Desalination and Water Treatment
www.deswater.com
1944-3994/1944-3986 © 2012 Desalination Publications. All rights reserved
doi: 10/5004/dwt.2012.2330

37(2012)350–358
January

Taylor & Francis
Taylor & Francis Group

Sewage treatment in an up-flow anaerobic sponge reactor followed by moving bed biofilm reactor based on polyurethane carrier material

Ahmed Tawfik[a,b,*], Nagwa Badr[b], Enas Abu Taleb[b], Waleed El-Senousy[b]

[a]*School of Energy Resources and Environmental Engineering, Egypt-Japan University of Science and Technology (E-Just), P.O. Box 179, New Borg El Arab City, Postal Code 21934, Alexandria, Egypt*
Tel./Fax: +2-03-4599520; email: Tawfik_8@yahoo.com; Tawfik8@hotmail.com; ahmed.tawfik@ejust.edu.eg
[b]*National Research Center, Water Pollution Research Department, El-Behouth St., Dokki, P.O. Box. 12622, Cairo, Egypt*

Received 11 October 2010; Accepted 30 June 2011

ABSTRACT

Comparison of the performance of an up-flow anaerobic sponge reactor (UASR) versus a classical up-flow anaerobic sludge blanket (UASB) reactor for sewage treatment was investigated. Both reactors were operated at a hydraulic retention time (HRT) of 6.0 h and organic loading rate (OLR) of 2.3 kg COD m^{-3}/d. The results obtained revealed that the UASR produced better effluent quality as compared to the UASB reactor. Residual values of COD_{total}, $COD_{soluble}$ and $COD_{particulate}$ in the treated effluent of UASR were 170 ± 54, 88 ± 36 and 82 ± 41 mg/l, respectively. Corresponding values in the UASB reactor effluent were 247 ± 69, 120 ± 40 and 127 ± 74 mg/l respectively. Furthermore, residual values of VFA-COD, oil and grease were quite less in the effluent of UASR. The removal efficiencies of faecal coliform (FC) and faecal streptococci (FS), in both reactors did not exceed one log_{10}. However, the geometric mean of residual bacterial count was less in case of UASR. Moreover; excess sludge production from UASR reactor was almost half that produced from the UASB reactor. Although, the UASR showed a better performance for COD fractions removal than the UASB reactor, the effluent quality still exceeds the limits for discharge and /or reuse in irrigation purposes. Therefore, moving bed biofilm reactor (MBBR) based on polyurethane carrier material was investigated as a post-treatment unit. The MBBR was operated at an OLR of 7.0 g COD m^{-2}/d and a HRT of 3.6 h. The reactor achieved a substantial reduction of COD_{total}, $COD_{particulate}$ and $COD_{soluble}$ resulting in an average effluent concentration of 63 ± 27, 19 ± 15 and 44 ± 27 mg/l respectively. Nitrate and nitrite data reveal that 68% of the ammonia removed occurred through nitrification. Moreover, the system achieved 70 ± 13% for TKj-N removal resulting an average value of 9.3 ± 3.9 mg/l in the treated effluent. The MBBR system provided an effluent quality of 2.9×10^4 MPN100 ml^{-1} for FC and 1.8×10^3 MPN 100 ml^{-1} for FS corresponding to the removal efficiencies of 99.87 and 99.85% respectively.

Keywords: Sewage; UASB; UASR; Sponge; MBBR; FC; Nitrification; Sludge

1. Introduction

Recently, implementation of expensive and sophisticated technologies for sewage treatment usually fails at short notice, especially in developing countries: no manpower, no finances for operation, maintenance of equipment, and no spare parts etc [1]. There is thus tremendous need to develop reliable and inexpensive technologies for sewage treatment in these low income countries. Anaerobic treatment represents a high potential for sewage treatment, and thus is a suitable and economical solution for most of developing countries [2].

*Corresponding author.

The anaerobic process can serve as a promising alternative, compared to conventional aerobic processes [3]. The up-flow anaerobic sludge blanket (UASB) reactor offers great promise, especially for developing countries that usually have moderate and hot climates [4]. However, problems with UASB reactor treating domestic wastewater always result from washout of biomass which will deteriorate the effluent quality [5].

The immobilization of anaerobic biomass on inert support material represents an important contribution to the improvement of the performance of the anaerobic reactors [6]. The support material acts as a physical protective factor against washout, thus being potentially attractive for biomass retention in the reactor. Biomass immobilization is normally achieved by retention in the void space of a matrix and by adhesion to its surface [7,8]. Weiland and WuIfert found that random support material in up-flow anaerobic reactors is preferred, because the installation costs for the random supported media are much lower than that for modular blocks, along with higher COD removal capacity which attributed to a higher amount of biomass being retained in the randomly packed bed reactor [9]. Huysman et al. reported that porous polyurethane foam (PPF) offers an excellent colonization matrix for the anaerobic reactors [10]. The PPF has a high specific surface area, which can reach up to 2400 m^2/m^3 and a high porosity of 97%. The PPF therefore, enables the retention over 15 gVSS L^{-1} in attached form [11]. Elmitwalli et al. showed that up-flow anaerobic reactor packed with clean vertical sheets of PPF is efficient in removing of $COD_{suspended}$ (>75%) from domestic wastewater even at a short HRT of 0.5 h and at a high up-flow velocity of 10 m/h [12]. In another study; comparison between a UASB reactor and an anaerobic hybrid (AH) reactor for the treatment of pre-settled sewage at an HRT of 8 h and a temperature of 13°C was investigated by Elmitwalli et al. [13]. The media used in the AH reactor consisted of porous polyurethane foam (PPF) sheets with knobs and situated in the sedimentation section of the reactor. The AH reactor removed 64% of the COD_{total} which was significantly higher by 4% than the efficiency obtained in the classical UASB reactor. In another study, the anaerobic filter (AF) reactor with vertical sheets PPF treating domestic wastewater at a temperature of 13°C showed a good removal efficiency of $COD_{suspended}$, viz. 81, 58 and 57% at HRT's of respectively 4, 2 and 3 h [12].

