

Application of cement kiln dust enhancing methane production using upflow anaerobic sludge blanket reactor for the treatment of palm oil mill effluent

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Anaerobic digestion of palm oil mill effluent (POME) for continuous biogas production has been carried out in an upflow anaerobic sludge blanket reactor (UASBR) using cement kiln dust (CKD). POME is used as the substrate carbon source and CKD as a neutralizing agent. The effects of the hydraulic retention time (HRT) 20 h and organic loading rate (OLR) 4.5 kg COD/m³h⁻¹ over 95% COD removal and 0.89 mL CH₄/L/h with a methane yield of 0.65 L CH₄/g COD_{removed} at 1600 mg/L CKD in UASBR have been studied. Without CKD (control) the reactor for the removal of COD only 10.5% and methane production up to 0.13 L CH₄/g COD. However, increasing the OLR to 4.5 kgCOD/m³h⁻¹ by reducing the hydraulic retention time (HRT 6 h) reduced the COD removal efficiency to 58% and methane production up to 0.43 L CH₄/g COD_{removed}. Considering this, the use of CKD containing UASBR might be practically and economically attractive for industrial scale biogas production and sludge reduction from industrial wastes and wastewater.

Keywords: Cement kiln dust, Methane, Organic loading rate, Hydraulic retention time, Solid sludge removal

Palm oil mill effluent is a thick brownish liquid having colloidal suspension of 95-96% water, 0.6-0.7% oil and 4-5% total solids. Including 2-4% suspended solids originating from the mixture of a sterilized condensate, separator sludge and hydro-cyclone wastewater¹. Average values of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are 55.9 and 26.3 gL⁻¹ respectively. The pH of resulting POME usually ranges from 4-5². The pH is one of the factors that influence the anaerobic digestion of POME, because methane producing bacteria require a neutral to slightly alkaline environment in order to produce maximum methane. Optimum pH for most of the microbial growth is between 6.8 and 7.2, when pH was lower than 4 and higher than 9.5 is not suitable^{3,4}.

A few studies have been done to using CKD as a treatment option for some other wastewaters⁵. The CKD is used instead of sodium hydroxide (NaOH) for the treatment of pulp and paper industry wastewater. Another study, used lime to raise the pH of the pulp and paper effluent above 11.4⁶. The use of lime as a chemical coagulant for the treatment of olive mill wastewater, one of the most effective forms of food processing wastewater due to the presence of high

organic material has been investigated⁷. The study evaluated lime concentrations from 5.0-30.0 gL⁻¹ and the optimum dosages was found between 25 and 27.5 gL⁻¹, which resulted in a pH of approximately 12.0. Several cases of reactor failure have been reported in earlier studies of wastewater treatment due to the accumulation of high volatile fatty acids (VFA) concentration, causing a drop in pH which inhibited methanogenesis^{8,9}. According to most methanogenic bacteria have optimal growth between pH 7 and 8, whereas VFA degrading bacteria have lower pH¹⁰. It was found that digester could tolerate acetic acid concentrations up to 4000 mgL⁻¹ without inhibition of gas production¹¹. To control the level of VFA in the system, alkalinity has to be maintained by recirculation of treated effluent^{2,12} or the addition of lime, caustic soda or bicarbonate of soda^{13,14}.

This paper emphasizes on the treatability of POME in batch fermentation to explore the effect on biogas production. Upflow anaerobic sludge blanket reactor with the application of CKD as one of the substrate for neutralizing digestion media is used. The study mainly focused on the effect CKD dosage on the process including volatile fatty acids (VFAs), alkalinity (Alk), COD removal, biogas production and sludge waste reduction.

Experimental Section

Samples Collection

The available dry-kiln CKD sample was collected from Pahang Cement located at 30 km east from Kuantan city. The plant that supplied CKD sample used in this study has rotary kiln that operate in the temperature range of 1370-1480°C. The CKD sample was washed with water and filtered to obtain approximate particle sizes. Table 1 summarizes the characterization of CKD sample used for POME treatment.

