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Performance of Anaerobic Hybrid and Mixing Reactors in Treating Domestic Wastewater

T. T. Tran[1], A. Nopharatana[2] and P. Chaiprasert[3,*]

[1] Joint Graduate School of Energy and Environment,
King Mongkut's University of Technology Thonburi,
Bangkok 10140, Thailand.

[2] Pilot Plant Development and Training Institute,
King Mongkut's University of Technology Thonburi,
Bangkok 10140, Thailand.

[3] School of Bioresources and Technology,
King Mongkut's University of Technology Thonburi,
Bangkok 10140, Thailand

* Corresponding author: pawinee.cha@kmutt.ac.th

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Abstract : Laboratory-scale anaerobic hybrid (AH) and mixing (MX) reactors of 5.5 l were used to study the treatment of domestic wastewater. Each reactor was seeded with 10 g VSS/l of granular sludge obtained from a full-scale up-flow anaerobic sludge blanket reactor treating soft drink wastewater. Domestic wastewater with 130 mg/l of BOD (350 mg/l of COD) was continuously fed by up-flow to the reactors. During the operating period of 65 days, the OLR in the AH reactor increased from 0.16 to 3.5 g COD/l.d. It was noticed that the minimum contact time for microorganisms and organic substances in terms of treatment efficiency was 4 h of HRT and 0.5 m/h of up-flow velocity. The removal of COD_d and methane production at OLR 2-3.5 g COD/l.d and HRT 4h was approximately 75-77% and 0.3 - 0.6 m^3- gas/m^3-reactor.d, respectively. In the MX reactor, OLR increased from 0.16 to 1.5 g COD/l.d, with decreased HRT from 30.6 to 5.7 h. COD_d and COD_t removal efficiencies were 54% and 46%, respectively, at OLR of 1.5 g COD/l.d (up-flow velocity of 0.29 m/h). The methane production was 0.02 m^3-gas/m^3- reactor.d. Higher biomass washout was found in the MX reactor (95 mgVSS/l) than that in the AH reactor (57 mgVSS/l). Better efficiency with the AH reactor was due to better biomass retention, whereas significant biomass-washout and the breakup of granules caused lower efficiency with the MX reactor.

Keywords: Anaerobic treatment, Domestic wastewater, Hybrid reactor, Mixing reactor.

Introduction

One of the most serious problems facing the world is water pollution. In developing countries, most organic wastes from communities flow directly into the environment, including water resources. In Thailand, urbanization and resultant pollution is one of the principle causes of growing water quantity and quality problems. The urban areas of 10 major provinces, with an estimated combined population of 12.1 million, are currently the focus of water pollution sources. The estimated BOD loading for those provinces is 640 tons/day. Particularly in Bangkok, with a population of 6.1 million in the metropolitan area alone, 325 tons of wastewater is generated daily [1]. For these urban areas, domestic wastewater has become the primary source of water pollution.

Anaerobic digestion is an attractive process for the treatment of low-strength wastewater, as less energy is needed for the process itself and less excess sludge is produced than in aerobic processes [2]. Various kinds of anaerobic processes have been developed during the past decade. Anaerobic hybrid (AH) reactor is the most dominant because it consists of a sludge bed in the lower part and packing media in the upper part, therefore combining the advantages of an up-flow anaerobic sludge blanket (UASB) and anaerobic fixed film (AFF) reactors [2]. The performance of an AH reactor depends on the contact of the wastewater with both the biomass in the sludge bed and the attached biomass in the anaerobic fixed film at the top of the reactor. Additionally, the AFF layer helps in retaining biomass inside the reactor, making it a practical candidate for treating low strength organic wastewater with a high flowrate or feed [3]. However, AH reactors have not been studied much for domestic wastewater treatment in tropical regions. Also the suitable conditions for operation have not yet been well established. The present research is to study and determine the performance of an AH reactor to treat domestic wastewater under the prevailing tropical conditions in Thailand.

