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ORIGINAL PAPER

Modeling and simulation of hybrid anaerobic/aerobic wastewater treatment system

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Abstract Modeling and simulation using GPS-X software for a packed bed up-flow anaerobic sludge blanket followed by a biological aerated filter were studied. Both treatment units were packed with a non-woven polyester fabric as a bio-bed. The system was operated at a hydraulic and organic loading rate of 9.65 $m^3/m^2/d$ and 2.64 kg BOD_5/m^3/day. Verification of the experimental results and calibration of the model were carried out prior simulation and modeling. Variables under consideration were HLR, OLR, and surface area of the packing material. HLR and OLR are increased incrementally until the break through point has been achieved. The results obtained from modeling indicated that the treatment system has great potential to be used as an ideal and efficient option for high hydraulic and organic loading rates up to 19.29 $m^3/m^2/d$ and 4.48 kg BOD_5/m^3/day. The model indicated that increasing the input HLR and OLR loads to the treatment system up to 50 % of the original values achieved removal efficiencies 98 % for TSS, 88 % for BOD_5, and 85 % for COD. Moreover, increasing the HLR to four times the original value (38.59 $m^3/m^2/d$) reduced the efficiency of the treatment system to 50 % for COD and BOD_5. However, the removal rates of TSS, TKN, and TP were not affected. Also, the modeling results indicated that increasing the surface area of the packing material increased the overall efficiency of the treatment system.

Keywords BAF · GPS-X software · Modeling · P-UASB · Packing material · Simulation

Introduction

Water is one of the most critical issues facing the world today especially with the developing and emerging countries. In Egypt there are big challenges facing the water and wastewater sectors. These challenges are obvious in the rapid growth and unbalanced distribution of the population, rapid urbanization, and water deterioration. Accordingly, this dilemma makes developing new affordable and appropriate technologies for wastewater treatment an urgent need. Among the promising low-energy and cost-effective treatment technology is the packed bed up-flow anaerobic sludge blanket (P-UASB). The P-UASB is a very promising anaerobic process which has been effectively used to treat variety of industrial and domestic wastewater (Lattenga 2008; Abou-Elela et al. 2013a). However, supporters of anaerobic wastewater treatment with the vast literature available dealing with the treatment of municipal wastewater using UASB system indicated that there still remain several unclear aspects needed to be clarified. For example, only limited data are available for UASB reactors treating sewage under extreme conditions, Most of the reported results refer to anaerobic systems operated with HRTs within 4–10 h, with an operational temperature higher than 20 °C (Foresti et al. 2001; Seghezzoa et al.

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1998). Therefore, the operational limits of UASB reactors for the treatment of municipal wastewater are still not clear (Leitãoa et al. 2006). Thus, several challenges remain to be solved in the future if the UASB process is to be implemented for treatment of domestic wastewater on a worldwide basis. Abou-Elela et al. (2013b, c) enhanced the performance of the UASB by using a non-woven polyester fabric (NWPF) as a packing material in the UASB for treating low-strength domestic wastewater. The removal efficiency in the P-UASB for COD was more than 70 % due to the entrapment and accumulation of biomass onto the high surface area of the NWPF. The duration of the experimental work started in 2013. The model kept running for 2 years at the Water Research Department, National Research Center, Cairo, Egypt.

However, the use of UASB alone is still a primary treatment and further post treatment is required to achieve a good-quality effluent suitable for wastewater reuse (El Gohary et al. 1998). One of the promising post wastewater treatments is the biological aerated filter (BAF) (Zhu and Chen 2000). BAF is a novel, flexible, and effective bioreactor that provides a small foot print process at various stages of wastewater treatment (Feng et al. 2012). In our study a pilot plant system consists of P-UASB followed by BAF was designed, constructed, and operated successfully for more than 2 years (Abou-Elela et al. 2015a, b).

