ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 6, November 2013

Performance of Ultrasonic Membrane Anaerobic System (UMAS) in Membrane Fouling Control

N.H.Abdurahman[1]; N.H.Azhari[2]
Faculty of Chemical & Natural Resources Engineering[1,] Faculty of Industrial Sciences & Technology[2],Universiti Malaysia Pahang

Abstract*— The primary objective of this study was to evaluate the effects of the organic loading rate (OLR) on the performance of an ultrasonic-assisted membrane anaerobic system (UAMAS) treating Palm Oil Mill Effluent (POME), based on the following indicators: (i) methane gas contents, (ii) chemical oxygen demand (COD) removal efficiency, and (iii) effluent variability (phenol, suspended solids, volatile fatty acids, and pH stability).Six steady states were attained as a part of a kinetic study that considered concentration ranges of 15,830 to 21,600 mg/l for mixed liquor suspended solids (MLSS) and 9,450 to 18,200 mg/l for mixed liquor volatile suspended solids (MLVSS). Kinetic equations from Monod, Contois and Chen & Hashimoto were employed to describe the kinetics of POME treatment at organic loading rates ranging from 0.5 to 15 kg COD/m^3/d. The removal efficiency of COD was from 93 to 98.7 % with a hydraulic retention time (HRT) of 4 days. The growth yield coefficient, Y, was found to be 0.59 g VSS/g COD, the specific microorganism decay rate was 0.26 d-^{1}, and the methane gas yield production rate was between 0.264 l/g COD/d and 0.47 l/g COD/d.

Index Terms— **COD reduction, kinetics, organic loading rate, POME, UAMAS,**

I. INTRODUCTION

Palm oil mill effluent (POME) waste is characterized by a high content of organic matter and pathogenic organisms. The disposal of POME without adequate treatment can cause a drastic effect on the environment and human health. Typically, 1.0 ton of crude palm oil production requires 5.0-7.5 tons of water, over 50.0 % of which ends up as POME. Moreover, POME is high in organic content (COD 50.0 g/l, BOD 25.0 g/l) and contains appreciable amounts of plant nutrients (Borja et al., 1996; Singh et al., 1999; Ahmad et al., 2005). If discharged, the untreated POME can cause considerable environmental problems. With the increasing demand for energy and cost-effective environmental protection technology, anaerobic digestion biotechnology has become the focus of worldwide attention (Singh et al., 1999). Moreover, anaerobic digestion can offers a positive effect on the environment because it combines waste stabilization with net fuel production and allows the effluent to be used as a fertilizer. POME consists of various suspended components. The POME nutrient content is too low for aerobic treatment processes but is sufficient for anaerobic processes (Chin et al., 1996). According to the most common characteristics of this waste, anaerobic digestion could be considered one of the most promising treatment alternatives (Kimchie et al., 1988; Hobson and Shaw, 1973; Hobson, 1974, 1981, 1992; Sanchez et al., 1995; Baader, 1990; Yang and Gan, 1998; Parkin and Owen, 1986). In anaerobic wastewater treatment, the loading rate plays an important role. In the case of nonattached biomass reactors, in which the hydraulic retention time is long, overloading results in biomass washout. This, in turn, leads to process failure. Fixed film, expanded and fluidized bed reactors can withstand higher organic loading rates. Even if there is a shock load resulting in failure, the system is rapidly restored to normal. In comparison to a Continuous stirred tank reactor (CSTR) system, fixed film and other attached biomass reactors are more stable. Moreover, a high degree of COD reduction is achieved even at high loading rates for a short hydraulic retention time. Several studies have used membrane anaerobic processes to treat a variety of wastewater sources (Fakhru'l et al., 1994; Nagano et al., 1992). Table 1 presents the recommended COD loading rates for various reactor configurations. The anaerobic fluidized bed appears to be able to withstand the maximum loading rate better than other high-rate reactors. The three widely used kinetic models considered in this study are shown in Table 2.This paper introduces a new technique, the ultrasonic-assisted membrane anaerobic system (UAMAS), for treating POME and producing a large amount of methane (no membrane fouling).In the paper, the kinetic parameters of the process are also determined, based on three known models: Monod (1949), Contois (1959) and Chen and Hashimoto (Chen et al., 1980).

TABLE 1: RECOMMENDED COD LOADING RATES FOR VARIOUS REACTOR CONFIGURATIONS

Anaerobic reactor type	Start-up period	Channeling effect	Effluent recycle	Gas-solid separation device	Carrier packing	Typical loading rates (kg COD/m^3 day)	HRT (d)
CSTR	-	Not present	Not required	Not required	Not essential	0.25-3	10-60
UASB	4-16	Low	Not required	Essential	Not essential	10-30	0.5-7
Anaerobic filter	3-4	High	Not required	Beneficial	Essential	1-4	0.5-12
AAFEB	3-4	Less	Required	Not required	Essential	1-50	0.2-5
(AFB)	3-4	Nonexistent	Required	Beneficial	Essential	1-100	0.2-5

TABLE 2: MATHEMATICAL EXPRESSIONS OF SPECIFIC SUBSTRATE UTILIZATION RATES FOR KNOWN KINETIC MODELS

Kinetic Model	Equation 1	Equation 2	
Monod	$U = \frac{k\,S}{k_s + S}$	$\frac{1}{U} = \frac{K_s}{K}(\frac{1}{S}) + \frac{1}{k}$	[14]
Contois	$U = \frac{U_{\max} \times S}{Y(B \times X + S)}$	$\frac{1}{U} = \frac{a \times X}{\mu_{\max} \times S} + \frac{Y(1+a)}{\mu_{\max}}$	[15]
Chen & Hashimoto	$U = \frac{\mu_{\max} \times S}{Y\,K\,S_o + (1-K)\,S\,Y}$	$\frac{1}{U} = \frac{Y\,K\,S_o}{\mu_{\max}\;S} + \frac{Y(1-K)}{\mu_{\max}}$	[16]