Raw POME was collected from a local oil palm mill working under Felda Oil Palm Industries (CPSC Oil Palm Plantation, Kuantan) 62 km west from Kuantan city. Table 2 summarizes the characteristics of POME. The POME sample was stored at 4°C before use. Different dilutions of POME were made by using tap water. Then the sample was pre-filtered by means of simple depth filtration to remove the coarse solids found in the suspension. The raw POME was initially passed through a filter bed, which consisted of minor stones with average size of 0.6 cm.

Table 1 — Characterization of CKD samples

Parameter	Dry-kiln CKD (% by weight)	Dry-kiln CKD (% by weight) ^a
pH	13.6*	-
CaO	51	44.9
SiO ₂	11.6	9.64
Al ₂ O ₃	6.1	3.39
Fe ₂ O ₃	3.3	1.10
MgO	1.1	1.29
K ₂ O	1.69	2.4
SO ₃	5.4	6.74
Na ₂ O	2.1	2.62
Cl-	3.5	4.5
Free lime	15.6	25.3
Particle size	<25 µm	1-40

* unitless parameter

^a Adaska and Taubert (2008)

Table 2 — Physico-chemical properties of the POME

Parameter	Concentration
pH	4.42 ± 0.12
Biological oxygen demand (BOD)	33,000 ± 2806
Chemical oxygen demand (COD)	62,000 ± 7842
Total suspended solid (TSS)	50,000 ± 654
Volatile suspended solids (VSS)	42,230 ± 2806
Soluble chemical oxygen demand (SCOD)	37,000 ± 1624
Oil and Grease	8,563 ± 2560
Total nitrogen (TN)	865 ± 35.6
TKN	1312 ± 55
NH ₃ -N	94 ± 9.165
Total Phosphorus	16.6 ± 4.35

*All parameters are in units of mg/L except pH.

The collected filtrate was passed through another filter bed that consisted of mixture of minor stones and sand (average diameter size of 300-600 µm) in the ratio of 1:2. Later, the filtrate from the second filter bed was subjected to simple surface filtration, under vacuum through a Whatman No. 41 filter paper (20-25µm) and finally a Whatman No. 40 filter paper (8µm) before proceeding to UASB process. The filtrate after surface filtration was named as pretreated POME as shown in Table 2.

Seed Sludge Formation

After preliminary treatment, the seeding was carried out to activate the microbes. Seeding was done for the sake of time as normal process of activation takes more time. Moreover, as the purpose of study was to evaluate the feasibility of CKD for potential treatment of POME. It was necessary to use activated sludge for proper monitoring of pH variation with CKD. A stock solution was prepared by the following macro and micro nutrients (values are in gL⁻¹): NH₄CL, 174; KH₂PO₄, 28.3; (NH₄)₂ SO₄, 28.3; MgCl₂, 25; KCL, 45; yeast extract, 3; FeCl₂.6H₂O, 2; H₃BO₃, 0.05; ZnCl₂, 0.05; CuCl₂.2H₂O, 0.038. The samples after nutrient addition were kept at room temperature for 20 day. The total volatile solids concentration of seeded sludge was 10 gL⁻¹. To ensure microbial activity, 5 mL of sludge was added to 50 mL diluted POME with COD of 5000 mgL⁻¹ in a 150 mL serum bottle. The produced gas was analyzed after one day and it was found to contain high methane contents (data not included). The result showed anaerobic activity of seed sludge.

The Lime Slacking and Bench Scale Experiments

Prior to experiment, lime slacking was conducted with different ratio of CKD as previously described¹⁵. Bench scale experiments were carried out with five 500 mL flasks of POME to examine then neutralizing effects of CKD. Five ratio of calcium hydroxide after CKD slacking were used to examine the neutralizing effects Fig. 1. Slacked solution of 10-35 mg CKD/l was found to be suitable for maintaining pH of 6.7-7.5. The reaction was slow but successfully maintained the pH of POME substrate in the reactor.

Experimental Setup and Reactor Operation

The experiment was performed by a 2 litre previously constructed upflow anaerobic sludge blanket reactor (UASBR). The reactor was continuously operated at 35°C. Heating was done by hot water circulating through jacket around the

reactor. The feed was introduced through bottom of the reactor by peristaltic pump with a flow rate of 0.52 l d^{-1} at a various hydraulic retention time (HRT) of 8 to 24 h. A gas-solid-liquid (GSL) separator was installed at top of the reactor for biogas capturing.

