Bioprocess Biosyst Eng (2010) 33:267–276
DOI 10.1007/s00449-009-0321-1

ORIGINAL PAPER

Treatment of domestic wastewater in an up-flow anaerobic sludge blanket reactor followed by moving bed biofilm reactor

A. Tawfik · F. El-Gohary · H. Temmink

Received: 30 December 2008 / Accepted: 14 April 2009 / Published online: 30 April 2009

Abstract The performance of a laboratory-scale sewage treatment system composed of an up-flow anaerobic sludge blanket (UASB) reactor and a moving bed biofilm reactor (MBBR) at a temperature of (22–35 °C) was evaluated. The entire treatment system was operated at different hydraulic retention times (HRT's) of 13.3, 10 and 5.0 h. An overall reduction of 80–86% for COD_{total}; 51–73% for $COD_{colloidal}$ and 20–55% for $COD_{soluble}$ was found at a total HRT of 5–10 h, respectively. By prolonging the HRT to 13.3 h, the removal efficiencies of COD_{total}, $COD_{colloidal}$ and $COD_{soluble}$ increased up to 92, 89 and 80%, respectively. However, the removal efficiency of $COD_{suspended}$ in the combined system remained unaffected when increasing the total HRT from 5 to 10 h and from 10 to 13.3 h. This indicates that, the removal of $COD_{suspended}$ was independent on the imposed HRT. Ammonia-nitrogen removal in MBBR treating UASB reactor effluent was significantly influenced by organic loading rate (OLR). 62% of ammonia was eliminated at OLR of 4.6 g COD m^{-2} day^{-1}. The removal efficiency was decreased by a value of 34 and 43% at a higher OLR's of 7.4 and 17.8 g COD m^{-2} day^{-1}, respectively. The mean overall residual counts of faecal coliform in the final effluent were 8.9×10^4 MPN per 100 ml at a HRT of 13.3 h, 4.9×10^5 MPN per 100 ml at a HRT of 10 h and 9.4×10^5 MPN per 100 ml at a HRT of 5.0 h, corresponding to overall $\log_{10}$ reduction of 2.3, 1.4 and 0.7, respectively. The discharged sludge from UASB–MBBR exerts an excellent settling property. Moreover, the mean value of the net sludge yield was only 6% in UASB reactor and 7% in the MBBR of the total influent COD at a total HRT of 13.3 h. Accordingly, the use of the combined UASB–MBBR system for sewage treatment is recommended at a total HRT of 13.3 h.

Keywords Sewage · UASB · MBBR · COD · Nitrification · Faecal coliform · Sludge

Introduction

Within the spectrum of anaerobic sewage treatment technologies, the up-flow anaerobic sludge blanket (UASB) reactor offers great promise, especially in developing countries that are usually located in hot and moderate climatic zones [1, 2]. These reactors remain robust high-rate treatment systems, generally without moving mechanical parts, limiting both capital and operating costs [3]. Like many high-rate systems, the UASB retains a high amount of biomass in the form of flocculant sludge, granules or aggregates of microorganisms. Furthermore, good contact between biomass and wastewater is ensured due to mixing as a result of biogas production. The configuration of these reactors has proven to be efficient in removing organic matter and total suspended solids (TSS), as well as in producing smaller amounts of excess sludge compared to aerobic reactors [4, 5]. However, the performance of the UASB reactors is affected by operational conditions, one of which is the hydraulic retention time (HRT). Castillo et al. [6] investigated the effect of different HRT's on a pilot-scale UASB reactor (750 l), fed with domestic wastewater

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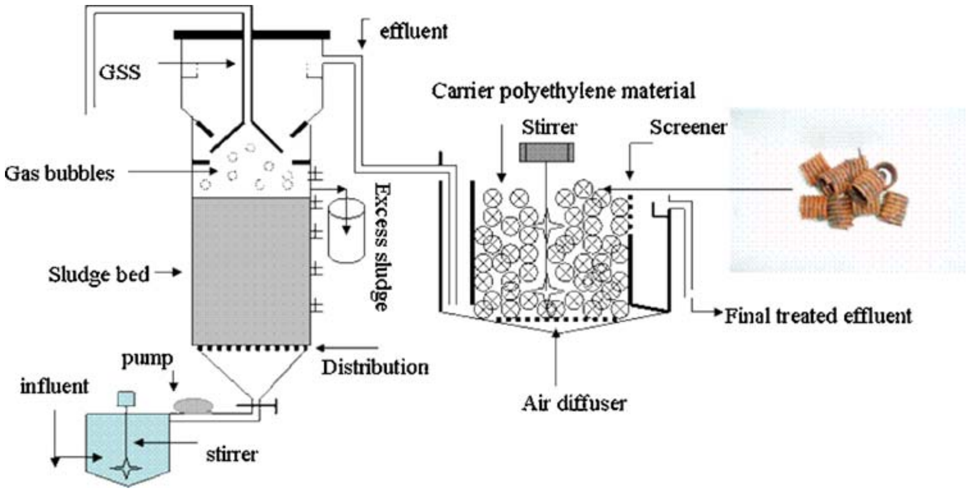

Fig. 1 Integrated up-flow anaerobic Sludge blanket (UASB)–moving bed biofilm reactor (MBBR) treating domestic wastewater

