Performance study of compartment-wise behaviour of modified anaerobic hybrid baffled (MAHB) reactor

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A modified anaerobic hybrid baffled (MAHB) reactor was used to study its suitability for treatment of recycled paper mill effluent (RPME) and to establish the relationship between operational parameters and reactor design. The present study highlights the configuration of MAHB reactor, its start up, the effect of hydraulic retention time (HRT) on treatment efficiency and performance evaluation of MAHB reactor while treating RPME wastewater. The start-up process was carried out at HRT of 4 days. The MAHB reactor was run with constant feeding COD of 3000 mg L−1 and HRT of 1, 3, 5 and 7 days. A start-up of 28 days was required for the MAHB reactor. Reactor performance evaluation of the compartment-wise profiles was carried out at different HRTs. Low pH of 6 – 6.2 and high volatile fatty acid concentration of 90 – 168 mg L−1 were recorded in the first compartment for each HRT due to acidogenesis and acetogenesis processes. System pH and alkalinity showed an increment profile while VFA concentration decreased as it moves from compartment 1 to 5. Biogas volume was high ( 6.56 L at higher HRT) with a decreasing pattern of methane content from 96 – 35 % from compartment 1 to 5. Contrarily, at low HRT of 1 day, although the biogas volume was lower, the methane content showed an increment of 42 – 64 %. The results indicate that MAHB reactor was successfully operated in treating RPME wastewater.

Keywords: modified anaerobic hybrid baffled (MAHB) reactor, anaerobic digestion process, recycled paper mill effluent (RPME).

INTRODUCTION

The application of anaerobic technology in treating industrial wastewaters highly depends on the performance of the reactor used. Thompson et al. [1] reported that about 80% COD removal efficiency was constantly achieved using anaerobic treatment, while Arshad and Hashim [2] obtained 58 % methane content with total organic carbon (TOC) and lignin removal efficiencies of 56 % and 51 %, respectively, at an OLR of 4.5 g TOC L−1per day and HRT of 18 h in treating the paper mill effluent. Another approach of treating paper mill effluent is by integrating two or more methods to take advantages of both processes. Shaw et al. [3] showed that a combination of aerobic reactor followed by anaerobic reactor is able to remove 66% of toxicity. From the survey, anaerobic baffled reactor (ABR) was one of the favorable systems in treating industrial waste. Although ABR were extensively used to treat different types of industrial waste, literature survey shows that there is lack of data on the anaerobic treatment of recycled paper mill effluent (RPME) wastewater by a novel modified anaerobic hybrid baffled (MAHB) reactor.

This novel MAHB reactor consists of five compartments which are a combination of regular suspended growth and fixed biofilm systems. The most significant advantage of this design is the ability to nearly perfectly realize the staged multi-phase anaerobic theory, allowing different bacterial groups to develop under more favorable conditions, low costs and without the associated control problems. The MAHB bioreactor combines suspended growth and attached growth processes in a single reactor to take advantage of both biomass types [1][4].

With a less expensive, simple configuration and a background of successful performance and having been judged to perform well for industrial wastewater of conventional ABR, this hybrid novel MAHB reactor was assumed to give better performance in terms of COD removal and methane production. Keeping this as an observation, the present study was carried out to investigate the
performance of the MAHB reactor treating RPME at different HRT in relationship of the compartmentalization behavior. The present study was also aimed to integrate various aspects like (a) performance of the reactor and compartment-wise variation of various parameters and (b) stable operation for a quite extended period in terms of COD removal efficiency, biogas production and performance of each different compartment of the MAHB reactor.

METHODS

Reactor configuration

A laboratory-scale modified anaerobic hybrid baffled (MAHB) reactor was fabricated using polypropylene. It consisted of 5 chambers (CH1–CH5) of equal size and volume, connected in series as shown in Fig 1.

![Fig. 1. Schematic diagram of 58 L capacity bench-scale continuous feed MAHB reactor.](image)

The whole unit is square in shape with length to width ratio (l/w) of 3.61 and l × b × h dimensions of 795 mm × 220 mm × 300 mm. To collect the biogas produced, five separate gas manifolds were provided and the biogas was finally led to the gas collection cum measurement assembly. The individual chamber was divided by a hanging baffle into five compartments, i.e., downcomer and upcomer. The volume of the downcomer was half that of the upcomer and the bottom portion of the baffle separating the two compartments was inclined at 45° and was stretched up to the center of the upcomer. The total volume of the modified anaerobic hybrid baffled (MAHB) reactor was 65 L with a net working volume of 58 L. The volume of the individual set of 5 compartments (CH1–CH5) was 11.6 L. The net volumes of the downcomer and the upcomer were 3.86 L and 7.74 L, respectively.

