Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 20(2008) 658–663
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Startup and operation of anaerobic EGSB reactor treating palm oil mill effluent

ZHANG Yejian[1], YAN Li[2], CHI Lina[1], LONG Xiuhua[1], MEI Zhijian[1], ZHANG Zhenjia[1,*]

1. School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China. E-mail: yjzhang2007@yahoo.com
2. College of Life and Environmental Science, Wenzhou University, Wenzhou 325000, China

Received 27 August 2007; revised 1 November 2007; accepted 23 January 2008

Abstract

A bench-scale expanded granular sludge bed (EGSB) reactor was applied to the treatment of palm oil mill effluent (POME). The reactor had been operated continuously at 35°C for 514 d, with organic loading rate (OLR) increased from 1.45 to 17.5 kg COD/(m^3·d). The results showed that the EGSB reactor had good performance in terms of COD removal on the one hand, high COD removal of 91% was obtained at two days' of hydraulic retention time (HRT), and the highest OLR of 17.5 kg COD/(m^3·d). On the other hand, only 46% COD in raw POME was transformed into biogas in which the methane content was about 70% (*V/V*). A 30-d intermittent experiment indicated that the maximum transformation potential of organic matter in raw POME into methane was 56%. Volatile fatty acid (VFA) accumulation was observed in the later operation stage, and this was settled by supplementing trace metal elements. On the whole, the system exhibited good stability in terms of acidity and alkalinity. Finally, the operational problems inherent in the laboratory scale experiment and the corresponding countermeasures were also discussed.

Key words: palm oil mill effluent; mesophilic; anaerobic digestion; expanded granular sludge bed (EGSB)

Introduction

Oil palm (*Elaeis guineensis*) is one of the most versatile crops in the tropical region, particularly in Malaysia and Indonesia. About 1.5 m^3 water are used to process one ton of fresh fruit bunches (FFB), and half of this quantity results in palm oil mill effluent (POME) (Chungsiriporn *et al*., 2006). On account of its extremely high biological and chemical oxygen demands, POME poses a great threat to the quality of the water environment nearby.

Over the past decades, many methods have been developed to control POME pollution, including crop irrigation, serving as animal fodder, decanting and drying (Edewor, 1986), evaporation (Ngan, 1999), simple skimming, coagulation (Ng *et al*., 1987; Ahmad *et al*., 2005a), flotation, adsorption (Ahmad *et al*., 2005b), ultrafiltration (Ahmad *et al*., 2003), and various biodegradation technologies. However, few has been put into full-scale application because of their unsatisfactory performance and/or high operating costs. Compared with the physical and chemical technologies, conventional biological treatment methods of anaerobic, facultative, and aerobic degradation are more widely used in the treatment of POME.

Aerobic treatment efficiency of POME was investigated using suspended growth in an activated sludge process, with a diffused aeration system (Vijayaraghavan *et al*., 2007). The treatability was also examined using attached growth in an aerobic rotating biological contactor (Najafpour *et al*., 2005).

Anaerobic biological systems offer more potential for the treatment of POME because of its highly organic characteristics, as these systems do not require high energy for aeration and allow the recovery of energy in the form of methane, in a closed system.

Nowadays, about 85% of POME treatment is based on the facultative anaerobic pond system in Malaysian palm oil mills. The use of conventional anaerobic lagoon or tank digester to treat POME is characterized by long residence time, often in excess of 20 d. A pond system, consisting of eight ponds in a series, was studied to evaluate its efficiency for POME treatment. After a total hydraulic retention time (HRT) of 60 d, residual COD and BOD_5 in the effluent were 1,725 and 610 mg/L, respectively (Chin *et al*., 1996). Another drawback of the conventional anaerobic digester is its difficulty in collecting and utilizing the methane generated, which has a detrimental greenhouse effect on the environment.

To shorten the treatment time needed, lessen the land required, and at the same time collect the biogas produced, high-rate reactors, such as, tank digester (Ho and Tan, 1985; Ugoji, 1997), anaerobic filter (Borja *et al*., 1994b), anaerobic fluidized reactor (Borja, 1995), anaerobic baffled

* Corresponding author. E-mail: zjzhang@sjtu.edu.cn.

reactor (Setiadi *et al*., 1996; Faisal and Unno, 2001), upflow anaerobic sludge bed (UASB) (Borja *et al*., 1994a; Borja *et al*., 1996a), and other hybrid reactors were put forward and evaluated in treating POME (Borja *et al*., 1996b; Najafpour *et al*., 2006).