(COD inf. = 600 mg l^{-1}), at temperatures ranging from 13 to 20 °C. Their results showed that the removal values of the different COD fractions increased by the increase of the HRT. However, there has been a tendency for this to become constant at a HRT more than 6 h. The reactor achieved 66% for COD removal at an HRT of 8 h. In another study, A'lvarez et al. [7] investigated the performance of an UASB reactor treating domestic wastewater at an HRT of 11 h and a temperature of 14 °C. After a start-up period of 75 days, the UASB removal values were 58% for TSS, 41% for COD$_{total}$ and 54% for total biochemical oxygen demand (BOD$_{5\ total}$). It is worth-mentioning however, that in spite of the advantages of the UASB reactors as an advanced primary treatment, post-treatment step is required to achieve the emission standards set by regulatory authorities. Yet it is not a priori clear which of the different post-treatment units can be the best alternative. The choice depends on: the required effluent quality; the available land area, the treatment cost, the simplicity and operational stability of the treatment system, the independence on imported equipment and material and operational flexibility. So far the results obtained from lab sale and full sale units suggest useful application of moving bed biofilm reactors (MBBR) systems for aerobic post-treatment [8, 9]. MBBR provides a long biomass retention time and accommodate high loading rates without any problems of clogging [10]. In a MBBR, the bacteria are fixed in a biofilm on a carrier. The carrier is suspended and moves freely in the reactor. The MBBR has been applied for organic matter removal [11], for nitrification [12], and for nutrient (N and P) removal [13].

The objective of this study is to assess the performance of the combined UASB–MBBR system for domestic wastewater treatment at different HRT's, consequently different OLR's. This will be carried out by monitoring the removal of the COD fractions (COD$_{suspended}$, COD$_{colloidal}$, COD$_{soluble}$), and faecal coliform (FC) removal as well as the nitrification rate. Also the characteristics of the sludge produced in the combined system will be considered.

Materials and methods

Up-flow anaerobic sludge blanket (UASB) reactor

A schematic diagram of the UASB reactor is shown in Fig. 1. The reactor had a working volume of 10 l and a height of 1.35 m. Eight ports for obtaining sludge samples are arranged along the reactor height, the first one at 0.1 m above the base of the column. The reactor is provided by a conical gas solids separator (GSS) at the top of the tank with a height of 0.2 m. The gas production was measured by a wet gas meter (Schlumberger P. Max: 100 m bar). Initially, the UASB reactor was inoculated with 6 l digested sludge. The initial concentration of the sludge in the reactor was 18 g VSSl^{-1}. The system was fed with raw sewage from a nearby sewer network (Dokki, Cairo) using a peristaltic pump. During the study period, temperature varied from 22 to 35 °C. The main characteristics of the domestic wastewater are given in Table 1.

Moving bed biofilm reactor (MBBR)

The MBBR consists of a reactor vessel with a volume of 8.0 l and a depth of 0.5 m (Fig. 1). The reactor was filled with 1158 carrier media. The carrier elements represent 70% of the total reactor volume [14]. The carriers are made of polyethylene, with a specific gravity of 0.95 and an effective specific surface area of 363 m^{-2} m^{-3}. The media is shaped in a cylindrical form and has a length of 1.8 cm and a diameter of 1.85 cm. Complete mixing of the media is ensured by means of a central stirrer with blades placed at 10 and 40 cm below top-water level; the stirrer is driven by a 0.37-kW geared electric motor at a rotational speed of

Table 1 Mean characteristics of domestic wastewater

Parameters pH	COD fractions (mg O_2 l^{-1})				Nitrogen (mg N l^{-1})		Faecal coliform (MPN per 100 ml)
	Total	Suspended	Colloidal	Soluble	NH_4-N	TKN	
6.9 (0.3)	740 (238)	488 (268)	63 (33)	189 (87)	27 (5)	40 (4)	1.1×10^7 (7.9×10^6)

Standard deviations are presented between brackets

Table 2 Operational conditions of the combined system (UASB–MBBR)

Operational conditions	HRT (h)		OLR		Flow rate (m^3 day^{-1})
	UASB	MBBR	UASB (kg COD m^{-3} day^{-1})	MBBR (g COD m^{-2} day^{-1})	UASB
Run 1	8	5.3	1.5	4.6	0.036
Run 2	6	4	2.4	7.4	0.048
Run 3	3	2	5.8	17.8	0.096

about 90 rpm. A screen is provided at the outfall end of the reactor to keep the media from clogging the effluent spout or passing out of the reactor. The MBBR was continuously operated and fed with UASB reactor effluent (Fig. 1). Pure oxygen is supplied from the bottom of the reactor through a diffuser. Dissolved oxygen (DO) is measured in the reactor by a portable DO-meter and the flow rate of oxygen was controlled by visual inspection of a flowmeter. In this way, the oxygen supply rate was adjusted in order to keep the concentration of DO fairly constant at a level of not less than 2.0 mg O_2 l^{-1} [14] during the whole experimental period.

Operational conditions

The operational conditions of the combined UASB–MBBR are shown in Table 2. The UASB–MBBR was operated for 290 days, 39–98; 130–183; and 210–290 days at HRT's of, respectively 8 + 5.3; 6 + 4 and 3 + 2 h. The first 38 days of operation were considered as a start-up period, while the periods from day 99 to 129 and from 184 to 209 were considered as acclimatization periods to the new HRT. Statistical analysis at different HRT's has been done according to Snedecor and Cochran [15].