Feed wastewater flow pattern

The wastewater was collected from Muda Paper Mill Bhd, Bandar Tasek Mutiara, Penang, Malaysia and refrigerated at 4°C. Prior to analysis, the samples were warmed to room temperature (25±2°C). The collected samples were analysed for the required parameters such as pH, total dissolved solids (TDS), volatile suspended solids (VSS), total suspended solids (TSS), total solids (TS), alkalinity, ammonia, biological oxygen demand (BOD) and dissolved oxygen (DO) according to the Standard Methods of Analysis of Water and Wastewater [5] and were intermittently mixed to feed the reactor with a consistent quality.

Table 1. Physicochemical characteristics of recycled paper mill effluent.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.36</td>
</tr>
<tr>
<td>Alkalinity (mg L⁻¹ as CaCO₃)</td>
<td>94</td>
</tr>
<tr>
<td>TSS (mg L⁻¹)</td>
<td>645</td>
</tr>
<tr>
<td>VSS (mg L⁻¹)</td>
<td>850</td>
</tr>
<tr>
<td>TDS (mg L⁻¹)</td>
<td>3345</td>
</tr>
<tr>
<td>TS (mg L⁻¹)</td>
<td>5320</td>
</tr>
<tr>
<td>BOD₅ (mg L⁻¹)</td>
<td>669</td>
</tr>
<tr>
<td>COD (mg L⁻¹)</td>
<td>4328</td>
</tr>
<tr>
<td>VFA (mg L⁻¹)</td>
<td>501</td>
</tr>
<tr>
<td>Ammonia (mg L⁻¹)</td>
<td>0.4</td>
</tr>
<tr>
<td>DO (mg L⁻¹)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The wastewater was fed to the reactor with the help of a variable speed peristaltic pump. The MAHB reactor was operated at various hydraulic retention times (HRTs) by varying the flowrate of influent wastewater (Qinf), thereby varying the organic loading rate (OLR). The average composition of RPME wastewater is shown in Table 1. The wastewater flows from the downcomer to the upcomer, within an individual chamber through the sludge bed formed at the bottom of the individual chambers. After receiving treatment in the particular chamber, wastewater enters the next chamber from the top. Due to the specific design and positioning of the baffle, the wastewater is evenly distributed in the upcomer and the vertical upflow velocity (Vup) could be significantly reduced. The treated effluent was collected from the outlet of CH5. The reactor was kept in a temperature controlled chamber maintained at 35°C.
MAHB reactor was monitored every two days for COD, pH and biogas produced while volatile fatty acids (VFA) and alkalinity were measured weekly. Samples were taken for analysis from all five compartments of MAHB at HRT of 1, 3, 5 and 7 days as the system achieved its steady state. Biogas composition was determined using Shimadzu gas chromatograph with a flame ionization detector (GC-FID) with a propack N column. Carrier gas was helium set at a flow rate of 50 mL min$^{-1}$, column temperature of 28°C, detector temperature of 38°C and injector temperature of 128°C. VFAs were measured using esterification methods. TriPLICATE samples were collected for each parameter reading to increase the precision of the results, and only the average value was reported throughout this study. Conventional parameters such as pH and alkalinity were measured according to the Standard Methods [5] while COD was measured using the spectrophotometer DR-2800 according to the reactor digestion method [6].

**RESULTS AND DISCUSSION**

**Start-up of MAHB reactor**

In this study, the MAHB reactor was filled with seed sludge taken form Malpom and allowed to rest for 12 days. Then, after 15 days, feeding of the RPME wastewater was resumed at a flow rate of 14.5 L per day at HRT of 4 days with a very low organic loading rate (OLR) of 0.1963 g CODL$^{-1}$per day. The resumed wastewater feeding helped the development of the sludge bed at the bottom of the individual compartments of the MAHB reactor. The acclimatization curve for determination of the start-up period is shown in Fig. 2.

![Fig. 2. Acclimatization curve for determination of the start-up period of MAHB reactor](image)

S-shaped acclimatization curve with three distinct phases was demonstrated during the acclimatization period. During phase I of the acclimatization period of 16 days (from day 12 until day 17), the observed SS and COD removal may be attributed to the interception of organics in the sludge bed. During the second phase of 5 days (17th – 21st day), a significant gain of up to 90% was observed in COD removal. The curve indicated that the COD reduction efficiency was related to the period of acclimatization. The steady state of increase in efficiency signified the adequate quantum of biosludge accumulation in the reactor [7]. The third phase of acclimatization lasted for 8 days (from day 21 until day 28). Last four consecutive observations revealed consistent COD removal efficiency of 85% and specific biogas yield of 0.25 L CH$_4$ per day. At this stage, the MAHB reactor was counted as matured or acclimatized. Therefore, the start-up period for the MAHB reactor was adjudicated to be 28 days. From previous studies, Lettinga et al. [8] took about 84 days for the start-up, whereas Kalogo et al. [9] required a period of 140 days of self-inoculated UASB. The anaerobic contact filter was started-up by feeding cow dung slurry and sewage sludge by Vijayaraghavan and Ramanujan [10] who needed 160 days to complete the start-up operation. The analysis of the requirements of start-up periods showed that the time consumed by the MAHB reactor was favorably comparable.