Computer models assist in developing a thorough understanding of the behavior of a system and in evaluating various system operating strategies. Recently, there has been a great demand for the application of mathematical models for biological treatment processes simulation. Using computer modeling of wastewater treatment plants is increasingly a reality and not just a laboratory-scale project. It offers clear advantages in terms of analyzing the performance of the treatment plant as well as better optimization and control tools, reducing the costs associated with laboratory analysis (Heijnen et al. 1999). The models allow beside the kinetic description of the treatment process carried out at the field, to simulate new scenarios toward the study of critical parameters for the process as well as optimization and control of the WWTP. Nevertheless, the efficiency of modeling depends on a good calibration, which is generally needed to adapt the simulation results to the real behavior of the WWTP. There have been many studies about the modeling of municipal WWTPs but there are only very few concerning the modeling of industrial WWTPs (Pereira 2014).

In this study the GPS-X software model was used to simulate the hybrid P-UASB/BAF processes. GPS-X is a modular, multipurpose modeling environment that uses an advanced user interface to facilitate dynamic modeling and simulation. The biological models available in GPS-X are ASM, ASM2d, ASM3, MANTIS, NEW GENERAL, and COMPREHENSIVE (MANTIS2) (Hydromantis 2013). The choice of the best model depends upon the processes that one is concerned about the data information available. Also, GPS-X program used in this study has a clear-cut graphical interface and uses specialized translator that converts the graphical process into material balance equations based on dynamic models.

Generally, the anaerobic/aerobic processes are complex systems in which a range of bacterial conversion and transport processes occur. Kinetics, stoichiometry, and transport processes play an important role in the conversion of contaminant. The library used in GPS-X to simulate the field data is the comprehensive model (Mantis 2D) which incorporates the most commonly observed biological, physical, and chemical processes in wastewater treatment plants developed and implemented in the simulating program by Hydromantis (2013).

Scope of work

The main objective of the present study was to verify and simulate the existing experimental results obtained from the pilot plant P-UASB/BAF treatment units using a simulating tool. The specific objective was to optimize the design and evaluate the efficiency of the operating conditions including the change in media surface area, HLR and OLR compared to actual design data.

Materials and methods

An integrated pilot plant treatment system for low-strength domestic wastewater was designed, manufactured, and installed within the vicinity of a wastewater treatment plant. The pilot plant treatment system consists of P-UASB reactor followed by a BAF unit. A final clarifier was used after BAF to sustain any biomass washed out and to enhance the quality of the treated effluent. The system was fed continually with pre-screened sewage at a flowrate of 7 m^3/d (hydraulic loading rate 9.65 m^3/m^2/d) and organic loading rate of 2.64 kg $BOD_5/m^3/d$. The system was operated since 2 years ago and is still running.

Description of the packing material

Sheets of non-woven polyester fabric (NWPF) were used as a new biomass holder in both the UASB and BAF units. Different configurations of the packing NWPF material were prepared. The NWPF in the UASB reactor was cut into pieces (5 × 5 cm) and shaped into rolls and fixed in plastic cylindrical frames and retained in a st.st basket. The basket was fixed in the upper part of the UASB at a distance of 60 cm under the gas–liquid–solid separator (GLSS).The height of the packing material was 30 cm and occupying a volume of 0.3 m^3.

In BAF rector, different configurations were used. Plate shapes of NWPF were fixed at a distance of 10 cm from bottom of the reactor and were arranged in vertical order at

Table 1 Operating conditions of the integrated treatment system

Operating conditions	Reactor		
	P-UASB	BAF	IPS
Dimensions (cm)	114*102*191	93*78*130	60*60*150
HRT (h)	6	3.2	1.49
Temperature (°C)	15-42	15-42	15-42
Up-flow velocity (m/h)	0.25	0.40	–
Flow rate (m^3/d)	7	7	7
HLR ($m^3/m^2/d$)	6.02	9.65	19.4
D.O (mg/l)	–	3–5	–
OLR (kg COD/m^3/day)	2.64	0.85	0.33
Packing material	Rolled NWPF	Rolled + Plates NWPF	–
Surface area m^2/m^3	100	100	–

Source: Abou-Elela et al. (2015a, b)