One other attractive reactor is the up-flow anaerobic sludge blanket (UASB). However, the treatment of low substrate concentration in the UASB often encounters problems due to the fact that the effective concentration inside the granules can be lower than that of the bulk liquid phase when the consumption of the substrate by bacteria is faster than the transport of substrate into the biofilms. Consequently, the application of UASB to treat domestic wastewater could be unsuitable [3]. The reactor design-related problem concerns the requirement for long retention time of biomass and good wastewater-biomass contact. Both requirements are dependent on the mixing intensity of the bulk liquid phase [4]. For this research, therefore, we modified the UASB by setting a mechanical mixer in the middle of the reactor (MX) to study the performance in treating domestic wastewater.

Materials and Methods

1. Anaerobic Reactors

Anaerobic hybrid (AH) and mixing (MX) reactors were used in this study. A 5.5 l acrylic cylindrical AH reactor (an internal diameter of 9.4 cm and height of 86.5 cm) and a 5.5 l acrylic cylindrical mixing-reactor (an internal diameter of 10 cm and a height of 100 cm) are shown in Figures 1a and 1b, respectively.

2. Starter Seeding

The anaerobic granular sludge used in the experiments was obtained from an industrial scale UASB reactor treating wastewater from a soft drink company. The sludge was acclimatized in domestic wastewater for 45 days before being used for the AH. After 2 months, the granular sludge was recuperated within 2 weeks, and then seeded into the MX reactor. Total amount of 55 g VSS of seed sludge was inoculated into each reactor.

(a) Anaerobic hybrid reactor (b) Anaerobic mixing reactor

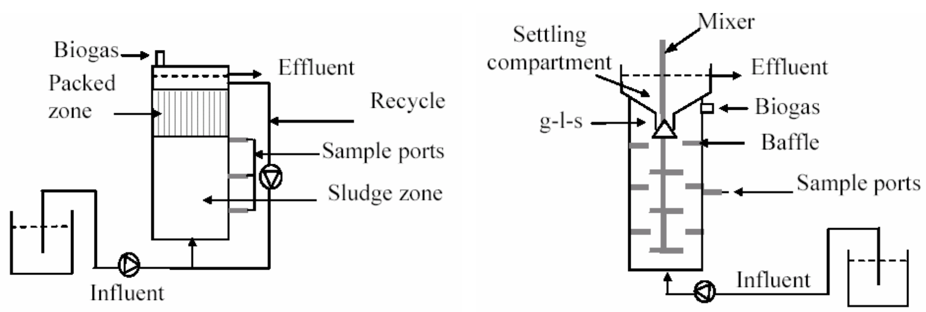


Figure 1. Laboratory AH (a) and MX (b) reactors.

3. Wastewater

The wastewater used in the experiments was domestic wastewater from King Mongkut's University of Technology Thonburi, Bangkhuntien campus. The characteristics of the domestic wastewater are shown in Table 1.

As reported by the wastewater treatment office at Huay Kwang Wastewater Treatment Plant (personal communication, 2003), the average chemical oxygen demand (COD) concentration was about 300-400 mg/l. Wastewater used for this study therefore was adjusted up to 400 mg COD /l by adding 0.1-0.15 g glucose/l for consistency of COD influent concentration.

Table 1. Domestic wastewater characteristics.