It should be emphasized here that, anaerobic treatment mainly is effective in removing organic matter, soluble and dispersed. For the removal of remaining portion of COD, ammonia and pathogens a proper post-treatment is required. Various aerobic treatment processes have been proposed for post-treatment such as the activated sludge process, trickling filter, sequencing batch reactor, rotating biological contactor, down flow hanging sponge (DHS) and moving bed biofilm reactor (MBBR) [2,14–20]. It is well known that bio-carrier is the core of MBBR, the properties of the carrier material can directly influence the ability for biofilm growth, the quantity of biomass and the effectiveness of treatment. The carrier material for MBBR should be provided with large surface area for micro-organism growth, no congregation and blocking and good dispersion during the operation. In this study, porous polyurethane foam (PPF) warped with perforated polypropylene material is selected.

This investigation has two objectives; the 1st one focuses on the comparison between the efficiency of an up-flow anaerobic sponge reactor (UASR) versus traditional UASB reactor treating domestic wastewater at an HRT of 6.0 h and OLR of 2.3 kg COD m^{-3}/d. While the other objective of this investigation is to assess the efficiency of moving bed biofilm reactor (MBBR) for treatment of the effluent of UASR at an HRT of 3.6 h and OLR of 7.0 g COD m^{-2}/d. Emphasis is afforded to the removal efficiency of the various COD fractions ($COD_{particulate}$ and $COD_{soluble}$) and for ammonia and pathogenic bacteria removal.

2. Material and methods

Three experiments were conducted in this investigation: **1.** comparison between the efficiency of UASR versus classical UASB reactor for removal of COD fractions and pathogenic bacteria at the same operational conditions (T = 17°C; HRT = 6.0 h and OLR = 2.3 kg COD m^{-3}/d) **2.** assessment the performance of MBBR system treating UASR reactor effluent and **3.** overall performance of the combined system (UASR-MBBR) at a total HRT of 9.6 h. All instillations (Figs. 1a and b) were fed with domestic wastewater collected in the combined sewer system of the Dokki area; Cairo, Egypt.

2.1. Domestic wastewater

The used domestic wastewater had the following average characteristics in mg/l: COD_{total} = 597 ± 221, $COD_{soluble}$ = 181 ± 61, $COD_{particulate}$ = 416 ± 220, NH_4–N = 23 ± 6, TKj-N = 56 ± 12, oil and grease = 112.8 ± 42, Total-P = 10.2 ± 3.2. A high content of faecal coliform (FC) and faecal streptococci (FS) in the wastewater was recorded. FC and FS count were $2.6 \times 10^8 \pm 2.1 \times 10^7$ and $1.4 \times 10^7 \pm 1.4 \times 10^5$ MPN 100 ml^{-1} respectively.

2.2. Lab scale anaerobic reactors

A schematic diagram of the experimental setup is presented in Figs. 1a and b. In the 1st experiment a

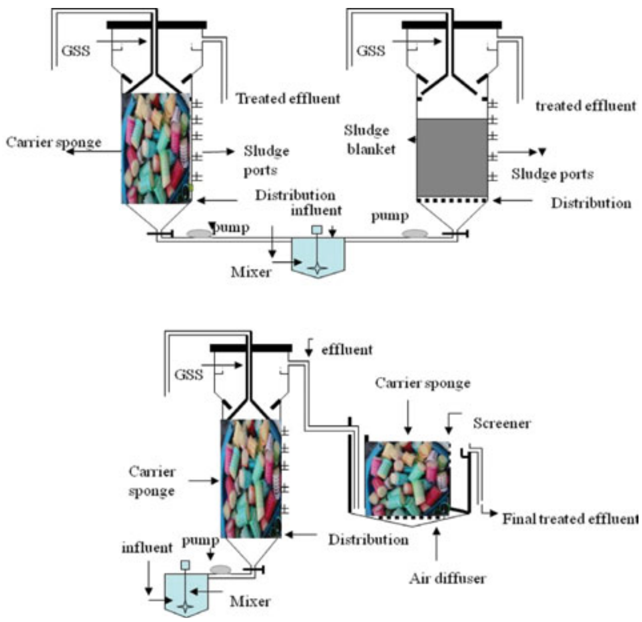

Fig. 1. Schematic diagram of the two experimental units (a) UASR versus classical UASB (b) MBBR treating the effluent of UASR.

two identical anaerobic reactors with a capacity of 5.5 l was used. The 1st reactor is a classical up-flow anaerobic sludge blanket (UASB) reactor. The 2nd reactor is up-flow anaerobic sponge reactor (UASR). The UASR reactor is filled with porous polyurethane carrier material (cylindrical shape) (3.5 mm height & 2.4 diameter) warped with perforated polypropylene material to be moveable even with an attached biomass; hence, reducing the potential of future clogging and channeling problems. The polyurethane carrier material criteria are presented in Table 1. Each reactor is provided with a conical shaped bottom and a gas solid separator (GSS). The height of the reactors are 70 cm and the internal diameter is 10 cm. Ports for obtaining excess sludge and sponge with biomass samples are arranged along the reactor height, the 1st one at 5.0 cm above the base of the column and the others at 15, 25, 40 and 55 cm. Both reactors were inoculated with 3.0 l flocculent sludge with the following characteristics: sludge volume (SV) = 780 ml/l, total solids (TS) = 12 mg/l, volatile solids (VS) = 8.5 mg/l, VS/TS ratio = 0.7 and methanogenic activity = 0.13 g COD $gVSS^{-1}$/d.

