Effect of organic loading rate (OLR) on modified anaerobic baffled reactor (MABR) performance

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Abstract
The performance of a Modified Anaerobic Baffled Reactor (MABR) treating synthetic wastewater at different Organic Loading Rate (OLR) was investigated. The MABR was seeded with anaerobic sludge taken from a local municipal wastewater treatment plant and fed continuously with glucose at an OLR of 0.258, 0.787 and 2.471 kg COD m^{-3} d^{-1} at a Hydraulic Retention Time (HRT) of 4 days. Results showed that 99.7% Chemical Oxygen Demand (COD) removal was achieved during the OLR of 0.258 kg COD m^{-3} d^{-1}. However, when the OLR was increased to 0.787 kg COD m^{-3} d^{-1}, a minor decrease in the COD removal efficiency (95%) was noted. Further increase of the OLR to 2.471 kg COD m^{-3} d^{-1} caused the reactor performance to deteriorate dramatically in a COD removal efficiency of 39.5%. Biogas yield was evaluated for the reactor system and followed similar decreasing trend (0.542, 0.524 and 0.214 l $g^{-1}COD_{destroyed}$ for the different OLRs respectively). There were no significant different in the pH profiles (6.71 – 7.01) during the first two OLRs (0.258 and 0.787 kg COD m^{-3} d^{-1}). However, during the final OLR (2.471 kg COD m^{-3} d^{-1}) the pH profile in MABR dropped to significantly as low as 4.01. Similar trend was also observed in the volatile acids (VA) profile where higher values (2880 mg/L) were found at highest OLR. The poor performance of the MABR at high OLR signifies that the microorganisms could not metabolise the organic substance and probably need more time for digestion.

Keywords
Modified anaerobic baffled reactor (MABR); effluent circulation, organic loading rate; synthetic wastewater

INTRODUCTION

Wastewater treatment engineering nowadays focuses on fulfilling these requirements; a) uncomplicated design, b) minimal construction and maintenance cost, and c) superior treatment success (Feng et al., 2008). Successful application of anaerobic technology for the treatment of industrial wastewaters is critically dependent on the development and the use of high rate anaerobic bioreactors. Among the high-rate anaerobic reactors, anaerobic baffled reactor (ABR) can be considered as one of the most convenient anaerobic treatment system. Apart of treating domestic wastewater, ABRs were extensively used in the treatment of recalcitrant wastewater such as palm oil mill effluent wastewater, swine wastes, pulp and paper mill black liquors, azo dyes containing wastewater, landfill leachate, synthetic tannery wastewater containing sulfate and chromium (III), treating whisky distillery wastewater, nitrogen containing wastewaters, sulfate containing wastewaters, textile dye wastewater, p-nitrophenol containing wastewaters, and brewery wastewater (Cui et al., 2014).

ABR can be described as a series of up-flow anaerobic sludge blanket (UASB) but requires no special granule formation for its operation. This is done by the narrow down-flow and the wide up-flow inside each compartment of the ABR (Grover et al., 1999). Series of vertical baffles forces the wastewater to flow under and over them as it passes from an inlet to outlet. Bacteria within the reactor gently rise and settle due to flow characteristics and gas production in each of its compartment. Some bacteria move horizontally down the reactor at relatively slow rate. Its design ensures contact of biomass with substrates without the need to use any mechanical mixing.

Wastewater can come into intimate contact with a large amount of active biomass as it passes through ABR while the effluent remains relatively free of biological solids. This configuration result in high Chemical Oxygen Demand (COD) removal. ABR is significantly able to separate acidogenesis and methanogenesis longitudinally down the reactor, allowing different bacterial groups to develop under most favourable conditions (Barber and Stuckey, 1999). The reactor is better than other bioreactors in terms of long sludge retention time (SRT), good confrontation to organic shock loading, its exclusive capability to separate phases of anaerobic microbial activity, retention of biomass without media or a solid-settling chamber, and also extremely stable to hydraulic shock loading too (Hu et al., 2009).