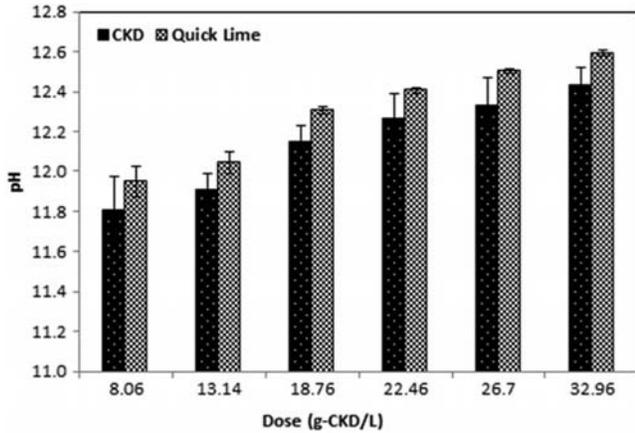


Fig. 1 — The pH results of filtered solution after slaking process, (values in mean \pm SD)

Four sampling ports were placed at suitable height of the reactor. The modification was done in previous UASBR by installing a stirrer with 5 rpm speed. Intermittent mixing was applied due to less volume of the reactor. The stirring is used to avoid settling of CKD in the reactor. The experimental setup of UASBR is shown in Fig. 2.

The UASBR was inoculated with 350 mL seed sludge. The acclimatization of sludge with POME was done by daily bench fed of diluted sludge (5 g COD/l) for five days. The average volatile suspended solids (VSS) of the sludge after 5 days bench fed were 11.3 L^{-1} . Continuous feeding was started with an initial organic loading rate (OLR) of $1.5\text{ kg COD m}^{-3}\text{h}^{-1}$ and hydraulic retention time (HRT) of 4 d. The HRT was kept constant throughout the start up study period. The influent COD concentration was 6 L^{-1} for the first 20 h, and then it was increased to 10 L^{-1} ($\text{OLR} = 2.5\text{ kg COD m}^{-3}\text{d}^{-1}$) for further 20 h. The third and last COD concentration