Table 1
Characteristics of the porous polyurethane foam (PPF)

Characters	UASR as a pre-treatment	MBBR as a post-treatment
Bulk density (kg/m^3)	30	30
Sponge shape	cylindrical	cylindrical
Effective surface area (m^2)	0.25	0.48
Pore size (mm)	0.63	0.63
Sponge volume (l)	1.3	1.65
Sponge volume/reactor volume (%)	30	63

2.3. MBBR as a post-treatment

A 3 L lab scale moving bed biofilm reactor (MBBR) was connected to the outlet of the UASR. Thus, the influent used for this reactor was already pre-treated anaerobically. An illustration of the lab-scale combined anaerobic/aerobic treatment process is provided in Fig. 1b. 63% of the total reactor volume of MBBR was equipped with polyurethane carrier material. The carriers have a high specific surface area, which could reach up to 256 m^2/m^3 having a high porosity of 90%. Physical properties of the polyurethane carrier material are presented in Table 1. Upon aeration, the polyurethane carrier material was fluidized perfectly with uniform distribution inside the reactor, and the dissolved oxygen (DO) concentration in the reactor was maintained at 2.0 mg/l by adjusting the aeration amount. The reactor was continuously fed with the treated effluent of UASR and operated at an HRT of 3.6 h and OLR of 7.0 g COD m^{-2}/d. The characteristics of biomass of the polyurethane carrier material were weakly determined. The harvested polyurethane carrier material was squeezed by distilled water and then total solids (TS) and volatile solids (VS) were measured in duplicate samples. TS and VS were calculated according to sponge volume.

2.4. Calculation

The sludge residence time (SRT) in both the UASB and UASR was calculated according to the following equation,

$$SRT = \left(\frac{V * X}{Q_w * X_w + Q * X_e} \right)$$

where V, reactor volume; X, average sludge concentration in the UASB reactor or attached biomass in the UASR ($mgVSSL^{-1}$); Q_w, excess suspended sludge (L/d); X_w, concentration of the excess sludge ($mgVSSL^{-1}$); Q, wastewater flow rate (L/d); X_e effluent concentration ($mgVSSL^{-1}$).

2.5. Statistical analysis

The performance of the two reactors was compared using the independent t-test according to Berthouex and

Brown [21]. The confidence intervals were estimated with the student's t-distribution. In the text, the mean values and standard deviations are given in this form: mean value (standard deviation). The 95% confidence interval is given in the format of ± [22].

2.6. Sampling and analytical techniques

Two times per week grab samples were taken at a certain time from the influent and the effluents of each treatment step. All analytical procedures were performed according to APHA [23]. Chemical oxygen demand (COD) was measured by the open reflux method and $COD_{soluble}$ was determined by the same procedure using a sample filtered through a membrane filter (0.45 μm); and $COD_{particulate}$ was calculated by the difference between unfiltered and filtered COD. Ammonia- nitrogen (NH_4–N) was determined by the titrimetric method after a preliminary distillation step and total Kjeldahl nitrogen (TKj-N) was measured using the macro-Kjeldahl procedure, total phosphorus (TP) was determined using the per-sulfate digestion method and molybidate colorimetric technique, while pH, and dissolved oxygen (DO) were measured using portable pH and DO meter. Volatile fatty acids (VFA), sludge analysis, faecal coliform (FC) and faecal streptococci (FS) were measured according to the methods described by APHA [23].

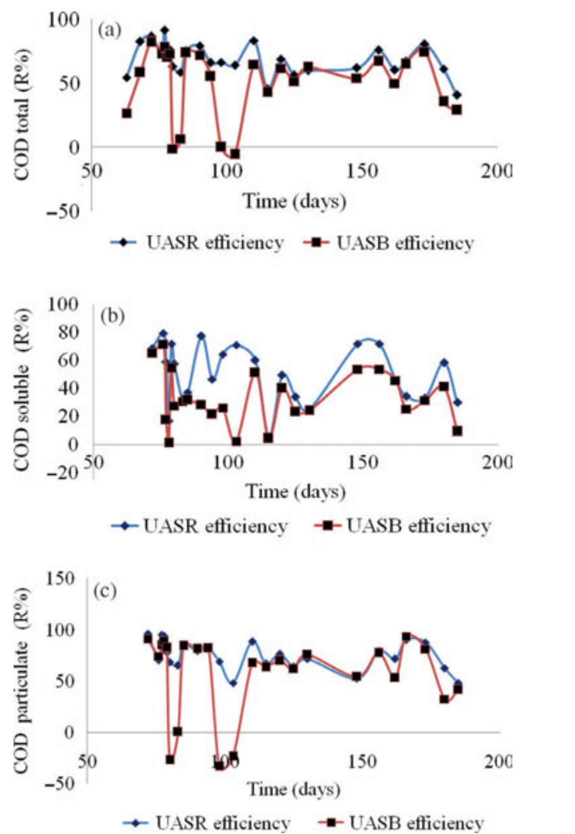

Fig. 2. (a) COD_{total} removal in an UASR versus UASB reactor treating domestic wastewater; (b) $COD_{soluble}$ removal in an UASR versus UASB reactor treating domestic wastewater; (c) $COD_{particulate}$ removal in an UASR versus UASB reactor treating domestic wastewater.

3. Results and discussion

3.1. Comparison between the performance of an UASR with a classical UASB reactor treating domestic wastewater at an HRT of 6.0 h and OLR of 2.3 kgCOD m^{-3}/d

The results presented in Figs. 2a, b and c show that the removal efficiencies of $COD_{total,}$ $COD_{soluble}$ and $COD_{particulate}$ via UASR were significantly higher than that of the classical UASB reactor at levels 0.1, 0.01 and 5%. Removal efficiencies of $COD_{total,}$ $COD_{soluble}$ and $COD_{particulate}$ were 72 ± 12, 51.4 ± 6 and 80 ± 13% for UASR as compared to 50.7 ± 26, 32 ± 19 and 56 ± 38% in the UASB reactor respectively. The higher potentiality of the UASR for removal of organic matter could be attributed to (1) the higher entrapment capacity of particulate matter by porous polyurethane foam (sponge) occupying the reactor (2) the presence of the biofilm improved the bio-sorption of organic matter and consequently biodegradation process (3) the attached biomass in the UASR provides a better contact with wastewater as compared to the suspended sludge in the sludge bed of the classical UASB reactor [2,4,6,18]. Furthermore, once the storage capacity of the classical UASB reactor is exhausted, the sludge bed lost its adsorption or retention capacity and consequently, unintentional washout of sludge together with the effluent was occurred within the operational period of 93–103 d (Figs. 2a and c). This leads to increase the concentration of COD_{total} and $COD_{particulate}$ in the treated effluent of UASB reactor. However, the reactor was recovered within few days as shown in Figs. 2a and c. The results obtained revealed that, UASR is not only a promising alternative to the UASB reactor for sewage treatment at a HRT of 6 h but also to other so far proposed systems, e.g., (1) UASB in combination with a sludge stabilization digester (UASB-Digester system) [24]. The combined system achieved a removal efficiency of 52% for COD_{total}, 79% for TSS and 60% for BOD_5 at 6–8 h of HRT (2) the two stage hydrolysis up-flow sludge bed (HUSB) + expanded granular sludge bed (EGSB) system (3) anaerobic filter (AF) in combination with anaerobic hybrid (AH) system and (4) hydrolytic up-flow sludge bed (HUSB) digester followed by UASB reactor for the treatment of domestic wastewater at HRT varied from 5.7 to 2.8 h for the first stage (HUSB digester) and from 13.9 to 6.5 h for the