II. MATERIALS AND METHODS

Raw POME was treated by UAMAS in a laboratory digester with an effective 200-liter volume. Fig. 1 presents a schematic representation of the ultrasonic-assisted-membrane anaerobic system (UAMAS), which consists of a cross-flow ultra-filtration membrane (CUF) apparatus, a centrifugal pump, and an anaerobic reactor. Several 25 kHz multi-frequency ultrasonic transducers were connected to the MAS system; 6 permanent transducers were bonded to two (2) sides of the tank chamber and connected to one (1) 250 watt unit of a 25 KHz Crest's Genesis Generator. The UF membrane module had a molecular weight cut-off (MWCO) of 200,000, a tube diameter of 1.25 cm and an average pore size of 0.1 μm. The length of each tube was 30 cm. The total effective area of the four membranes was 0.048 m². The maximum operating pressure on the membrane was 55 bars at 70 ºC, 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 a total height of 250 cm. The operating pressure in this study was maintained between 2 and 6 bars by manipulating the gate valve at the retentate line after the CUF unit.

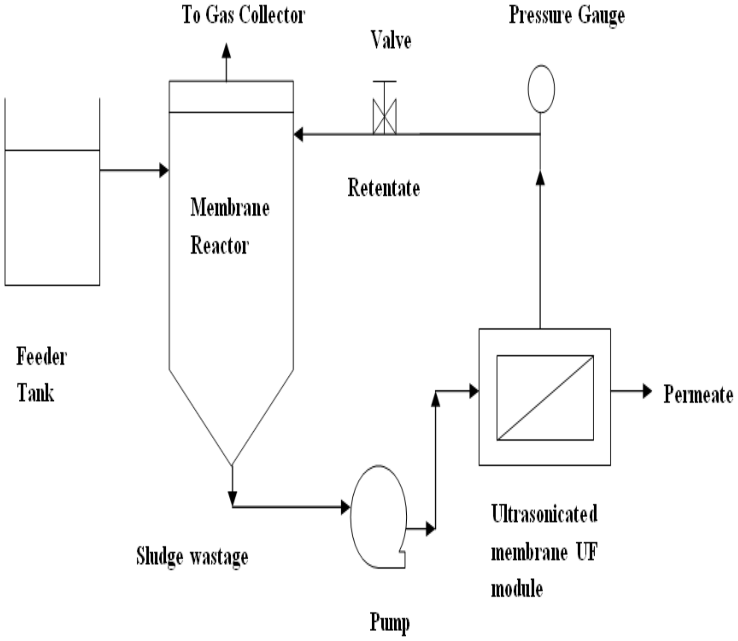

Fig.1. Experimental schematic for UAMAS

Fig.2. Experimental set-up for UAMAS

A. *Palm Oil Mill Effluent*

Raw POME samples were collected from a palm oil mill in Kuantan, Malaysia. The wastewater was stored in a cold room at 4°C prior to use. Samples were analyzed for chemical oxygen demand (COD), total suspended solids (TSS), pH, volatile suspended solids (VSS), substrate utilization rate (SUR), and specific substrate utilization rate (SSUR).

B. *Bioreactor Operation*

The ultrasonic-assisted membrane anaerobic system, UAMAS Performance, was evaluated under six steady-state conditions with influent COD concentrations ranging from 57,000 to 77,000 mg/L and organic loading rates (OLR) between 0.5 and 15 kg COD/m3/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-liter water displacement bottle was used to measure the daily gas volume. The produced biogas contained only CO2 and CH4, so the addition of sodium hydroxide solution (NaOH) to absorb CO2 effectively isolated the methane gas (CH4).

TABLE 3: SUMMARY OF RESULTS (SS: STEADY STATE)

Steady State (SS)	1	2	3	4	5	6
COD feed, mg/L	57000	62000	70600	63000	69200	77000
COD permeate, mg/L	741	1860	2824	4410	3668	5390
Gas production L/d	277.8	334.4	381	484	520	580
Total gas yield, L/g COD/d	0.473	0.361	0.445	0.430	0.374	0.290
% Methane	77	74.0	71.8	68.4	73.0	67.8
Ch_4 yield, l/g COD/d	0.470	0.431	0.411	0.394	0.295	0.264
MLSS, mg/L	15830	14815	16169	19400	21000	21600
MLVSS, mg/L	9450	11200	13000	15481	17325	18200
% VSS	60.00	75.60	80.40	79.80	82.50	84.00
HRT, d	16.00	12.00	8.00	6.00	5.00	4.00
SRT, d	860	320	132	32.6	14.56	10.6
OLR, kg COD/m^3/d	0.5	2.0	4	11.0	13.0	15.0
SSUR, kg COD/kg VSS/d	0.198	0.240	0.261	0.281	0.290	0.320
SUR, kg COD/m3/d	0.346	0.852	3.424	6.281	8.552	9.867
Percent COD removal (UAMAS)	**98.7**	**97.0**	**96.0**	**93.0**	**95.0**	**93.0**
VFA feed (mg/L)	**360**	**490**	**740**	**870**	**1300**	**1480**
VFA permeate (mg/L)	**402**	**510**	**794**	**940**	**920**	**870**

TABLE 4: RESULTS OF THE APPLICATION OF THREE KNOWN SUBSTRATE UTILIZATION MODELS

Model	Equation	$R^2 (\%)$
Monod	$U^{-1} = 2025\ S^{-1} + 3.61$ $K_s = 498$ $K = 0.372$ $\mu_{Max} = 0.261$	95.1
Contois	$U^{-1} = 0.306\ X\ S^{-1} + 2.78$ $B = 0.111$ $u_{Max} = 0.346$ $a = 0.115$ $\mu_{Max} = 0.482$ $K = 0.567$	99.4
Chen & Hashimoto	$U^{-1} = 0.0190\ S_o\ S^{-1} + 3.77$ $K = 0.006$ $a = 0.006$ $\mu_{Max} = 0.351$ $K = 0.383$	98.6

