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Utilization of BioWin™ simulator in simulating the integrated anaerobic fluidized bed-UASB/aerobic moving bed biofilm system

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ABSTRACT

BioWin simulation model has been applied to two different anaerobic/aerobic systems. The first system was an anaerobic fluidized bed coupled with an up-flow anaerobic sludge blanket (UASB) reactor followed by a hybrid moving bed biofilm reactor (AFB-UASB/HMBBR). The second system was classical UASB followed by an activated sludge process (UASB/ASP). The model has been validated against the experimental results obtained from pilot plant reactors which are used to treat domestic wastewater at different hydraulic retention times (HRTs). The BioWin model showed a good representation of the measured data for the chemical oxygen demand (COD) for the two simulated systems. On the other hand, the applied model could give an approximate prediction for the removal ratio of the overall treatment process, including all measured parameters (biochemical oxygen demand (BOD), total suspended solids (TSS)) except for the ammonia removal ratio. Two pilot plants consisting of a combined AFB-UASB/HMBBR and UASB/ASP were tested for treating domestic wastewater. The investigated systems were operated for 116 d at a retention time of 4.5, 2.25 and finally at 1.5 h. The efficiency of the anaerobic stage in terms of COD ranged from 40% to 45%, while it was 40%–50% for BOD and 40%–43% for TSS. The overall removal efficiencies for the COD, BOD, and TSS in the system were 89%–93%, 90%–93%, and 91%–92% respectively. The experimental results of the present study indicated that the integrated AFB-UASB/HMBBR system that is applied to treat domestic wastewater is effective in the removal of COD, BOD as well as TSS fractions even at low HRT of 1.5 h. Also, the system shows high stability and performance recovery against operational problems.

Keywords: Simulation; BioWin; Anaerobic fluidized bed; Up-flow anaerobic sludge blanket; Activated sludge process; Hybrid moving bed biofilm reactor; Domestic wastewater treatment

1. Introduction

Aerobic methods of wastewater treatment such as activated sludge process (ASP) and hybrid moving bed biofilm reactor (HMBBR) have shown operational flexibility as well as high organic and nutrient removal. However, these methods have drawbacks including high capital, operating costs and large amounts of sludge that need to be treated [1,2]. To overcome these drawbacks, anaerobic treatment methods, especially the high rate anaerobic processes such as upflow anaerobic sludge blanket (UASB) reactor, were introduced as a viable alternative to the conventional aerobic treatment methods. The high rate anaerobic processes have many advantages including the easiness of operation, the low cost in construction and operation, the biogas production, the small footprint, and the production of low amounts of excess sludge [3,4]. Nevertheless, like many high-rate systems, the water quality of the effluent from the UASB reactors does

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not meet the environmental legislation. Thus, these reactors are usually integrated with additional treatment units to satisfy the environmental regulations.

It is well known that the performance of UASB reactors depends strongly on the characteristics and concentration of the sludge blanket. Thus, the performance of a UASB reactor can be enhanced by providing a surface area of the biofilm carriers, which can be achieved by the addition of certain media (material) to the reactor [5]. The added material can be either in a packed form (fixed bed reactor) or in a fluidizing one (fluidized-bed reactor). Compared to fixed bed reactors, fluidized bed reactors have the following advantages: (i) they incorporate the best features of suspended and attached growth into one process, (ii) they are more stable, easy in operation and highly efficient in operating processes. Various biofilm carrier materials (including sand, glass beads, plastics, ceramic tiles, electric corrugated pipe, etc) have been investigated by researchers [6]. In the present study, plastic media were used as packing material for the fluidization process.

As mentioned above, the high rate of UASB treatment reactors requires a post-treatment process to achieve the desired effluent standards. This can be accomplished with the combined anaerobic/aerobic systems, which can comply with the discharge standards in terms of carbon and ammonium removal. Several post-treatment systems were tested by many researchers including ASP, the sequencing batch reactor, trickling filter (TF) and the submerged aerated biofilter [4,7–9]. The combined UASB–aerobic systems can lead to a high reduction in sludge production and energy consumption [10]. Many researchers recommended the HMBBR system for the post treatment and reported that it has achieved a high performance [11–13].

In the present study, an integrated anaerobic fluidized bed coupled with UASB reactor followed by HMBBR as a post-treatment (AFB-UASB/HMBBR) system will be characterized and simulated.

The UASB reactor was modified by adding moving (fluidized) plastic media. The media provided surface area for the additional anaerobic bacteria growth besides the sludge blanket. This was proposed to enhance reactor performance. The post-treatment unit was an HMBBR in which the plastic media were used as a supporting surface for aerobic bacteria growth.

To study the potential of the (AFB-UASB/HMBBR) process and estimate its prospects for biotechnology, both physical and mathematical simulations are required.

The mathematical simulation is a popular technique that is used to study the dynamic behavior of the wastewater treatment process. This technique provides more accurate predictions within a shorter time at a reduced cost. Mathematical simulation is necessary for a better understanding of the wastewater treatment plant which can, in turn, help to optimize the different operational parameters and maximize the plant efficiency [14]. There are several commercial software products, including BioWin, GPS-X, and WEST, used in modeling the biological processes involved in wastewater treatment. In the present study, the BioWin 5.3 (Envirosim, Canada) was used to conduct the simulation). BioWin is used to design, upgrade, and optimize all types of WWTPs with physical, biological, and chemical process models [14,15].

BioWin is successfully used to simulate several processes for municipal wastewater treatment plants, including the ASP, the integrated fixed-film activated sludge (IFAS) process, the moving bed biofilm reactor (MBBR), and the biological aerated filter (BAF) systems [16,17]. BioWin was also applied to assess six different wastewater treatment models (based on two technologies: a TF and an activated sludge). For all models, each process was operated one by one in the BioWin simulation to determine the most appropriate treatment system [15]. BioWin software was also used to simulate the biofilm membrane bioreactor (BFMBR) that was used for the treatment of dairy wastewater at different hydraulic retention times (HRTs). It was concluded that there is a good agreement between the predicted and the measured values for the effluent chemical oxygen demand (COD), total nitrogen and total phosphorus under different HRTs [18].

According to the available review, the BioWin simulator is rarely used to simulate the integrated UASB/ASP system and it has never been used to simulate the AFB-UASB/HMBBR system. The present study aims to develop and simulate the (AFB-UASB/HMBBR) system using the BioWin simulator. In addition, the conventional UASB/ASP system will be simulated. The applied model will be validated against the experimental results obtained from pilot plant reactors which are used to treat domestic wastewater at different HRT. To the best of the authors' knowledge, the proposed system configuration was not investigated before. The validated model can be further used to design full-scale plants.

2. Materials and methods

The BioWin simulator (version 5.3, EnviroSim Associates Ltd., Canada) was used to simulate two integrated anaerobic/aerobic processes (AFB-UASB/HMBBR) as well as the processes (UASB/ASP) for domestic wastewater treatment. BioWin is a computer simulation package that is able to dynamically simulate the wastewater treatment process. BioWin uses a generally activated sludge/anaerobic digestion model (ASDM), which allows users to model different aerobic and anaerobic biological processes simultaneously. The BioWin ASDM has more than fifty state variables and over eighty process expressions. The BioWin model is unique in that it merges the ASP with the anaerobic biological one. The BioWin simulator presently includes two modules: A steady-state module, and an interactive dynamic simulator [19,20].

Fig. 1 shows the flow diagram of the experimental model. The present arrangement of the AFB-UASB/HMBBR system has been depicted in BioWin. The AFB integrated with the UASB reactor was constructed as a cylindrical tank with a 465 L volume. The inflow manifold was introduced at the reactor bottom to ensure even influent distribution. The fluidized bed system has been filled partially with plastic media (500 m^2/m^3 specific surface area), which represents 23% of the reactor volume and fills the middle third of the reactor above the sludge blanket. To ensure fluidization of the media, the effluent was recycle using a pump from the top third of the reactor and the recycled stream entered the reactor at a level of 35 cm above the reactor bottom.