Table 2 Average experimental results of the integrated treatment system

Parameters	Unit	Raw	Packed-UASB	% R	BAF	%R	IPS	Overall %
pH value	–	7.39	7.18	3	7.58	3	7.62	
Turbidity	NTU	120.46	129.93		6.55	95	5.58	95
Total suspended solids (TSS)	mg/l	194.50	41.7	79	17.9	91	11.1	94
Volatile suspended solids (VSS)	mg/l	123.00	30.22	75	15.14	88	8.29	93
Total chemical oxygen demand (COD)	mg O_2/l	378.10	121.44	68	47.18	88	37.68	90
Soluble chemical oxygen demand (s COD)	mg O_2/l	143.40	77.8	46	27.50	81	20.6	86
Biological oxygen demand (BOD_5)	mg O_2/l	199.10	59	70	20.00	90	14.2	93
Ammonia	mg/l	20.15	23.57	−17	8.93	56	7.4	63
Total Kjeldahl nitrogen (TKN)	mg/l	34.67	30.51	12	14.50	58	11.89	66
Nitrite	mg/l	0.02	0.01	50	0.66		0.42	
Nitrate	mg/l	0.14	0.13	7	4.14		3.73	
Total phosphorous (TP)	mg/l	3.34	2.34	30	1.50	55	0.98	71
Total sulfide	mg S/l	7.98	11.26	−41	2.80	65	2.2	72
Oil, grease, and all extractable matters coliform	mg/l	113.43	33.04	71	18.81	83	14.29	87

% R: percentage removal

Source: Abou-Elela et al. (2015a, b)

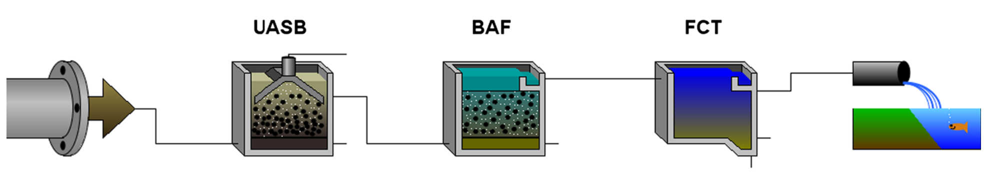

Fig. 1 Simulation model built using the comprehensive library in GPS-X

a distance of 5 cm apart from each other's. The void spaces between each two successive plates were filled with rolled NWPF to increase the surface area for microorganism's propagation. Detailed description of the pilot plant treatment system was reported previously (Abou-Elela et al. 2015a, b). The operating conditions and average experimental results of the performance of the integrated treatment system are shown in Tables 1 and 2, respectively, while Fig. 1 illustrates a schematic diagram of the treatment module running on GPS-X. A sap shot during model simulation is depicted in Fig. 3. The operational parameters and calculations performed on the model were similar to those in the experimental work using a packing material with a surface area of 100 m^2/m^3.

The comprehensive library (MANTIS2), the most commonly observed biological, physical, and chemical processes in wastewater treatment plants developed by Hydromantis (2013), was selected for this simulation. The mathematical equation used herein within each layer of the biofilm is shown in Eq. (1), whereas Eq. (2) illustrates the diffusion of the state variables from the bulk liquid into the biofilm.

$$A_a \delta_L \left(\frac{\mathrm{d}s^L}{\mathrm{d}t}\right) = Q_L\left(S^L_{j-1} - S^L_j\right) - K_M A_a \left(S^L_j - S^{BLi}_j\right) + K_{ML} A_a \left(S^o - S^L_j\right) \quad (1)$$

$$\underbrace{\left(\frac{\partial s^L}{\partial t}\right)}_{\text{Accumulation in liquid film}} = \underbrace{-D_s \frac{d^2 s}{dy^2}}_{\text{Diffusion into biofilm}} + \underbrace{\left(S^B_{j-1} - S^L_j\right)\left[\frac{Q_B}{A\delta_B}\right]}_{\text{Advection between biofilm layers}} - \underbrace{R_S}_{\text{Reduction Rate}} \quad (2)$$

For modeling and simulation the following steps were carried out:

1. Portraying the existing pilot plant (anaerobic/aerobic) treating municipal wastewater in terms of influent and physical data of the main unit operation.
2. Construction of the layout of the plant in GPS-X as well as the characterization of the input components, followed by calibration of the model.
3. Fitting of the model in order to obtain a better approximation to the reality of the treatment process.
4. A series of different scenarios were simulated in order to analyze the effect of incremental increase of the OLR by 10, 20, 30, 40, 50 and 70 % of the actual design data. The HLR was increased to 4 times its actual value to examine the failure of the system. Also, the effect of different surface areas of the packing material were investigated using 10 (l/m) till 100 (1/m) with an incremental increase

Table 3 Different increases in concentrations of different parameters in BAF

	Actual influent organic conc. (mg/l)	Actual exp. effluent from P-UASB (mg/l)	% RR from UASB	10 % increase in influent to P-UASB	New conc. from UASB based on RR calculated	20 % increase in influent to P-UASB	RR %	30 % increase in influent to P-UASB	RR %	40 % increase in influent to P-UASB	RR %	50 % increase in influent to P-UASB	RR %	70 % increase in influent to P-UASB	RR %
TSS	194.5	42	79	214	78.5	233	78.5	278	78.4	327	78	417	78	456	75
COD	378.1	121	68	416	67.8	454	67.8	541	67.8	635	67	811	67	1163	52
BOD	199.1	59	70	219	70	239	70.3	285	71	334	70	427	70	613	54
TKN	34.67		12	38	10.5	42	12	50	12	58	12	74	12	116	10
TP	3.34	2	30	4	25	4	25	5	40	6	33	7	28	9	30

of 10 (1/m). Moreover, the removal rates of organic content, nitrogen, and phosphorus were examined.

Results and discussion

The following sections demonstrate the results obtained from the model validation. The sensitivity analyses were done to examine the performance of the integrated model and its impact on the water quality when exposed to various organic loading rates, different surface areas of the media and increasing the flow rate to four times the designed value.

Model validation

In order to proceed with the parameters required to be tested for the constructed system, validation of the experimental work had to be performed. This was achieved where the effluent concentration of TSS from the simulated BAF unit was 14.6 compared to 18 mg/l, for COD, it was 46.5 compared to 47 mg/l, for BOD_5, it was 17.8 compared to 20 mg/l, for TKN, it was 24 compared to 34 mg/l and finally for TP, it was 2.3 from simulation compared to 3 mg/l from the experimental model. Since the validation step has been accomplished successfully, further investigations on the operating performance level of the integrated system were analyzed as will be presented in the following section.

Effect of increasing the BAF influent concentrations of different parameters on the performance of the treatment system

The concentrations of TSS, COD, BOD, TP, and TKN in the BAF unit were increased incrementally by 10, 20, 30, 40 50 and 70 % in order to validate and simulate the results of these different concentrations. The experimental results showed that the BAF achieved 79 % removal rate (RR) for TSS, 68 % RR for COD, 70 % RR for BOD_5, 12 % RR for TKN, and 30 % RR for TP. Hence these values were used to estimate the effluent concentrations of these parameters to test the sensitivity of the integrated system when the influent concentrations increased as mentioned above. Table 3 shows the different increases in the concentrations of different parameters with the corresponding removal rates. A comparison between the different loads of concentrations and the corresponding removal efficiencies achieved are shown in Fig. 2.