Parameters	Range	Mean $\pm$ SD
pH	6.5 – 7.8	7.0 $\pm$ 1.2
Alkalinity (mg $CaCO_3$/ml)	120 - 380	221 $\pm$ 100
TVA (mg/l)	30 - 70	51 $\pm$ 10
COD (mg/l)	170 - 500	325 $\pm$ 70
BOD_5 (mg/l)	130 - 155	130 $\pm$ 15
SS (mg/l)	75 - 210	140 $\pm$ 75
VSS (mg/l)	50 - 170	120 $\pm$ 60
TKN (mg N/l)	35 - 50	40 $\pm$ 10
Phosphorus (mg P/l)	4 - 7	6 $\pm$ 2

4. Operation

Both reactors were started at an organic loading rate (OLR) of 0.16 gCOD/l.d and a hydraulic retention time (HRT) of 33 h. Following this, the OLR was gradually increased together with reduced HRT. The AH reactor performance was observed intensively during the experiment of 64 days in order to obtain the suitable OLR and HRT. Meanwhile, the observation was carried out for MX reactor to determine the performance of mixing intensity on the reactor at rotation speed of 28 rounds per minute (rpm). The experiment was carried out until the COD removal efficiency dropped to less than 50%.

5. Sampling and Analysis

Influent, effluent and sample-port samples from both reactors were collected and tested every day for pH, total volatile acid (TVA), alkalinity, total COD (COD_t) and dissolved COD (COD_d). Influent and effluent samples were collected on the minimum basis of once a week for total kjedahl nitrogen (TKN), phosphorus, total suspended solids (TSS) and volatile suspended solid (VSS). GF filter paper with a pore size of 1.2 μm was used for determination of VSS and COD_d. The analyses were carried out according to APHA-standard methods for the examination of water and wastewater (2001). Using the previous work of Soto *et al.* (1993) [5] and Orhan *et al.* (2001) [6] as a reference, the microbial activities were tested under anaerobic conditions in 120 ml glass bottles sealed with rubber septum retained with screw caps. Each bottle contained 100 ml of mineral medium (pH 7) and a known amount of sludge VSS. The following substrates were used to determine microbial activities:

i) Glucose for acidogenic activity.
ii) Acetic acid for methanogenic activity.

Sludge volume index (SVI) was measured for the initial granules and the remaining granules at the end of the experiment in the mixing reactor. The settle ability characteristics were measured in a 100 ml cylindrical column. The sludge front height variation versus time was monitored for 30 min. The SVI (ml/g) was defined as:

$$SVI = \frac{H_{30}}{H_0 C_0}$$

where C_0 is TSS (g/ml), H_0 and H_{30} is the sludge front height (cm) at $t = 0$ and $t = 30$ minutes [7].

Results and Discussion

1. The Operating Conditions of AH and MX

The operating conditions of the AH reactor during the experiment (Figure 2a) was step increased organic loading rate (OLR) from 0.16 to 3.5 g COD/l.d with flowrate increased from 4.08 to 42.62 l/d. For the first 55 days, the AH was fed continuously with domestic wastewater at a strength of around 350 mg COD/l to give an OLR of approximately 2.7 g COD/l.d. During this period, the hydraulic retention times (HRT) were reduced from 33 h to 3.1 h. Following this, the OLR was increased to 3.5 g COD/l.d by increasing the influent COD concentration up to 600 mg/l and 33 l/d of feeding flow rate, while 4 h of HRT was maintained. The liquid recirculation rate and total flow rate in the AH were 52 l/d and 85 l/d, respectively, resulting in an up-flow velocity of 0.5 m/h.

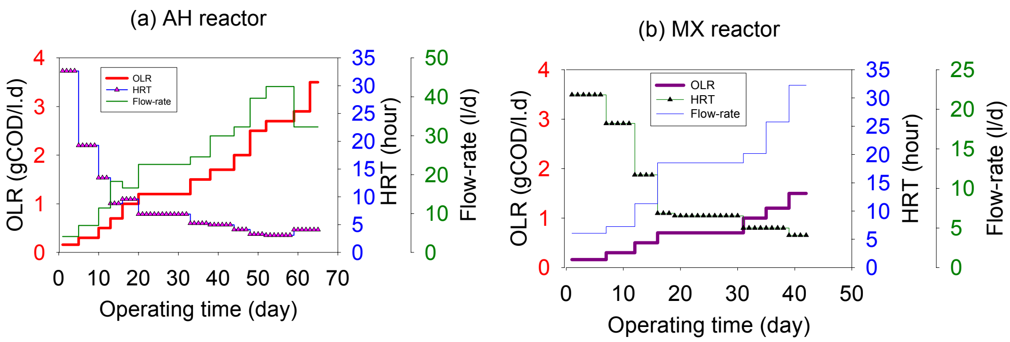


Figure 2. The operating conditions in AH (a) and MX (b) reactors.