Expanded granular sludge bed (EGSB) reactor, a modification of UASB, has been primarily developed, to improve substrate-biomass contact within the treatment system, by expanding the sludge bed and intensifying hydraulic mixing. Consequently it has a better reactor performance and stability than the UASB. Many researchers, including this research group, have done a lot of study on EGSB in such areas as flow pattern, kinetics, toxicity inhibition, and startup and operation characteristics. Moreover, EGSB reactors have been successfully applied to treat many kinds of wastewater, such as, brewery wastewater, starch wastewater, molasses alcohol slops, domestic and municipal wastewater, and so on. However, the use of EGSB reactors in treating POME has not been reported in the literature to date. The main objectives of the present research were to explore the feasibility of mesophilic anaerobic digestion of POME by using an EGSB reactor.

1 Materials and methods

1.1 Experimental setup

The schematic diagram of the bench-scale EGSB reactor used in this study is shown in Fig.1. The EGSB reactor was made up of a plexiglass column with an internal diameter of 11 cm and an overall height of 195 cm. The total volume of the reactor was 21,560 ml and the working volume was 20,500 ml (excluding head space). The column consisted of three parts: bottom, middle, and top. The bottom part of the column, with a height of 12 cm was the influent distribution area. The middle part served as the main biochemical reaction section, with a height of 156 cm and a height-per-diameter ratio of 15. The top part, with a height of 27 cm, played the role of a gas-liquid-solid separator, which had the function of allowing the separation of biogas and washed-out solids from the liquid phase. An inverted funnel shaped gas separator was used to conduct the biogas to the wet gas flow meter, to measure the volume of the biogas produced. Thirteen sampling ports were placed at suitable distances along the height of the column, and the effluent was collected from the top of the reactor. A liquid upflow velocity (V_{up}) of 3.5 m/h was maintained by applying effluent recirculation. The EGSB reactor was operated under mesophilic condition (35°C) and its temperature was maintained by circulating hot water through the reactor jacket.

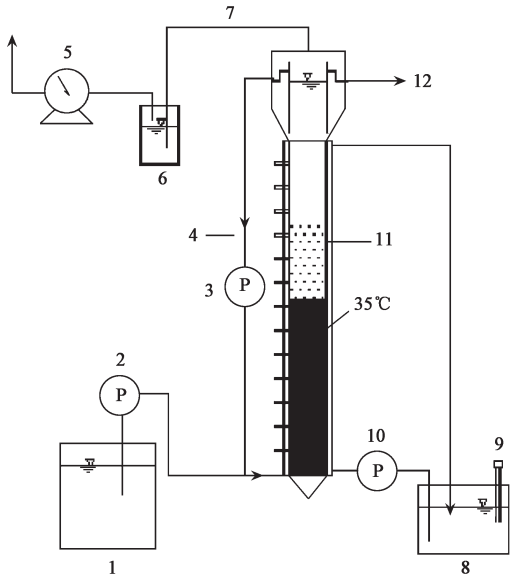

Fig. 1 Schematic diagram of anaerobic expanded granular sludge bed reactor treating POME. (1) feed tank; (2) peristaltic pump; (3) recirculation pump; (4) sampling ports; (5) gas meter; (6) gas seal; (7) gas; (8) water bath; (9) heater; (10) centrifuge pump; (11) water jacket; (12) effluent.

The aerobic reactor, although it is not the core, and as the authors have discussed in this article, plays important role in eliminating the acidity produced in EGSB, and diluting the raw POME by circulating its effluent back to EGSB. The aerobic reactor is also made of a plexiglass column, with an internal diameter of 15 cm and an overall height of 108 cm, and the working volume is 19,700 ml. A PVC (polyvinyl chloride) flexible filler was used as the support medium. The temperature in the aerobic reactor is kept constant at 25°C by a temperature controller.