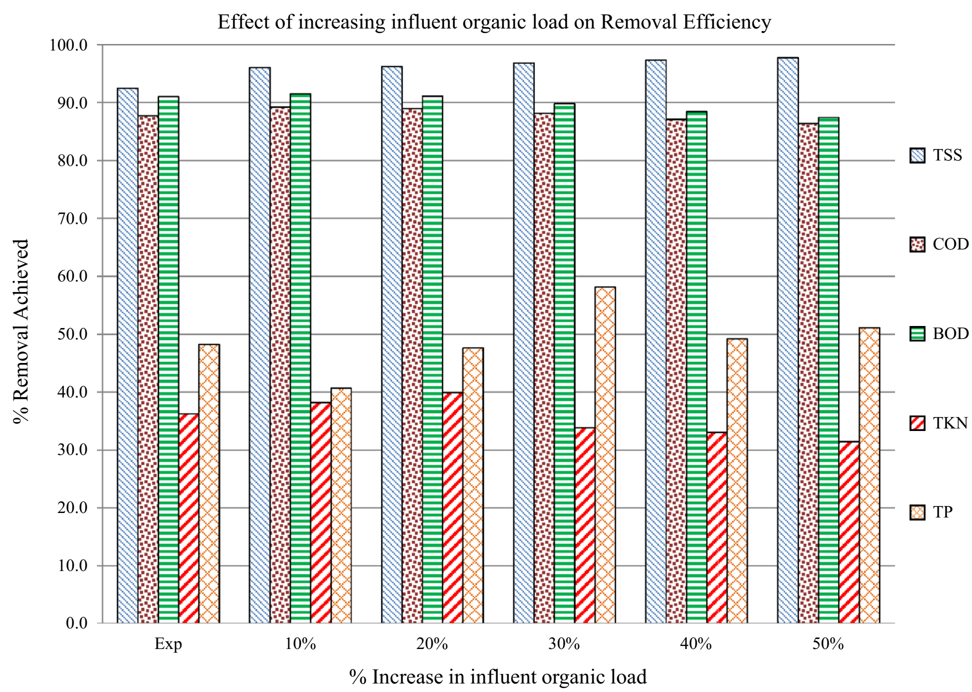

Fig. 2 Comparison between the removal efficiency of different increase in loads in the integrated system

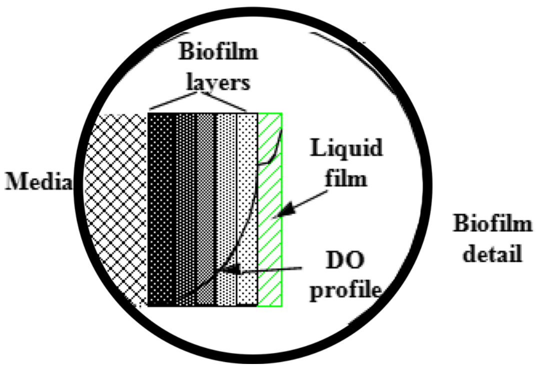

Fig. 3 DO profile along the biofilm layer (Hydromantis 2013)

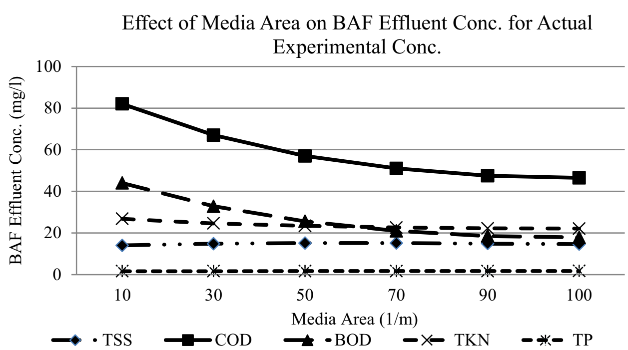

Fig. 4 Effect of surface area on BAF effluent concentration at the designed loading rate

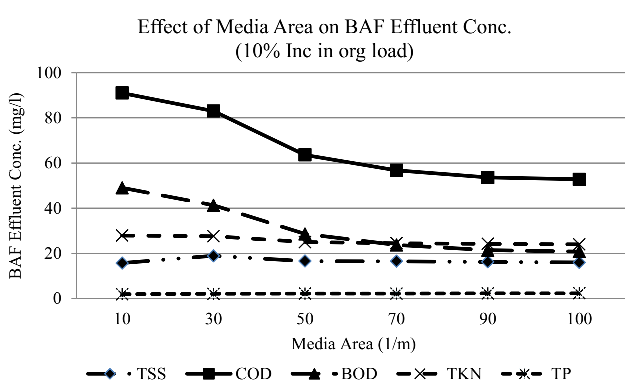

Fig. 5 Effect of surface area on the efficiency BAF unit (10 % increases in concentration)