Characteristics of biofilm carriers

Representative samples of colonized carrier media were taken from the reactor three times in each run. The harvested carriers with biomass was washed in a sodium hypochlorite solution (6% active chlorine) and then exposed to ultrasound for 3.0 h with a rinse step every hour with the chlorinated solution and a final rinse with deionized water [16]. The concentration of biomass is expressed as g VSS l^{-1} media to be able to calculate the sludge residence time (SRT). Volatile suspended solids (VSS) of the attached biofilm on the carrier amounted to 7.6 (HRT = 5.3 h), 9.0 (HRT = 4 h), and 11 gVSS/l media (HRT = 2 h). The calculated biofilm thickness was ranged from 420 to 750 μm and from 720 to 934 μm depending on the applied loading rate.

Microscopic examination test show that there were a large numbers of ciliates and rotifers in the biofilm adhered to the carrier elements.

Excess sludge in the combined UASB–MBBR

The sludge bed of the UASB reactor was kept below tap 5, ca. 80 cm from the UASB bottom, by opening this tap once a week for discharging the sludge accumulated above. Additionally, the sludge from the MBBR was daily discharged and collected in a storage tank of 10 l for measurement of total and volatile solids. The sludge residence time (SRT) of the UASB and MBBR was calculated according to the following equation;

$$\mathrm{SRT} = \left(\frac{VX}{Q_w X_w + Q X_e}\right)$$

where: V, reactor volume; X, average biomass concentration of the reactor (mg $VSSl^{-1}$); Q_w, excess sludge (l day^{-1}); X_w, concentration of the excess sludge (mg $VSSl^{-1}$); Q wastewater flow rate (l day^{-1}); X_e effluent concentration (mg $VSSl^{-1}$) and according to Zeeuw [17] $X_e = \mathrm{COD}_{\mathrm{suspended}}/1.4$.

Sampling and analytical methods

Grab samples of the influent and the effluents of the UASB and MBBR were collected and immediately analysed for pH, temperature and dissolved oxygen (DO). The COD was analysed using the micro-method as described by APHA [18]. Raw samples were used for COD$_{\text{total}}$, 4.4-µm folded paper filtered (Schleicher and Schuell 595 1/2) samples for COD$_{\text{filtrate}}$ and 0.45-µm membrane filtered (Schleicher and Schuell ME 25) samples for dissolved COD (COD$_{\text{soluble}}$). The COD$_{\text{suspended}}$ and COD$_{\text{colloidal}}$ were calculated by the difference between COD$_{\text{total}}$ and COD$_{\text{filtered}}$, COD$_{\text{filtered}}$ and COD$_{\text{soluble}}$, respectively. Ammonia, total Kjeldahl nitrogen (TKN), nitrite, nitrate, sludge analysis and faecal coliform (FC) was determined according to APHA [18].

Results and discussion

Effect of HRT on the performance of the combined UASB–MBBR system

COD fractions removal

The results presented in Table 3 and Fig. 2 indicate that decreasing the total HRT from 13.3 to 10 h and from 10 to 5 h exerted a negative impact on the efficiency of the total system (UASB–MBBR) as reflected in the residual COD fractions values (COD$_{\text{total}}$, COD$_{\text{suspended}}$, COD$_{\text{colloidal}}$ and COD$_{\text{soluble}}$). At a total HRT of 13.3 h, the total process provided a final effluent quality with 54 mg l^{-1} COD$_{\text{total}}$, 6 mg l^{-1} COD$_{\text{colloidal}}$ and 37 mg l^{-1} COD$_{\text{soluble}}$. Approximately, the same result, at a total HRT of 13.3 h, was achieved in the MBBR system treating chemically pre-treated sewage [10] at shorter HRT of 8.0 h. Residual COD values at a total HRT of 10 and 5.0 h were 95 and 142 mg l^{-1} for COD$_{\text{total}}$, 65 and 97 mg l^{-1} for COD$_{\text{soluble}}$, respectively. As expected, the UASB reactor achieved a poor removal efficiency of COD$_{\text{colloidal}}$ as shown in Table 3. This low removal efficiency mainly can be due to a poor physical removal in the system [19]. On the other hand, an almost complete removal of COD$_{\text{colloidal}}$ was achieved in the MBBR, i.e. only 6, 12 and 17 mg l^{-1} remained in the final effluent when operated at HRT's of 5.3, 4 and 2 h, respectively. The removal of COD$_{\text{colloidal}}$ in the MBBR occurred mainly due to adsorption followed by hydrolysis and biodegradation.

The results in Table 3 revealed that the removal of COD$_{\text{suspended}}$ in the combined system was not significantly affected by decreasing the total HRT from 13.3 to 10 h and from 10 to 5 h. The major part of COD$_{\text{suspended}}$ was removed in the UASB reactor, and little additional removal occurred in the MBBR system (Table 3). At a total HRT's of 13.3, 10 and 5.0 h, percentage removal values for the combined system were 96, 96 and 94%, respectively. This indicates that the removal of COD$_{\text{suspended}}$ independent on the imposed HRT.