1.2 Palm oil mill effluent

The POME samples were collected from the Sungai Burung Palm Oil Mill, located in the state of Sabah, Malaysia, and were preserved in PVC containers at a temperature of less than 4°C, but above freezing point, to prevent the wastewater from undergoing biodegradation on account of microbial action. A detailed description of the composition and features of the wastewater is summarized in Table 1.

Table 1 Characteristics and composition of raw POME (unit: mg/L, except pH)

Parameter	Value	Parameter	Value
pH	4.8	Ca	607.3
COD	79,723.2	Cu	5.08
BOD	35,432.5	Fe	61.17
Total solid (TS)	67,200	K	5,533
Suspended solid (SS)	49,300	Mg	1,065
Volatile suspended solids	35,935	Mn	8.572
Kjeldahl nitrogen	873.6	Na	87.92
Ammoniacal nitrogen	173.8	P	277.7
Volatile fatty acid[a] (VFA)	2,287	S	400
Total alkalinity[b] (TA)	523	Si	99.67
Oil and grease	17,410	Sn	3.669
Al	6.299	Zn	6.83
Ba	0.4802		

[a] Volatile fatty acid, expressed as HAc (acetic acid); [b] total alkalinity, expressed as $CaCO_3$ (calcium carbonate)

1.3 Inoculum (seed sludge)

The inoculum for seeding was a mixture of 3 L of digested sludge and 9 L of granular sludge. The digested sewage sludge, which contained 22,450 mg/L suspended solids

(SS) and 19,560 mg/L volatile suspended solids (VSS) was initially screened to remove the debris. The anaerobic granular sludge, which contained 97,975 mg/L SS and 67,040 mg/L VSS was taken from a UASB reactor treating beer wastewater. The granular sludge was methanogenically active as the biogas bubbles were apparently observed stripping from the water surface during the sampling time. The initial VSS of the seed sludge were 662,040 mg, about 69% of the total SS.

1.4 Analytical methods

Biogas production was measured daily with a wet gas flow meter, making correction for atmospheric pressure and temperature. Methane and carbon dioxide concentration were determined by GC2010A gas chromatography (Shimadzu, Japan) with a stainless steel column (300 cm × 0.3 cm) packed with active carbon (30–60 mesh) using thermal conductivity detection (TCD). Volatile fatty acid (VFA) was analyzed with HP5890 series II gas chromatograph (HP, USA) equipped with a flame ionization detector (FID). Elemental composition was analyzed with inductively coupled plasma (ICP) emission spectrophotometry (Thermo Electron, USA) after being predigested in aqua regia.

The following parameters were also analyzed: COD, BOD_5, alkalinity, ammonia nitrogen, and Kjeldahl nitrogen, and the analyses were carried out according to the standard procedures (APHA, 1999).

1.5 Startup and operation scheme

To recover the microbial activity of the seed granular sludge that had been conserved for six months, glucose solution of 3,000 mg/L COD was fed at the beginning of the operation. Reactor pH was adjusted to 7.0 using saleratus ($NaHCO_3$). Supplementary nutrients nitrogen (NH_4Cl) and phosphorous (KH_2PO_4) were added to yield a COD:N:P ratio of 250:5:1, and 50 ml stock solution was added to supply the trace metal elements. The stock solution per liter consisted of: 2,000 mg of $FeCl_3{\cdot}4H_2O$; 50 mg of H_3BO_3; 44 mg of $ZnCl_2$; 40 mg of $CuCl_2{\cdot}2H_2O$; 30 mg of $AlCl_3$; 500 mg of $MnCl_2{\cdot}4H_2O$; 175 mg of $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$; 150 mg of $CoCl_2{\cdot}6H_2O$; and 100 mg of $NiCl_2{\cdot}6H_2O$.

In the first three days, the EGSB reactor was operated in a batch-feed mode to recover microbial activity. After that, diluted POME (initially, tap water was used to dilute raw POME, with $NaHCO_3$ adjusting pH; later, after the aerobic reactor was put into operation, discharge from the aerobic reactor was recycled, and alkalinity addition was not required anymore.) was fed to the EGSB reactor continuously. The experimental procedure is illustrated in Fig.2. When effluent COD, VFA, total alkalinity (TA), and biogas production rate became comparatively constant (a variation of less than 3%), influent COD was raised stepwise from 4,331 to 35,000 mg/L in 8–111 d according to Fig.2.