III. RESULTS AND DISCUSSION

A. Semi-continuous Ultrasonic-assisted Membrane Anaerobic System (UAMAS) Performance

Table 3 summarizes the UAMAS performance at six steady-state conditions achieved after a short and successful start-up period. The steady-state conditions were established at different HRTs and influent COD concentrations. The kinetic coefficients of the selected models were derived from Eq. (2) in Table 2 by using a linear relationship; the coefficients are summarized in Table 4.In this study, the UAMAS pH was maintained in an optimum range (6.8-7) to minimize the effects on methanogens that might influence biogas production, while the influent COD concentrations was increased from 57,000 to 77,000 mg/L (for the six steady-state conditions). The organic loading rate (OLR) was adjusted by gradually increasing the influent COD and decreasing the HRT. COD removal efficiencies between 93-98.7% were achieved (Table 3).During this period, the influent COD was adjusted to obtain OLR values between 0.5 and 15 kg COD/m^3/d. a significant correlation was noted to exist between the influent and effluent COD (R^2:0.994), and increasing influent COD resulted in a deterioration of the effluent quality in terms of COD, which varied between 741 and 5,390 mg/L, as shown in Fig.3. During the experimental operation period, the initial OLR was set at 0.5 kg COD/m^3/d, and the HRT was 16 days. The OLR then increased to 2.0, 4.0, 11.0, 13.0 and 15.0 kg COD/m^3/d by reducing the HRT to 16.0, 12.0, 8.0, 6.0, 5.0, and 4.0 days, correspondingly. At the first steady state, the MLSS concentration was approximately 15,830 mg/L, whereas the MLVSS concentration was 9,450 mg/L, equivalent to 60% of the MLSS. This low result can be attributed to the high suspended solids contents in the POME. At the six steady-state conditions, however, the volatile suspended solids (VSS) fraction in the reactor increased to 84% of the MLSS. This indicates that the long SRT of UAMAS facilitated the decomposition of the suspended solids and their subsequent conversion to methane (CH_4); this conclusion is supported by (Nagano et al., 1992).

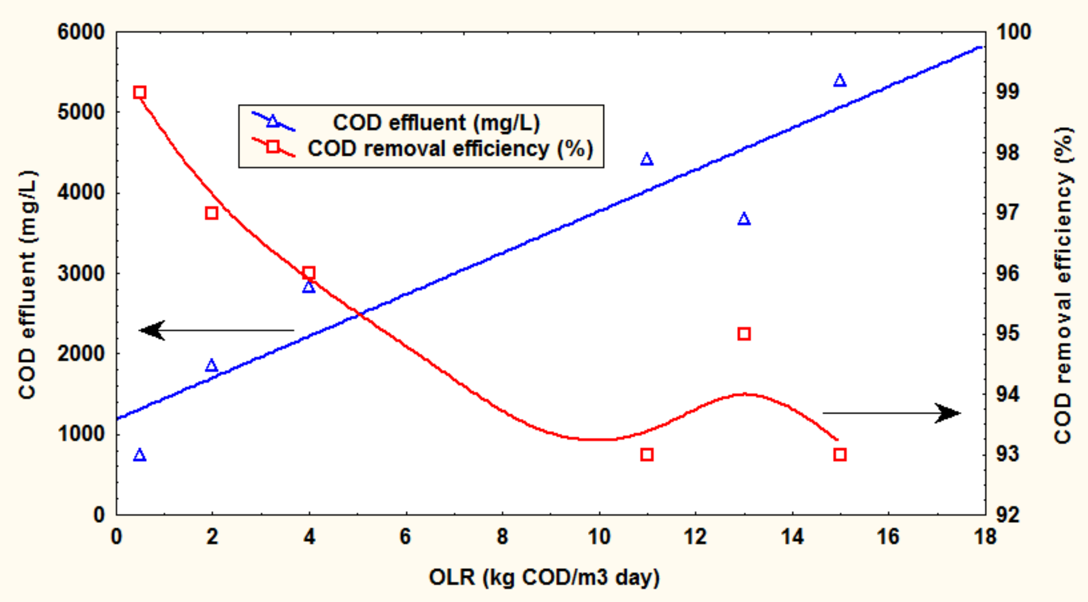

Fig.3: Relationship between OLRs and COD removal efficiency and the effect of OLRs on the effluent COD (straight line)

The hydraulic retention time (HRT) was determined to be a crucial design criterion, particularly for the treatment of POME effluent with concentrated influent COD. Fig.4 shows the percentages of COD removal efficiency by UAMAS at various HRTs. Short HRT values (4days) resulted in poor COD removal efficiency (93%) compared with a high HRT (16 days) that yielded a COD removal of 98.7%.This result was higher than the 85% COD removal observed for POME treatment using anaerobic fluidized bed reactors (Idris et al., 1998),the 91.7-94.2% removal observed for POME treatment using MAS (Fakhru'l Razi et al., 1999), and the 93.6-97.5% removal observed for POME treatment using MAS (Abdurahman et al., 2011). At 35°C, the optimum HRT was found to be 16 days, which gave the highest average COD removal of 98.7%. However, the biogas production was highest for a 16-day HRT and significantly different from that with HRTs of 12, 8, 6, 5, and 4 days. At low HRTs with high OLRs, the organic matter was degraded to volatile fatty acids (VFAs). 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.