**Performance evaluation of MAHB reactor**

**Compartment-wise profile during HRT variation**

Performance of MAHB reactor was subjected to four changes in HRT by increasing the feed flow rate. Figure 3 illustrates the COD removal efficiency and VFA concentration at different compartments of MAHB reactor. From the obtained results, it is seen that at each different HRT of 1, 3, 5 and 7 days, the COD removal efficiency shows an increasing pattern from compartment 1 to 5. COD removal efficiency was low at HRT of 1 day with an average of 50 – 92% from compartment 1 to 5.

![Fig. 3. COD removal and VFA concentration variation of each compartment of the MAHB reactor. Compartments are numbered in the sequence of flow pattern from compartment 1 to 5 at steady state.](image)
From the obtained results it follows that at each different HRT of 1, 3, 5 and 7 days, the COD removal efficiency shows an increasing pattern from compartment 1 to 5. COD removal efficiency was low at HRT of 1 day with an average of 50 – 92% from compartment 1 to 5.

As the HRT was increased, the COD removal efficiency started to increase to a range of 79 – 94%, 80 – 97% and 84 – 96% for HRT of 3, 5 and 7 days, respectively. This result shows that the retention times play an important role for the microbes inside to digest the substrate. Similar patterns were recorded by Krishna et al.[11], which indicates that COD removal efficiency of each compartment increased in the sequence of flow pattern from compartment 1 to 5. It is essential to note that as the HRT increased, the compartment-wise COD removal efficiency increased. In compartment 1, as the HRT increased, significant increase of COD removal efficiency was recorded. This shows that most of the organic matter was removed in the first compartment [12] while treating low-strength RPME wastewater using MAHB reactor.

In addition, VFA concentration tends to decrease with high HRT. The maximum VFA concentration achieved was 167 mg L\(^{-1}\) in compartment 1 at HRT 1. As the wastewater moves from compartment 1 to 5, the concentrations of VFA decreased for all HRTs. This is a result of the conversion of VFA into final products such as hydrogen, carbon dioxide and acetate for methane production.

The VFA profile demonstrated that the main biochemical activities occurring in the first few compartments are hydrolysis and acidogenesis [13, 14]. For the last few compartments, methanogenesis appeared to be dominant. These observations implied that the MAHB reactor promoted a systematic selection in the different compartments in such a manner as to bring out phase separation. Wang et al. [15] also reported that the total VFA concentration decreased along the reactor from compartment 2 while treating high-strength wastewater using conventional ABR.

**System pH and alkalinity for different compartments**

The pH and alkalinity profiles for the MAHB reactor at different HRTs are shown in Figure 4. Slightly lower pH was noted in compartment 1 for each different HRT in a range of 6.1 to 6.3. As the wastewater moves towards the later compartments, a gradual increase in pH was achieved. The pH was found close to 7 (6.3 – 6.55) at the rear end of the MAHB reactor. Similar patterns were also recorded by Dama et al. [16] who reported that earlier compartments had a lower pH as acidogenesis and acetogenesis take place in those compartments. It was also observed that during every shift to the next HRT, the pH in the first two chambers dropped rapidly, while other chambers (CH3–CH5) were found to be less affected.

This indicated that accumulation of fatty acids was restricted up to CH3 only, unaffecting the methanogenesis occurring in the rest of the chambers.

**Fig. 4.** pH and alkalinity variation of each compartment of MAHB reactor. Compartments are numbered in the sequence of flow pattern from compartment 1 to 5 at steady state.

This was due to the fact that hydrolysis, acidogenesis and acetogenesis occur in the initial chambers. Furthermore, degradation of VFA results in the increment of pH from compartment 1 to compartment 5 [17]. The distinct pH profile shows an indication of the degree of different phases created within the system. Similar alkalinity profiles were noted in the compartment-wise arrangement of the MAHB reactor.

**Gas Production and Composition**

Figure 5 illustrates the biogas volume and the methane content for each compartment at different HRTs. Overall, the biogas volume for HRT 3 was higher (range of 3 to 6.6 L per day) than for HRT 1 (range of 1.3 to 3.2 L per day) due to the longer hydraulic retention times which give enough time for the anaerobic process to take place in each compartment. For HRT 1 day, the total biogas volume increased from 2.2 to 3.2 L per day from compartment 1 to 3 but then decreased to 1.8 L per day in compartment 5 and vice versa for HRT 3. For longer HRTs, the travelling time to move up and down the compartment of the reactor is longer, which contributes to a larger biogas volume. However, most of the nutrients were already converted to methane in the first three compartments.
compartments. This explains the decrement of biogas volume at the last two compartments.