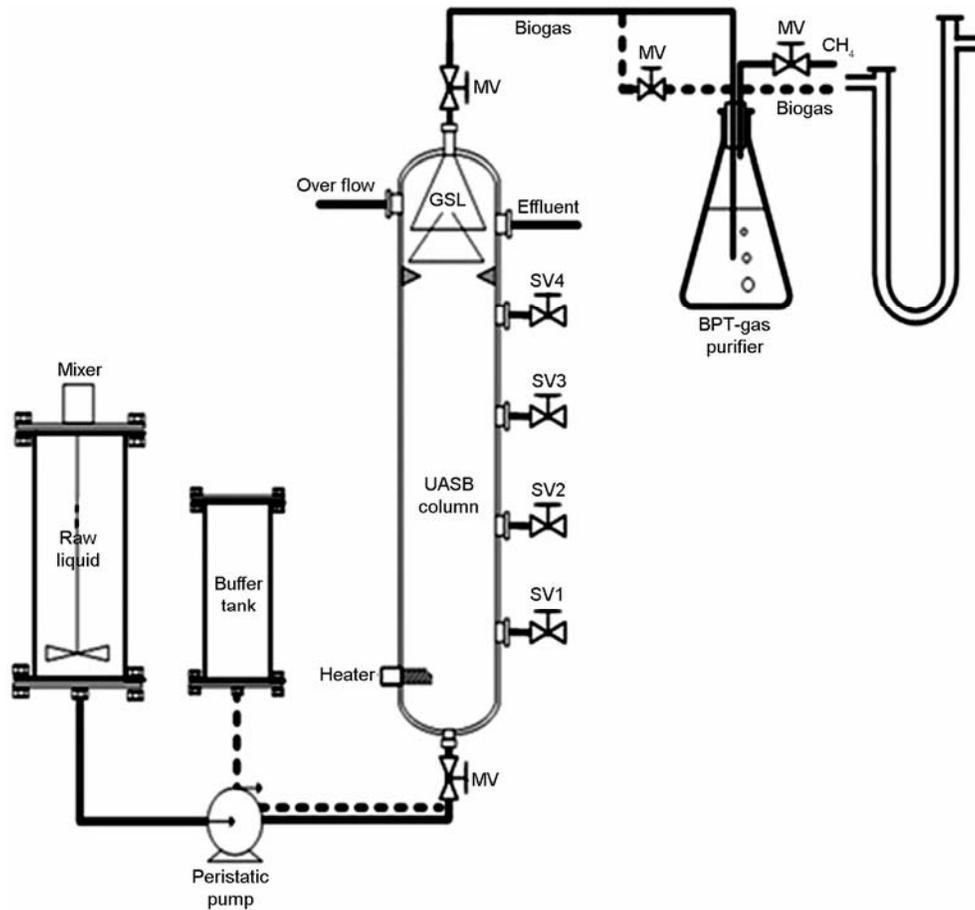


Fig. 2 — Schematic diagram of UASBR. Experimental setup of UASBR: PHT-POME holding tank; PP-Peristaltic pump; FM- Flow meter; MV- Manual valve; M- Mixture; SV- Sampling valve; CKD- Cement kiln dust tank (slaking solution); BPT- Biogas purification tank; WT- Water tank; TS- Temperature sensor; HP- Heating probe; P- Pump

was 16 gL^{-1} ($\text{OLR} = 4.5 \text{ kg COD m}^{-3}\text{h}^{-1}$) from 32 to $\text{OLR} = 5 \text{ kg COD m}^{-3}\text{h}^{-1}$ 24 d. The reactor was monitored daily for volatile fatty acids, alkalinity, COD and biogas production while temperature and pH were monitored quarterly in a day.

Analytical methods

Palm oil mill effluent

Biochemical oxygen demand (BOD), COD, VFA, pH, TS, total suspended solid (TSS), total Kjeldahl nitrogen (TKN) and oil and grease were determined according to standard methods APHA¹⁶. Alkalinity was measured by the direct titration method¹⁷. Gas volume was measured by using a displacement of acidified water (pH 2-3) and methane by KOH solution displacement in a serum bottle was described previously¹⁸.

Cement kiln dust

Particle size analyzer (Model 2000E, Malvern) was used to determine the particle size distribution of the different CKD samples. A major oxide analysis of each unhydrated CKD sample was done using ICP-OES (Vista-PRO Radial, Varian). Samples were first set by using lithium metaborate/tetraborate fusion. Sulphur contents were analyzed using a sulphur analyzer (CS 600, LECO). The rapid sugar method was used to determine the available lime content as outlined in ASTM standard C 25-06.

Statistical analysis

All data was analyzed by using data analysis toolbox in EXCEL 2007 version software. Correlation (r) was calculated to analyze the effect of pH on different operating and performance parameter.

Results and Discussion

Batch test studies

The batch test performance of the different doses of CKD, concentrations of POME, VSS, and VFA in the

influent and the COD removal efficiencies were shown in Table 3. To determine the superior effective ratio of the CKD in UASBR from a ratio of 200 to 1800 mgL^{-1} (Table 3). The batch test performed with 1600 mgL^{-1} CKD indicated neutral pH 7.6 was showing healthy microbial activity by continuous reduction (14.2 to 69%) of initial COD concentration. Interestingly, alkalinity increased from 0.2 to 4.5 L^{-1} with decreasing VFA and COD (Table 3). POME contains about 0.85 L^{-1} acetate in terms butyrate decreased up to 0.44 L^{-1} , and high volatile suspended solid 2.5 L^{-1} were more effective for POME conversion 95%. In contrast, the lipid-rich waste contains long chain fatty acids, especially palmitate (higher than 50 mg g^{-1} dry weight) and oleate (higher than 200 mgL^{-1}), that were hydrolysis products of fat and oil and these have been reported to restrain bacterial growth and methane formation¹⁹. The suspended solids concentration of POME in the acidogenic reactor was increased to 10.8 L^{-1} , an accumulation of organic solids in the reactor was observed.