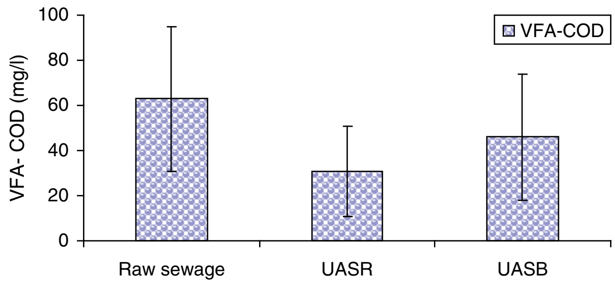

Fig. 3. VFA-COD values in the effluent of UASR and UASB reactor treating domestic wastewater.

second stage (UASB digester) [25–27]. COD_{total} removal varied from 49 to 65% for the total process.

The residual VFA-COD concentration in the final effluent of UASR was 31 ± 20 mg/las compared to 46 ± 28 mg/l for the UASB reactor effluent corresponding to the removal efficiency of 51% for UASR and 27% for UASB reactor (Fig. 3). The removal efficiency of oil and grease (O&G) in the UASB reactor (50.3 ± 3.4%) was significantly lower than that found for the UASR (69.8 ± 2.7%) at a level 5 and 10% (Table 2). This can be attributed to higher entrapment and/or adsorption capacity of the packed material occupied the UASR. On the other hand, the UASB reactor achieved significantly (level 0.01%) higher phosphorous removal efficiency (61.1 ± 5.4%) than the UASR (37.0 ± 3.2%) as shown in Table 2. This could be due to the short sludge residence time imposed to the UASB reactor (51.0 d) and precipitation of phosphorous in a particulate form [8].

The results presented in Table 2 show that the removal efficiency of FC and FS did not exceed one log_{10}. It is however, worth mentioning that the geometric mean of residual counts were insignificantly higher in the UASB reactor effluent compared to that present in the UASR effluent.

3.1.1. Retained biomass and excess suspended sludge from UASR and UASB reactor

The average attached biomass and retained sludge concentration in the UASR and UASB reactor was around 20.0 $gVSSL^{-1}$ sponges and 15.0 $gVSSL^{-1}$ respectively (Table 2). Characteristics of the excess sludge disposed from the two reactors are presented in Table 2. Sludge production in the anaerobic reactors may be attributed to (1) flocculation of non-biodegradable particulate matter, forming the inert sludge mass fraction and (2) the biological sludge mass that is generated as a result of anaerobic conversion in the reactor [22]. The calculated sludge residence time (SRT) was

Table 2
Efficiency of UASR versus UASB reactor treating domestic wastewater at an HRT of 6.0 h and OLR of 3.2 kg COD m^{-3}/d

Samples parameters	Unit	Wastewater	UASR eff.	%R	UASB eff.	%R
O&G	mg/l	112.8 ± 42	34 ± 6.5	69.8 ± 2.7	56 ± 3.4	50.3 ± 3.4
TP	mg/l	10.8 ± 3.2	6.8 ± 2.3	37.0 ± 3.2	4.2 ± 1.2	61.1 ± 5.4
FC	MPN 100 ml^{-1}	$2.6 \times 10^8 \pm 2.1 \times 10^7$	$2.3 \times 10^7 \pm 2.1 \times 10^5$	91.1 ± 1.3	$2.9 \times 10^7 \pm 0.9 \times 10^5$	88.8 ± 2.7
FS	MPN 100 ml^{-1}	$1.4 \times 10^7 \pm 1.4 \times 10^5$	$1.2 \times 10^6 \pm 0.9 \times 10^4$	91.4 ± 1.7	$1.8 \times 10^6 \pm 1.9 \times 10^4$	87.1 ± 3.2
Retained biomass						
TS (105°C)	g/l		30 ± 12		23 ± 8	
VS (550°C)	g/l		20 ± 7.9		15 ± 6.5	
Excess suspended sludge						
TS (105°C)	g/l		0.076 ± 0.02		0.16 ± 0.01	
VS (550°C)	g/l		0.05 ± 0.01		0.1 ± 0.05	
Sludge production	g/m^3		47.5 ± 13		95 ± 18	
Sludge yield coefficient	gVSS g COD $removed^{-1}.d^{-1}$		0.14 ± 0.6		0.23 ± 0.9	
SRT	D		82		51	

longer (82.0 d) in the UASR as compared to that of the UASB reactor (51 d) and consequently, sludge production was lower in the UASR as shown in Table 2. This is reflected in the sludge yield coefficient constituting only 14% of the influent COD in the UASR and up to 23% in the UASB reactor. Likely, A´lvarez et al. found that the overall excess biomass generation from UASB reactor treating domestic wastewater reached 21.6% of influent VSS. Lower excess biomass generation of 7% of influent COD_{total} was recorded in the UASB-Digester system treating domestic wastewater [24,27].

3.2. Performance evaluation of moving bed biofilm reactor (MBBR) treating the effluent of UASR at an HRT of 3.6 h and OLR of 7.0 g COD m^{-2}/d

3.2.1. Removal of COD fractions

The COD_{total}, $COD_{particulate}$ and $COD_{soluble}$ removal data found in MBBR operated at an OLR of 7.0 g COD m^{-2}/d and a HRT of 3.6 h are depicted in Figs. 4a, b and c.