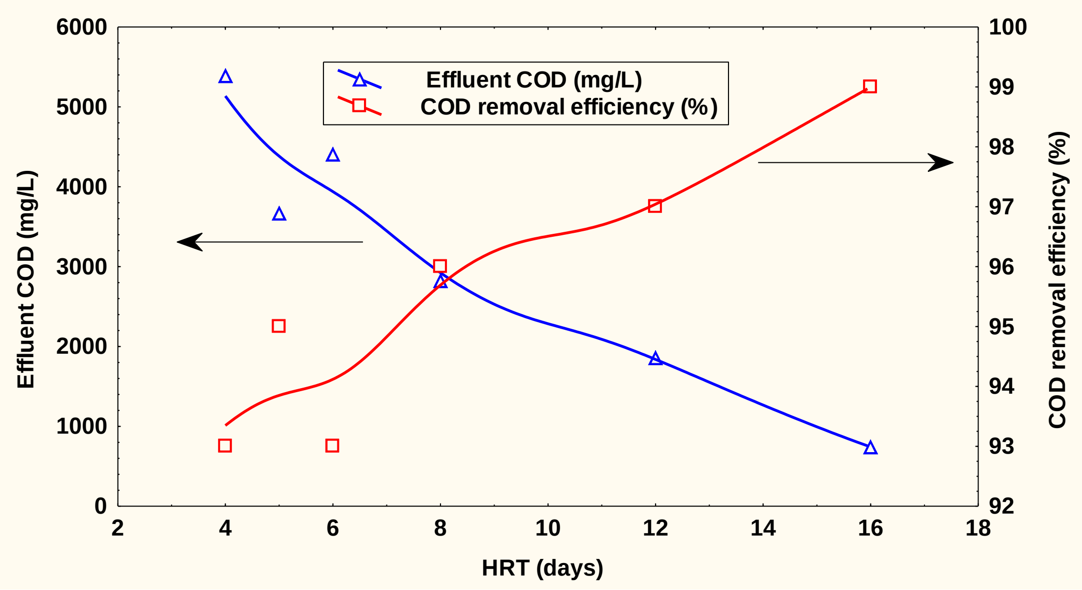

Fig.4: Effect of HRT on the COD removal efficiency and the effluent COD

The three kinetic models fit the data well (R^2> 99%) for the ultrasonic-assisted membrane anaerobic system treating POME, as shown in Figs. 5-7. The Contois and Chen & Hashimoto models performed better, implying that the digester performance depends on the organic loading rates. These two models suggested that the predicted permeate COD concentration (S) is a function of the influent COD concentration (So). In the Monod model, however, S is independent of S_o. The excellent fit of these three models (R^2> 99.4%) suggests that the UAMAS process is capable of handling sustained organic loads between 0.5 and 15.0 kg m^3/d.