Reactor Stability

The pH of reactor with POME using CKD was better and cheaper than other expensive neutralizing agents (Fig. 2 and Table 3). Upon adding doses of CKD the key parameters of reactor stability such as the reactor pH, effluent VFA and alkalinity were monitored. The rate of HRT, OLR loading and the doses of CKD for each day run of reactor for the treatment of POME were shown in Tables 3 and 4. The CKD gradually affected the substrate pH and the alkalinity of the wastewater and also influenced the organic constituents (Fig. 3 and Table 3). The reactor starting was pH of 4.7, but when CKD was added (doses of 200-1800 mg/L), the pH increased up to a maximum of 7.6. This change may have been caused by accumulation of fatty acids, which can halt rapid

Table 3 — Effect of CKD on various parameters in POME effluent treated during batch fermentation time of 42 days

CKD (mg/L)	OLR $\text{kg COD}/(\text{m}^3 \text{ d})$	pH	VFA (g/L)	SLR (g/L)	VSS (g/L)	Alkalinity (g/L)	COD (%)	POME conversion %	Acetate (g/L)	Butyrate (g/L)
200	1.5	4.7	1.5	0.9	0.5	0.5	14.2	35	0.25	0.76
400	2.0	4.8	1.6	1.5	0.7	1.2	35.5	45	0.35	0.73
800	2.5	4.9	1.2	2.2	0.9	1.9	45	55	0.45	0.68
1000	3.0	5.3	0.99	3.5	1.3	2.3	56	65	0.55	0.64
1200	3.5	5.5	0.93	4.1	1.6	2.9	61	75	0.63	0.55
1400	4.0	6.5	0.66	3.3	1.9	3.5	65	85	0.74	0.48
1600	4.5	7.6	0.55	1.8	2.4	4.5	69	95	0.85	0.44
1800	5.0	7.9	1.5	2.2	1.5	3.2	55	65	0.53	0.49
control	5.0	7.2	1.9	1.5	0.5	1.5	10.5	35	0.15	0.55

Table 4 — Process control parameters for reactors stability and microbiological activity at OLR 4.5 kg COD/m³ d

HRT h	Q L/h	V _{up} m/h	F/M g-COD/ g-VSS.h	VFA/Alka.	Reactor VSS (mg/L)	MLSS mg/L	SMA mg COD/mg -VSS h	SVI mL/g
8	0.87	0.25	0.39	0.59	445	850	950	145
12	2.2	0.45	0.35	0.56	665	1130	1160	165
16	2.9	0.55	0.39	0.42	825	1550	1650	185
20	3.6	0.95	0.27	0.40	1205	2570	2750	265
24	4.2	0.61	0.45	0.28	745	1640	1750	210