During the start-up period of the MX, the raw domestic wastewater was fed continuously. The concentration of influent was 360 $\pm$ 80 mg/l. The OLR of the MX reactor was gradually increased from 0.16 g COD/l.d to 1.5 g COD/l.d by decreasing HRT from 30.6 h to 5.7 h (Figure 2b). Maximum feeding flow rate was 23 l/d, corresponding to the up-flow velocity of 0.29 m/h. Instead of recirculation, mixing was provided by a mechanical mixer, which was set to operate constantly at 28 rpm.

Due to the fact that pH, TVA and alkalinity are the principal environmental factors which affect the rate of methanogenesis in anaerobic microbial conversion, these three factors were therefore measured every day during the experiment. The results are shown in Figure 3. pH values during the operation were neutral (6.7 $\pm$ 0.3) which is the optimum range for anaerobic bacteria. The buffer capacity of both systems was controlled by adding bicarbonate solution in the amount of 0.15 - 0.2 g/l. The ratio of TVA to alkalinity inside both systems was maintained at the optimum value of less than 0.4.

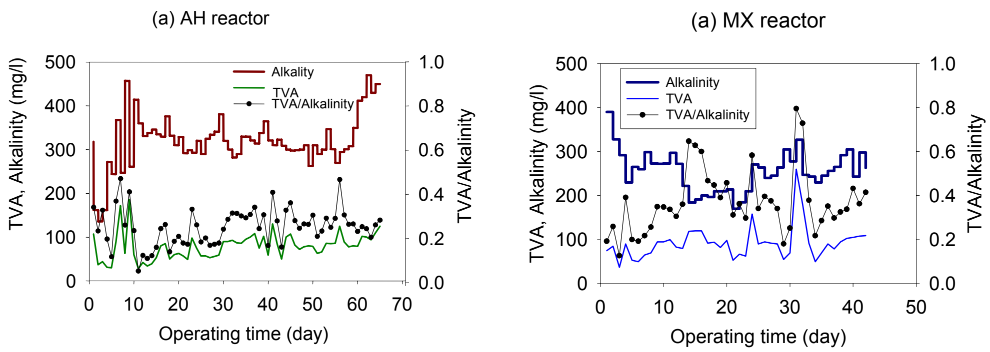


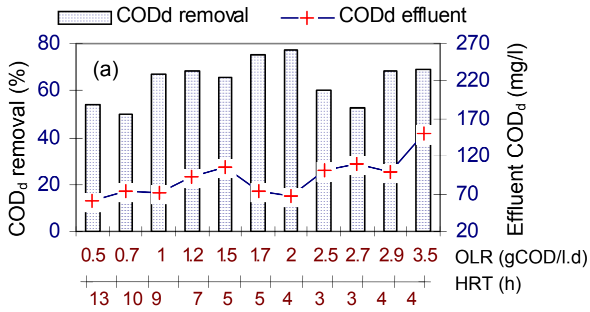
Figure 3. Alkalinity, TVA, and TVA/alkalinity inside AH (a) and MX (b) reactors.