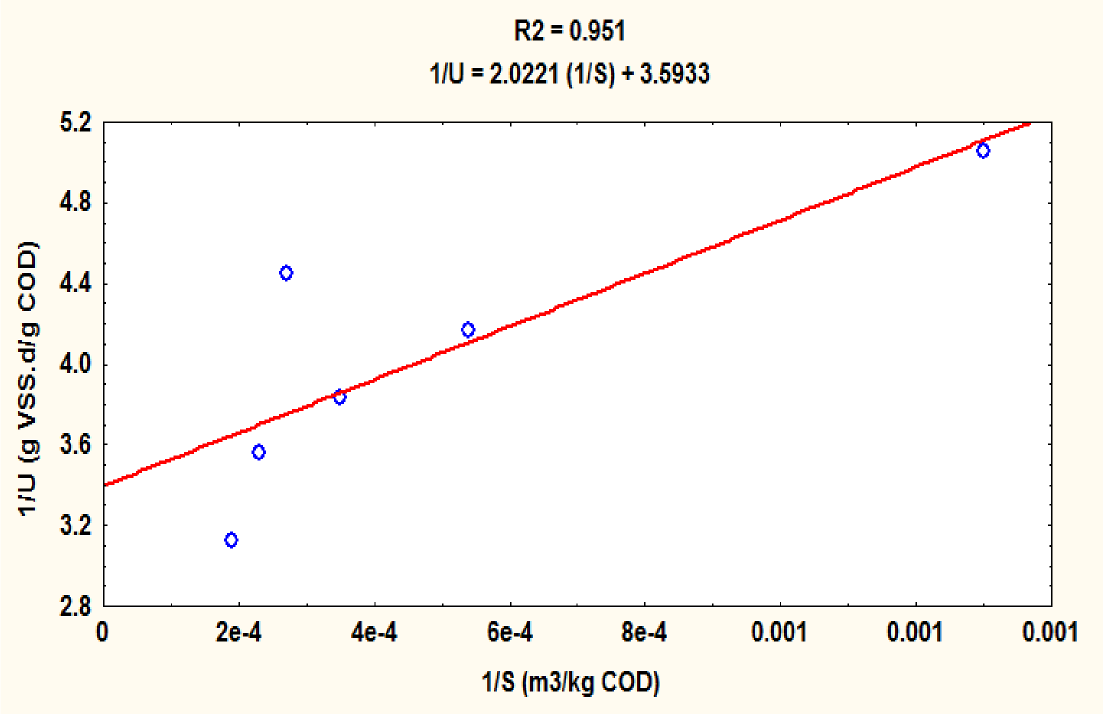

Fig.5. Monod model

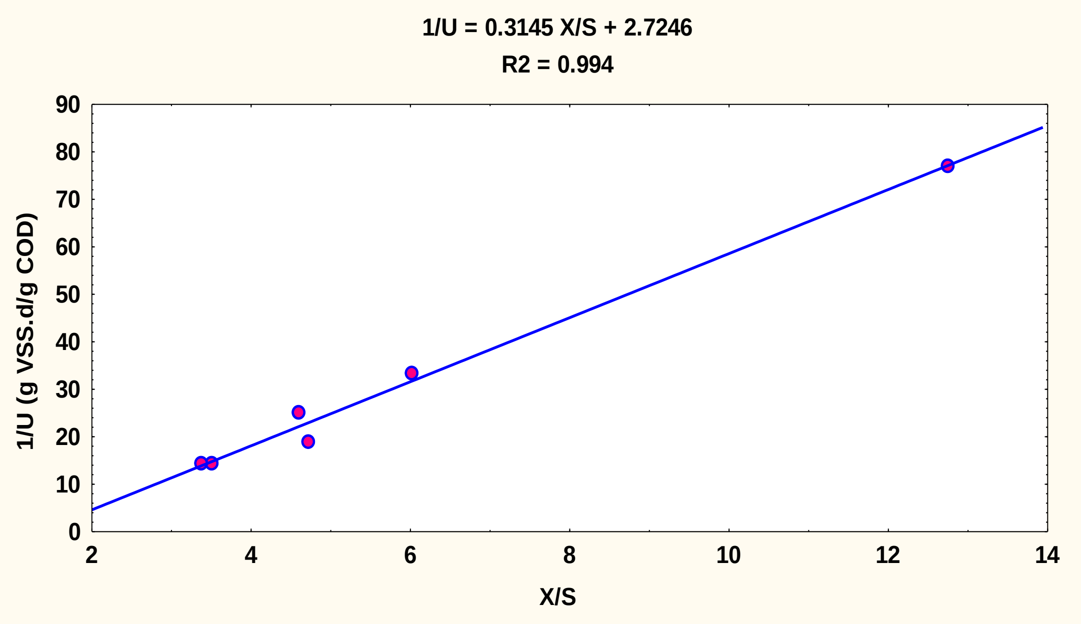

Fig.6. Contois model

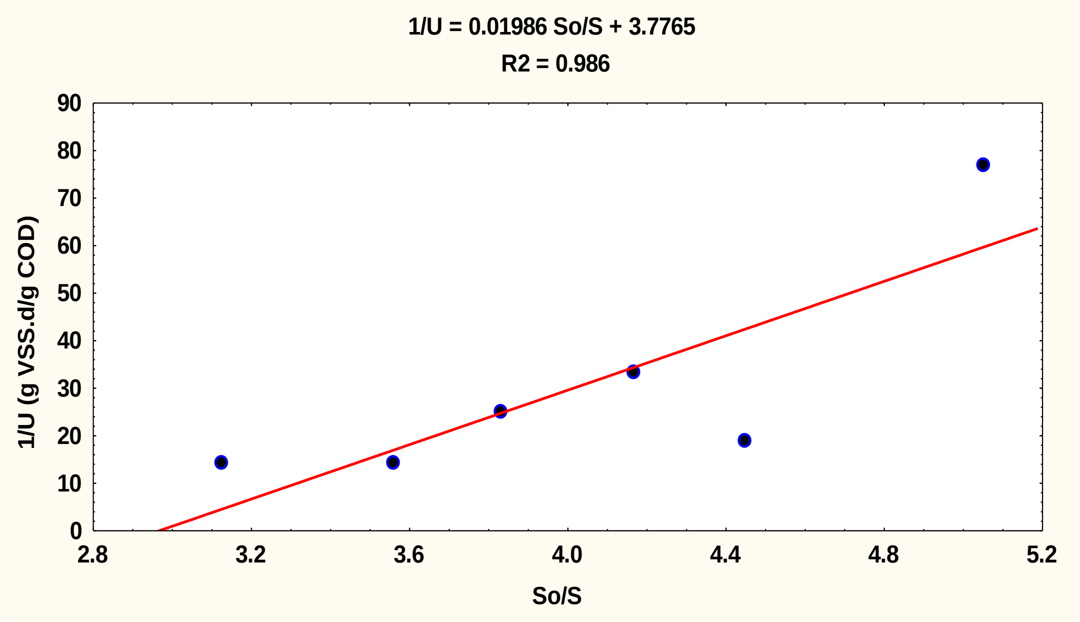

Fig.7. Chen and Hashimoto model

Volatile fatty acids (VFAs) in the influent and effluent were also measured throughout the study. Depending upon the dilution factor, the levels of VFAs in the influent varied between 360 and 1,480 mg/L (Table 3). The measurement of the VFAs indicated that some of the influent COD could be attributed to the VFAs in the effluent, which occurred at concentrations between 402 and 940 mg/L (Fig.4).

B. Determination of the Biokinetic Coefficients

Table 3 shows the six steady-state results obtained under the different experimental conditions studied for UAMAS. The kinetic coefficients were evaluated and are summarized in Table 4. Substrate utilization rates (SUR) and specific substrate utilization rates (SSUR) were plotted against OLRs, as shown in Figure 8. The SURs had generally increased with increasing OLRs, which indicated that the bacterial population in the UAMAS had multiplied (Abdullah et al., 2005). This augmentation of the biomass concentration led to a matching rise in the specific substrate utilization rates, SSURs, signifying that the increasing rate of influent COD fed into the reactor was matched by the rate of COD consumption by the bacteria populations. The biokinetic coefficients of growth yield (Y),the specific micro organic decay rate (b) and the K values were calculated from the slope and intercept, as shown in Figs. 9 and 10. The maximum specific biomass growth rates (μ_{max}) were in the range between 0.261 and 0.482 d^{-1}. All of the kinetic coefficients that were calculated from the three models are summarized in Table 4. The small values of μ_{max} are suggestive of relatively high amounts of biomass in the UMAS (Zinatizadeh et al., 2006). According to (Grady et al., 1980), the values of parameters μ_{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 μ_{max} and K will depend on the substrates.