The HMBBR system consisted of an aerobic bioreactor with a working volume of 525 L and a settling tank with a volume of 150 L. The same plastic media were used in the aerobic bioreactor with a filling ratio 30% of the reactor volume. All the activated sludge from the settling tank was circulated to the HMBBR tank while the excess sludge was withdrawn from the HMBBR and was fed to the AFB-UASB reactor.

It is worth mentioning that the BioWin model is a COD-based model, that is, the main input parameters are the total COD and total Kjeldahl nitrogen (TKN) in addition to their fractions. These inputs were used to predict all other parameters including biochemical oxygen demand (BOD), total suspended solids (TSS), and ammonia.

BioWin dynamic simulation was implemented to simulate the two tested systems. BioWin simulator was able to simulate the reality of complex processes with reasonable efficiency. The processes were simulated using the same dimensions, wastewater characteristics, temperatures, and flow rates of the experimental pilot plant. Fig. 2 depicts the BioWin configuration used to simulate the AFB-UASB/HMBBR system as well as the UASB/ASP system.

2.1. BioWin simulation of UASB/ASP

UASB/ASP system was simulated using BioWin 5.3 software. All system components were included in the simulation model. Fig. 2a shows the BioWin 5.3 layout of the pilot plant model. The wastewater was introduced using the COD influent element. It was utilized to set up the influent wastewater characteristics. COD influent was adjusted to be a variable input type. The different values of influent characteristics of wastewater were inserted using the same measured experimental values in the corresponding dates and time. Parameters (like COD, TKN, pH), and the discharge were adjusted for each run. Influent wastewater stream was directed to the UASB.

UASB unit is not found in the BioWin simulator, so The BioWin configuration used to simulate a UASB process

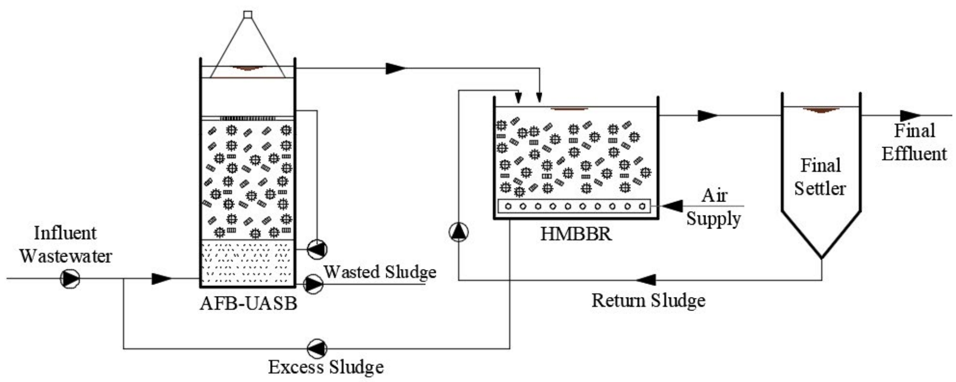

Fig. 1. Flow diagram of the experimental model.

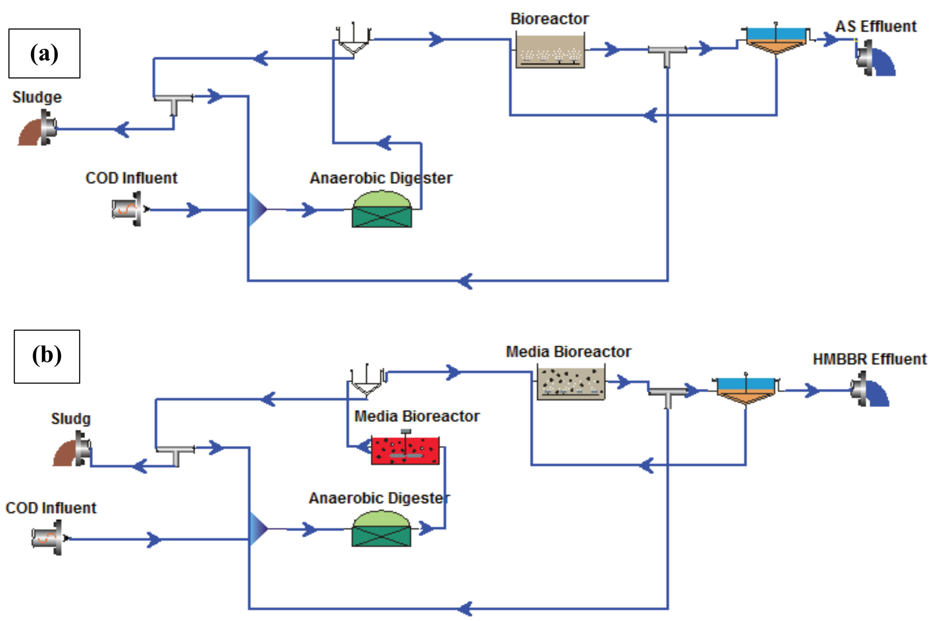

Fig. 2. BioWin model layout for (a) UASB/ASP and (b) AFB-UASB/HMBBR (adapted from BioWin 5.3).

is shown in Fig. 2. One of the most significant aspects of this configuration is that the UASB process is represented by an anaerobic digester element coupled to a point settler element [21]. The anaerobic digester element was operated with a scheduled temperature pattern using the actual measured ambient temperature. The point settler element was operated with a constant removal percent (from 99.8% to 99.9%) to allow accumulation of a TSS concentration in the digester that is typical of these processes. The underflow rate of the point settler is set to allow a reasonably high recirculation ratio in the UASB for each run.

On the underflow pipe of the point settler, there was a splitter to get rid of the excess sludge. Having passed the anaerobic unit, the wastewater flowed into an aeration tank then into a settling tank. The settling tank was considered an ideal clarifier. The splitter is shown after the aeration tank was used to allow a reasonably high recirculation ratio of waste activated sludge to the UASB.

2.1.1. Wastewater characterization and model calibration

Raw wastewater characterization was performed according to the STOWA protocol for wastewater characterization [22]. A measurement campaign, for 7 d, was developed to assure a well working model. BioWin's typical and measured fractions of raw wastewater are listed in Table 1. Stoichiometric and kinetic parameters, for the same source of wastewater, were measured by Abdo et al. [23] the main measured and calibrated parameters used in the present simulation are shown in Table 1.

BioWin simulation started first with the default values of stoichiometric and kinetic parameters and wastewater fractions of raw water. Then the measured and calibrated parameters were applied. The model calibration was performed according to the sequence advised by STOWA protocol for calibration [22]. A sensitivity analysis study performed by Liwarska-Bizukojc and Biernacki [24] was the guidance for adjusting the parameters shown in Table 1.

With the same concept and configuration, the AFB-UASB/HMBBR system was simulated. The AFB-UASB as shown in Fig. 2b was simulated by an anaerobic digester element coupled to media bioreactor and then to a point settler element. HMBBR reactor was used instead of the conventional ASP. The media bioreactor was simulated using the same dimensions and flow rates of the experimental pilot plant. The media volume used in the BioWin simulation was 30% of the reactor volume.

2.2. Experimental system description and operational conditions

An experimental program was executed in which two different pilot-scale systems (AFB-UASB/HMBBR and UASB-ASP) were set-up and tested in parallel. This allowed the two systems to be operated and tested under the same climatic conditions and the same influent wastewater characteristics. The experimental work was performed to check the effect of several parameters on the physical phenomena, including the effect of fluidized media on the UASB performance, the effect of the post-treatment unit, the effect of the moving bed on the ASP, and the effect of HRT on the integrated systems. The results of the experimental work were utilized for the validation of the applied simulation model.

The two systems were fed with raw wastewater from the Al-Qenayat wastewater treatment plant located on Zagazig (Sharkia, Egypt). The fed wastewater was taken after the grit removal unit. Each of the two anaerobic reactors (AFB-UASB and UASB) was configured as a cylindrical tank with a 465 L volume. The measured samples were collected along with the height of the UASB reactor.