A HRT of 3 d was kept constant throughout the startup duration, and after that, the HRT was shortened to 2 d in the later operation stage. Anaerobically digested POME

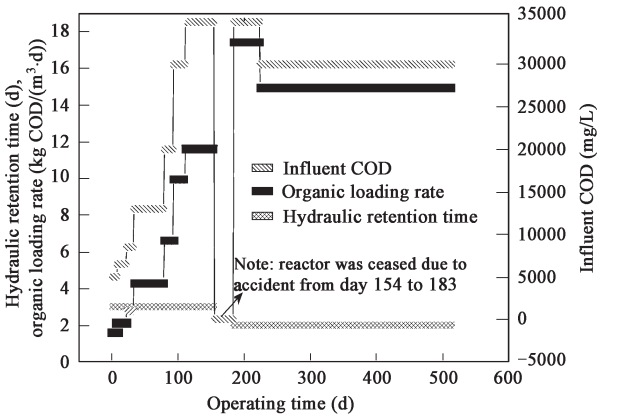

Fig. 2 Startup and operation strategy for EGSB reactor.

from the EGSB reactor was pumped into an aerobic biofilm reactor for further digestion. Discharge from the aerobic reactor had a pH between 8.5–9.0, and was recycled back to the EGSB reactor. The purpose was to supply alkalinity by blending the raw POME with low COD and a high alkalinity recycled stream. Without pumping the aerobic effluent back to EGSB, to take 4 L of raw POME diluted with 16 L of tap water as an example. A pH of 4.74, 100 g of $NaHCO_3$ would be needed to adjust the pH to 6.35. Admittedly, effluent recirculation alleviated the need for the addition of alkalinity to the feed of the EGSB reactor, which could reduce the running costs especially when done on a large-scale process.

Once a steady state was achieved, samples were collected and subjected to the analysis of the following parameters: feed and effluent COD, effluent TA, effluent bicarbonate alkalinity (BA), effluent VFA, reactor pH, gas production, and composition.

2 Results and discussions

2.1 Startup stage

After only 2-d operation, little bubbles were found to be attached on the granular sludge, meanwhile, COD removal efficiency in the EGSB reactor reached more than 85%. All these evidences indicated that the granular sludge had regained its anaerobic activity. From then on, diluted POME was fed to the EGSB reactor continuously.

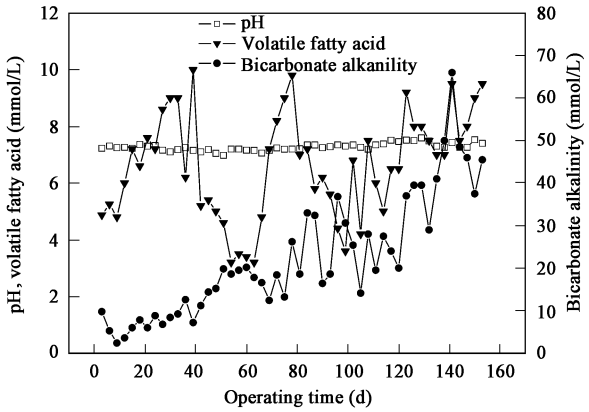

Fig. 3 Change of acidity and alkalinity during the startup stage.

Changes in acidity and bicarbonate alkalinity in the effluent from the EGSB reactor during the startup stage is shown in Fig.3. As can be seen, the pH is comparatively stable, varying from 6.98 to 7.53, which is suitable for efficient methanogenesis, indicating that the system has sufficient alkalinity to neutralize organic acids coming from the influent and from the hydrolysis and fermentation stage. System stabilization is also validated by the ratio of VFA/TA, which is in the range of 0.1–0.3 at all times. BA in the effluent presents an ascending tendency, rising from 2.4 to 66 mmol/L during the startup stage. Unlike pH and BA, VFA in the effluent from the EGSB reactor changes regularly. After the organic loading rate is raised, the concentration of the effluent VFA will rise remarkably in a comparatively short time of less than one day. However, after two to three days operation, it will reconvert again, even a slightly higher than the former steady value. The sudden increase in OLR will result in organic shocks to the microorganisms, and the microflora will need time for acclimation to the new environment. However, the response of the acid producing fraction of the microbial consortium is consistently more rapid than that of the methanogens. The increase in effluent VFA implies that the acidogenic bacteria produce more VFA than what can be utilized by the acetogenic and methanogenic bacteria. However, the self-regulation capability inherent in the biological system, makes it possible for the biology consortium to acclimate itself to the new environment. After two to three days, a new balance is obtained, and VFA concentration regresses to the former level.

