Bulgarian Chemical Communications, Volume 48, Number3 (pp. 440– 445) 2016

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

S. R. Hassan[1], N. Q. Zaman[2,3], I. Dahlan[3,4]*

[1]*Faculty of Agro Based Industry, Universiti Malaysia Kelantan, Campus Jeli, 17600, Jeli, Kelantan, Malaysia*
[2]*School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Pulau Pinang, Malaysia.*
[3]*Solid Waste Management Cluster, Science and Engineering Research Centre, Universiti Sains Malaysia, Engineering Campus, Seri Ampangan, 14300 Nibong Tebal, Pulau Pinang, Malaysia*

[4]*School of Chemical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Pulau Pinang, Malaysia.*

Received November 25, 2014, Revised November 2, 2015

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^{-1}*per* 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

* To whom all correspondence should be sent:
E-mail: chirvan@usm.my

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.

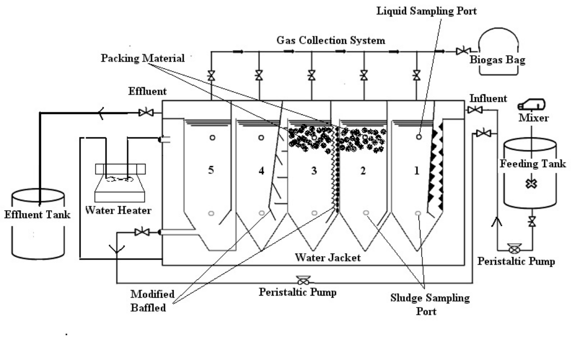

Fig. 1. Schematic diagram of 58 L capacity bench-scale continuous feed MAHB reactor.

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^o 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.

Parameter	Concentration
pH	6.36
Alkalinity (mg L^{-1} as $CaCO_3$)	94
TSS (mg L^{-1})	645
VSS (mg L^{-1})	850
TDS (mg L^{-1})	3345
TS (mg L^{-1})	5320
BOD_5 (mg L^{-1})	669
COD (mg L^{-1})	4328
VFA (mg L^{-1})	501
Ammonia (mg L^{-1})	0.4
DO (mg L^{-1})	1.5

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℃.

Sampling and Analysis

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 ℃, 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.

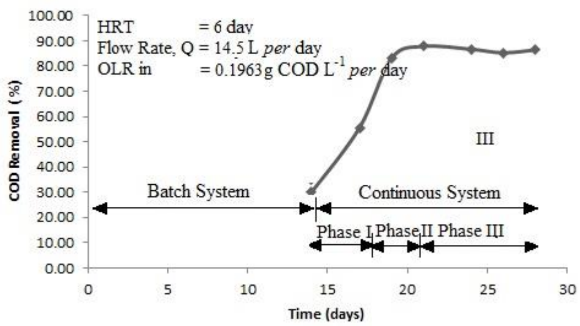

Fig. 2. Acclimatization curve for determination of the start-up period of MAHB reactor

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.

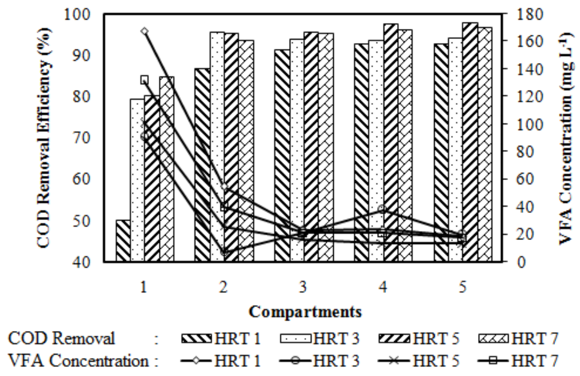

Fig. 3. COD removal and VFA concentration variation of each compartment of the MAHB reactor. Compartments are numbered in the sequence of flow pattern from compartment 1 to 5 at steady state.

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.

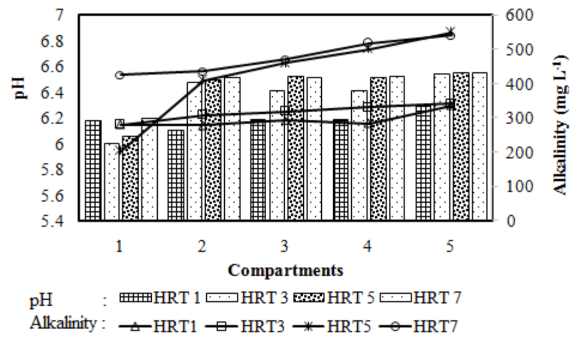

Fig. 4. pH and alkalinity variation of each compartment of MAHB reactor. Compartments are numbered in the sequence of flow pattern from compartment 1 to 5 at steady state.

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. This explaines 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. Thes results are in agreement with previous research by Liu *et al*. [19].

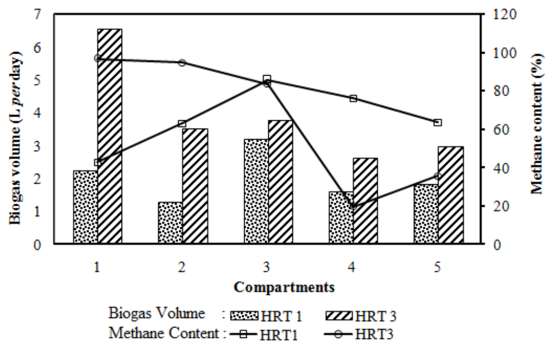

Fig. 5. Gas production variation of each compartment of the MAHB reactor at HRT of 1 day and 3 days.