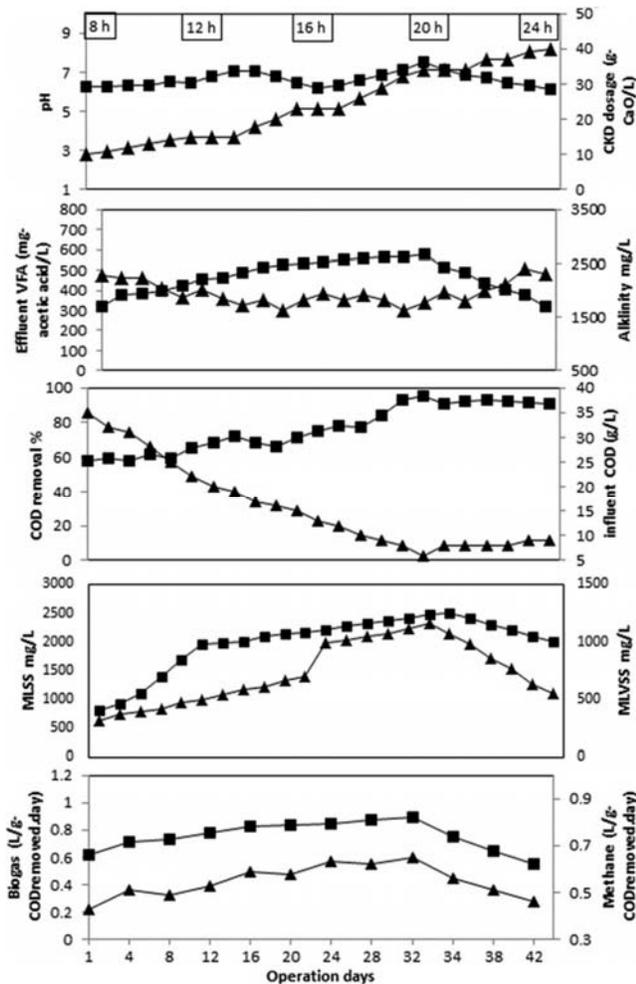


Fig. 3 — Effect of different HRT on reactor performance for the COD and methane production at concentration of CKD 1600 mg/L.

methane production²⁰. Moreover, adding further CKD may also reduce the acidity by converting acetates into methane. This may be due to the reason that fatty acids accumulation in which acids formation mainly have a say in acidity of substrate and can stop the rapid methane production²¹. Moreover, it might also be considered that CKD dosage might not be enough to overcome the acidity. Furthermore, due to non-recycling of the effluent, there is a possibility of

reduction in substrate pH. Because, effluent pH is normally ranging from 7-7.9 and recycling can contribute to maintain the pH in a great extent. A lower pH might due the change in metabolic reaction, resulting in a shift in intermediate production pathway from the acid production phase to the solvent production phase²². The recycling was not carried out in this study as the purpose was only to investigate the effect of CKD on reactor pH. As CKD dosage was increased from 200-1800 mgL⁻¹, the system showed an increasing pH till the end of the experimental period. This might has several reasons like acidogenesis started converting to acetogenesis which contributes to overcome the acidity. Moreover, further CKD dose might mitigate in lowering the acidity along with acetogenesis. Furthermore, the methanogenesis process might decrease rapidly, which allow other acids to convert into acetates for methane formation. A correlation (r) of 0.78 was found thus showing a stronger effect of CKD on pH. As pH has a dominating effect on substrate degradation²³, CKD can be a potential neutralizing agent instead of other buffering solutions. CKD is a waste material from cement industry and a freely available product which can easily be used as buffering agent in anaerobic treatment of POME.

The initial value of 322 mgL⁻¹ VFA at OLR of 1.5 g COD m⁻³d⁻¹ (Fig. 3) could be attributed to as coming from the effluent after POME treatment. The effluent VFA concentration was increased gradually whereby; the alkalinity also increased with OLR and CKD dosage. The maximum effluent VFA concentration was 434 mgL⁻¹ of HRT 20 at OLR 4.5 kg COD m⁻³d⁻¹ while alkalinity accounted 2400 mgL⁻¹. The VFA/alkalinity ratio was 0.39 which shows the suitability of microbial growth. Similar findings were seen where alkalinity was in the range of 1.57-3.02 gL⁻¹ and VFA/alka ratio was a maximum of 0.237². The results showed increase in effluent VFA with increase in OLR 5 kgCOD m⁻³h⁻¹ and CKD dosage was 1800 mgL⁻¹ (Table 3 and 4)²⁴ and recorded alkalinity between 2.16-2.79 mgL⁻¹ throughout the

study with VFA/alka ratio ranging from 0.14 to 0.38. Whereas, effluent VFA between 953 mgL⁻¹ acetic acid²⁵ concluded that the drop in reactor pH from 7 to 6.6 caused high accumulation of VFA in the UASBR. Observed VFA²⁶ 160 mgL⁻¹ acetic acid with relative alkalinity of 3.05 gL⁻¹. They worked at very low VFA/alkalinity ratio of 0.06. The correlation between VFA and alkalinity was found -0.014 showing almost no effect of VFA on alkalinity. Thus system operated at stable conditions at OLR 4.5 kg COD m⁻³d⁻¹ with tolerable VFA/alkalinity ratio and pH²⁷.