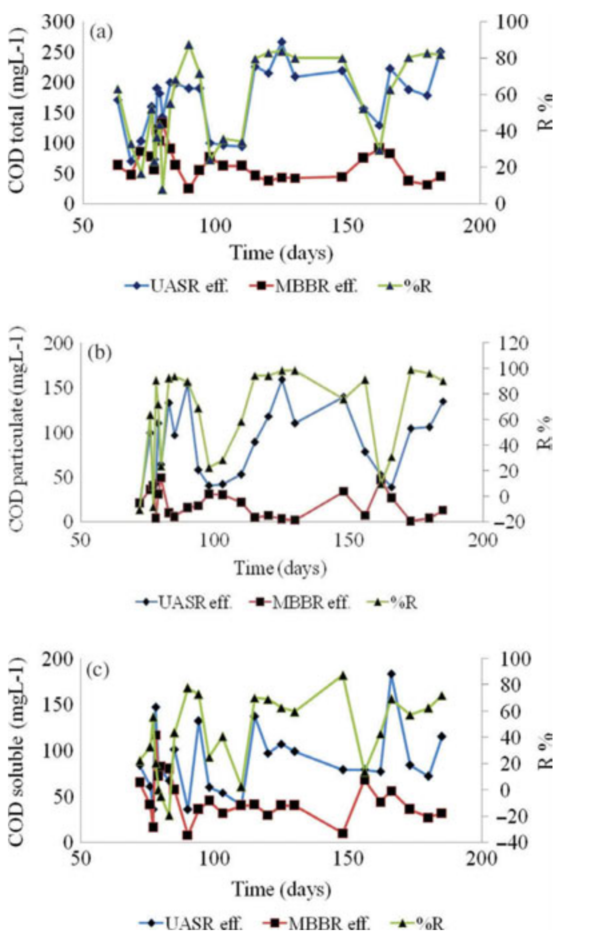

Fig. 4. (a) Time course of CODtotal in the MBBR treating the effluent of UASR; (b) Time course of CODparticulate in the MBBR system treating the effluent of UASR; (c) Time course of CODsoluble in the MBBR system treating the effluent of UASR.

The results clearly show that the MBBR based on polyurethane carrier material achieved a substantial reduction of COD_{total} resulting in an average effluent concentration of 63 ± 27 mg/l. These results are comparable to that obtained by Tawfik et al. and Wang et al. [2,28]. They used MBBR based on polyethylene carrier material for treatment of either anaerobically or chemically pretreated effluent at longer HRT of 6.0 h. In another study, MBBR system treating UASB reactor effluent was operated at an intermittent aeration mode (0.5 h on /2.5 h off) (DO = 9 mg/l during aeration, decreasing to 2.0 mg/l during no aeration), and at an HRT of 2.4 h [29]. The system achieved a removal efficiency of 40–70% for COD_{total}. The results presented in Fig. 4b furthermore, show that the reactor achieved an almost complete removal of $COD_{particulate}$ i.e., only 19 ± 15 mg/l of this COD fraction remained in the final effluent.

This excellent performance towards the removal of dispersed $COD_{particulate}$ can be attributed to the entrapment and/or adsorption followed by hydrolysis and degradation within the biofilm [30]. The $COD_{soluble}$ concentration measured in the treated effluent of the MBBR ranged from 8 to 117 mg/l with an average value of 47 ± 27 mg/l (Fig. 4c).

3.2.2. Nitrification efficiency

The results presented in Fig. 5a reveal that 81 ± 12% ammonia was eliminated at an HRT of 3.6 h and OLR of 7.0 g COD m^{-2}/d. The calculated nitrification rate according to nitrite and nitrate production amounted

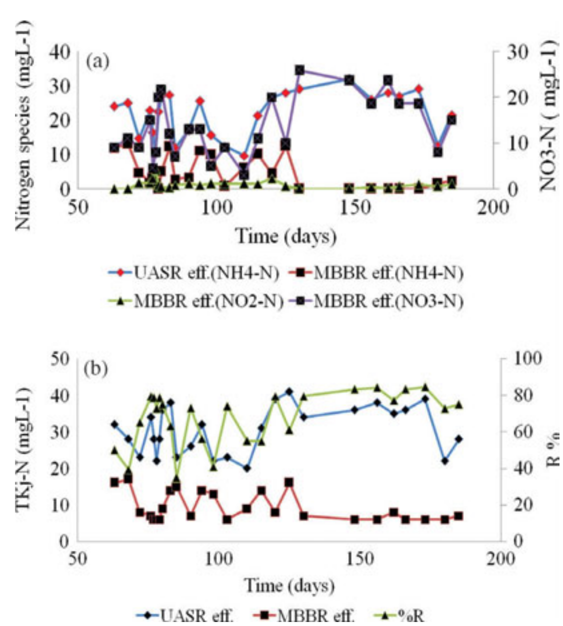

Fig. 5. (a) Nitrogen species in the MBBR system treating the effluent of UASR; (b) TKj-N removal in the MBBR system treating the effluent of UASR.

Table 3
Summary of overall performance characteristics of the combined system (UASR-MBBR) at a total HRT of 9.5 h