In the current study, we have modified the ABR reactor with the inclusion of several baffles in each compartment of the reactor system. The Modified Anaerobic Baffled Reactor (MABR) is an enhancement of the existing ABR where each compartment was further divided by slanted baffles to encourage mixing within each compartment, and within each compartment down-comer and up-comer regions were created. In reactor operation, increment of the Organic Loading Rate (OLR) is one of the major causes that initiate unsteadiness to the anaerobic utilization; which is primarily due to the sensitivity of the anaerobic microorganism to organic excess (Kundu et al., 2013). Therefore, this study aims to observe the effect of different OLR to the MABR system.

MATERIALS AND METHODS

Modified Anaerobic Baffled Reactor (MABR)

The MABR was a rectangular box consists of four identical Plexiglas compartments with a total active volume of 28 litres (4 compartments of 7 litres). The operational set-up, the flow diagram and the reactor design are presented in Figure 1. Each compartment was further divided by slanted (45^o) baffles to encourage mixing within each compartment, and within each compartment down-comer and up-comer regions were created. This provided effective mixing and contact between the wastewater and biomass at the base of each up-comer. The passage of liquid from one compartment to another was through an opening measuring 10 mm x 50 mm located about 23 mm from the top of each compartment. The outlet of MABR was connected to a plastic U-tube to control the level of wastewater and to trap the solids. Gas production was monitored separately for each compartment using an optical gas-bubble counter having a measurement range of 0-1.5 l/hr and precision within ±1%. Each compartment was installed with a heater, and the temperature was maintained at 37°C. A digital temperature probe located in each compartment provided the constant operation temperature. Peristaltic pumps (Longer Pump BT100-2J) were used to control the influent feed rate to the first compartment of the MABR.

Seed sludge and substrate

The reactor was seeded with anaerobic digested sewage sludge (Bunus sewage treatment plant, Kuala Lumpur). The Total Solids (TS) and total volatile solids (TVS) were 30100 mg/l and 9525 mg/l respectively. As for the substrate, glucose was used in this study with the ratio of macronutrient deficiency correction is selected as COD: N: P = 250:5:1.

Reactor operation

This study was carried out after the MABR was started successfully and operated for the HRT studies (data not provided). The MABR was set to a constant HRT of 4 days, and the effluents were recycled as feed by the ratio of 2:1 (effluents flow: feed flow). For this study, three different OLRs were tested where each of the OLR was operated with four feeding cycle. Only the last three cycles for each OLR were then been taken samples of and analyzed. The first feed cycle sampling were neglected due to the adaptation of the microorganism inside the MABR to the new organic loading condition. The study takes the total of 48 days to be completed with 16 days each for different OLR. Table 1 shows the reactor operating condition during the treatment process. The reactor was seeded with anaerobic digested sewage sludge (Bunus Sewage Treatment Plant, Kuala Lumpur). The Total Solids (TS) and total volatile solids (TVS) were 30100 mg/l and 9525 mg/l respectively. As for the substrate, glucose was used in this study with the ratio of macronutrient deficiency correction is selected as COD: N: P = 250:5:1.

Sampling and Analysis

Supernatant liquor, gas and sludge samples were taken separately from each compartment. In addition, gas production rate was determined using an optical bubble counter. Samples were analysed for every end of feed cycle (each feed cycle followed the operation HRT). COD, pH, alkalinity, volatile acids (VA), suspended solids (SS), and volatile suspended solids (VSS) were conducted according to Standard Method (APHA, 2012).