The activated sludge reactor was used as a post-treatment unit for the classical UASB. For the AFB-UASB reactor, the post-treatment unit was the HMBBR reactor. The settled activated sludge of the final settling tank was circulated to the aeration tank. The excess aerobic sludge withdrawn from the aeration tank was fed to the bottom of the anaerobic reactor. The sludge retention time (SRT) on the UASB reactor was approximately 60 d, which was adequate for sludge stabilization. The stabilized sludge was removed from the UASB reactor once a week.

The AFB-UASB/HMBBR system was operated for 116 d through which the HRT changed from 4.5 to 2.25 and then to 1.5 h. while for the UASB-ASP system, the HRT changed from 4.5 to 2.25 h. The sludge retention time (SRT) for the anaerobic reactor was 60 d and it was only 10 d for the aerobic reactor. The reactors were operated at the ambient

Table 1
An outline of calibrated BioWin model parameters (Only changed parameters are listed)

Parameter		Default value	Adopted value
Characterization of raw wastewater			
Fbs (gCOD/g of total COD), readily biodegradable (including acetate)		0.16	0.216
Fus (gCOD/g of total COD), non-biodegradable soluble		0.05	0.03
Fup (gCOD/g of total COD), non-biodegradable particulate		0.13	0.264
Calibrated stoichiometric and kinetic parameters			
Heterotrophic bacteria	Max. spec. growth rate (1/d)	3.2	4.88
	Aerobic decay rate (1/d)	0.62	0.64
Nitrifying bacteria	Max. spec. growth rate (1/d)	0.9	0.88
Stoichiometric parameters	Ordinary heterotrophic yield (aerobic)	0.666	0.57
	Ammonia oxidizing yield (mgCOD/mgN)	0.15	0.24

temperature. Table 2 outlines the details of design and operation regarding this configuration, including food/microbe (F/M) ratio and organic loading rate (OLR).

2.2.1. Sampling and analytical methods

The samples were taken from the system inlet to characterize the influent wastewater. Also, samples were taken from the effluent of each unit to evaluate its performance. The air and water temperature, pH, and dissolved oxygen were measured daily on-site. The COD, BOD, TSS, and ammonium were determined according to the Standard Methods for the examination of water and wastewater [25]. The biomass concentration in the ASP and HMBBR reactors expressed as TSS and volatile suspended solids (VSS), was also measured. For the anaerobic reactors, samples were collected and measured along with the reactor height (at heights of 10, 35, 60, 105, and 125 cm). The dissolved oxygen (DO) levels were monitored with a DO meter to keep the DO level around 2 mg/L in the aeration tanks. The temperature was measured by a thermocouple probe connected to a thermometer. The pH was measured by WTW inoLap pH level 2 instruments. The steady-state in this study is defined as a condition under which every parameter does not change significantly (±10%) for at least one week.

2.3. Model validation

The applied model was dynamically validated using the experimental measurements. The calibrated model was used for simulating the whole system to investigate the ability of the BioWin simulator to deal with such complicated systems. Several attempts have been made to adjust the operational factors to improve the applied model results.

The BioWin prediction accuracy was evaluated by the calculation of the average relative deviation (ARD) [26]:

$$\text{ARD} = \frac{1}{N} \times \sum_{i=1}^{N} \frac{\left|\left(m_i - p_i\right)\right|}{m_i} \times 100\%$$

where m_i is the measured value, p_i is the predicted value and N is the number of the observations. For the results obtained from the dynamic simulations, including COD, BOD_5, TSS and NH_3, the ARD values were calculated.

3. Results and discussion

The characteristics of the influent wastewater utilized in the present experimental work are presented in Table 3.

The experimental results were collected after a startup period extended for about 2 months. On the other hand, it took 10 d to reach a steady-state after changing the HRT. The BioWin simulator took about 50 d to reach a steady-state as a startup period. Also, the same period was required for each HRT to reach a steady state. The experimental results were compared with the computational ones of the applied mathematical model using the BioWin simulator. These results presented and discussed below.

3.1. COD removal

Fig. 3 shows the experimental vs. predicted COD results of the AFB (integrated with UASB reactor and coupled with

Table 2
Reactors (systems) operating parameters

System	Run	HRT (h)		Flow rate (m^3/d)	F/M		OLR (kg COD/m^3 d)		Operating period
		Overall system	UASB		Anaerobic	Aerobic	Anaerobic	Aerobic	
AFB-UASB/ HMBBR	I	4.5	2.1	5.3	0.7–2.3	1.1–2.0	3.2–10.8	2.2–4.1	16 September–25 October
	II	2.25	1.05	10.6	4.8–10.5	4.6–6.7	9.6–21.0	6.3–9.1	26 October–5 December
	III	1.5	0.7	15.9	8.0–17.2	11.2–20.1	15.4–33.1	9.1–16.2	6 December–10 January
UASB/ASP	I	4.5	2.1	5.3	0.4–1.4	1.0–2.8	3.2–10.8	1.9–5.6	16 September–5 December
	II	2.25	1.05	10.6	1.5–3.2	3.0–6.6	10.3–22.1	4.7–10.5	6 December–10 January

Table 3
Influent wastewater characteristics

Parameter	HRT (h)	COD (mg/L)	BOD_5 (mg/L)	NH_3 (mg/L)	TSS (mg/L)	pH	T (°C)
			HYBRID UASB-HMBBR				
Run I	4.5	280–949	218–484	6–23.5	263–329	7–7.5	15–27
Run II	2.25	419–920	290–500	5–37	268–331	7–7.5	15–21
Run III	1.5	450–969	455–558	7–24	216–367	7–7.5	13–19
			UASB-ASP				
Run I	4.5	280–949	218–500	5–37	263–331	7–7.5	15–27
Run II	2.25	450–969	455–558	7–24	216–367	7–7.5	13–19

HMBBR). The presented data show the performance of the AFB-UASB and the HMBBR reactors during the whole operation period of 116 d. During the operation period, the HRT was decreased from 4.5 to 2.25 h and finally to 1.5 h. As the figure indicates, the predicted results coincide approximately with the measured experimental results for most days of operation. Fig. 4 shows the experimental results for the UASB/ASP system compared with the predicted COD values for HRTs (4.5 and 2.25 h). As depicted in the figure, there is a good agreement between the experimental data and the model's predictions.

Table 4 presents the arithmetic average values of the results for the AFB-UASB/HMBBR and the UASB/ASP systems. For the integrated AFB-UASB/HMBBR system, according to the table, the predicted removal ratios following the anaerobic unit were 50%, 42%, and 32% respectively for HRTs of 4.5, 2.25, and 1.5 h. The experimental removal ratios were 45%, 38%, and 40% for HRTs of 4.5, 2.25 and 1.5 h. On the other hand, the table indicates also that the removal ratios following the aerobic unit (the overall system removal ratio) were 94%, 90.5%, and 88% respectively for HRTs of 4.5, 2.25, and 1.5 h while the overall experimental removal

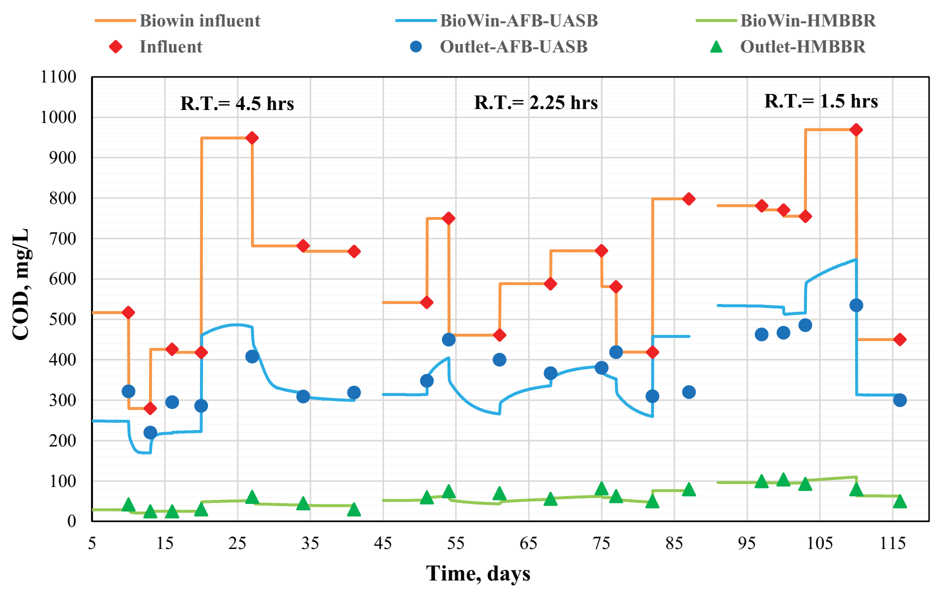

Fig. 3. Predicted vs. measured COD for AFB-UASB/MBBR.