Figure 4a illustrates the biogas production rate during the startup stage. By comparing Fig.3 and Fig.4a. It can be found that the gas production rate has undergone changes opposite to VFA. When effluent VFA concentration is at a high level, the proportion of COD transformed into methane is accordingly small, which results in a low gas production rate. Apparent COD removal efficiency during the startup stage is shown in Fig.4b. As shown in the figure, although COD concentration is raised from 5,000 to 35,000 mg/L in the first 150 d, the effluent COD is consistently less than 2,500 mg/L and the average COD removal efficiency is kept as high as 92%, indicating that the anaerobic reactor is in good condition for digesting POME.

2.2 Later operation stage

Apparent COD removal efficiency during the later operation stage is illustrated in Fig.5a. During the first 399 d, COD reduction rate was well above 90% with a mean value of 92.7%, which indicated that the processing system was in good condition. However, because of an accident that happened on day 405, with the heat preservation system, the temperature in the EGSB reactor fell to the room temperature of 15°C in the next two days. In the following

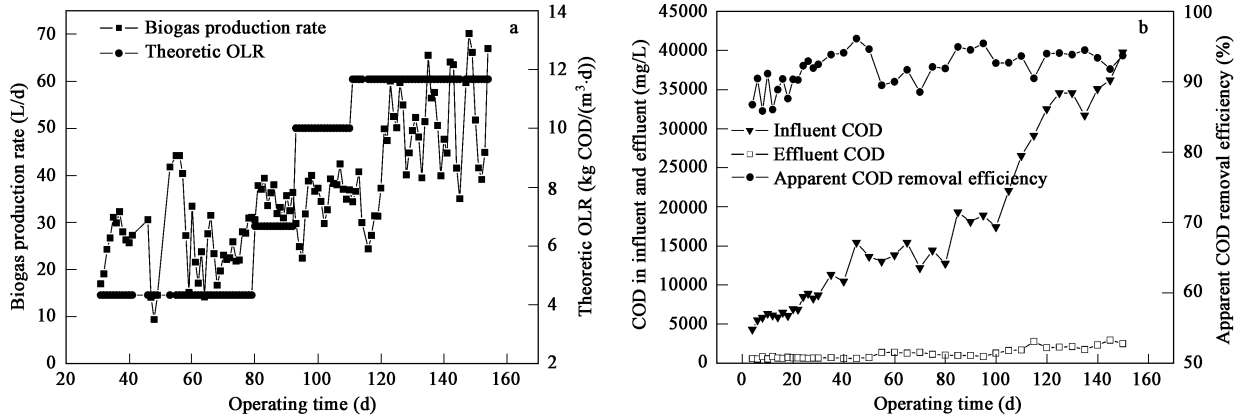

Fig. 4 Biogas production rate (a) and apparent COD removal efficiency (b) during startup stage.