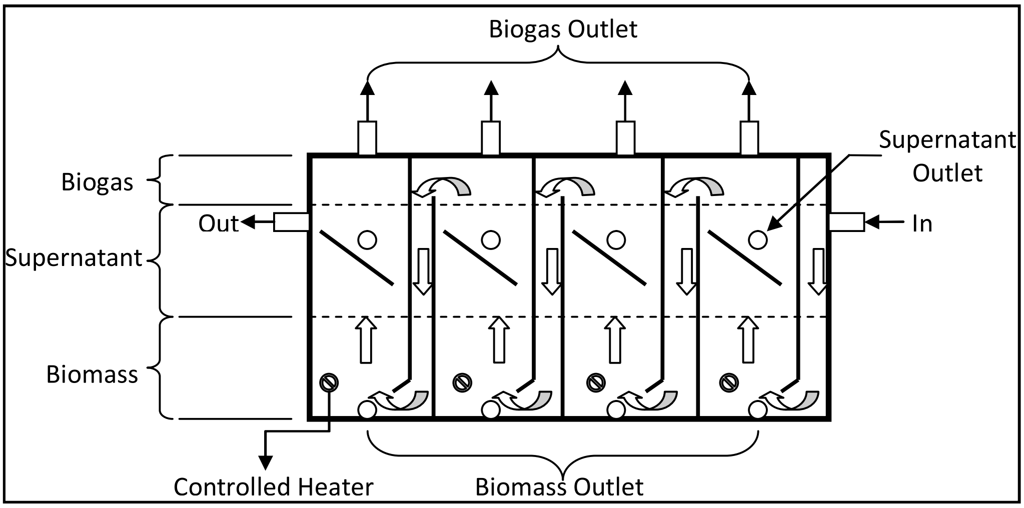

Figure 1. Design and flow diagram of MABR system.

Table 1. Reactor operating conditions during the effect of OLR study.

HRT (d)	COD feed (average) (mg/l)	OLR (average) ($kgCODm^{-3}d^{-1}$)	Operation day
4	1032	0.258	1
4	3148	0.787	17
4	9884	2.471	33

RESULTS AND DISCUSSION

COD Removal

Figure 2 shows the COD removal profile and the fractional contribution of all the compartments in the MABR system treating synthetic wastewater. The total COD removal efficiency was 99.7% when the reactor was operated at an OLR of 0.258 $kgCODm^{-3}d^{-1}$. However, when the OLR was increased slightly to 0.787 $kgCODm^{-3}d^{-1}$, a minor reduction of the COD was observed (95%). A further increase of the OLR to 2.471 $kgCODm^{-3}d^{-1}$, resulted in a dramatic reduction of the COD removal efficiency to 39.5%. The drastic increase of the OLR caused a dramatic decrease in the MABR overall COD reduction. This complies with other effects of OLR studies in anaerobic reactors (Borja (1995). The fractional contribution of COD removal by each compartment of the MABR shows similar trends for all the OLRs studied with the order of C1>C2>C3>C4 which is a normal pattern for anaerobic bioreactors that have different compartments or stages (Alkarimiah et al. 2011). During the OLR of 0.258 $kgCODm^{-3}d^{-1}$, the average COD removal efficiency in C1 was 89.8%, with other compartments (C2, C3, and C4) contributed less than 10%. When the OLR was increased to 0.787 $kgCODm^{-3}d^{-1}$, the average COD removal efficiency in C1 decreased to 43.5%, and the excess organic loading was successfully distributed in C2, with an average COD removal efficiency of 33.2%. The remaining compartments (C3 and C4) contributed less than 10% of the total COD removal. On the other hand, at an OLR of 2.471 $kgCODm^{-3}d^{-1}$ the average COD removal efficiency in C1 falls below 20%, with C2, C3 and C4 contributed less than 10%.