Table 3 COD fractions (COD$_{\text{suspended}}$ COD$_{\text{colloidal}}$ and COD$_{\text{soluble}}$) in an UASB–MBBR treating domestic wastewater at different HRT's

Parameters Samples	COD fractions (mg l^{-1})			
	Total	Suspended	Colloidal	Soluble
Run 1				
Sewage	699 (190)	409 (239)	71 (33)	219 (85)
UASB effluent	203 (50)	49 (26)	53 (33)	101 (34)
%R*	69 (10)	85 (10)	17 (41)	46 (29)
MBBR effluent	54 (8)	12 (2)	6 (3)	37 (7)
%R*	71 (10)	69 (17)	85 (11)	58 (20)
Overall removal efficiency	92 (1.3)	96 (2)	89 (9)	80 (10)
Run 2				
Sewage	733 (236)	485 (199)	64 (34)	185 (103)
UASB effluent	244 (73)	80 (51)	42 (16)	122 (37)
%R*	64 (13)	80 (15)	9 (69)	24 (24)
MBBR effluent	95 (21)	17 (4)	12 (3)	65 (16)
%R*	57 (17)	63 (43)	64 (23)	42 (21)
Overall removal efficiency	86 (6)	96 (2)	73 (22)	55 (28)
Run 3				
Sewage	803 (301)	603 (349)	49 (27)	151 (53)
UASB effluent	293 (71)	122 (66)	44 (18)	127 (36)
%R*	58 (22)	74 (23)	10 (41)	15 (12)
MBBR effluent	142 (23)	25 (7)	19 (5)	97 (17)
%R*	49 (14)	69 (25)	51 (20)	20 (16)
Overall removal efficiency	80 (9)	94 (5)	51 (23)	20 (54)

Standard deviations between brackets

%R*: percentage removal

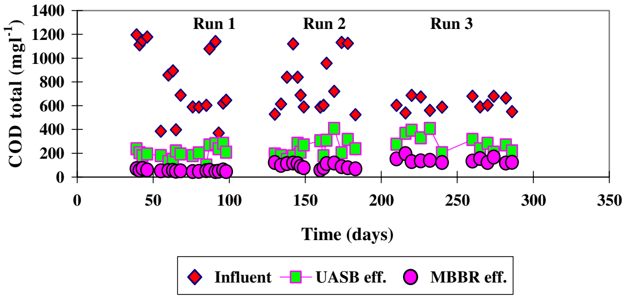

Fig. 2 Variation of COD$_{\text{total}}$ in the combined system at different HRT's

The fate of the COD in the domestic wastewater fed to the combined UASB–MBBR units during experimental runs 1, 2 and 3 is presented in Figs. 3 and 4. Approximately 12.7, 4.4 and 16.2% of the influent COD could not be accounted for COD balance in the test runs 1, 2 and 3, respectively. These results are in agreement with Singh and

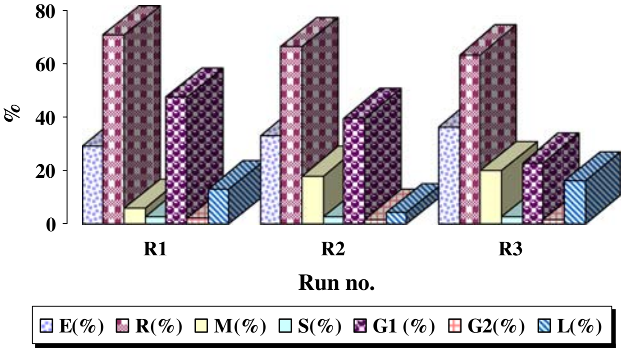

Fig. 3 COD balance for UASB reactor during experimental runs 1, 2 and 3. *Slices* represent the terms of the balance as percentage (%) of influent COD: E (%): effluent COD; R(%): removed COD; M (%):COD converted to biomass; S(%):COD assimilated by sulphate reducing bacteria (approximately 0.67 g COD per g SO_4 reduced) [22]; G1(%): COD converted to CH_4; G2 (%): dissolved CH_4 in the treated effluent (calculated according to Henry's law) and L (%): unaccounted fraction of COD

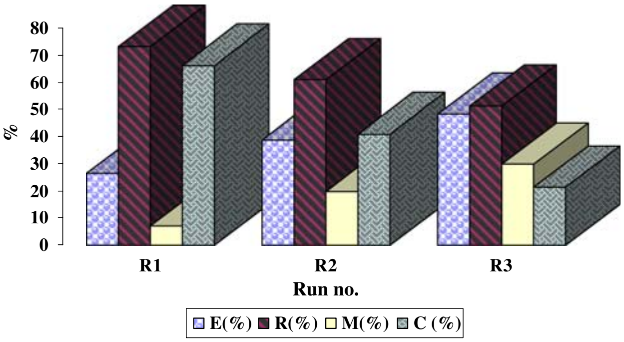

Fig. 4 COD balances for MBBR treating UASB reactor effluent during experimental runs 1, 2 and 3. *Slices* represent the terms of the balance as percentage (%) of influent COD: E (%): effluent COD; R (%): COD removal; M (%): sludge production and C (%): COD conversion

Viraraghavan [20] who found a COD gap of about 10–15% of the total input COD of the UASB reactor treating sewage at 20 °C. This is partially attributed to COD consumption for cell synthesis. A higher value of unaccounted COD of 40.8–41.5% was recorded for anaerobic filter (AF) treating municipal wastewater [21].

Figure 4 shows the COD balance in the MBBR system treating UASB reactor effluent. The average COD removal efficiency R (%) was 73.3% (HRT = 5.3 h), 61% (HRT = 4 h), and 51.5% (HRT = 2.0 h), of which a fraction of 7, 20 and 30% is discharged as surplus sludge *M* (%). The remaining portion of the removed COD (66.4, 41 and 21.5%) can be due to (1) biological conversion C (%) of biodegradable organic matter, and (2) assimilation of heterotrophic and autotrophic bacteria.