2. Performances of Anaerobic Hybrid Reactor

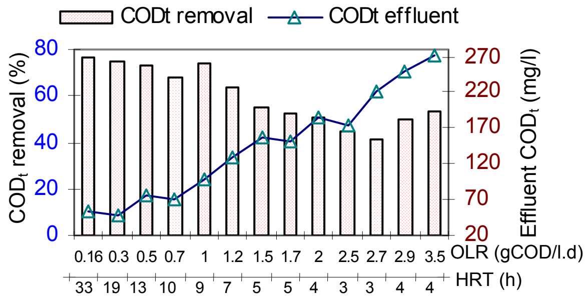
Removal of Organic Matter

Overall organic matter removal in terms of COD_t and COD_d removal efficiencies were studied in relation to the OLR, HRT and flow rate. The treatment performance in terms of COD_d and COD_t removal are shown in Figures 4a and 4b, respectively.

During the study, COD_d removal efficiency eventually increased to the expected value (Figure 4a). The maximum COD_d removal efficiency of 77 ± 1% was achieved at the OLR of 2 g COD/l.d. The significant improvement of COD_d removal could be the result of the increased SMA and biomass population. Afterward, this efficiency decreased dramatically as the HRT sank below 4 h. The efficiency reduced by almost 25% for COD_d and percentage of COD_t removal was also down to 10%. One factor that may have negatively affected treatment efficiency in this case, could have resulted from the short contact time between microorganisms and organic food.



(a)



(b)

Figure 4. The treatment efficiencies in terms of COD_d (a) and COD_t (b) in AH reactor.

In Figure 4b, as OLR increased to 1 g COD/l.d, the COD_t, removal efficiency was not drastically affected. COD_t removal then decreased progressively, while OLR increased up to 2.7 g COD/l.d, with the HRT lowering down to 3 h. The COD_t removal declined from 75 ± 3% to 41 ± 1%. This feature could be attributed to the less contact time between insoluble organic matter and microorganisms which was due to the step increase in flow rate that incurred a sharp reduction of HRT, resulting in low efficiency of hydrolytic fermentative microorganisms in degrading insoluble organic substances. This was probably the reason for this decrease of the COD_t removal efficiency.

Regarding performance of the reactor, OLR was increased to 3.5 g COD/l.d at constant HRT of 4 h, which was the shortest HRT satisfying COD_t removal efficiency above 50%. COD removal in terms of treatment efficiency showed good performance. The effluent quality in terms of COD_t and COD_d concentration was 270 ± 30 and 130 ± 5 mg/l, respectively. The improvement efficiencies to 54% ± 5 and 75% ± 1 for COD_t and COD_d demonstrated that AH could treat domestic wastewater at OLR of 3.5 g COD/l.d and HRT of 4 h with 75% of COD_d removal.

As can be seen from Table 2, during the experiment the biomass washout was less than 48 ± 17 mg/l. The average VSS and TSS removal efficiencies of the system were 61 % and 78 % at OLR of 3.5 g COD/l.d, with an up-flow velocity of 0.5 m/h, demonstrated that the media made a major contribution in retaining biomass inside the reactor. As a result, the efficiencies of the system were improved.

COD Removal in Sludge Zone and Packed Zone

The AH reactor consists of two main parts, namely the packed zone and the sludge zone (Figure 1a). The efficiencies of each part of the reactor were studied at the operating condition of OLR 2 g COD/l.d and HRT of 4 h. As presented in Figure 5, the majority of organic substances and TSS were removed at the sludge zone and remaining organic substances were also removed in the packed zone.

Table 2. Concentration of TSS and VSS in influent and effluent of AH reactor.

OLR (gCOD/l)		0.16	0.3	0.5	1	1.2	1.5	1.7	2	2.5	2.7	2.9	3.5
TSS (mg/l)	Influent	110	140	120	183	150	180	228	172	172	190	283	284
	Effluent	85	30	35	75	52	43	50	63	73	45	53	63
VSS (mg/l)	Influent	85	109	110	158	142	120	113	140	129	135	123	158
	Effluent	65	21	20	40	30.8	40	50	57	63	67	62	63

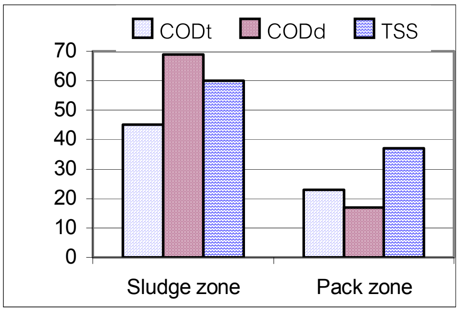


Figure 5. Efficiencies of TSS, COD_d and COD_t in packed zone and sludge zone of AH reactor.