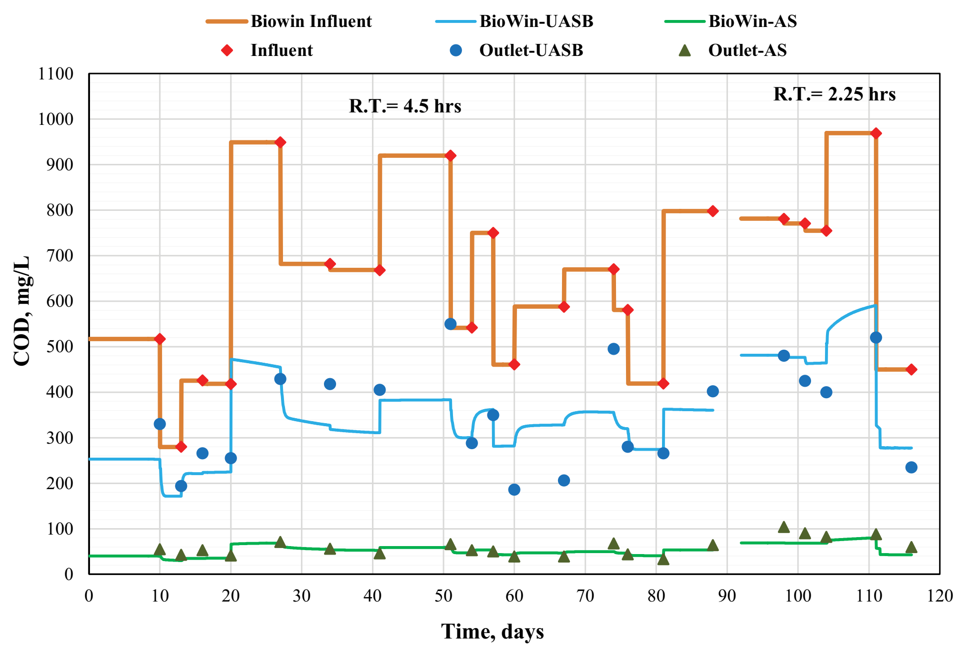

Fig. 4. Predicted vs. measured COD for UASB/ASP.

Table 4
Experimental and simulated effluent COD at different HRTs

	Influent	Anaerobic effluent		Aerobic effluent (overall system effluent)	
		Experimental	BioWin	Experimental	BioWin
AFB-UASB/HMBBR					
Run I					
Mean value	563	308	280	37	33
Removal ratio%		45	50	93	94
ARD%		17		17	
Run II					
Mean value	601	374	347	67	57
Removal ratio%		38	42	89	90.5
ARD%		17		14	
Run III					
Mean value	745	450	508	85	92
Removal ratio%		40	32	89	88
ARD%		12		15	
UASB/ASP					
Run I					
Mean value	604	332	308	51	47
Removal ratio%		45	49	92	92
ARD%		20		16	
Run II					
Mean value	745	412	458	85	66
Removal ratio%		45	38.5	89	91
ARD%		12		22	

ratios were 93%, 89%, and 89%. The results indicate that there is an excellent agreement with the predicted values. For the UASB/ASP system, the predicted removal ratios for the UASB reactor were 49% and 38.5%, respectively for HRTs of 4.5 and 2.25 h while the experimental value for the two HRTs was 45%. For the overall system (integrated UASB/ASP), the predicted overall removal ratios were 92 and 91% respectively for HRTs of 4.5 and 2.25 in comparison with the experimental values which were 92% and 89% respectively.

The model showed a good representation of the measured data for COD. The ARD between the simulated data and the measured data for the two investigated systems at different HRTs was calculated and presented in Table 4. ARD values (approximately for all cases) were less than 20% and were considered acceptable according to [26].

The comparison between the predicted and experimental results indicates that the BioWin can accurately predict the overall process efficiency for the two simulated systems (AFB-UASB/HMBBR and UASB/ASP). The model could also predict the performance of the anaerobic unit for both systems.

As presented above, for the AFB-UASB/HMBBR and UASB/ASP systems, the experimental results indicated that the HRT has minor effects on the removal ratio.

The integrated anaerobic /aerobic system that was tested in the present study showed a high removal ratio even at the low HRT. The HRT reduced from 4.5 to 2.25 and finally to 1.5 h. The overall removal ratios of AFB-UASB/HMBBR were 93%, 89%, and 89%. For the UASB/ASP system; when reducing HRT from 4.5 to 2.25 the removal ratio decreased from 92% to 89%. No significant difference between the removal efficiencies for the two investigated systems. On the other hand, the AFB-UASB/HMBBR shows high stability and performance recovery against operational problems. The obtained removal ratio in the present study is comparable to published results. For example, Jafari et al. [27] studied the performance of an integrated anaerobic/aerobic system for the treatment of currant wastewater. In their system, an AFB reactor (with cylindrical particles made of PVC as a biomass carrier) was integrated with a moving bed bioreactor. They concluded that the total COD removal ratio at a 24 h HRT was about 94%. Machdar et al. [28] also observed that the combined UASB/DHS (down-flow hanging sponge) system achieved 84% COD removal at HRT of 8 h producing a final effluent of 58 mg/L COD. Cao and Ang [29] tested the UASB-AS system for the treatment of dilute domestic sludge (COD of 376 mg/L) and reported a removal ratio of 86% at HRT of 12.3 h. The effluent COD value for the UASB-AS system at HRT of 2.25 h was 85 mg/L. this observation is consistent with that of de Almeida et al. [30] who investigated the UASB/TF system treating municipal wastewater with an influent COD equaling 526 mg/L at HRT of about 7.7 h and found that the effluent COD equals 74 mg/l with a removal ratio reaching about 85%.

The removal ratio of the anaerobic unit for the investigated systems achieved low COD removal ranging from 40%

to 45%. This is because it is operated at short HRT ranging from 0.7 to 2.1 h. These observations are matched with the results of La Motta et al. [31] who compared AFB Reactor (with granular activated carbon as the support media) with the UASB reactor operated at a 3.2 h HRT and observed that the COD removal ratio of AFB reactor was about 43%. For treating distillery wastewater by thermophilic AFB reactor, Perez et. al. [32] found that the COD removal ratio (75%) was achieved at a 15.6 h HRT for influent COD concentration of 30,000 mg/L. Lew et al. [33] compared classical UASB with a hybrid UASB-filter, in which the gas-liquid-solid separator was replaced by plastic filter rings. The COD removal percent for both reactors were approximately the same. The efficiency was about 55% at a 2 h HRT and 38% at a 1 h HRT.