Nitrification efficiency

The nitrification efficiency in the MBBR treating UASB reactor effluent at different organic loading rates (OLR's) is shown in Table 4 and Fig. 5. The results show that increasing the organic loading rate (OLR) from 4.6 to 7.4 and from 7.4 to 17.8 g COD m^{-2} day^{-1}, results in an increase of the ammonia concentration in the final effluent from 13 to 18 and from 18 to 21 mg l^{-1}, respectively. At OLR of 4.6, 7.4, and 17.8 g COD m^{-2} day^{-1}, ammonia was removed by a value of 62, 28 and 19%, while at the same time 11, 4.4 and 0.3 mg l^{-1} of nitrate were, respectively produced. Based on these results, it can be concluded that the OLR imposed to the MBBR reactor should remain below 7.4 g COD m^{-2} day^{-1} to enhance the nitrification process as also found by Rusten et al. [14] for MBBR treating pre-settled sewage.

The results presented in Fig. 6 revealed that the nitrification rate in MBBR was strongly dependant on $COD_{suspended}$/N ratio. A low nitrification rate was achieved in the MBBR at the high influent $COD_{suspended}$/N ratio of 2.1 and 3.1, the nitrification rate was 0.1 and 0.03 g $NO_3 + NO_2$ m^{-2} day^{-1} as compared to $COD_{suspended}$/N ratio of 1.36, the nitrification rate amounted to 0.26 g $NO_3 + NO_2$ $m^{-2}day^{-1}$. This can be attributed to attachment of the suspended solids on the surface of the nitrifying biofilm where they take away oxygen which otherwise would have been available for nitrifiers [23].

Nitrogen loss

The nitrogen removal in the MBBR treating UASB reactor effluent was 26% at an OLR of 4.6 g COD m^{-2} day^{-1} as compared to 16% at higher OLR's of 7.4 and 17.8 g COD m^{-2} day^{-1} (see Table 4; Fig. 7). The nitrogen loss can be due to (1) assimilation of biomass (2) denitrification occurring in the anoxic zone of the biofilm [24].

Faecal Coliform (FC) removal

The results in Fig. 8 show that a significantly improved FC reduction at increasing the HRT from 5.0 to 10 h and from 10 to 13.3 h. The mean overall residual counts of FC at an HRT's of 13.3, 10 and 5 h were 8.9 × 10^4, 4.9 × 10^5 and 9.4 × 10^5 MPN per 100 ml, corresponding to overall $\log_{10}$ reduction of 2.3, 1.4 and 0.7, respectively. The results obtained revealed that FC removal mainly proceeds in the MBBR system as shown in Fig. 8.

The results presented in Figs.9 and 10 show that the removal of FC only significantly improved once the concentration of the dispersed $COD_{suspended}$ and $COD_{colloidal}$ has become very low and the HRT has increased from 2 to 5.3 h. Apparently, dispersed COD removal is very

Table 4 Nitrogen species removal in an MBBR treating UASB reactor effluent at different OLR's

Parameters Samples	Nitrogen species (mg l^{-1})					Nitrification rate g $NO_3 + NO_2$-N (m^{-2} day^{-1})
	TKN	NH_4-N	NO_2-N	NO_3-N	Nitrogen loss	
Run 1						
Sewage	38 (5)	31 (5)				
UASB effluent	36 (4)	34 (5)				
%R*	5 (4)	−9.7 (4)				
MBBR effluent	15 (3)	13 (3)	0.4 (0.2)	11 (2)	10 (5)	0.3 (0.05)
%R*	58 (9)	62 (9)			26 (12)	
Overall removal efficiency	60 (9)	59 (10)			30 (12)	
Run 2						
Sewage	41 (4)	24 (3)				
UASB effluent	37 (5)	24 (3)				
%R*	9 (9)	0.0				
MBBR effluent	26 (3)	18 (2)	0.4 (0.2)	4.4 (1.2)	7 (5)	0.14 (0.04)
%R*	30 (10)	28 (10)			16 (12)	
Overall removal efficiency	37 (7)	27 (10)			25 (9)	
Run 3						
Sewage	42 (5)	25 (3)				
UASB effluent	35 (6)	27 (3)				
%R*	17 (16)	−8 (5)				
MBBR effluent	29 (7)	21 (2)	0.17 (0.1)	0.33 (0.1)	5 (2)	0.03 (0.01)
%R*	17 (7)	19 (10)			16 (7)	
Overall removal efficiency	31 (15)	14 (11)			29 (15)	

Standard deviations between brackets

%R*: percentage removal

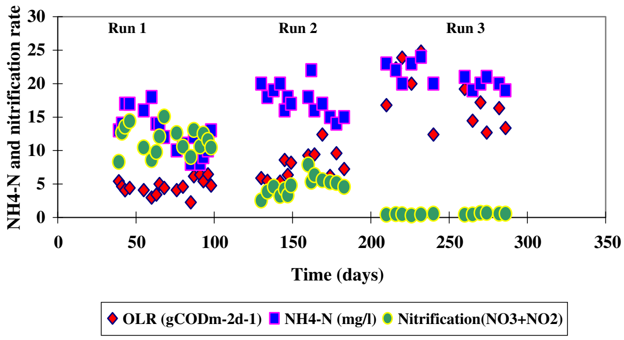

Fig. 5 Variation of the OLR (g COD m^{-2} day^{-1}); NH_4-N and nitrification rate in the MBBR system treating anaerobically pretreated sewage