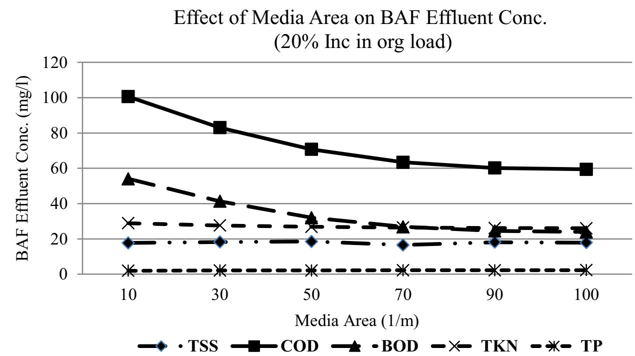

Fig. 6 Effect of surface area on the efficiency of BAF unit (20 % increases in concentration)

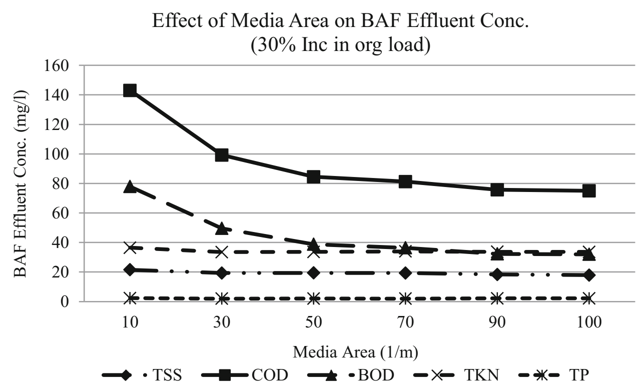

Fig. 7 Effect of surface area on the efficiency of BAF unit (30 % increases in concentration)

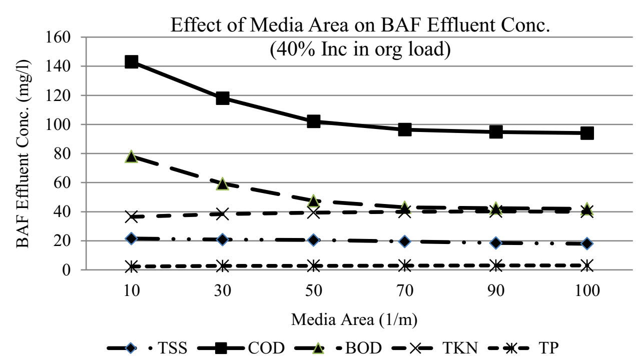

Fig. 8 Effect of surface area on the efficiency of BAF unit (40 % increases in concentration)

The results showed that as the influent organic load increased up to 50 % of the original value, the RR of TSS, COD, and BOD_5 has slightly decreased but maintained a RR above 80 % and with effluent concentrations that comply with the Egyptian Code of Practice for wastewater reuse. However, increasing the organic loading rate to

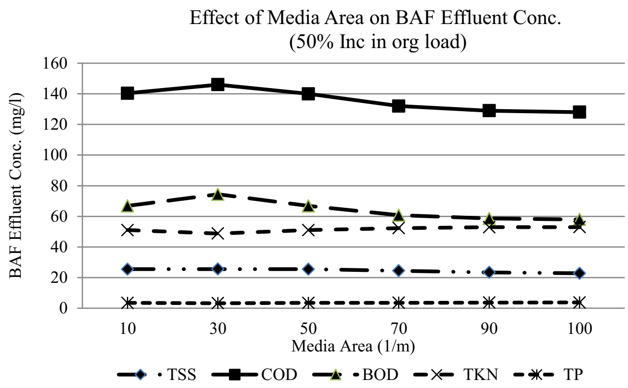

Fig. 9 Effect of surface area on the efficiency of BAF unit (50 % increases in concentration)

70 % from the original value decreased the removal rates of TSS, COD, and BOD to 75, 52, and 54 %, respectively.