3.2. BOD removal

The predicted values of BOD are estimated and derived from the COD values. As mentioned above, the BioWin applied model is a COD-based model. Fig. 5 and Table 5 show the experimental vs. predicted BOD results for the two investigated systems. For all cases, the predicted BOD values were lower than the measured ones. The model could not

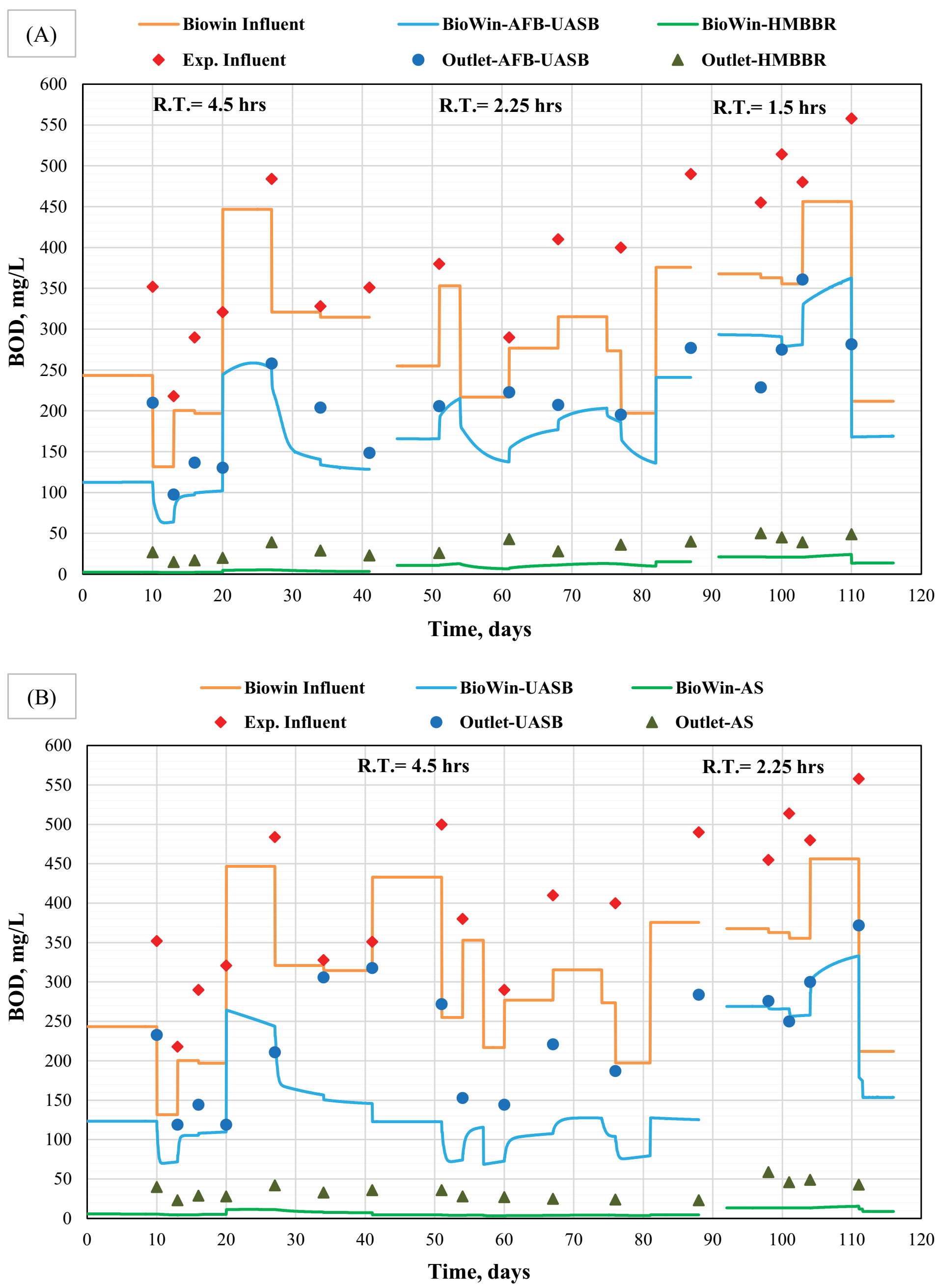

Fig. 5. Predicted vs. measured BOD for (a) AFB-UASB/HMBBR and (b) UASB/ASP.

Table 5
Experimental and simulated BOD at different HRTs

	Influent		Anaerobic effluent		Aerobic effluent	
	Experimental	BioWin	Experimental	BioWin	Experimental	BioWin
AFB-UASB/MBBR						
Run I						
Mean value	335	265	169	128	24	3.1
Removal ratio			49.4	51.6	92.7	99.0
Run II						
Mean value	394	280	222	182	35	11.3
Removal ratio			43.7	35	91.1	96
Run III						
Mean value	502	385	287	306	46	22
Removal ratio			42.9	20.5	90.9	94
UASB/ASP						
Run I						
Mean value	370	283	209	120	30	5.5
Removal ratio			43.7	57.5	91.8	98
Run II						
Mean value	502	385	300	281	49	14
Removal ratio			40.3	27	90.2	96

predict accurately the measured values, on the other hand, the overall removal ratio could be predicted approximately. This is because the BioWin simulates the organic BOD while the measured values represent the total BOD (i.e. carbonaceous + nitrogenous BOD_5), as the Nitrification inhibitor was not applied to the BOD test. The model under-prediction values of the effluent BOD may be due to the presence of soluble microbial products in the effluent. These products were not accounted for by ASM models [34].

Accordingly, the integrated anaerobic /aerobic systems tested in the present study show high stability even at a low HRT, and no significant difference between the removal efficiencies for the two systems.

The integrated anaerobic/aerobic systems were operated at HRT of 4.5 hrs and achieved an effluent BOD_5 value of 24 mg/L, and an overall removal ratio of 92%. This value is consistent with the results published by Sumino et al. [35]. They investigated the feasibility of a pilot UASB integrated with an aerated fixed bed reactor for municipal sewage treatment with an influent BOD ranging from 148 to 162 mg/L under ambient conditions. It was reported that the mean effluent values of BOD ranged from 11 to 25 mg/L with an average removal ratio of 88%.

The integrated anaerobic/aerobic systems in the current study were operated at HRT of 1.5 h to investigate the system behavior at the high hydraulic loading rate. The effluent BOD_5 value was 46 mg/L with an overall removal ratio of 90%. These results are comparable to those reported by Hendy et. al. [36] who compared the performance of the AS reactor vs. that of the HMBBR in the process of wastewater treatment. The characteristics of the wastewater were similar to those used in the present work and the reactors were operated at HRT of 2 h. The effluent BOD_5 was found to be approximately 100 and 80 mg/L for the AS and HMBBR respectively. The removal ratio of the anaerobic unit in the present study achieved low BOD removal which ranged from 40 to 50%. This may be due to the operation at a short HRT (0.7–2.1 h). Sumino et al. [35] examined the performance of a UASB/aerated fixed bed reactor and reported that the UASB could only achieve BOD removal of 60% at an HRT of 12 h.

3.3. TSS removal

Fig. 6 and Table 6 show the experimental TSS vs. the predicted values for the two investigated systems. The model exhibited an acceptable prediction of the experimental data of the overall integrated system, but it failed to predict the experimental data of the anaerobic unit. This may be attributed to the fact that the UASB process was simulated by an anaerobic digester element (coupled with a point settler element).

For the two investigated systems, stable effluent TSS concentration (around 25 mg/L) was observed, even with the fluctuation in the influent TSS concentration. The TSS removal ratio was around 91%. These results are similar to those reported by Goncalves et al. [37] who studied the UASB reactor in combination with a submerged aerated biofilter (SABF) in Brazil. They observed that at an HRT of 6.5 h the average removal ratio of the TSS was 94%. Also, Keller et al. [38] investigated the performance of the combined UASB-SABF system. Their results revealed that the final effluent TSS was 23 mg/L with a removal ratio of 86%.

The removal ratio of the anaerobic unit for the systems investigated in the present study achieved a low TSS removal ratio which ranged from 40% to 43%. La Motta et al. [31] compared the performance of the AFB reactor against the performance of a UASB reactor at an HRT of 3.2 h. They reported that the TSS removal ratio of the AFB reactor was about 60%.

