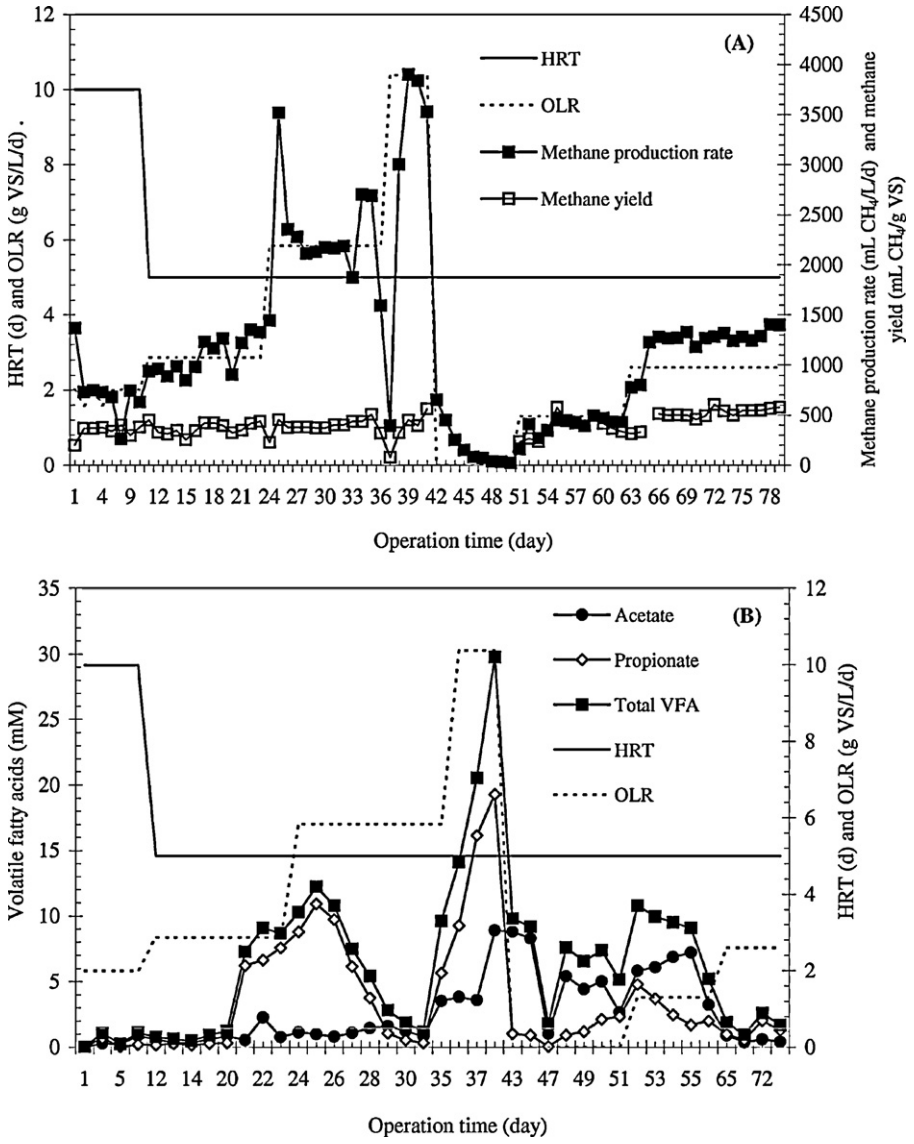

Fig. 2. EGSB reactor performance of the anaerobic digestion process of POME and deoiled POME; (a) methane production rate, methane yield, HRT and OLR; and (b) VFA concentrations.

control than EGSB reactor, which would be preferable for the small scale industries.

3.3. UASB and EGSB treatment of deoiled POME

After both reactors were recovered from organic overload of POME, the deoiled POME was subsequently used as substrate, starting with the OLR of 1.3 gVS/(L-reactor.d). The results from both reactors are shown in Figs. 1 and 2, and the reactor performances are summarised in Table 3. A stable operation of both UASB and EGSB reactor could be achieved for 100% deoiled POME at an OLR of 2.6 g VS/(L-reactor.d), with more than 90% COD removal (Table 3). The methane yield was slightly higher in the UASB reactor (600 mL-CH_4/gVS-added) compared to the EGSB reactor (555 mL-CH_4/gVS-added). The methane production from UASB and EGSB reactor corresponded to 98% and 91% of the maximum methane potential of deoiled POME determined from the batch assays. The UASB reactor was also more stable than the EGSB reactor as seen from lower VFA accumulation when increasing the OLR. However, both reactors were considered to be very stable at the OLR of 2.6 gVS/(L-reactor.d) with 100% concentration of deoiled POME as seen from high methane production and low VFA concentration, which indicating that higher OLR could be possible by decreasing the HRT. Moreover, since the deoiled POME contained mainly easily biodegradable components such as carbohydrate and VFA, and very low content of suspended solids which could interfere the process, the maximum OLR could possibly even be higher than 5.8 gVS/(L-reactor.d) compared to treatment of POME.

4. Conclusions

Both POME and deoiled POME are good substrates for biogas production. The methane potential of POME and deoiled POME were determined from the batch assays as 503 and 610 mL-CH_4/gVS-added, respectively. Both UASB and EGSB could efficiently treat POME at the maximum OLR of 5.8 gVS/(L-reactor.d) with more than 90% COD removal and the methane yield of 438 mL-CH_4/gVS-added. The methane yields of deoiled POME at the OLR of 2.6 gVS/(L-reactor.d) were 600 and 555 mL-CH_4/gVS-added for UASB and EGSB, respectively. The UASB reactor had more stable methane production and lower VFA concentration compared to the EGSB reactor under the treatment of both POME and deoiled

POME. Deoiled POME had higher methane potential and was easier to degrade compared to POME due to lower content of suspended solids and high content of easily degradable organics such as VFA, lipid.

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