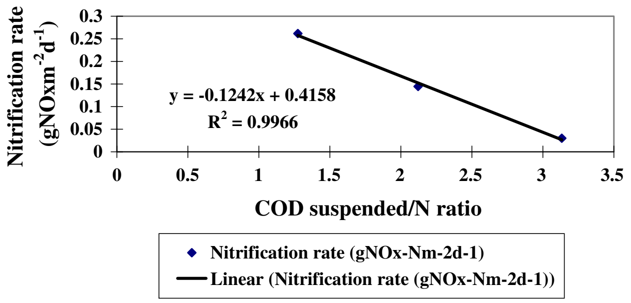

Fig. 6 Relationship between the $COD_{suspended}$/N ratio and nitrification rate in the MBBR system treating anaerobically pretreated sewage

important to achieve a satisfactory FC removal. The fraction of FC attached on the suspended solids will be removed as a result of sedimentation; while the free dispersed FC (attached to colloidal particles will be adsorbed on the carrier material [25]. However, longer HRT is required for removal of FC in the colloidal form. Tawfik et al. [26] found that the removal of *Escherichia coli* (*E. coli*) in the colloidal form is limiting step in the biofilm system.

Excess sludge production

The characteristics of the excess sludge of the combined UASB–MBBR are presented in Table 5. The sludge volume index (SVI) of the wasted sludge from the UASB and MBBR system is below 74 ml g TS^{-1}, which indicates

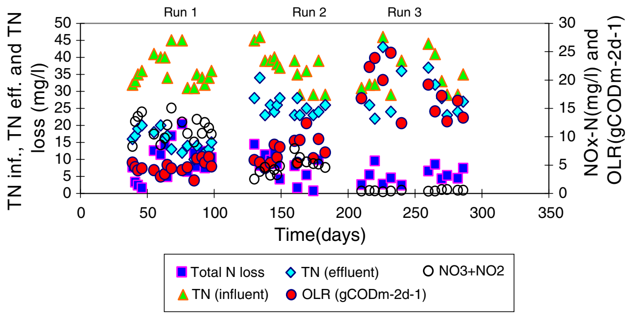

Fig. 7 Nitrogen loss, nitrification rate and organic loading rate (g COD m^{-2} day^{-1}) of the MBBR system treating anaerobically pretreated sewage

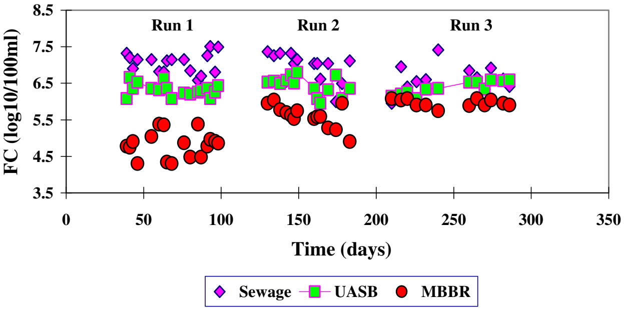

Fig. 8 Variation of FC ($\log_{10}$) at different HRT's

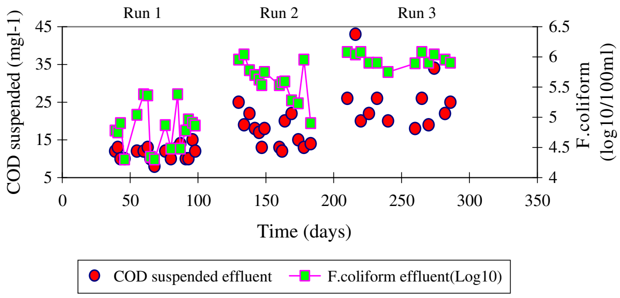

Fig. 9 $\mathrm{COD_{suspended}}$ and faecal coliform (FC) in the treated effluent of MBBR

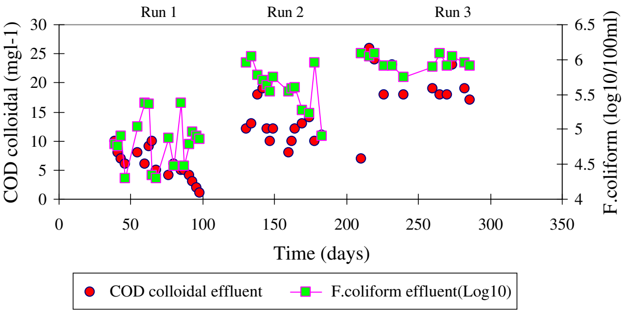

Fig. 10 $\mathrm{COD_{colloidal}}$ and faecal coliform (FC) in the treated effluent of MBBR

excellent settleability. The VSS/TSS ratio of 0.5–0.6 indicates that the wasted sludge from the UASB reactor is well stabilized, while the wasted sludge from MBBR still needs post-stabilization [27] as the VSS/TSS ratio of this sludge was higher than 0.5. The sludge yield coefficient is strongly affected by the imposed SRT, because the results in Table 5 reveal that the sludge yield coefficient in a combined system (UASB–MBBR) operated at a SRT (21 days for UASB + 5.0 day for MBBR) is almost three times higher than at a SRT (118.3 days for UASB + 22 days for MBBR). However, the combined UASB–MBBR still produced a relatively low amount of wasted sludge compared to conventional activated sludge processes [28].