The success of the BAF reactor to accommodate up to 50 % more than the original designed value could be attributed to its capability for retaining a high concentration of sludge in the packing material, meanwhile high efficiency of solids, liquids and water phase separation is attained. Figure 2 shows that the RR after BAF reactor decreased to less than 40 % for TKN and less than 60 % for TP. These results may be due to the lack of air flow supplied to the system which was maintained at 5 m^3/d for the actual influent loading rate. As the biofilm thickness increases, the rate of dissolved oxygen penetrating the layer decreases as illustrated in Fig. 3. Also, according to

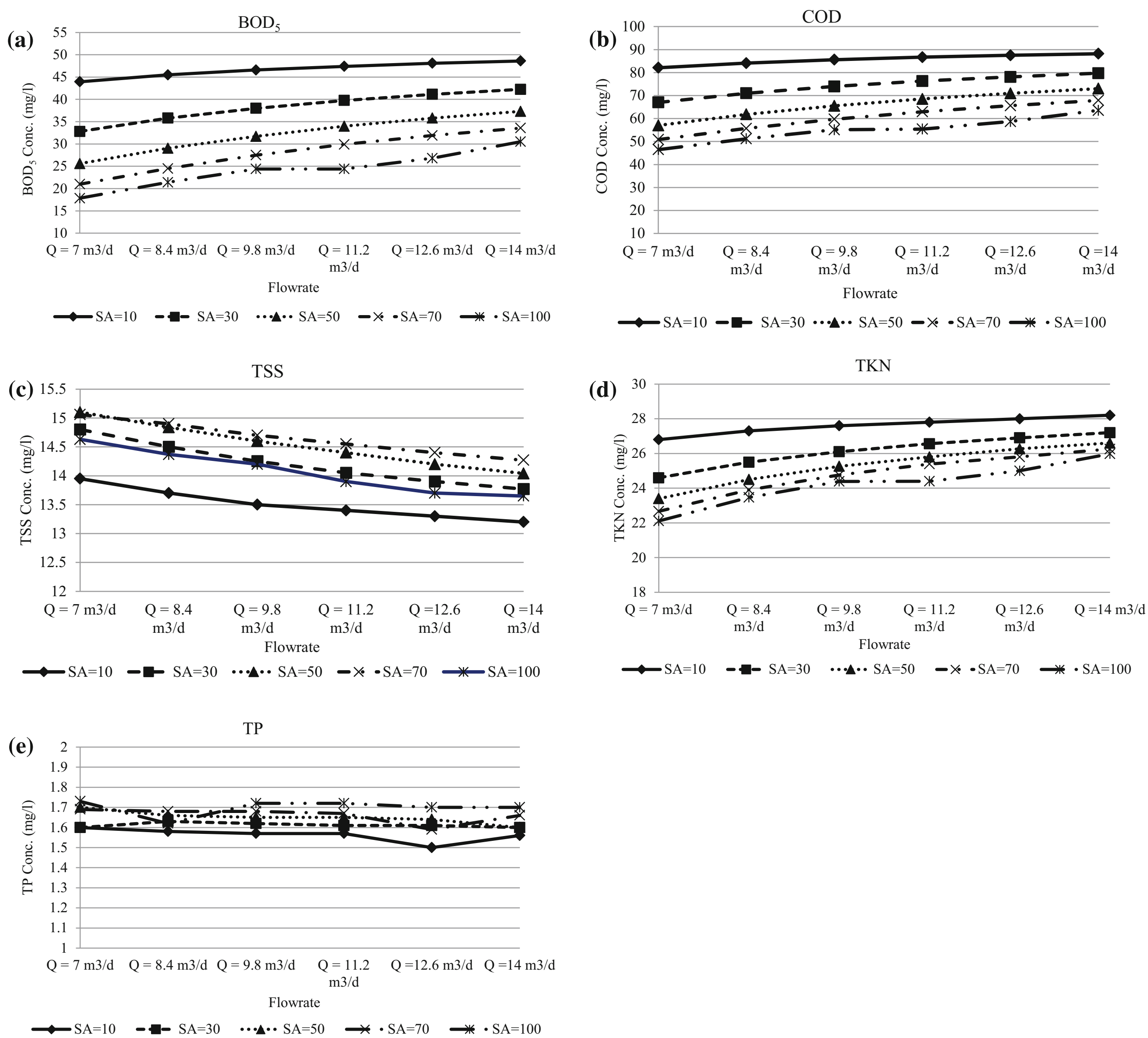

Fig. 10 Effect of increasing media surface area and influent flowrate on BAF effluent concentration for BOD_5 (**a**), COD (**b**), TSS (**c**), TKN (**d**), and TP (**e**)