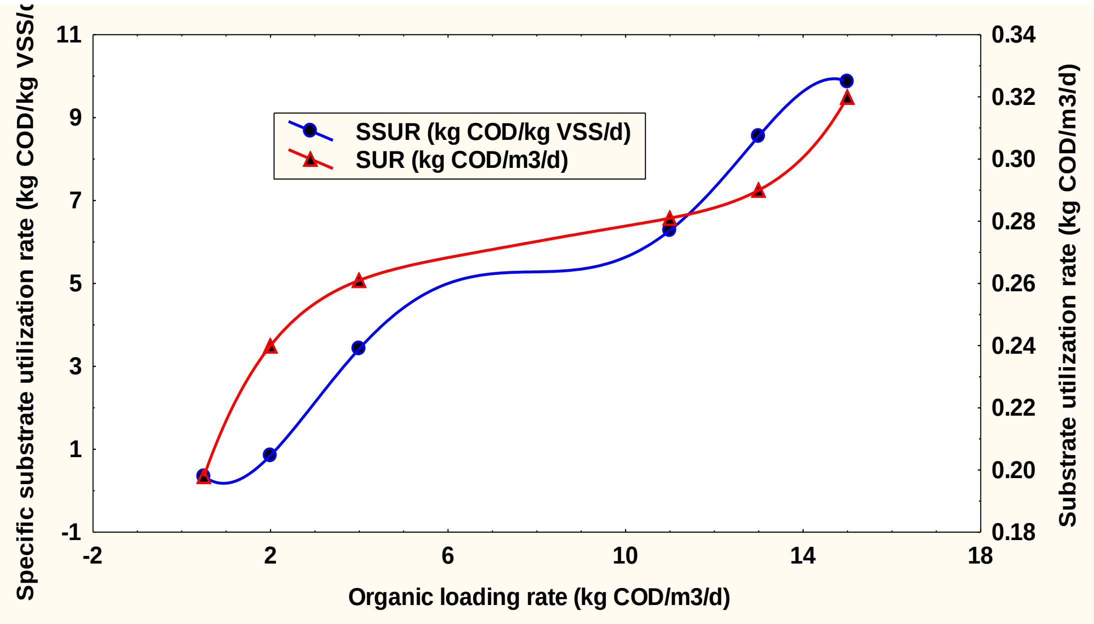

Fig.8. Organic loading rate vs. SUR & SSUR

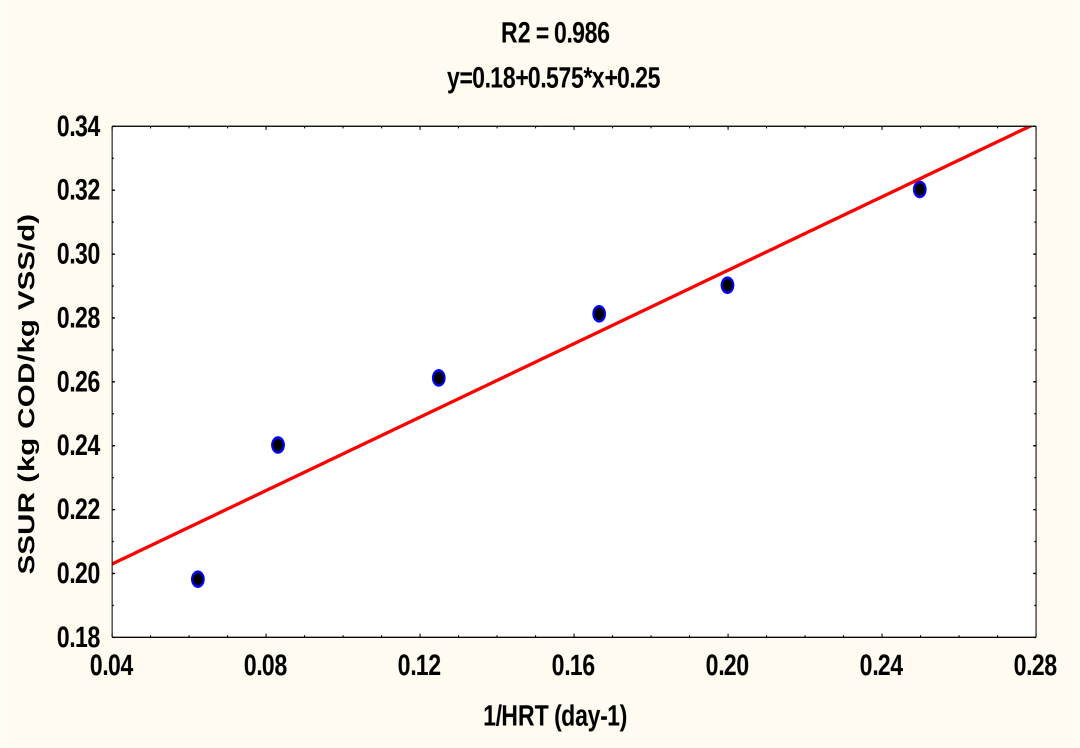

Fig.9. Determination of the growth yield, Y, and the specific biomass decay rate, b