Discussion

The results obtained in this study indicated that the combined system consisting of UASB–MBBR system treating domestic wastewater at a total HRT of 13.3 h is very effective for removal of COD fractions, ammonia and FC. The total system removed over 92% of $\mathrm{COD_{total}}$; 96% of $\mathrm{COD_{suspended}}$ 89% of $\mathrm{COD_{colloidal}}$ and 80% of $\mathrm{COD_{soluble}}$. These results are similar to those reported for UASB–septic tank in combination with MBBR treating black wastewater [13]. The combined system removed 92% of $\mathrm{COD_{total}}$ and 99% of $\mathrm{BOD_7}$. A lower removal efficiency of COD (71.3–77.1%) was achieved in an MBBR treating domestic wastewater at an HRT of 6 h [10]. This indicates that the introduction of an UASB reactor (as a pretreatment) prior to MBBR (as a post-treatment) increased the removal efficiency of COD. Comparison of the results obtained from the present study with that published by other investigators indicates a considerable variation depending on the treatment system and the operating conditions. Kim et al. [29] reported a similar COD removal value (92%) for aerobic filter in combination with UASB reactor at a total HRT of 13.5 h (8 h for UASB + 5.5 h for aerobic filter). COD removal ranging from 90 to 94% has been found by Tawfik et al. [30] at lower HRT (10.7 h) using a combined system consisting of UASB–down flow hanging sponge (DHS) system. Sousa and Foresti [2] investigated UASB-sequencing batch reactor (SBR) for sewage treatment. The total system achieved an overall removal efficiency of 95% of COD. An UASB-activated sludge (AS) system treating domestic wastewater was investigated by Sperling et al. [31]. The integrated system achieved a removal efficiency of COD (85–93%) at a total HRT of 7.9 h (4.0 h UASB + 3.9 h aerobic reactor). Coletti et al. [32] achieved similar removal efficiencies of 95% ($\mathrm{BOD_5}$) and 88% (COD) in a compartmentalized UASB reactor followed by activated sludge system. Bodík et al. [3] studied sewage

Table 5 Characteristics of wasted sludge in a combined UASB–MBBR treating domestic wastewater at different HRT's

Parameters Samples	SV* (ml l^{-1})	SW* (105 °C) (gl^{-1})	SW (550 °C) (gl^{-1})	SVI* (ml g TS^{-1})	VSS/ TSS	SYC* (g sludge g COD $removed^{-1} day^{-1}$)	SRT* (day^{-1})
Run 1							
UASB reactor	220	6	3	39	0.5	0.06	118.3
MBBR	100	2	1.4	50	0.7	0.07	22
Run 2							
UASB reactor	593	10	6	59	0.6	0.18	51.0
MBBR	140	4	2.4	35z	0.6	0.2	11.4
Run 3							
UASB reactor	890	12	6	74	0.51	0.2	21
MBBR	160	7	5.2	23	0.74	0.3	5.0

*SV** sludge volume, *SW** sludge weight, *SVI** sludge volume index, *SYC** sludge yield coefficient, *SRT** sludge residence time

treatment system consisting of an anaerobic baffled filter reactor followed by aerobic post-treatment (hanging polypropylene cords). The HRT in anaerobic and aerobic unit were 15 and 4 h, respectively. The total process achieved the following removal efficiencies; COD (78.6–83.0%); BOD_5 (92.5–94.0%) and TSS (80.9–92.7%).

$COD_{suspended}$ removal values for the UASB–MBBR were 96, 96 and 94% at a total HRT's of 13.3, 10 and 5.0 h, respectively. Similar removal efficiency of 92% for TSS was achieved using UASB–AS system at a HRT of 9.9 h [31]. In another study, UASB reactor in combination with a submerged aerated biofilter provided 94% for TSS removal [4].

The results of the average concentration of ammonia, nitrate and nitrite and their removal efficiencies (Table 4) showed that when DO = 2 mg l^{-1} and OLR = 4.6 g COD m^{-2} day^{-1}, the nitrification efficiency reached above 62%, which was in consistent with Painter [33] who reported that a DO value of at least 2.0 mg l^{-1} is essential to maintain complete nitrification in biological wastewater-treatment systems. Wang et al. [10] investigated the nitrification efficiency in MBBR system treating domestic wastewater at different DO levels (6, 4, 2 and 1 mg l^{-1}). The results showed that when DO > 2 mg l^{-1}, the efficiency of nitrification reached 94.3%. Increasing DO concentration up to 6 mg l^{-1} slightly improved the nitrification efficiency by a value of only 9.0%. When DO was lowered to 1 mg l^{-1}, the ammonia removal amounted to 56%.