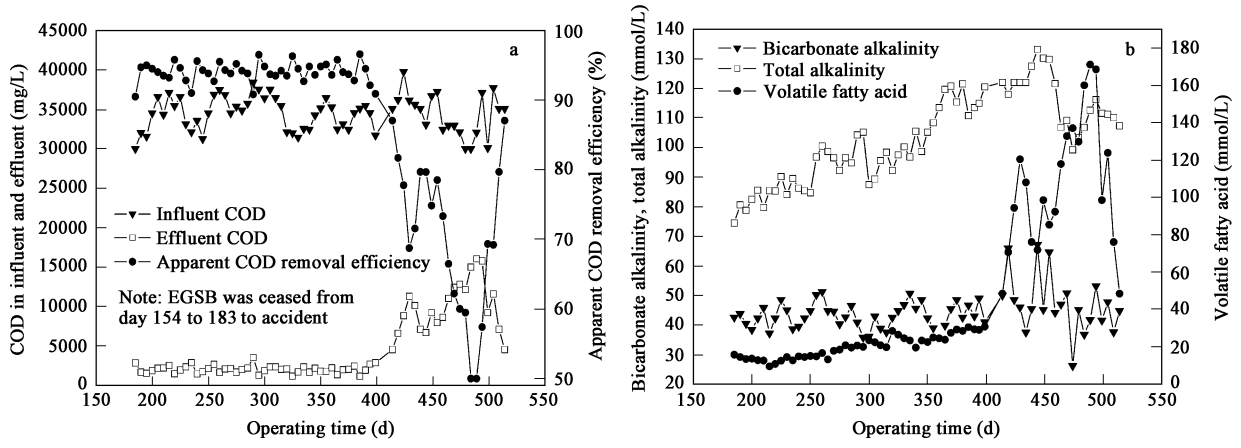

Fig. 5 Apparent COD removal efficiency (a) and change of acidity and alkalinity (b) during the later operation stage.

90 d, COD removal efficiency declined from 91% (on day 399 d) to only 50% (on day 489). VFA concentration increased from 31 to 171 mmol/L (Fig.5b). Supposing all the VFA was acetic acid (the assumption is reliable in a single-phase anaerobic system when it is in a steady-state. In this experiment, the proportion of acetic acid was about 87.5% (*n*/*n*) of total VFA, the authors may deduce that about 60% effluent COD could be attributed to VFA. This further proved the estimation that approximately two-thirds of the anaerobic effluent COD was caused by VFA (Borja, 1995). Comparing Figs.5a and 5b carefully, the authors could find that when VFA increased, COD removal efficiency would decrease simultaneously, hence, there was a negative correlation between the two parameters, just as the foregoing phenomenon observed during the startup stage.

The trend of VFA accumulation in the anaerobic system might eventually lead to acidity failure. Therefore, to reduce the VFA concentration and improve treatment efficiency, 50 ml trace metal elements stock was supplemented on day 489. It was found that the effect of trace metal element supplementation was remarkable (Fig.5a and 5b). After only a month, effluent COD decreased from 16,044 to 4,548 mg/L, COD removal efficiency improved from 50% to 87%, and effluent VFA decreased from 171 to only 48 mmol/L, correspondingly. Performance improvement after trace metal addition verified that trace metals were necessary for the activation of key enzymes for methanogenesis, and lack of sufficient trace metals may be a reason for the failure of anaerobic digestion.

2.3 Anaerobic digestibility of POME

As shown in Figs.4b and 5a, apparent COD removal efficiency at the steady state was invariably in the range of 89% and 96%, however, the biogas produced was comparatively low. By taking into account 70% methane content (*V*/*V*) in biogas and using the measured biogas production data, the COD to methane conversion ratio was calculated and illustrated in Fig.6. Conversion ratio fluctuated between 33%–50%, whereas, the average COD conversion efficiency was 46%. It was noticed that a big gap existed between the two parameters: apparent COD removal efficiency and COD conversion ratio.

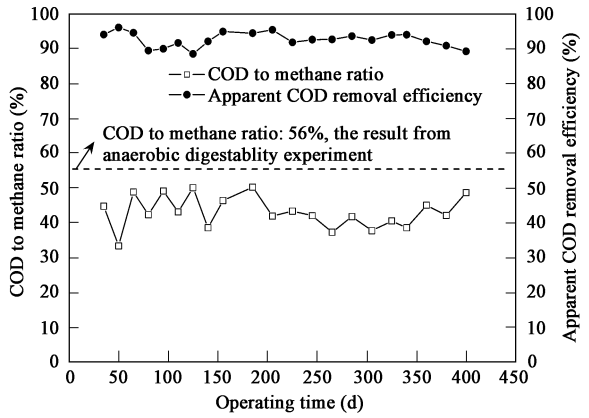

Fig. 6 COD to methane conversion ratio and apparent COD removal efficiency at steady state.