The percentage of COD_d removed at the sludge zone was 69 ± 10%. However, relatively low COD_d was removed at the packed zone (17 ± 3%), due to the low concentration of organic matter remaining in the upper zone. 23 and 37% of COD_t and TSS were removed at the packed zone, respectively. It could be inferred from this experiment that the media in the packed zone played a very important role as a filter and to entrap cells in order to decrease biomass washout from the AH reactor, as well as being the support zone for organic matter removal and increased efficiency.

Biogas Production

Apart from organic matter removal efficiencies, biogas production is another parameter that can be used to evaluate the performance of the anaerobic system. In this experiment, CH_4 content increased along with increasing OLR and achieved 61 ± 2 % at OLR of 2 g COD/l.d (Figure 6).

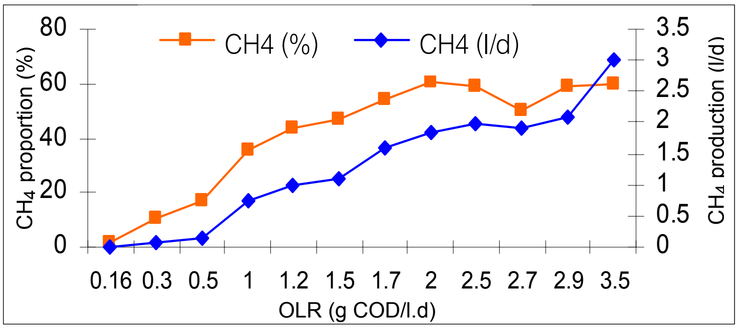


Figure 6. CH_4 production against organic loading rate in AH reactor.

Methane production refers only to the fraction of COD_t that was removed. Theoretically, 1 kg of COD removed produces 0.5 m^3 of biogas composition (Frostell, 1985), and it was based on this ratio that the volume of CH_4 was calculated. Methane production increased from 6.25 ml/d (0.001 m^3-gas/m^3-reactor.d) to 1.9 l/d (0.34 m^3- gas/m^3- reactor.d) from OLR of 1.6 to 2.7 g COD/l.d. A maximum value of 3.1 l CH_4/d was achieved at an OLR of 3.5 g COD/l.d. The suitable operating condition of the AH reactor was based mainly on the COD removal efficiency. It was therefore set at OLR of 2 gCOD/l.d, at which 1.8 l CH_4/d (0.33 m^3- gas/m^3- reactor.d) was produced. These results accord with those found in the experiments of Elimitwalli *et al.,* (1999) [8] treating domestic wastewater at HRT of 8 h, which was reported at 1.2 l/d (0.32 m^3- gas/m^3-reactor.d).

3. Performance of Anaerobic Mixing Reactor

Due to the fact that 28 rpm is the rotation speed that provided a quiet settling compartment (observation result), this speed was applied constantly during the experiment. The efficiency step fell from 74 $\pm$ 9 % to 54 $\pm$ 16 % for COD_d and from 64 $\pm$ 2 % to 46 $\pm$ 7 % for COD_t, while OLR increased from 0.16 to 1.5 g COD/l.d (Figure 7). Compared to the AH reactor, the efficiencies of the MX were relatively low. It is assumed that the mixing intensity of the mechanical mixer at rotation speed of 28 rpm in this experiment had a negative effect on the granules. As cited in [9], it was also found in the experiment of De Man (1986) that the UASB combined mechanical mixer could only be used properly if the right combination of rotation speed and superficial liquid velocity is applied.