TCH Parameters	Unit	Sewage	UASR eff.	%R	MBBR eff.	%R	Overall removal efficiency
COD_{total}	mg/l	597 ± 221	170 ± 54	72 ± 12	63 ± 27	63 ± 12	89.4 ± 12
$COD_{soluble}$	mg/l	181 ± 61	88 ± 36	51.4 ± 6	44 ± 27	50 ± 11	76 ± 13
$COD_{particulate}$	mg/l	416 ± 220	82 ± 41	80 ± 13	19 ± 15	77 ± 13	95.4 ± 10
NH_4-N	mg/l	23 ± 6	24 ± 7	−4.3 ± 2	4.6 ± 3.0	81 ± 12	80 ± 13
NO_2-N	mg/l	–	–	–	1.5 ± 0.9	–	–
NO_3-N	mg/l	–	–	–	14 ± 6.5	–	–
TKj-N	mg/l	56 ± 12	31 ± 7	45 ± 13	9.3 ± 3.9	70 ± 13	83.4 ± 7
FC	MPN 100 ml^{-1}	$2.6 \times 10^8 \pm 2.1 \times 10^7$	$2.3 \times 10^7 \pm 2.1 \times 10^5$	91.1 ± 1	$2.9 \times 10^4 \pm 1.1 \times 10^4$	99.87 ± 1.9	99.98 ± 1.7
FS	MPN 100 ml^{-1}	$1.4 \times 10^7 \pm 1.4 \times 10^5$	$1.2 \times 10^6 \pm 0.9 \times 10^4$	91.4 ± 2	$1.8 \times 10^3 \pm 0.9 \times 10^2$	99.85 ± 1.5	99.98 ± 1.8

to 0.6 ± 0.24 gNm^{-2}/d. Hem et al. investigated the effect of the OLR on the nitrification efficiency in a moving bed biofilm reactor (MBBR) treating municipal wastewater [31]. An OLR of 2–3 $gBOD_7$ m^{-2}/d resulted in a nitrification rate in the range 0.3–0.8 gNO_3-N m^{-2}/d, while at an OLR of 1–2 $gBOD_7$ m^{-2}/d, it was in the range of 0.7–1.2 gNO_3-N m^{-2}/d and it almost stopped at an OLR exceeding 5.0 g BOD_7 m^{-2}/d. The results obtained in Fig. 5a shows that dissolved oxygen (DO) of 2.0 mg/l is sufficient for almost complete nitrification, as also found in earlier MBBR study [28]. The nitrification efficiency of 90%,was achieved in MBBR system treating chemically pretreated effluent at DO level of 2.0 mg/l .On the other hand; Odegaard found that the critical DO is above 2–3 mg/l when nitrification would be occurred in MBBR and the nitrification efficiency increased by 70% when DO concentration increased from 5 to 8 mg/l [32,33].The results in Fig. 5b show that the system achieved a removal efficiency of 70 ± 13% for TKj-N resulting in an average value of 9.3 ± 3.9 mg/l in the treated effluent. The results for nitrogen balance made across the MBBR system indicate that 20.1 ± 12.8% nitrogen remained unaccountable in the system. A higher total nitrogen (TN) removal efficiency of 62.5% was achieved in an MBBR system treating chemically pretreated effluent at an HRT of 6 h and DO = 2 mg/l [28]. These results certainly supported the hypothesis that simultaneous nitrification denitrification (SND) was caused by an oxygen diffusion limitation into the biofilm thereby generating anoxic conditions inside the biofilm. Luostarinen, et al. found that application of intermittent aeration mode (0.5 h aeration (DO = 9 mg/l) and 2.5 h no aeration (DO = 2.0 mg/l) improved the nitrogen removal in MBBR system treating UASB reactor effluent [34]. Under these conditions, 65–70% of nitrogen was removed. Probably, this nitrogen removal was occurred by aerobic denitrification.

3.2.3. Faecal coliform (FC) and faecal streptococci (FS) removal

The results presented in Table 3 show that the MBBR based on polyurethane carrier material provided an effluent quality of 2.9×10^4 MPN 100 ml^{-1} for FC and 1.8×10^3 MPN 100 ml^{-1} for FS, corresponding to the removal efficiency of 99.87 and 99.85% respectively. The precise mechanism of FC removal using porous polyurethane foam (PPF) fed with UASB reactor effluent has been investigated by Tawfik et al. [35]. They found that the most important removal mechanism of FC via PPF was the adsorption process, followed by predation. Die off and sedimentation process was a relatively minor removal mechanism in the system.

3.2.4. Biomass growth in the MBBR

The attached biomass concentration in the MBBR was measured to assess the biofilm growth along the period of the study. The biomass was gradually increased as shown in Fig. 6. During steady state operational conditions the average biomass concentration in the reactor was estimated to be 10 ± 1.2 $gVSSL^{-1}$ sponge. Tawfik et al. investigated the dead and live micro-organisms inside and outside the polyurethane foam (sponge) fed with anaerobic effluent [36]. They found that, the fraction of active bacteria is 66% in the sponge.

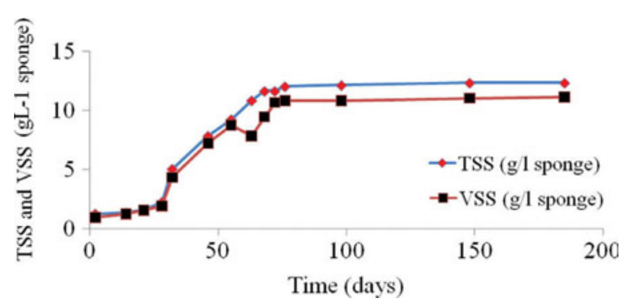

Fig. 6. Biomass growth in the MBBR treating the effluent of UASR.

3.3. Overall efficiency of the combined system consisting of UASR and MBBR for sewage treatment at a total HRT of 9.6 h

The combination of UASB reactor followed by MBBR was proposed by Tawfik et al. as an option for the treatment of domestic wastewater [2]. In this investigation, this process was further developed i.e., up-flow anaerobic sponge reactor was used instead of UASB reactor as a pretreatment step to overcome washout of the sludge and for more efficient removal of particulate and organic matter. Moreover, MBBR based on polyurethane carrier sponge material was investigated as a post-treatment unit for removal of FC and NH_4-N. Table 3 provides a summary of overall performance characteristics. The combination of UASR with MBBR was able to achieve a $COD_{total;}$ $COD_{soluble}$ and $COD_{particulate}$ removal efficiencies of 89.4, 76 and 95.4% at a total HRT of 9.6 h. Thus, very little COD_{total} remained in the final treated effluent (i.e., 63 mgCODL^{-1}) and the quality of this effluent was similar to that obtained by Bodık et al., who investigated a combined anaerobic baffled filter reactor and aerobic post-treatment (hanging polypropylene cords) at a longer total HRT of 19 h [37]. The total process achieved lower removal efficiencies of 78.6–83% for COD and 80.9–92.7% for particulate organic matter. Likely, COD removal ranging from 90 to 94% has been found by Tawfik et al. at longer HRT (10.7 h) using a combined system consisting of UASB–down flow hanging sponge (DHS) system [18]. Sousa and Foresti investigated the combination of UASB and sequencing batch reactor (SBR) for sewage treatment [16]. 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. [14]. The integrated system achieved a removal efficiency of COD (85–93%) at a total HRT of 7.9 h (4.0 h UASB and 3.9 h aerobic reactor).