The methane content of the total biogas produced was determined every two days until it reached steady state. The order of the compartments from 1 to 5 shows that the methane content of the total biogas increased in sequence under HRT of 1 day (OLR = 3 g CODL⁻¹ per day) but decreased for HRT of 3 days (OLR = 1 g CODL⁻¹ per day). These results were in accordance with the conclusion of former studies by Uyanik [18] who indicated that acidogenic reactions were dominant in the earlier compartments of the MAHB reactor. However, at HRT of 3 days (with high OLR), the accumulation of VFA resulted in reduction of methane percentage through the rear of the reactor. The methane content, which can be a valuable indicator of the performance of the MAHB reactor shows a stepped up value from 42% to 64% as the HRT decreases under the average OLR of 3 g CODL⁻¹ per day. These results are in agreement with previous research by Liu et al. [19].

![Fig. 5. Gas production variation of each compartment of the MAHB reactor at HRT of 1 day and 3 days.](image)

Obviously, high methane content suggests high activity of methanogenic bacteria. The methanogenic bacteria can be divided into two main groups due to differences in substrate utilization - hydrogenotrophic and acetotrophic methanogens [20]. Hydrogenotrophic methanogens only use CO₂ and H₂ as their substrate. The partial pressure of hydrogen acts as a main indicator to describe disturbances and stability in AD. For that reason, hydrotrophic methanogens activity is crucial for the efficiency and stability of AD in processing of simple soluble types of substrates (i.e. ethanol, propionate, dextrose and acetate) and numerous types of wastewater. For acetotrophic methanogens, such as *Methanosarcinales* genus, they use simple compounds such as acetate as their substrate. More than 70% of biomethane are produced by acetate degradation. Methanogenic bacteria that bind hydrogen are found to belong to *Methanobacteriaceae* family [21].

For cellulose (lignin) saccharification, the microbes that facilitate the process might consist of hydrolyzing and acid producing microorganisms. The primary route is the initial cleavage of ether-linked subunits followed by subsequent degradation of substituted aromatic rings where the derivatives of vanillic acid, cinnamic acid and syringic acid are the important constituents of lignin. For this AD process, fermenting bacteria (i.e., methanogenic bacteria) and acetogenic bacteria are responsible for breaking this ether-linked and aromatic ring bond [22].

**CONCLUSIONS**

The present study revealed that HRT significantly influences the compartment-wise profile of MAHB reactor in terms of COD removal, VFA concentration, pH and alkalinity, methane content and biogas volume in treating RPME wastewater. The pH profile shows an increment within a range of 6.3 to 6.6 as the RPME wastewater moves towards the end of the MAHB reactor. Maximum alkalinity obtained was between 335 and 548 mg L⁻¹ in compartment 5 for each different HRT. The maximum methane content was 96.8% with total biogas volume of 6.56 L per day at HRT of 3 days (OLR of 1 g CODL⁻¹ per day) in the MAHB reactor. High COD removal of 98.0% was achieved at HRT 5 of 0.6 g CODL⁻¹ per day. Therefore, the optimum HRT for anaerobic treatment of RPME in MAHB reactor was 5 days. Moreover, high COD removal and methane content was achieved in the MAHB reactor.

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**REFERENCE**

Izследване на секционното поведение на модифициран анаеробен хибриден реактор с прегради (МАHB)

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(Резюме)

Използван е модифициран анаеробен хибриден реактор с прегради (МАHB) за изучаването на приложимостта му за третиране на отпадъчни води от рециклирането на хартия (RPME) и установяването на връзката между работните параметри и оформлението на реактора. Определени са конфигурацията на реактора, пусковият процес се звършва при възраст 28 дни. Работата на реактора се оценява по секционните профили за различни HRT. В първото отделение се наблюдават pH от 6 – 6.2 и високи концентрации на летливи мастни киселини от 90 до 168 mg L⁻¹ при всяко времепребивване заради ацидогенезата и ацетогенезата. pH и алкалността на системата оказва нарастване на профила по дължината на реактора, докато концентрациите на мастните киселини намалява от отделение 1 до отделение 5. Обемът на биогаз е голем (6.56 L при високи HRT) с намаляване на съдържанието на метан от 96 до 35 % от отделение 1 до 5. Отбелязано, при малки HRT (1 ден) вече се появява биогаз, съдържанието на метан нараства от 42 до 64 %. Резултатите показват, че МАHB-реакторът работи успешно за пречистването на отпадъчни води от рециклирането на хартия.