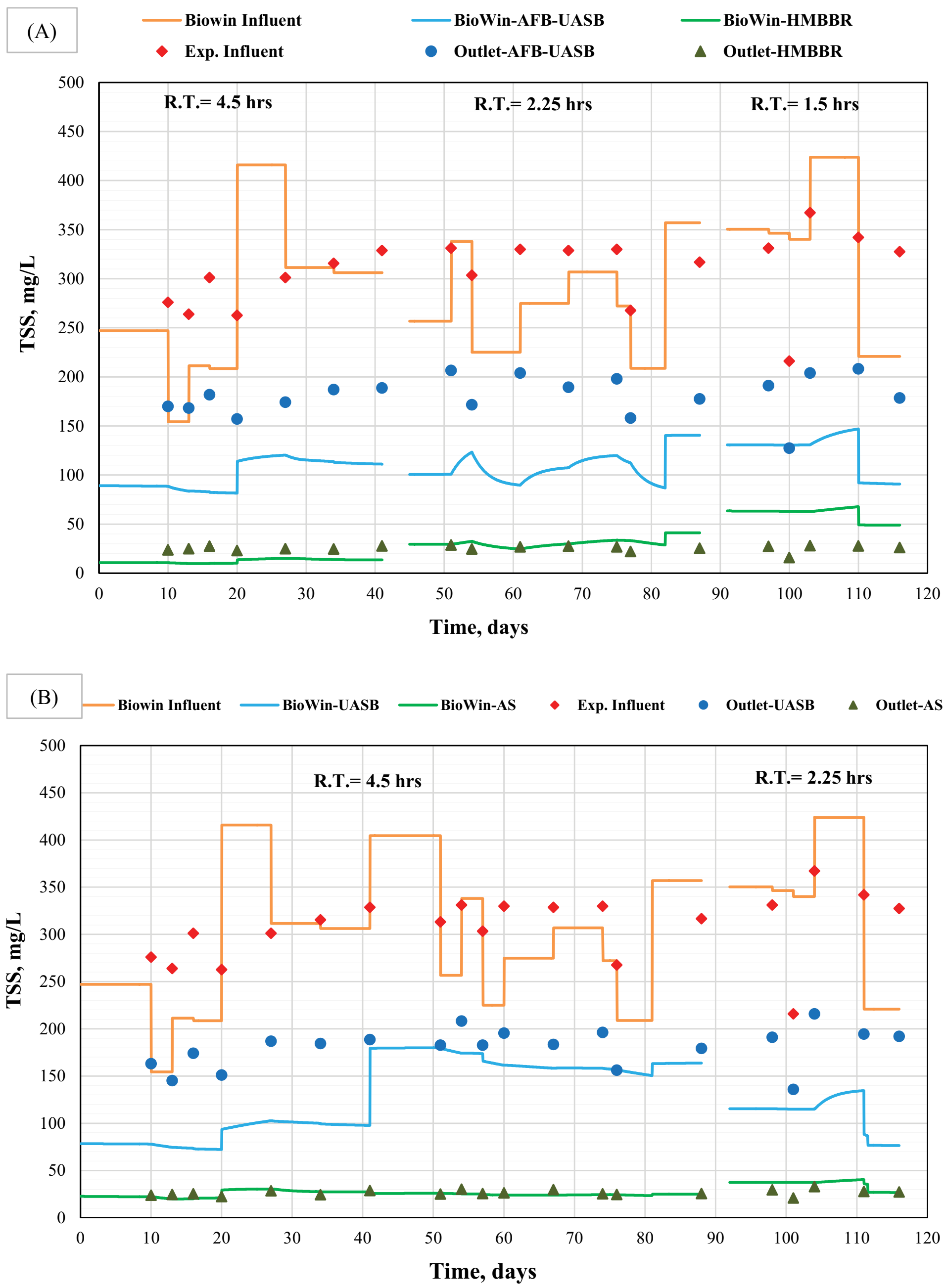

Fig. 6. Predicted vs. measured TSS for (a) AFB-UASB/HMBBR and (b) UASB/ASP.

3.4. Ammonia removal

Table 7 and Fig. 7 depicts the model's prediction compared with the measured concentrations of ammonia as well as the ammonia removal efficiencies for the influent and effluent ammonia. The comparison showed that there is a high discrepancy between the predicted and measured values. This discrepancy may be due to the influent Ammonia concentrations were created using the BioWin influent specifier based on influent COD values. Improving the model prediction may require more samples and precautions in the process of wastewater characterizations. This is because the characteristics of wastewater vary widely during the study period as shown in Table 3. On the other hand, the uncertainty in the experimental measurements may cause some sort of discrepancy between the predicted and measured values.

The integrated AFB-UASB/HMBBR system achieved a low removal ratio of ammonia. The removal ratios were 66%, 52%, and 53%, regarding HRT of 4.5, 2.25, and 1.5 h. The achieved nitrification efficiency was comparable to that achieved by Tawfik et al. [13] who investigated a laboratory-scale UASB reactor followed by an HMBBR for the treatment of domestic wastewater. The ammonia

Table 6
Experimental and simulated TSS at different HRTs

	Influent		Anaerobic effluent		Aerobic effluent	
	Experimental	BioWin	Experimental	BioWin	Experimental	BioWin
AFB-UASB/MBBR						
Run I						
Mean value	293	265	175	97	25	12
Removal ratio			40	63	91	95
Run II						
Mean value	315	290	186	113	26	32
Removal ratio			41	61	92	89
Run III						
Mean value	317	336	182	126	25	61
Removal ratio			43	63	92	82
UASB/ASP						
Run I						
Mean value	305	286	179	128	26	24
Removal ratio			41	55	91	91.5
Run II						
Mean value	317	336	186	111	28	36
Removal ratio			41	67	91	89

Table 7
Experimental and simulated ammonia at different HRTs

	Influent		Anaerobic effluent		Aerobic effluent	
	Experimental	BioWin	Experimental	BioWin	Experimental	BioWin
Hybrid UASB-MBBR						
Run I						
Mean value	11.5	15	13.6	17.4	3.9	0.8
Removal ratio					66	95
Run II						
Mean value	17.4	17.7	14.8	18.3	8.3	1.3
Removal ratio					52.3	93
Run III						
Mean value	14.7	24.5	10.0	28	6.9	1.9
Removal ratio					53.1	92
UASB-ASP						
Run I						
Mean value	15.0	17	13.9	19.6	3.4	1.5
Removal ratio					77.4	91
Run II						
Mean value	14.7	18	8.9	17.8	7.0	1.3
Removal ratio					52.4	93

removal ratio was 62%, 28%, and 19% at an HRT of 13.3, 10, and 5 h.

The low removal ratios achieved by the systems investigated in the present study may be due to the short HRT, that is, time is not sufficient to complete the nitrification process. Moawad et al. [39] concluded that the complete nitrification of ammonia occurred after 5 h of aeration. At the short HRT, an increase in the carbon loading leads to an increase in the heterotrophic bacteria (both in the attached and suspended biomass). Consequently, it results in a decrease in the nitrifier numbers because there is more competition for space, oxygen, and substrate with the heterotrophic bacteria [40,41].

For the UASB/ASP system, the experimental results showed that decreasing the HRT from 4.5 to 2.25 h reduced