Reactor Performance

The effect of HRT on COD removal and methane production by reactor was operated at different OLR (1.5 to 5 4.5 kg COD m⁻³h⁻¹), HRTs (24 to 8 h) but at a constant pH of 7.5, a temperature of 37 °C, and CKD concentration of 1600 mgL⁻¹. The COD removal efficiency was increased above 60% during first week of experiment (Fig. 3), the corresponding COD concentration of influent stream was 6 gL⁻¹ (OLR = 1.5-3.0 kg COD m⁻³h⁻¹). As the HRT increased from 8-20 h so the COD removal efficiency was 95% at 4.5 OLR. In this study COD removal efficiency up to 95% was achieved from HRT of 20 h at 32 d with OLR of 4.5 kg COD L⁻¹. A strong relationship was found between COD removal efficiency and influent COD concentration ($r = 0.95$). For this study, CKD used a stabilizing and neutralizing agent for POME treatment which contributed in high COD removal efficiencies even at 5 gL⁻¹ influent COD concentrations. The system seemed to be stable and further increases of influent COD could be accomplished at same HRT of 20 h for further decrease at 24 h HRT. COD removal rate could reach a maximum and then start to decrease which is a sign of insufficient microbial biomass accumulation in the reactor to carry the additional organic load²⁸. In this study, the microbial biomass was sufficient to control further organic loads in terms of high COD concentrations at HRT 20 h (34 d).

Based on the foregoing results, CKD 1600 mgL⁻¹ and OLR 4.5 kg COD m⁻³h⁻¹ were used in UASBR operation. After 42 d of batch operation, the continuous operation was started at a stepwise decreasing HRT from 24 h to 8 h (Fig. 3). The methane production rate increased from 0.89 mL CH₄/L/h. Methane yield increased from 0.55 L CH₄/g COD added to 0.89 L CH₄/g COD added as the HRT was decreased from 24 to 20 h. Furthermore, the methane production rate was drastically decreased

when the HRT decreased from 20 to 8 h. By contrast, previous reports showed a decrease in methane production rate in suspended cell systems caused by cell washout at low HRT²⁹. The methane yield in general decreased as the HRT decreased. The methane yield values were within the range, but the methane yield significantly decreases from 0.89 mLCH₄/g COD added to 0.62 L CH₄/g COD added when the HRT was shorter to 8 h. At a longer HRT of 24 h, both methane production rate and yield were reduced.

The flow rate (Q) in this study was increased from 0.87 to 3.7 L/h. The higher feed flow rates contribute in sludge and solids wash out. A similarly high upflow velocity (V_{up}) 0.95 m/h was also take part in sludge and solids wash out (Table 4). The VFA degraded since more VSS and MLSS were developed. During the acclimatization phase the SVI and MLSS steadily rose to the levels of 265 mL gL⁻¹ and 2570 mL L⁻¹ respectively at HRT 20 h (Table 4). However, the SMA 2750 mg COD/mg-VSSh⁻¹ increased and F/M 0.27 g-COD/ g-VSS.h decreased, when the CKD concentration in the reactor increased from 1600 mgL⁻¹ at HRT 20 h. The lower methane production performance at MLSS and SMA ratio of might have been caused by the use of a large amount of substrate for growth, thus directing substrate utilization away from methane fermentation³⁰. In contrast, the methane percentage and COD removal efficiency were negatively impacted when the CKD doses of 1600 mgL⁻¹ above or lower. This could have been caused by increased VFA/ALK ratio 0.40.

Suspended Solids removal

Figure 4 illustrates the suspended solids concentration along with four sampling ports with

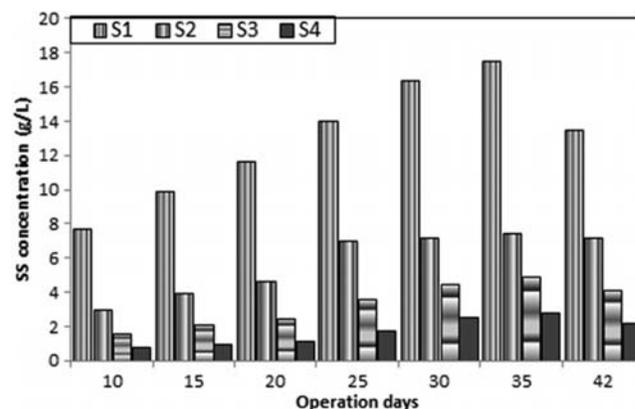


Fig. 4 — Effect of different days on reactor performance for the solids removal at concentration of 1600 mg/L.