The following intermittent experiment was designed to reveal the anaerobic digestibility and transformation potential of POME, which would explain the phenomenon. A conical flask (250 ml) and water bath shaker (temperature: 35°C; vibrating frequency: 60 r/min) were used. Two parallel flasks were loaded with 50 ml raw POME diluted by 150 ml tap water, and the control experiment was made by the third flask filled with 200 ml tap water. In the three flasks, except for the substrate, other factors such as seed sludge, alkalinity, and trace metal element supplementations were all identical. In the two parallel experiments, influent COD concentration was 6,855 mg/L, and effluent COD concentrations after a 30-d experiment were 809.6 and 769.1 mg/L, respectively. However, the summation methane produced was 268 and 264 ml (standard temperature and pressure, STP), respectively. Apparent COD reduction efficiency was as high as 89%, but only 56% of organic matter in raw POME was transformed into methane. In the later experiment, when only the dissolved portion of POME (the above substrate was filtered with the help of qualitative filter paper) was used instead of diluted POME, the apparent COD removal and conversion rate were increased to 98.6% and 95%, respectively. From the experiment, the authors could find out not only the anaerobic digestibility of POME, but also make the reason for the low methane transformation rate clear.

The particulates–plant cell debris and fragments, on the one hand, did not appear to be easily hydrolysable on account of their high lignin content, and hence, low digestibility (Ho *et al*., 1984). On the other hand, they settled to the bottom of the reactor shortly after entering the reactor, because the particulate matters had a higher specific gravity than water. Therefore, no reflection of particulate COD was presented in the effluent sample. As a result, the apparent COD reduction efficiency could be as high as 90%, whereas, the actual conversion ratio was only about 46%. To improve the COD conversion ratio, and also to avoid SS accumulating in the anaerobic reactor, pretreatment should be made to enhance the hydrolysis and fermentation efficiency.

3 Operational problems and countermeasures

Some of the operational problems inherent in the laboratory scale experiment and countermeasures are listed here.

3.1 Scum formation

It was observed that excessive surface scum entered into the gas outlet line, and choked it, thus a high pressure buildup in the EGSB reactor was created, resulting in the spillage of the contents, even granular sludge. Scum was formed because of the presence of oil and grease in the raw POME, and no pretreatment had been made before entering the anaerobic reactor. One modification was to furnish a certain scum breaking mechanism on the digester surface. This could be realized by using an independently rotatable top rake, which served to break up the scum and release the entrapped gas.

3.2 Sludge flotation

Granular sludge flotation occurred twice in the experiment when OLR was raised excessively. However, when this happened, almost all granular sludge floated to the surface. The specific gravity of granular sludge was lowered after oil and grease were adsorbed on it, coupled with the abundant biogas bubbles adhering to it. To minimize the possibility of sludge flotation, a stepwise raise of OLR should be observed.

3.3 Blockage of pipeline

Pipelines were frequently choked not only by oil and grease separated from the influent, but also by inorganic mineral compound sedimentation. Regular manual cleaning of the sediment from the pipelines was required, to prevent it from clogging.

3.4 Corrosion and blockage of gas meter

The presence of water vapor, hydrogen sulfide, and carbon dioxide in biogas caused rusting and blockage of the gas meter. Therefore, anticorrosive gas meters are recommended.

4 Conclusions

Anaerobic digestion of POME was carried out in an EGSB reactor. The reactor had been operated at 35°C for 514 d, and OLR was increased step by step from 1.45 to 17.5 kg COD/(m^3·d). The reactor exhibited high efficiency in treating this high strength organic wastewater. Apparent COD removal 91% was achieved at HRT of 2 d and OLR of 17.5 kg COD/(m^3·d), but only 46% organic matter in POME was transformed to methane. The reactor was stable in terms of acidity and alkalinity during most of the operation time, and the alkalinity supplementary was unnecessary for pH adjustment after the effluent was recirculated from the aerobic reactor, indicating that the system had sufficient alkalinity to neutralize VFA. However, an accumulation of VFA was observed after 489 d operation, and this was solved by supplementing trace metal elements. The operational problems inherent in the laboratory scale experiment and countermeasures were also given. Longer term running at higher OLR in larger scale bioreactors was required to assess the stability and potential of the EGSB reactor.

Acknowledgements

The authors would like to express their gratitude to Sungai Burung Palm Oil Mill, Malaysia, for the financial support granted for the realization of this study, and for providing the sample of POME to conduct this research.