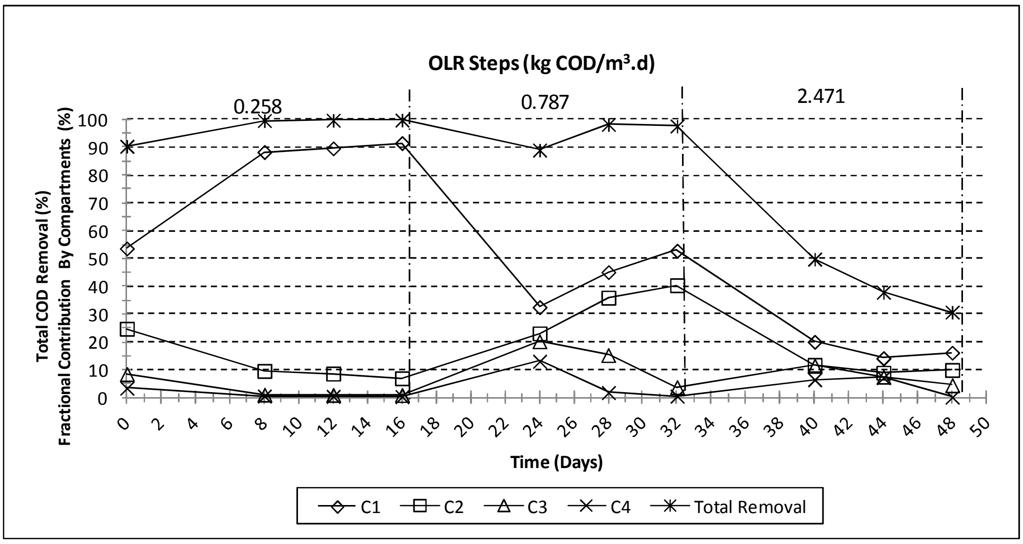

Figure 2. Total COD reduction (%) of MABR and fractional contribution (%) to the total COD reduction by each compartment at different OLR.

pH

Figure 3 showed the pH profile across the MABR system when the OLR was gradually increased. It can be seen that the profile follows the order of C1<C2<C3<C4, which is a common pattern in ABRs system. However, no significant different in the pH profiles was observed in all the compartments, due to the effect of effluent circulation. It is known that in ABR system, the front compartments were populated mostly with the fast growing acidogens (Zhang et al., 2009). In the later compartments, the slow growing methanogens were predominated, and this causes the difference in the pH profile across the reactor system. However, due to the effluent recirculation more methanogens were introduced in the initial compartments of the reactor, and this caused the

pH values for each compartment to be quite similar. During the OLR of 0.258 kgCODm^{-3}d^{-1} the pH in C4 was quite stable with an average value of 6.78. A slight decrease in the pH profile was observed at OLR of 0.787kgCODm^{-3}d^{-1}, probably due to the adaptation of the microorganism to the new organic loading condition. A pH of 7.01 in C4 signifies that the reactor could adapt to this OLR. However, further increase of the OLR to 2.471 kgCODm^{-3}d^{-1} resulted in a sudden drop in the pH profile to 4 and 5. This acidic condition is not suitable for the anaerobic digestion and proof that the MABR system could not withstand the high OLR (Wang et al., 2005). At elevated OLR, the organic substances were not well metabolized by the anaerobic bacteria and more production of VFA's leads to the lower level of pH.