increasing CKD dosage. At CKD and OLR, loading was 1600 mgL^{-1} and $4.5 \text{ kg COD m}^{-3}\text{h}^{-1}$ respectively. Suspended solids concentration was 17.5 mgL^{-1} at first sampling port, while only 2.5 mgL^{-1} was at fourth sampling port. Similarly first and second sampling ports showed higher concentration of suspended solids with increased CKD dosage. This high accumulation of suspended solids might be due to heavy particles of CKD which contribute to faster settling of the solids^{31,32}. Moreover, CKD may affect the granule to SVI-SMA formation and allow excessive solids to settle down at 0.96 m/h flow velocity. The flow rate in this study was found 3.6 l/h . The feed flow rates contribute in sludge and solids settle down or wash out. Moreover, high gas turbulence may affect in blow the solids upward direction causing a relatively high washout from the digester. The suspended solids removals are embedded in Fig. 4. Increased CKD dosage did not reduce the suspended solids removal. 80% of suspended solids have been observed at $1600 \text{ CKD mgL}^{-1}$. At $1800 \text{ CKD mgL}^{-1}$ the suspended solids removal was 650%. The influent contained a high proportion of suspended solids which can be difficult to microbiologically hydrolyze within the short HRT^{33,34}. The operation of the UASBR with increasing CKD dosage seemed not to cause excessive solids washout although the OLR was run to maximum of $4.5 \text{ kg COD m}^{-3}\text{h}^{-1}$.

Abbreviations

UASBR upflow anaerobic sludge blanket reactor	TN total nitrogen (mg/L)
POME palm oil mill effluent	TS total solids (mg/L)
CKD cement kiln dust	TVS total volatile solids (mg/L)
HRT hydraulic retention time (day)	V volume reactor (l)
l liter	VFA volatile fatty acid (mg/L)
COD chemical oxygen demand (mg/L)	TVFA:Alk total volatile fatty acid:alkalinity
Methane CH_4	VSS volatile suspended solids (mg/L)
BOD biochemical oxygen demand (mg/L)	SSV sludge settling velocity (m/h)
PEG Polyethylene glycol	SMA specific methanogenic activity (mg CH_4 COD/mg VSS. d)
O&G oil and grease (mg/L)	SRT solid retention time (d)
OLR organic loading rate ($\text{kg/m}^3\text{/d}$)	SS suspended solid (mg/L)
Q flow rate (L/day)	t time (day)
SRT solid retention time (d)	MLVSS mixed liquor volatile suspended sludge (mg/L)
SS suspended solid (mg/L)	Food microorganism ratio F/M (g-COD/g-VSS.d)
t time (day)	Upflow velocity V_{up} (m/h)
MLSS mixed liquor suspended sludge (mg/L)	
SVI sludge volume index (ml/L)	

Conclusion

Cement kiln dust can be proposed to be used in this study as an alkaline source to neutralize the POME and as a degradable organic source with aim to reduce the chemical cost for pH adjustment and reuse waste CKD to reduce the environmental pollution impact for POME. The reactor pH is successfully attained at 7.7 without any serious problem. The sludge fractions were sufficiently and continuously removed from the reactor in order to retain the heavier sludge to promote SMA and SVI growth in and on the sludge. The VFA/ALK ratio remained below 0.40, which supported the proper bacterial growth. The UASBR is not allowed to operate for less than the flow rate because the washout of microorganisms reduces the performance of anaerobic digestion. The UASBR with CKD generated an optimal biogas production rate of $0.89 \text{ mL CH}_4\text{/g COD}$ and a methane yield of $0.56 \text{ biogas/g COD added}$, when operated at a HRT of 20 h and a OLR $4.5 \text{ kgCOD m}^{-3}\text{h}^{-1}$, CKD concentration of 1600 mg COD/L . Additionally, the maximum COD removal efficiency in the reactor found to be 95%.

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