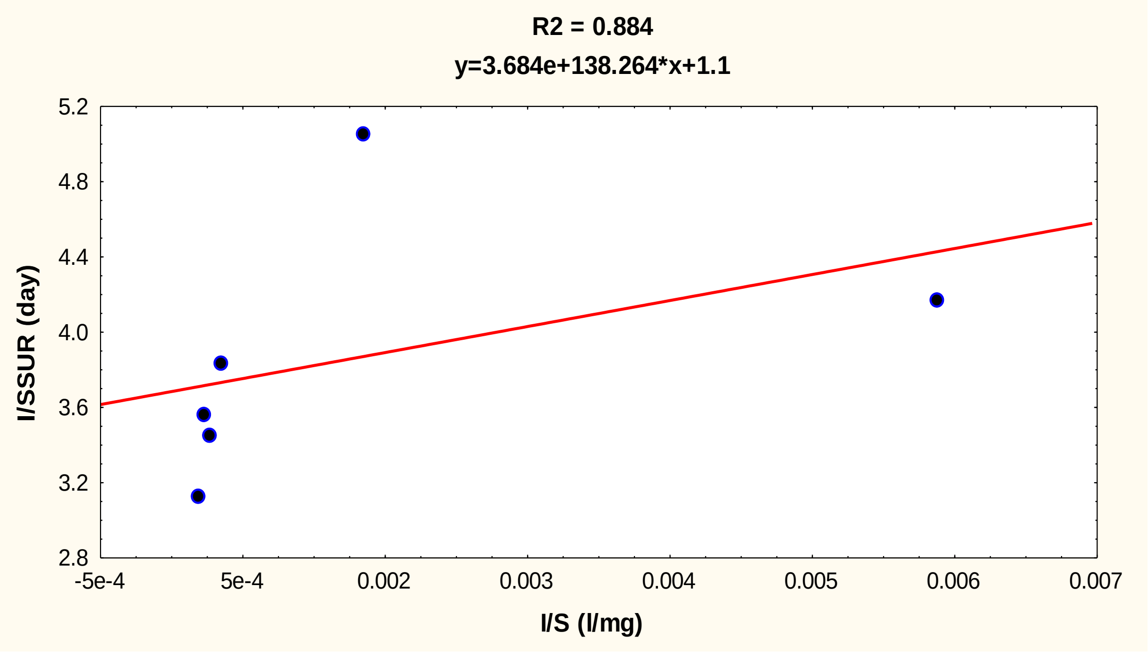

Fig.10. Determination of the maximum specific substrate utilization and the saturation constant, K

IV. GAS PRODUCTION AND COMPOSITION

Many factors must be adequately controlled to ensure the performance of anaerobic digesters and prevent failure. For POME treatment, these factors include pH, mixing, operating temperature, nutrient availability and organic loading rates in 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 that might influence the 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 mechanical mixing and biogas recirculation. Fig. 11 shows the gas production rate and the methane content of the biogas. The methane content generally declined with increasing OLRs. Methane gas contents ranged from 67.8% to 77%, and the methane yield ranged from 0.264 to 0.47 CH_4/g COD/d. The declining methane content may be attributed to the higher organic loading rate, which favors the growth rate of acid-forming bacteria over methanogenic bacteria. Thus, the methane conversion process was adversely affected by reducing the methane content, and this led to the formation of carbon dioxide at a higher rate. The gas production showed an increase from 277.8 to 580 liters per day during the study.

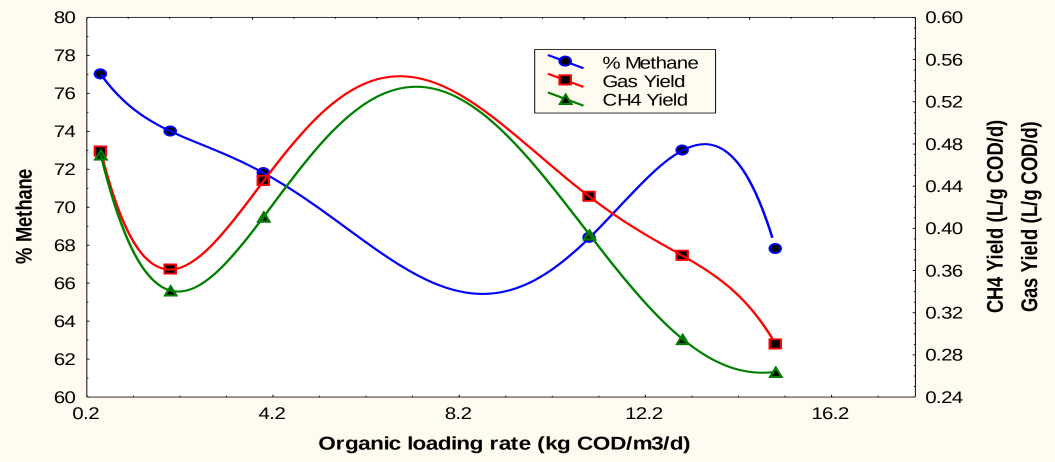

Fig.11. Gas production and methane content

V. CONCLUSION

The UAMAS bioreactor was found to be an improvement over existing techniques and a successful biological treatment process for achieving a high COD removal efficiency in a short period of time (no membrane fouling by introduction of ultrasonication). Palm oil mill effluent wastewater containing between 57,000 mg/L and 77,000mg/L of COD was treated in a 200-L UAMAS operated at 35°C. The best COD removal (98.7%) for POME treatment in a UAMAS reactor has obtained at an OLR of 0.5 kg m^{-3} d^{-1} and an HRT of 16 days. The VFA production in UAMAS and the methane production in UAMAS increased with the increasing OLR. The maximum VFA accumulation of 1480 mg/L was achieved at an OLR of 15 kg COD/m^3/d and an HRT of 4 days in a UAMAS reactor. Nevertheless, the maximum gas production was 580 L/d at an OLR of 15 kg COD/m^3/d. The UAMAS produced a biogas containing 77% methane. The high degree of methanization suggested that most of the soluble and suspended organics in the palm oil mill effluent (POME) wastewater were degraded during treatment in the UAMAS.