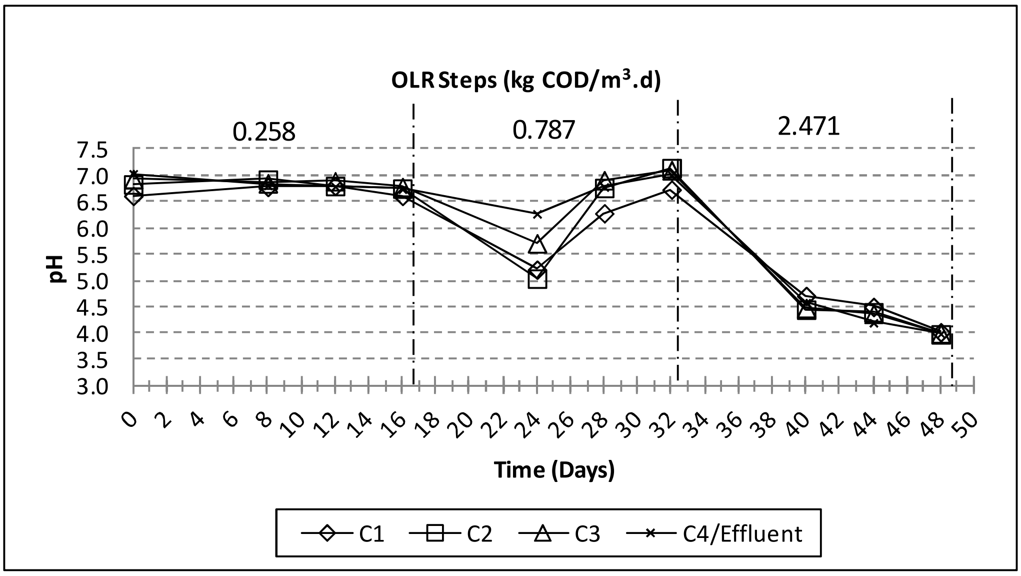

Figure 3. pH profile in each compartment of MABR at different OLR.

Volatile Acid (VA)

Volatile Fatty Acids (VFAs) can be used as a tool to evaluate anaerobic reactor performance. The more VFAs being utilized inside the reactor, the better the reactor performances is. According to Damasceno et al. (2007), total Volatile Acid (TVA) of lower than 150 mg/l in an anaerobic reactor indicates that the reactor was operating in a stable condition. During the degradation process of glucose in an anaerobic reactor, VFA of Acetic (VA) is the primary VFA that occurs, hence the importance to evaluate its degradation (Jeong et al., 2008). In general, if the pH of the reactor system is high, the VA should be lower, and in the current study, this profile was observed clearly (Figure 3 and 4). During the OLR of 0.258 kgCODm^{-3}d^{-1}, the average VA was lower than 150mg/l HOAc, confirming stable reactor performance. A high VA was noted in C1 and C2 of the reactor system when the OLR was increased to 0.787 kgCODm^{-3}d^{-1}. However, a stable VA was observed in C3 and C4, similar to the previous OLR, suggesting that stable reactor performance in these two compartments. An increase of the OLR to 2.471 kgCODm^{-3}d^{-1} demonstrated sudden increase in the VA (2800 mg/l HOAc) in all the compartments of the MABR system, confirming accumulation of VA during this high OLR (Rana et al., 2014).

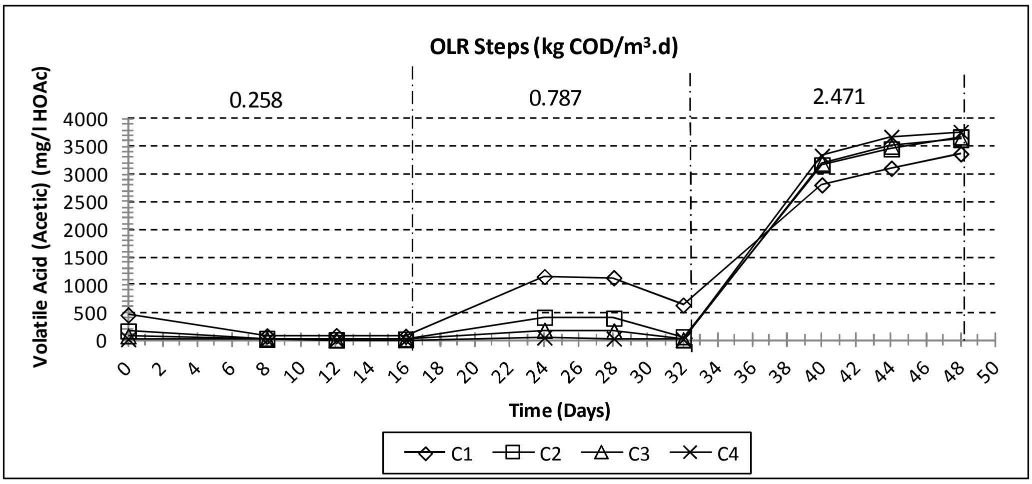

Figure 4. VA profile at each stage of MABR at different OLR.