An intensive nitrification process was observed during the whole period in MBBR reactor. The average removal of the NH_4-N was 81%. Approximately, the same removal efficiency of ammonia was achieved in the MBBR based on polyethylene carrier material treating anaerobically pretreated sewage at longer HRT of 5.3 h [2]. The results obtained with UASR–MBBR system, operated at a total HRT of 9.6 h show a high percentage removal of FC (99.98%), and FS (99.98), corresponding to 3.95 and 3.89$\log_{10}$ reduction respectively. 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 [38]. The removal efficiency of 99.8% for FC by a combined process (UASB–DHS) system was obtained by Tawfik et al. [4]. The major part of FC was removed in the MBBR system treating UASR effluent indicating that, the biofilm play a role for removal of FC. Sylvaine et al. 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 [39]. Biofilm without protozoa and a clean surface each removed similar quantities of bacteria.

4. Conclusions

- UASR produced a better effluent quality than classical UASB reactor treating domestic wastewater at the same operating conditions (HRT= 6 h & OLR = 2.3 kg COD m^{-3}/d).The removal efficiencies of COD-total; CODsoluble and CODparticulate were 72 ± 12, 51.4 ± 6 and 80 ± 13% for UASR as compared to 50.7 ± 26, 32 ± 19 and 56 ± 38% in the UASB reactor respectively.
- The sludge production from the classical UASB reactor is almost double that of UASR reactor. Therefore, the use of UASR as a pretreatment step for domestic wastewater treatment is recommended. However, optimization of UASR treating domestic wastewater is required.
- The MBBR based on polyurethane carrier material treating the effluent of UASR achieved a substantial reduction of CODtotal, CODparticulate and COD soluble resulting in an average effluent concentration of 63 ± 27, 19 ± 15 and 44 ± 27 mg/l respectively. 81 ± 12% ammonia was eliminated. Nitrate and nitrite data reveal that 68% of the ammonia removed occurred through nitrification. Moreover, the system achieved 70 ± 13% for TKj-N removal resulting an average value of 9.3 ± 3.9 mg/l in the treated effluent. The MBBR provided an effluent quality of 2.9 × 10^4 MPN100 ml^{-1} for FC and 1.8 × 10^3 MPN100 ml^{-1}for FS, corresponding to the removal efficiency of 99.87 and 99.85% respectively. In view of the results obtained here; we recommended to use MBBR based on polyurethane carrier material for post-treatment of the effluent of UASR treating domestic wastewater at an HRT of 3.6 h and OLR of 7.0 g COD m^{-2}d.

Acknowledgement

The 1st author would like to express his gratitude to Prof. Dr. M. Kamel technical assistance.

References

[1] S. Aiyuk, I. Forrez, D.K. Lieven, A. van Haandel and W. Verstraete, Anaerobic and complementary treatment of

domestic sewage in regions with hot climates-A review, Bioresour. Technol., 97 (2006) 2225–2241.

[2] A. Tawfik, F. El-Gohary and H. Temmink, Treatment of domestic wastewater in an Up-flow Anaerobic Sludge Blanket (UASB) reactor followed by Moving Bed Biofilm (MBBR)Reactor, Bioprocess Bio-systems Engineering journal,33(2) (2010) 267–276.

[3] G. Lettinga, Anaerobic digestion and wastewater treatment systems, Antonie van Leeuwenhoek, 67 (1995) 3–28.

[4] A. Tawfik, F. Gohary, A. Ohashi and H. Harada, Optimization of the performance of an integrated anaerobic-aerobic system for domestic wastewater treatment, Water Sci. Technol., 58(1) (2008) 320.

[5] M.M. Alves, J.A. Vieira, R.M. Pereira and A. Pereiram Mota, Effect of lipids and oleic acid on biomass development in anaerobic fixed bed reactors,?PART I: biofilm growth and activity, Wat. Res., 35(1) (2001) 255±263.

[6] H. El-Kamah, A. Tawfik, M. Mahmoud and H. Abdel-Halim, Treatment of high strength wastewater from fruit juice industry using integrated anaerobic/aerobic system, Desalination, 253 (2010) 158–163.

[7] F. El-Gohary, A. Tawfik, M. Badawy and M. Ali, Potentials of anaerobic treatment for catalytically oxidized olive mill wastewater (OMW), Bioresour. Technol., 100(7) (2009) 2147–2154.

[8] A. Tawfik, M. Sobhey and M. Badawy, Treatment of a combined dairy and domestic wastewater in an up-flow anaerobic sludge blanket (UASB) reactor followed by activated sludge (AS system), Desalination, 227(1–3) (2008) 167–177.

[9] P. Weiland and K. WuIfert, Anaerobic treatment of?silage using different pilot-scale fixed bed reactors in?up and downflow mode of operation, Proc. 5th Int.?Symp. On Anaerobic Digestion, Bologna, Italy, May (1988) pp.147±154.

[10] P. Huysman, P. Meenen, P. Assche and W. Verstraete, Factors affecting the colonization of non porous and porous packing materials in model up-flow methane reactors, Biotechol. Lett.. 5(9) (1983) 643−648.

[11] A. Tilche and M.M. Vieira, Discussion report on reactor design of anaerobic filters and sludge bed reactors, Wat. Sci. Technol., 24(8) (1991) 193–206.

[12] T. Elmitwalli, M. van Dun, G. Zeeman, H. Bruning and G. Lettinga, The role of filter media in removing suspended and colloidal particles in anaerobic reactor treating domestic sewage, Biores. Technol., 72(3) (2000) 235–240.