Concerning the restrictive factors of the mixer, the SVI values were measured to compare the settle ability characteristics between the original granules and those at the end of the experiment in the MX. SVI of the initial seed was 8.26 ml/g, while at the end it was 14.3 ml/g. The low SVI of the original granule indicated good sedimentation characteristics and high biomass concentration, whereas the higher SVI value of the bulk sludge at the end of the experiment reflected less settling ability. From our observations, it was easy to recognize the smaller size of the granules after 48 days compared to the original ones.

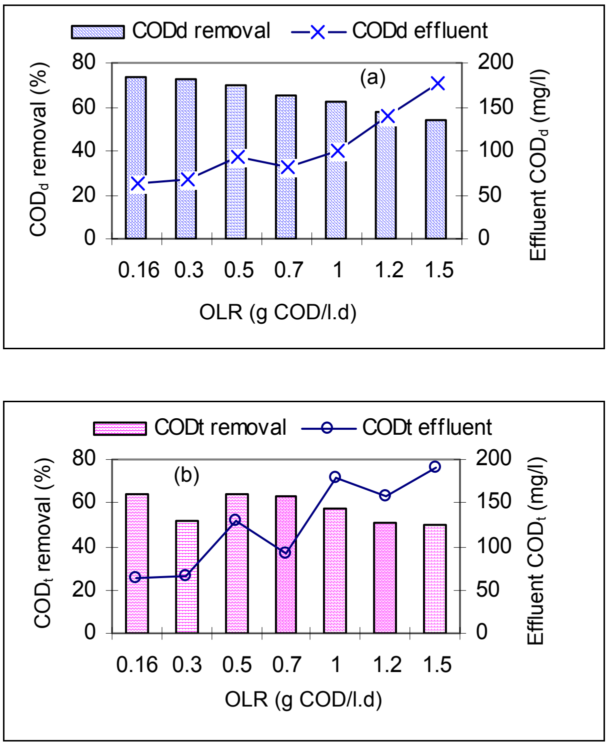


Figure 7. The treatment efficiencies in terms of COD_d (a) and COD_t (b) in MX reactor.

As a result of this higher SVI, another serious problem that occurred in the MX was an unacceptable amount of washout of sludge. As can be seen from Figure 8, biomass washout from the MX increased with an increasing OLR. At the OLR of 1.5 g COD/l.d, giving the up-flow velocity of 0.29 m/h, it was 94 mgVSS/l. The biomass washout was comprised of non-degradable volatile suspended solids and the biomass of the broken granules. This probably was the main reason for the lower OLR that can be treated in a MX reactor.

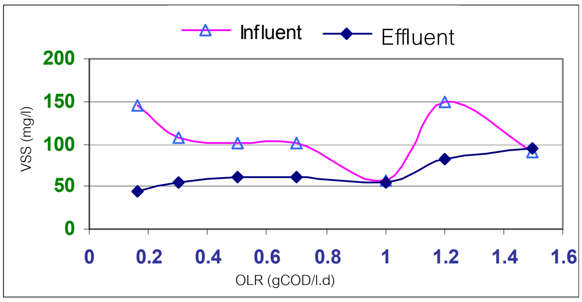


Figure 8. VSS in influent and effluent of MX reactor.

4. Microbial Activities and Biomass

Although both reactors were inoculated with the same source of seed, the improvement of the microbial activities (acetic acid and glucose used as substrates) and the increase in the biomass population were different.