Solid Washout and Biogas Yield

Both solid washout and biogas production can be an obvious sign of an anaerobic reactor performance. Figure 5 shows the VSS and biogas profile in each compartment of the MABR system at different OLR. At OLR of 0.258 kgCODm^{-3}d^{-1}, low VSS was observed in C4 (20mg/l) of the reactor system confirming low solid wash out from the reactor. During this period of OLR, the average biogas yield was 0.542 l/g-^{1} COD $_{\text{Destroyed}}$. A slight increase in the VSS was observed at OLR of 0.787 kgCODm^{-3}d^{-1} with C4 having an average VSS of 43 mg/l. For this second OLR, the average biogas yield decreased slightly to 0.514 l/g-^{1} COD $_{\text{Destroyed}}$. In spite of this, a much different situation was noted during the OLR of 2.471 kgCODm^{-3}d^{-1} where an average VSS of 200 mg/l was evaluated in C4, suggesting high solid washout from the reactor system. The average biogas yield during this period was 0.401 l/g-^{1} COD $_{\text{Destroyed}}$, confirming low reactor performance. These results could be compared to the COD removal profile where the biogas yield was high when high COD removal efficiency in the reactor.

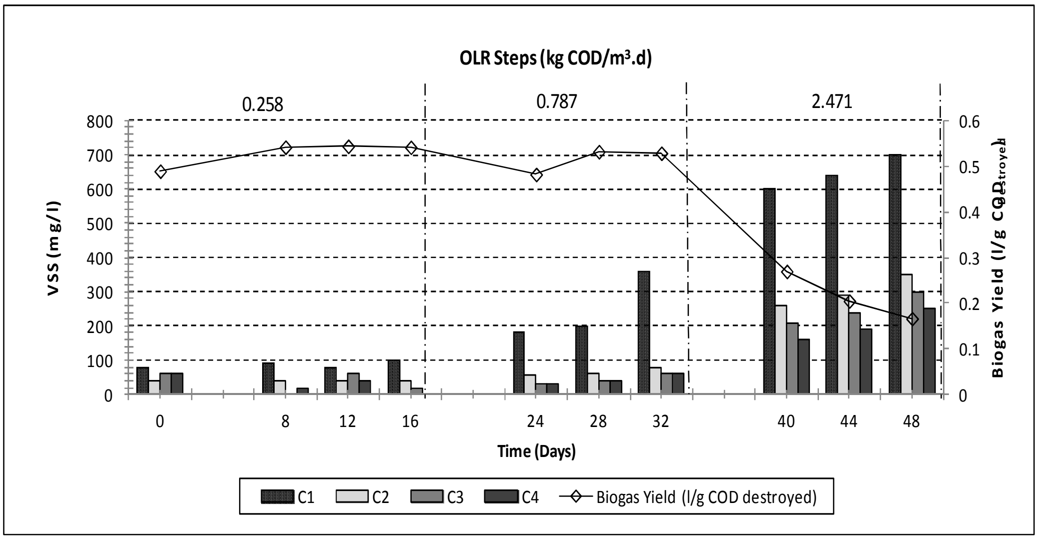

Figure 5. Sludge washout and biogas yield of MABR at different OLR.

CONCLUSIONS

It can be concluded that the reactor could not perform well at OLR of 2.471 kg COD m^{-3} d^{-1} probably due to the high organic substances which could not be metabolised by the microorganisms. At lower OLR (0.258 and 0.787 kg COD m^{-3} d^{-1}) the metabolism was high where the microorganisms can digest the organic substances. In consideration of all the parameters that have been studied in this experiment, the results clearly show that the reactor could be operated efficiently at an OLR of 0.787 $kgCODm^{-3}d^{-1}$.

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