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 CO_2 and H_2 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.

Acknowledgement*: The authors acknowledge the financial support from the Universiti Sains Malaysia (RU-I A/C.1001/PJKIMIA/814148) and MyBrain15 Scholarship (KPM(B) 870204115782).*

REFERENCE

1. G.Thompson, J. Swain, M. Kay, C.F. Forster, *Bioresource Technology*, **77**, 275 (2001).
2. A. Arshad, N.H. Hashim. *International Journal of Environmental Research*, **6**, 1735 (2012).
3. C.B. Shaw, C.M. Carliell, A.D. Wheatley, *Water Research*,, **36**, 1993 (2002).
4. S. R. Hassan, H. M. Zwain, I. Dahlan, *Journal Advance Science Research*, **4**, 07 (2013).
5. L.S. Clescerl, A.E. Greenberg, A.D. Eaton, eds. Standard methods for the examination of water and wastewater, American Public Health Association, American Water Works Association, Water Environment Federation, Washington, 1998.

6. S.R. Hassan, H. M.Zwain, N. Q. Zaman, I. Dahlan, *Environmental Technology*, **35,** 3(2013).
7. M. Hutnan, M. Drtil, L. Mrafkova, J. Derco, J. Buday, *Bioprocess Engineering*, **21**, 439 (1999).
8. G. Lettinga, J. Field, J. van Lier, G. Zeeman, L.W. HuishoffPol, *Water Science and Technology*, **35**, 5 (1997).
9. Y. Kalogo, J.H. MBouche, W. Verstraete, *Journal of Environmental Engineering*, **127**, 179 (2001).
10. K. Vijayaraghavan, T.K. Ramanujam, *Bioprocess Engineering*, **20**, 499 (1999).
11. G.V.T.G. Krishna, P. Kumar, P. Kumar, *Journal of Environmental Management*, **90**, 166 (2009).
12. C. Polprasert, P. Kemmadamrong, F.T. Tran, *Environmental Technology*, **13**, 857 (1992).
13. J.C. Akunna, M. Clark, *Bioresource Technology*, **74**, p? (2000).
14. M.I. Baloch, J.C. Akunna, *Journal of Environmental Technology*, **129**, 1015 (2003).
15. J. Wang, Y. Huang, X. Zhao, *Bioresource Technology*, **93**, 205 (2004).
16. P. Dama, J. Bell, K.M. Faxon, C.J. Brouckaert, T. Huany, C.A. Buckley, *Water Science Technology*, **26**, 263 (2002).
17. M.I. Baloch, J.C. Akunna, P.J. Collier, *Bioresource Technology*, **98**, 1849 (2007).
18. S.Uyanik, P.J. Sallis, G.K. Anderson, *Water Research*, **36**, 933 (2002).
19. X. Liu, N. Ren, Y. Yuan, *Bioresource Technology*. **100**, 104 (2009).
20. B. Demirel, P. Scherer, *Reviews in Environmental Science and Bio/Technology*, **7**, 173 (2008).
21. D.R. Boone, D.P. Chynoweth, R.A. Mah, P.H. Smith, A.C. Wilkie, *Biomass and Bioenergy*, **5**, 191 (1993).
22. J.J. Ko, Y. Shimizu, K. Ikeda, S.K. Kim, C.H. Park, S. Matsui, *Bioresource Technology*, **100**, 1622 (2009).

ИЗСЛЕДВАНЕ НА СЕКЦИОННОТО ПОВЕДЕНИЕ НА МОДИФИЦИРАН АНАЕРОБЕН ХИБРИДЕН РЕАКТОР С ПРЕГРАДИ (МАНВ)

С.Р. Хасан[1], Н.К. Заман[1], И. Дахлан[2]*

[1]*Училище за строително инженерство, Саинс-университет в Малайзия, 14300 Нибонг Тебал, Пулау Пинанг, Малайзия*

[2]*Училище по химично инженерство, Саинс-университет в Малайзия 14300 Нибонг Тебал, Пулау Пинанг, Малайзия*

Постъпила на 25 ноември, 2014 г.; коригирана на 2 ноември, 2015 г.

(Резюме)

Използван е модифициран анаеробен хибриден реактор с прегради (МАНВ) 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, пускането му в действие и ефекта на времепребиваването (HRT) върху ефективността на пречистване и работата на реактора. Пусковият процес се зивършва пру времепребиваване от 4 дни. МАНВ-реакторът работи с постоянно захранване с ХПК от 3000 mg L^{-1} и времепребиваване HRT от 1, 3, 5 и 7 дни. Пусковият период е 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 времепребиваване заради ацидогенезата и ацетогенезата. pH и алкалността на системата показва нарастване на профила по дължината на реактора, докато концентрациите на мастните киселини намалява от отделение 1 до отделение 5. Обемът на биогаза е голям (6.56 L при високи HRT) с намаляване на съдържанието на метан от 96 до 35 % от отделение 1 до 5. Обратно, при малки HRT (1 ден), въпреки че бемът на биоагз е малък, съдържанието на метан нараства от 42 до 64 %. Резултатите показват, че МАНВ-реакторът работи успешно за пречстването на отпадъчни води от рециклирането на хартия.