References

Ahmad A, Ismail S, Bhatia S, 2003. Water recycling from palm oil mill effluent (POME) using membrane technology. *Desalination*, 157(1): 87–95.

Ahmad A, Ismail S, Bhatia S, 2005a. Optimization of coagulation-flocculation process for palm oil mill effluent using response surface methodology, *Environ Sci Technol*, 39(8): 2828–2834.

Ahmad A, Sumathi S, Hameed B, 2005b. Residual oil and suspended solid removal using natural adsorbents chitosan, bentonite and activated carbon: a comparative study. *Chem Eng J*, 108(1): 179–185.

APHA, 1999. Standard Methods for the Examination of Water and Wastewater (20th ed.). Washington DC: APHA, AWWA.

Borja R, Banks C, Khalfaoui B, Martin A, 1994a. Anaerobic digestion of palm oil mill effluent using an up-flow anaerobic sludge blanket (UASB) reactor. *Biomass Bioenergy*, 6(5): 381–389.

Borja R, Banks C, Sanchez E, 1994b. Treatment of palm oil mill effluent by upflow anaerobic filtration. *J Chem Technol Biotechnol*, 1(2): 103–109.

Borja R, 1995. Comparison of an anaerobic filter and an anaerobic fluidized bed reactor treating palm oil mill effluent. *Process Biochem*, 30(6): 511–521.

Borja R, Banks C, Sanchez E, 1996a. Anaerobic treatment of palm oil mill effluent in a two-stage up-flow anaerobic sludge blanket (UASB) system. *J Biotechnol*, 45(2): 125–135.

Borja R, Banks C, Khalfaoui B, Martin A, 1996b. Performance evaluation of an anaerobic hybrid digester treating palm oil mill effluent. *J Environ Sci Health A*, 31(6): 1379–1393.

Chin K, Lee S, Mohammad H, 1996. A Study of palm oil mill effluent treatment using a pond system. *Water Sci Technol*, 34(11): 119–123.

Chungsiriporn J, Prasertsan S, Bunyakan C, 2006. Minimization of water consumption and process optimization of palm oil mils. *Clean Technol Environ Policy*, 8(3): 151–158.

Edewor J, 1986. A comparison of treatment methods for palm oil mill effluent (POME) wastes. *J Chem Technol Biotechnol*, 36(5): 212–218.

Faisal M, Unno H, 2001. Kinetic analysis of palm oil mill wastewater treatment by a modified anaerobic baffled reactor. *Biochem Eng J*, 9(1): 25–31.

Ho C, Tan Y, Wang C, 1984. The distribution of chemical constituents between the soluble utilisation/treatment. *Agricultural Wastes*, 11: 61–71.

Ho C, Tan Y, 1985. Anaerobic treatment of palm oil mill effluent by tank digesters. *J Chem Tech Biotechnol*, 35B: 155–164.

Najafpour G, Yieng H, Younesi H, Zinatizadeh A, 2005. Effect of organic loading on performance of rotating biological contactors using palm oil mill effluents. *Process Biochem*, 40(8): 2879–2884.

Najafpour G, Zinatizadeh A, Mohamed A, Isa MH, Nasrollahzadeh H, 2006. High-rate anaerobic digestion of palm oil mill effluent in an upflow anaerobic sludge-fixed film bioreactor. *Process Biochem*, 41(2): 370–379.

Ng W, Goh A, Tay J, 1987. Palm oil mill effluent (POME) treatment: an assessment of coagulants used to aid liquid-solid separation. *Biological Wastes*, 21(4): 237–248.

Ngan M, 1999. Innovations in management of palm oil palm effluent. Kuala Lumpur: The Planter. 75: 381–389.

Setiadi T, Husaini, Djajadiningrat A, 1996. Palm oil mill effluent treatment by anaerobic baffled reactors: recycle effects and biokinetic parameters. *Water Sci Technol*, 34: 59–66.

Ugoji E, 1997. Anaerobic digestion of palm oil mill effluent and its utilization as fertilizer for environmental protection. *Renewable Energy*, 10(2): 291–294.

Vijayaraghavan K, Ahmad D, Aziz M, 2007. Aerobic treatment of palm oil mill effluent. *J Environ Manage*, 82(1): 24–31.