The initial activities in the AH using glucose and acetic acid as substrate were 0.0118 and 0.017 g COD-CH_4/g VSS.d, respectively. At the OLR of 3.5 g COD/l.d (after 65 days), the specific methanogenic activities (SMA) of suspended biomass using acetic acid increased to 0.09 g COD-CH_4/g VSS.d. Additionally, the microbial activities of suspended biomass using glucose also increased to 0.03 g COD-CH_4/g VSS.d, while the attached biomass showed a higher value of SMA (0.18 g COD-CH_4/g VSS.d), compared to the suspended biomass of 0.09 g COD-CH_4/g VSS.d (Table 3).

Table 3. Change in volume and SMA of biomass inside the AH reactor.

Operating day	SMA ($g\ COD\text{-}CH_4\ g\ VSS.d$)		Biomass (gVSS/reactor)		
	Suspended	Attached	Suspended	Attached	Total
0	0.01	-	55 ± 3	0	55 ± 3
21	-	-	46 ± 2	0.47 ± 0.07	46 ± 2
65	0.09	0.18	56 ± 4	0.95 ± 0.14	57 ± 7

Compared to previous studies, higher activity of biomass in terms of gram COD removed per gram initial VSS was achieved in this study. In the experiment of Elmitwalli *et al.,* (1999, 2002) [2, 8], the AH reactor removed about 0.0089 and 0.00748 g COD/g initial VSS, but it was much higher in this experiment with 0.02 g COD/g initial VSS.

Apart from the SMA, the change in biomass population was also considered. After 15 days, granules at the bottom of the AH reactor were removed unintentionally. Thus, after 21 days suspended biomass was reduced (Table 3). The insignificant increase in the amount of attached biomass probably could be attributed to the very low strength of wastewater and low substrate in the upper part of the reactor.

Table 4. Change in volume and microbial activity of biomass inside the MX reactor.

Operating day	Microbial activities ($g\ COD\text{-}CH_4/g\ VSS.d$)		Biomass (gVSS/reactor)
	Using glucose as substrate	Using acetic acid as substrate	
0	-	0.003	55 ± 3
21	0.01	0.004	-
42	0.03	0.015	58 ± 2

As shown in Table 4, after 42 days at which the OLR was 1.5 g COD/l.d, the SMA in the MX increased from 0.003 to 0.015 g COD-CH_4/g VSS.d. After 21 days (from the 21st day to the 42nd day), microbial activity using glucose as substrate increased three times, from 0.01 to 0.03 g COD-CH_4/g VSS.d. Meanwhile, the SMA was improved almost 4 times, from 0.004 to 0.015 g COD-CH_4/g VSS.d.

The change in biomass population was also taken into account. Due to the large amount of biomass washout, at the end of the experiment total biomass increased only 3 g VSS inside the reactor, from 55 ± 3 to 58 ± 2 g VSS.

Conclusions

The AH reactor investigated in the present study represents an efficient treatment process for domestic wastewater at ambient tropical temperatures (25-30°C). With the average influent COD concentration of less than 400 mg/l, at the OLR of 2 g COD/l.d and HRT of 4 h, the efficiencies for COD_d and COD_t were 77% and 51% respectively. At this operating condition, a flow rate was applied at 85 l/d, which includes 52 l/d for recirculation and 33 l/d for feeding. The system also performed well in terms of the increase of the SMA of suspended biomass. After 2 months, the SMA increased almost 10 times compared to the initial run.

Despite treating the same wastewater source, the MX reactor was not as successful in terms of operation as the AH unit. The rotation speed of 28 rpm was too high, which had a negative effect on the granules, resulting in an increase of biomass washout. Compare to the AH reactor, it was more difficult to maintain biomass inside the MX reactor. In the other words, the media inside the AH reactor probably worked better than the gas-liquid-solid separator in the MX reactor in terms of cell entrapment.

These results revealed that the anaerobic treatment of domestic wastewater (COD less than 400 mg/l) in an AH reactor is a feasible option in tropical regions. Conversely, the application of an MX reactor to treat low strength wastewater needs further study to ascertain the optimum rotation speed and the appropriate adjustments required to maintain biomass inside the system.

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