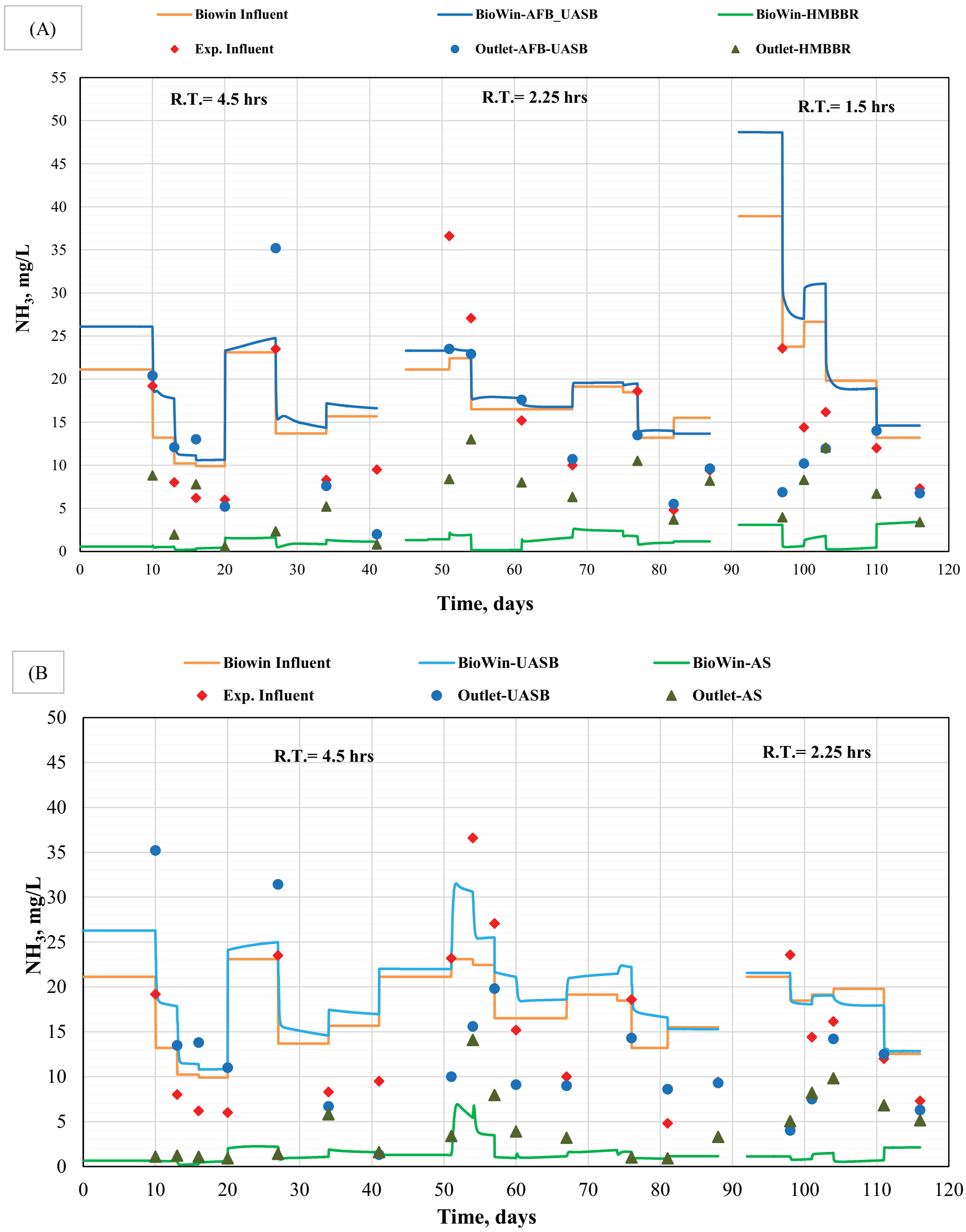

Fig. 7. Predicted vs. measured ammonia for (a) AFB-UASB/HMBBR and (b) UASB/ASP.

the removal ratio from 77% to 52%. These values were slightly better than the ones measured by Hendy et. al. [36] for ASP at approximately the same HRT, since the resulting values for removal efficiencies were 70% and 34% for the HRT of 4 and 2 h, respectively. Machdar et al. [28] also reported a 61% removal ratio of ammonia for a combined UASB/DHS (down-flow hanging sponge) operated at an HRT of 8 h.

Consistent with several studies, the present results showed also that nitrogen removal was very low or non-existent in the anaerobic stage [39,42] and the nitrification process was done in the aeration tank only. This is because organic nitrogen is decomposed into ammonia during the anaerobic process, and it is not removed from the system, so its concentration increases in the anaerobic effluent [8].

3.5. Sludge profile in anaerobic reactors

Table 8 shows the sludge accumulation and distribution in the anaerobic reactors at different HRTs. These results revealed that the solids retain inside the AFB-UASB and UASB reactors tend to accumulate in the lower portion of the reactor while the media and the biomass attached to it remain in the upper portion of the AFB-UASB reactor. The total mass of the solids retained in the AFB-UASB reactor reduced from 2 to 0.85 and then to 0.8 kg TS as the HRT reduced from 4.5 to 2.25 and finally to 1.5 hrs. The total mass of solids in the UASB was higher than its counterpart on the AFB-UASB since it was around 3 kg TS. In this context, La Motta et al. [31] accounted for solid accumulation (about 6 kg TSS) in the UASB reactor.

Table 8
Retention of solids inside the anaerobic reactors

Port height (m)	Volume served (m^3)	HRT (h)		
		4.5	2.25	1.5
		AFB-UASB		
0.1	0.08	13,600	4,520	4,480
0.35	0.08	6,250	1,850	1,500
0.6	0.11	1,450	1,150	1,170
1.05	0.10	1,550	1,500	1,460
1.25	0.06	900	970	1,040
Total mass		2 kg TS	0.85 kg TS	0.81 kg TS
		UASB		
0.1	0.08	31,400	26,820	
0.35	0.08	2,200	2,750	
0.6	0.11	2,050	2,040	
1.05	0.10	1,620	1,780	
1.25	0.06	1,200	1,150	
Total mass		3.2 kg TS	2.85 kg TS	

4. Conclusion

BioWin simulation models have been applied to tackle the treatment processes of two different integrated anaerobic/aerobic systems. The first system is the AFB coupled with the UASB reactor followed by HMBBR. The second system is the classical UASB followed by an ASP as a post-treatment unit. For the COD, the BioWin model showed a good representation of the measured data for both investigated systems at different HRTs. More improvement is required for BOD, TSS and ammonia prediction. On the other hand, the predicted removal ratios of the overall treatment process are in agreement with the experimental values regarding all parameters with the exclusion of ammonia, there is a discrepancy between the model and the experimental data. This may be because the BioWin model is based on COD and the other parameters are calculated from the measured COD values. The experimental results of the present study indicated that the integrated AFB-UASB/HMBBR system, used in treating domestic wastewater, is effective in removing COD, BOD as well as TSS fractions even at the low HRT of 1.5 h. The system removed over 89% of COD, 91% of BOD, and 92% of TSS. These values for the UASB/ASP system were 89% of COD, 90% of BOD, and 91% TSS at a 2.25 h HRT. No significant difference between the removal efficiencies of the two systems. On the other hand, the AFB-UASB/HMBBR shows high stability and performance recovery against operational problems. The applied model is a valuable design tool, which can provide a confirmation to the understanding of the processes taking place in the integrated Anaerobic/aerobic systems.