The nitrogen removal in the MBBR treating UASB reactor effluent amounted to 26% at an OLR of 4.6 g COD m^{-2} day^{-1}. These results are in agreement with the studies by Tawfik et al. [34] who found that 22% of the nitrogen remained unaccountable in a rotating biological contactor (RBC) system treating UASB reactor effluent. Total nitrogen losses of up to 30% have been recorded in the aeration tank of full scale, biological nitrogen removal (BNR) processes treating domestic wastewater [35]. Intermittently aerated MBBR treating anaerobically pretreated wastewaters at an OLR of 0.023–0.093 kg COD m^{-3} day^{-1} was investigated by Luostarinen et al. [13]. The reactor removed 57% of total nitrogen (TN). Improvement of nitrogen removal in an integrated system consisting of UASB and MBBR may occur by using UASB reactor for denitrification in combination with methanogens as described by several researchers [29, 36]. In the UASB reactor any external electron donor is not required, and denitrification at the inlet of the reactor would improve the COD removal. A combined system consisting of an UASB reactor and an aerobic membrane bioreactor (MBR) was operated at 28–30 °C for the treatment of low-strength synthetic wastewater. The nitrified effluent from MBR was recirculated into the UASB with a ratio of 50–800%. Under these conditions, the denitrification became the preferred pathway rather than methanogenesis in the UASB reactor. The combined system achieved total nitrogen (TN) removal efficiency of up to 82.8% [37]. Jun et al. [38] reported a maximum TN removal efficiency of 70% with a recirculation ratio of 300% at a total HRT of 24 h for the treatment of raw sewage in a combined up-flow anaerobic sludge reactor and aerobic bio-filtration system.

Our results obtained with UASB–MBBR system, operated at a total HRT of 13.3 h show a high percentage removal of FC (98.8%), corresponding to 2.3 $\log_{10}$ reduction. These results are comparable to those obtained in other biofilm systems, i.e. RBC system achieved a removal efficiency of 99–99.8% for *E. coli* at longer retention time Tawfik et al. [36]. The removal efficiency of FC by a combined process (UASB–DHS) system was investigated by Tawfik et al. [30]. The total process achieved 99.8% for FC removal.

The major part of FC was removed in the MBBR system treating UASB reactor effluent indicating that, the biofilm play a role for removal of FC. Two possible mechanisms have been reported for FC removal by biofilm processes

[25]. The first mechanism involves adsorption of FC onto the biofilm, while the second mechanism involves the removal of FC through predation by other microbes such as protozoa, and metazoans, i.e. Se′las et al. [39] observed in a sand column that pathogenic bacteria removal was better in the presence of a biofilm than without it. Bellamy et al. [40] explained the removal of bacteria in slow sand filters by adsorption of the bacteria on the biofilm attached to sand grains. However, adsorption of pathogenic bacteria to the media is influenced by several factors such as the content of organic matter, the degree of biofilm development, temperature; ionic strength and pH value [41]. The other causes of pathogenic bacteria removal in the MBBR system could be predation (filter feeding) [26]. Sylvaine et al. [42] studied the efficiency of pathogenic bacteria removal (1) with a biofilm surface and active protozoa, (2) with a biofilm surface and inactivated protozoa, (3) with a clean surface. Protozoa in the presence of a biofilm were responsible for 60% of bacteria removal. Biofilm without protozoa and a clean surface each removed similar quantities of bacteria. Further investigation for mechanism removal of FC in MBBR system is required.

The discharged sludge from the UASB reactor treating domestic wastewater is rather well stabilized, i.e. VSS/TSS ratio = 0.5–0.6 at imposed operational conditions. Therefore, the UASB reactor can simultaneously treat domestic wastewater and stabilize sludge produced. In this case, a conventional digestion tank can be eliminated from the process, especially in tropical and subtropical countries where the temperature exceeding 20 °C. It is known the investment cost of the digestion system generally amounts to 30–40% of the total cost of the whole sewage treatment plant. Accordingly, a large portion of the investment can be saved by using UASB reactor for sewage treatment. Moreover, the mean value of the net sludge yield coefficient found amounted to only 0.06, 0.18 and 0.2 g sludge g COD removed^{-1} day^{-1} for the UASB reactor when operated at SRT's of 118.3, 51 and 21 days, respectively. The excess sludge fraction corresponding to only approximately, 6% of the total influent COD at an HRT of 8.0 h and to 20% at the shorter one (HRT = 3 h). Similar results has been achieved by Seghezzo et al. [43] who found that the excess sludge from the UASB reactor treating presettled sewage at an HRT of 6.3 h was 0.18 kg sludge kg COD removed^{-1} day^{-1} .

Conclusions

1. COD$_{\text{total}}$ removal in the combined UASB–MBBR is significantly influenced by the HRT and OLR. The overall removal efficiencies in this study were 92, 86 and 80% at HRT's of 13.3, 10 and 5.0 h, respectively.
2. Ammonia removal in the MBBR was significantly influenced by the OLR. The overall ammonia removal ranged from 47 to 75% at 4.6 g COD m^{-2} day^{-1} and from 26 to 47% at 7.4 g COD m^{-2} day^{-1}. At OLR of 17.8 g COD m^{-2} day^{-1}, the ammonia removal was largely deteriorated (9–51%).
3. As the overall HRT increased, faecal coliform (FC) removal increased. The mean overall log$_{10}$ reduction was 2.3 and 1.4 at total HRT of 13.3 and 10 h, respectively. There was a very low FC reduction of 0.7 log$_{10}$ at a total HRT of 5.0 h.
4. The sludge yield coefficient in a combined system (UASB–MBBR) operated at a total SRT (21 days for UASB + 5.0 days for MBBR) is almost three times higher than at a total SRT (118.3 days for UASB + 22 days for MBBR).
5. In view of these results, we recommend to use a combined UASB–MBBR system for sewage treatment at an HRT of 8 and 5.3 h, respectively.

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