[13] T. Elmitwalli, M. Zandvoort, G. Zeeman, H. Bruning and G. Lettinga, Low temperature treatment of domestic sewage in up-flow anaerobic sludge blanket and anaerobic hybrid reactors, Wat. Sci. Technol., 39(5) (1999) 177–185.

[14] M.V. Sperling, V.H. Ferrier and C.A.D. Chernicharo, Performance evaluation of an UASB-activated sludge system treating municipal wastewater, Wat. Sci. Tech., 43(11) (2001) 323–328.

[15] A.C. Chernicharo and M.C.P. Nascimento, Feasibility of a pilot – scale UASB/trickling filter system for domestic sewage treatment, Wat. Sci. Tech.. 44 (4) (2001) 221–228.

[16] J.T. Sousa and E. de, Foresti, Domestic sewage treatment in an up-flow anaerobic sludge blanket sequencing batch reactor system, Wat. Sci. Tech., 33 (3) (1996) 73–84.

[17] A. Tawfik, A. Klapwijk, F. El-Gohary and G. Lettinga, Potentials of using a rotating biological contactor (RBC) for post-treatment of anaerobically pre-treated domestic wastewater, Biochem. Eng. J., 25 (2005) 89–98.

[18] A. Tawfik, A. Ohashi and H. Harada, Sewage treatment in a combined up-flow anaerobic sludge blanket (UASB)- Down flow hanging sponge (DHS) system, Biochem. Eng. J., 29(3) (2006) 210–219.

[19] A. Ruiz-Marin, S.C. Garcia, J.Z. Loria, F. Solana and Y.C. Lopez, Assessment of *Luffa cylindrica* as support in biofilms reactors for the biological treatment of domestic wastewater, Water Air Soil Pollut., 199 (2009) 13–21.

[20] M. Rodgers and X.M. Zhan, Moving medium biofilm reactors, Environmental Science and Bio/Technology, 2 (2003) 213–224.

[21] P.M. Berthouex and L.C. Brown, Statistics for environmental engineers, Florida, USA: CRC Press LCC, 1994.

[22] N. Mahmoud, G. Zeeman, H. Gijzen and G. Lettinga, Anaerobic sewage treatment in a one-stage UASB reactor and a combined UASB-Digester system, Water Res., 38 (2004) 2348–2358.

[23] APHA, Standard Methods for the Examination of Water and Wastewater 21st ed., American Public Health Association/ American Water Works Association/Water Environment Federation (2005) Washington DC, USA.

[24] J.A. A'lvarez, Anaerobic Treatment of Municipal Wastewater on a Pilot-Scale Plant, Ph.D. Thesis (2004) University of A Corun˜ a, A Corun˜ a, Spain.

[25] G. Zeeman, W. Sanders, K.Y. Wang and G. Lettinga, Anaerobic treatment of complex wastewater and waste activated sludge—application of an upflow anaerobic solid removal (UASR) reactor for the removal and prehydrolysis of suspended COD, Water Sci. Technol., 35 (1997) 121–8.

[26] T.A. Elmitwalli, K.L.T. Oanh, G. Zeeman and G. Lettinga, Treatment of domestic sewage in a two-step anaerobic filter/ anaerobic hybrid system at low temperature, Water Res., 36 (2002) 2225–32.

[27] J.A.A ´ lvarez, E. Armstrong, M. Go´mez and M. Soto, Anaerobic treatment of low-strength municipal wastewater by a two-stage pilot plant under psychrophilic conditions, Bioresour. Technol., 99 (2008) 7051–7062.

[28] X.J. Wang, S.Q. Xia, L. Chen, J.F. Zhao, N.J. Renault and J.M. Chovelon, Nutrients removal from municipal wastewater by chemical precipitation in a moving bed biofilm reactor, Process Biochem., 41(4) (2006) 824−828.

[29] S. Luostarinen, S. Luste, L. Valentı´n and J. Rintala, Nitrogen removal from on-site treated anaerobic effluents using intermittently aerated moving bed biofilm reactors at low temperatures, Water Res., 40 (2006) 1607–1615.

[30] T. Larsen and P. Harremoes, Degradation mechanisms of colloidal organic matter in biofilm reactors, Water Res., 28(6) (1994) 1443–1452.

[31] I. Hem, B. Rusten and H. Ødegaard, Nitrification in a moving bed biofilm, Water res., 28 (1994) 1425−1433.

[32] H. Odegaard, Advance compact wastewater treatment based on coagulation on moving bed biofilm processes, Water Sci. Technol., 42(12) (2000) 33–48.

[33] B. Rusten, O. Kolkinn and H. Ødegaard, Moving bed biofilm?reactors and chemical precipitation for high efficiency treatment?of wastewater from small communities, Water Sci. Technol., 35(6) (1997) 71–79.

[34] S. Luostarinen, S. Luste, L. Valentı´n and J. Rintala, Nitrogen removal from on-site treated anaerobic effluents using intermittently aerated moving bed biofilm reactors at low temperatures, Water Res., 40 (2006) 1607–1615.

[35] A. Tawfik, A. Ohashi and H. Harada, The influence of physical-chemical and biological factors on the removal of Faecal coliform through down flow hanging sponge (DHS) system treating UASB reactor effluent, Water Research Journal, 40(9) (2006) 1877–1883.

[36] A. Tawfik, H. Ohashi and H. Harada, Effect of sponge volume on the performance of down-flow hanging sponge (DHS) system treating UASB reactor effluent, Bioprocess bio- systems engineering journal, 33 (2010) 779–785.

[37] I, Bodı´k, K. Kratochvı´l, E. Gaparikova and M. Hutnˇan, Nitrogen removal in an anaerobic baffled filter reactor with aerobic posttreatment, Bioresour. Technol., 86(1) (2003) 79–84.

[38] A. Tawfik and A. Klapwijk, Polyurethane rotating disc system for post-treatment of anaerobically pre-treated sewage, J. Environ. Manage., 91 (2010) 1183–1192.

[39] C. Sylvaine, A. Yves, L. Abdel and L.C. Pierre, Bacteria removal in septic effluent: influence of biofilm and protozoa, Water Res., 40 (2006) 3109–3114.