APPENDIX

A. Nomenclature

COD : chemical oxygen demand (mg/l)

OLR : organic loading rate (kg/m^3/d)

CUF : cross-flow ultra-filtration membrane

SS : steady state

SUR : substrate utilization rate (kg/m^3/d)

TSS : total suspended solids (mg/l)

MLSS : mixed liquid suspended solids (mg/l)

HRT : hydraulic retention time (day)

SRT : solids retention time (day)

SSUR : Specific substrate utilization rate (kg COD/kg VSS/d)

MAS : Membrane Anaerobic System

UAMAS : Ultrasonic-assisted Membrane Anaerobic System

MLVSS : mixed liquid volatile suspended solid (mg/l)

VSS : volatile suspended solids (mg/l)

MWCO : molecular weight cut-off

BLR : biological loading rate

U = specific substrate utilization rate (SSUR) (g COD/g VSS/d)

S = effluent substrate concentration (mg/l)

So = influent substrate concentration (mg/l)

X = microorganism concentration (mg/l)

$\mu_{\max}$: Maximum specific growth rate (day-1)

K : Maximum substrate utilization rate (COD/gVSS/day)

K_s : Half velocity coefficient (mg COD/l)

X : Microorganism concentration (mg/l)

b = specific microorganism decay rate (day-1)

Y = growth yield coefficient (g VSS/g COD)

T : time

REFERENCES

[1] Borja, R., Banks, C.J. and Sanchez, E. 1996. Anaerobic treatment of palm oil mill Effluent in a two-stage up-flow anaerobic sludge blanket (UASB) system. J. Biotechnol. 45: 125-135.

[2] Singh, G., Huan, L.K., Leng, T. and Kow, D.W. 1999. Oil palm and the environment. SDN. BHD, Kuala Lumpur.

[3] Ahmad, A.L., Ismail, S. and Bhatia, S. 2005. Membrane treatment for palm oil mill Effluent effect of transmembrane pressure cross flow velocity. Desalination. 179:245-255.

[4] Chin, K.K., Lee, S.W. and Mohammed, H.H. 1996. A study of palm oil mill effluent treatment using ponding system. Water Sci Technol. 34 (11): 119-123.

[5] Kimchie, S., Lumbroso, R.E., Geller, Z., Abramovitch, D., Shelef, G. 1988. A integrative Treatment process for piggery wastes based on anaerobic digestion. In: Tilche, A., Rozzi, A. (Eds.), Proceeding of the fifth International Symposium on Anaerobic Digestion. Monduzzi Editore S.P.A., Bologna, Italy, pp. 635-639.

[6] Hobson, P.N., Shaw, B.G., 1973. The anaerobic digestion of wastes from an intensive Pig unit. Water Res. 7, 437-449.

[7] Hobson, P.N., Shaw, B.G., 1974. The bacterial population of piggery waste anaerobic digesters. Water Res. 8, 507-516.

[8] Hobson, P.N., 1981. Anaerobic digestion of animal excreta and other agricultural wastes. Trib. Cebedeau 34 (455), 437-441.

[9] Hobson, P.N., 1992. Treatment of animal wastes and uses of treated residues. Biotechnologies for pollution control and energy. In: Proceedings of the Third Workshop Group on Biogas Production Technologies. CNREE Network on Biomass Production and Conversion for Energy, Braunschweig, Germany, pp. 48-70.

[10] Sanchez, E., Monroy, O., Canizares, R.O., Travieso, L., 1995. Comparative study of piggery waste treatment by upflow sludge beds anaerobic reactors and packed bed reactors. J. Agric. Eng. Res. 62, 71-76.

[11] Baader, W., 1990. Biogas technology and implementation in the Federal Republic of Germany. In: Proceedings of the International Conference on Biogas, Pune, India, January 1990.

[12] Yang, P.Y., Gan, C., 1998. An on-farm swine waste treatment system in Hawaii. Biores. Technol. 65, 21-27.

[13] Parkin, G., Owen, W., 1986. Fundamentals of anaerobic digestion of wastewater sludges. J. Env. Eng. 112 (5), 867-1120.

[14] Monod, J. Growth of bacteria cultures. Annu Rev Microbial. (1949): 3:371-394.

[15] Contois, DE. Kinetics of bacteria growth: relationship between population density and space growth rate of continuous Cultures. J. Gen Microbiol. (1959): 21:40-50.

[16] Chen, Y. R.; A.G Hashimoto. Substrate Utilization Kinetic Model for Biological Treatment Processes, Biotechnol. Bioengn., (1980): 22, 2081-2095.

[17] Fakhru'l-Razi. A. Ultrafiltration membrane separation for anaerobic wastewater treatment. Water.Sci. Technol (1994): 30 (12): 321-327.

[18] Nagano, A.; E. Arikawa., and H. Kobayashi. (1992). The Treatment of liquor wastewater containing high-strength suspended solids by membrane bioreactor system. Wat. Sci Tech., (1992): 26 (3-4), 887-895.

[19] Idris, B.A; A. Al-Mamun. Effect of scale on performance of anaerobic fluidized bed reactor (AFBR) treating palm oil mill effluent, Proc. Fourth International Symposium on Water Management Problems in Agro-Industry, Istanbul, Turkey (1998), pp.206-211.

[20] Fakhru'l-Razi. A; M.J.M.M. Noor. Treatment of palm oil mill effluent (POME) with the membrane anaerobic system (MAS). (1999).Water Sci. Technol. 39 (10-11), 159-163.

[21] Abdullah, A. G.; Liew, Idris. A., Ahmadun. F.R., Baharin, B. S., Emby, F., Noor, M. J. Megat., Mohd. Nour.A.H. A Kinetic study of a membrane anaerobic reactor (MAR) for treatment of sewage sludge. (2005). Desalination 183, 439-445.

[22] Zinatizadeh, A. A. L.; A. R. Mohamed; G. D. Najafpour. Kinetic evaluation of palm oil mill effluent digestion in a high rate up-flow anaerobic sludge fixed film bioreactor. (2006). Process Biochemistry Journal 41, 1038-1046.

[23] Grady, C. P.L.; H. C. Lim. Biological Wastewater Treatment: Theory and Applications. New York. (1980). Macel Dekker Inc.pp. 220-222, 870-876.

[24] Abdurahman, H.N.; Y.M.Rosli.; N.H.Azhari. Development of a membrane anaerobic system (MAS) for palm oil mill effluent (POME) treatment. (2011). Desalination, 266, 208-212.