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References

[1] L. Seghezzo, G. Geeman, J.B. Van Lier, H.V.M. Hamelers, G. Letinga, A review: the anaerobic treatment of sewage in UASB and EGSB reactors, Bioresour. Technol., 65 (1998) 175–190.
[2] M.V. Sperling, V.H. Freire, C.A.D. Chernicharo, Performance evaluation of an UASB-activated sludge system treating municipal wastewater, Water Sci. Technol., 43 (2001) 323–328.
[3] B. Mrowiec, J. Suschka, Anaerobic Wastewater Treatment Process, E. Plaza, E. Lewin, Eds., Research and Application of New Technologies in Wastewater Treatment and Municipal Solid Waste Disposal in Ukraine, Sweden, and Poland, Stockholm, Sweden, 2010, pp. 177–184.
[4] S. Chong, T.K. Sen, A. Kayaalp, H.M. Ang, The performance enhancements of upflow anaerobic sludge blanket reactors for domestic sludge treatment-a state of the art review, Water Res., 46 (2012) 3434–3470.
[5] A. Tilche, S.M. Vieira, Domestic report on reactor design of anaerobic filters and sludge bed reactors, Water Sci. Technol., 24 (1991) 193–206.
[6] B. Mownica, B. Manimekalai, Performance evaluation of fluidized bed biofilm reactor using Kaldnes K1 for domestic wastewater, Int. J. Sci. Res. Dev., 5 (2017) 617–623.
[7] S.C. Oliveira, M. von Sperling, Performance evaluation of UASB reactor systems with and without post-treatment, Water Sci. Technol., 59 (2009) 1299–1306.
[8] A.A. Khan, R.Z. Gaur, V.K. Tyagi, A. Khursheed, B. Lew, I. Mehrotra, A.A. Kazmi, Sustainable options for post treatment of UASB effluent treating sewage: a review, Resour. Conserv. Recycl., 55 (2011) 1232–1251.
[9] T. Bressani-Ribeiro, P.G.S. Almeida, E. Volcke, C.A.D.L. Chernicharo, Trickling filters following anaerobic sewage treatment: state of the art and perspectives, Environ. Sci.: Water Res. Technol., 4 (2018) 1721.
[10] A. Elawwad, M. Hazem, Minimization of sludge production in an integrated UASB–continuous flow sequencing batch reactor system, Desal. Wat. Treat., 91 (2017) 206–213.
[11] M. Ji, J. Yu, H. Chen, P.L. Yue, Removal of slowly biodegradable COD in combined thermophilic UASB and MBBR systems, Environ. Technol., 22 (2001) 1069–1079.
[12] S. Luostarinen, J. Rintala, Anaerobic on-site black water and kitchen waste treatment using UASB-septic tanks at low temperatures, Water Sci. Technol., 54 (2006) 143–149.
[13] A. Tawfik, F. El-Gohary, H. Temmink, Treatment of domestic wastewater in an up-flow anaerobic sludge blanket reactor followed by moving bed biofilm reactor, Bioprocess. Biosyst. Eng., 33 (2010) 267–276.
[14] C. Moragaspitiya, J. Rajapakse, W. Senadeera, I. Ali, Simulation of dynamic behavior of a biological wastewater treatment plant in South East Queensland, Australia using Bio-Win Software, Eng. J., 21 (2016) 0125–8281.
[15] C. Khattiyavong, H.S. Lee, Performance simulation and assessment of an appropriate wastewater treatment technology in a densely populated growing city in a developing country: a case study in Vientiane, Laos, Water, 11 (2019) 1012.
[16] M. McGehee, J. Gellner, J. Beck, C. White, T. Bruton, D. Howard, BioWin Modeling of a Three Reactor IFAS System, in: Proc. Water Environment Federation 82nd Annual Technical Exhibition & Conference, Orlando, FL, USA, 2009.
[17] H. Rupp, G. Roy, B. Tautic, J. Bushey, Pilot Study Confirms Design of IFAS System for Nitrogen Reduction in Connecticut, Water Environment Federation Specialized Conference on Nutrient Removal, Washington, D.C., 2009.
[18] V. Ravi Sankar, S. Chandran, D. Pradeep Pandiyan, Performance assessment, kinetics and modelling of biofilm membrane bioreactor for the treatment of dairy wastewater, J. Environ. Biol., 39 (2018) 565–574.
[19] V. Katic, Improving the Design of a Full Scale Wastewater Treatment Plant with the Use of the Complex Activated Sludge Model, Master Thesis, Politecnico di Milano, Como Campus M.Sc. in Environmental and Geomatic Engineering, 2016.

[20] A. Elawwad, Optimized biological nitrogen removal of high-strength ammonium wastewater by activated sludge modelling, J. Water Reuse Desal., 8 (2018) 393–403.

[21] The BioWin Advantage Volume 2 Number 2: April 2011 Simulating Upflow Anaerobic Sludge Blanket Reactors, Available at: https://www.envirosim.com/bwa/bwa22.pdf.

[22] J.J. Hulsbeek, J. Kruit, P. Roeleveld, M. van Loosdrecht, A practical protocol for dynamic modelling of activated sludge systems, Water Sci. Technol., 45 (2002) 127–136.

[23] A. Abdo, N. Nagy, A. Nagieb, I. Hendy, Calibration and Identification of Activated Sludge Model No 1 (ASM1) for Modeling and Simulation of Egyptian Wastewater Treatment Plants, Ph.D. Thesis, Zagazig University, 2017.

[24] E. Liwarska-Bizukojc, R. Biernacki, Identification of the most sensitive parameters in the activated sludge model implemented in BioWin software, Bioresour. Technol., 101 (2010) 7278–7285.

[25] APHA, Standard Methods for the Examination of Water and Wastewater, 21st ed., American Public Health Association/American Water Works Association/Water Environment Federation, Washington, D.C., 2005.

[26] E. Liwarska -Bizukojc, D. Olejnik, R. Biernacki, S. Ledakowicz, Calibration of a complex activated sludge model for the full-scale wastewater treatment plant, Bioprocess. Biosyst. Eng., 34 (2011) 659–670.

[27] J. Jafari, A. Mesdaghinia, R. Nabizadeh, M. Farrokhi, A.H. Mahv, Investigation of Anaerobic Fluidized Bed Reactor/Aerobic Moving Bed Bio Reactor (AFBR/MMBR) System for Treatment of Currant Wastewater, Iran. J. Public Health, 42 (2013) 860–867.

[28] I. Machdar, Y. Sekiguchi, H. Sumino, A. Ohashi, H. Harada, Combination of a UASB reactor and a curtain type DHS (down flow hanging sponge) reactor as a cost-effective sewage treatment system for developing countries, Water Sci. Technol., 42 (2000) 83–88.

[29] Y.S. Cao, C.M. Ang, Coupled UASB-activated sludge process for COD and nitrogen removals in municipal sewage treatment in warm climate, Water Sci. Technol., 60 (2009) 2829–2839.

[30] P.G.S. de Almeida, C. Chernicharo, C.L. Souza, Development of compact UASB/trickling filter systems for treating domestic wastewater in small communities in Brazil, Water Sci. Technol., 59 (2009) 1431–1439.

[31] E.J. La Motta, H. Padron, E. Silva, J. Luque, A. Bustillos, P. Corzo, Pilot plant comparison between the AFBR and the UASB reactor for municipal wastewater pretreatment, J. Environ. Eng., 134 (2008) 265–272.

[32] M. Perez, L. Romero, D. Sales, Comparative performance of high rate anaerobic thermophilic technologies treating industrial wastewater, Water Res., 32 (1998) 559–564.

[33] B. Lew, S. Tarre, M. Beliavski, M. Green, UASB reactor for domestic wastewater treatment at low temperatures: a comparison between a classical UASB and hybrid UASB-filter reactor, Water Sci. Technol., 49 (2004) 295–301.

[34] A. Eldyasti, M. Andalib, H. Hafez, G. Nakhla, Z.J. Comparative, Modeling of biological nutrient modeling from landfill leachate using a circulating fluidized bed bioreactor (CHYBRID UASB), J. Hazard. Mater., 187 (2011) 140–149.

[35] H. Sumino, M. Takahashi, T. Yamaguchi, K. Abe, N. Araki, S. Yamazaki, S. Shimozaki, A. Nagano, N. Nishio, Feasibility study of a pilot-scale sewage treatment system combining an up-flow anaerobic sludge blanket (UASB) and an aerated fixed bed (AFB) reactor at ambient temperature, Bioresour. Technol., 98 (2007) 177–182.

[36] I. Hendy, D. El Monayeri, S. Al Mokadem, A. Nagieb, Modeling of Biofilm-ASP, Ph.D. Thesis, Zagazig University, 2013.

[37] R. Goncalves, V. Araujo, V.S. Bof, Combining up-flow anaerobic sludge blanket (UASB) reactors and submerged aerated biofilters for secondary domestic wastewater treatment, Water Sci. Technol., 40 (1999) 71–79.

[38] R. Keller Passamani, R.F. Franca, F. Passamani, L. Vaz, S.T. Cassini, Pathogen removal efficiency from UASB + BF effluent using conventional and UV post-treatment systems, Water Sci. Technol., 50 (2004) 1–6.

[39] A. Moawad, U.F. Mahmoud, M.A. El-Khateeb, E. El-Molla, Coupling of sequencing batch reactor and UASB reactor for domestic wastewater treatment, Desalination, 242 (2009) 325–335.

[40] S. Wijeyekoon, T. Mino, H. Satoh, T. Matsuo, Effects of substrate loadings rate on biofilm structure, Water Res., 38 (2004) 2479–2488.

[41] M.F. Knutsen, Robustness of Nitrifying Biofilter Functionality: Role of Competition Between Heterotrophic and Nitrifying Bacteria on Ammonium Removal Efficiency and Microbial Community Structure, Norwegian University of Science and Technology, 2017.

[42] E. Foresti, M. Zaiat, M. Vallero, Anaerobic processes as the core technology for sustainable domestic wastewater treatment: consolidated applications, new trends, perspectives, and challenges, Rev. Environ. Sci. BioTechnol., 5 (2006) 3–19.