Pramanik et al. (2012), maintaining high levels of dissolved oxygen to oxidize ammonia; a successful nitrification process would be achieved via the presence of the nitrifying bacteria. However, in case of lack or limited amounts of oxygen, ammonia oxidation would be inhibited but not ceased. This could explain the reason behind the high levels of effluent TKN since the concentration of DO recorded from the simulation was less than 2.0 mg/l when the influent concentration of organic loads increased. Zhu and Jenni (2007) indicated that it was essential to maintain adequate DO in the fixed film process compared to the suspended growth processes because of the nature of diffusion transport with fixed film.

Effect of increasing surface area of packing media versus different increases of (COD, BOD, TSS, TKN, TP) on BAF performance

The effect of the surface area of the packing material on the removal efficiency achieved from the BAF reactor at the designed loading rate is illustrated in Fig. 4. Figures 5, 6, 7, 8, 9 shows the variation of surface area from 10 to 100 1/m with different influent concentrations of different parameters are shown in The results indicated that as the surface area increased from 10 to 100 (1/m), the percentage removals of COD and BOD improved by 65 and 66 % with corresponding residual values of 43 and 20 mg/l. This could be attributed to the fact that as the area of the attached media increased, the biofilm developed increased. The NWPF media acts as a deep submerged filter and incorporates suspended solids and organic matters (Abou-Elela et al. 2013c).

Effect of various hydraulic loading rates on the performance of the BAF reactor for different surface area of the packing media

A sensitivity analysis has been performed for the above mentioned experimental setup to test the performance of the BAF unit when exposed to higher flow rates at different surface areas of the packing media. The values of flow rates examined were 7 up to 14 m^3/d corresponding to hydraulic loading rates (9.65–19.29 m^3/m^2/d) for media surface areas 10, 30, 59, 70, and 100 m^2/m^3, respectively.

The simulation results shown in Fig. 10a–d) illustrate that the increase in flow rate from 7 to 14 m^3/d had a slight effect on the residual values of BOD_5, COD, and TKN. This could be attributed to the fact that as the flow rate increased, the hydraulic retention time decreased along with the increase in the amount of oxygen required to be supplied to the system to cope with the available biomass. This complies with that mentioned earlier by Pramanik et al. (2012). Furthermore, as the flow rate increased, the residual TSS slightly decreased, whereas that for TP remained nearly unchanged as illustrated in Fig. 10c and e. The results indicated that the residual concentration of TSS was slightly decreased with increasing the HLR up to 19.29 m^3/m^2/d using surface area of packing material (100 l/m). This proved that the treatment system can accommodate a hydraulic loading rate up to four times its original designed load with the use of NWPF.

Conclusion

After conducting the experimental work and validating, the results obtained demonstrated various aspects. First, the system showed promising results for the validation of the experimental work. Second, by increasing OLR up to 4.48 kg BOD_5/m^3/day, the treatment system still achieved high removal rates for TSS (98 %), COD (90 %), BOD_5 (93 %). Third, the system was able to withstand the variations in the influent flow and hydraulic loading rates up to twice its actual designed value (19.29 m^3/m^2/d). However, increasing the HLR to four times 38.59 m^3/m^2/d resulted in 50 % reduction in its efficiency. Fourth, increasing the surface area of the packing material increased the overall removal efficiency of the concerned parameters under investigation. The 100 1/m media surface area showed the highest removal efficiency for all the parameters compared to the other surface areas of the packing media.

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Nomenclature

For Eq. (1): As defined by Hyrdomantis (2013)

A_a	Area of biofilm through which transport is occurring (m^2)
δ_L	Thickness of attached liquid layer (m)
S_j^L	Substrate concentration in liquid film horizontal section (mg/L)
t	Time (days)
S_j^{BLi}	Substrate concentration at biofilm liquid interface section j (mg/L)
S^o	Substrate liquid-film substrate concentration (mg/L)
Q_L	Volumetric flowrate of attached liquid layer (L/d)
K_M	Mass transfer coefficient from liquid to biofilm (m/d)
K_{ML}	Oxygen transfer coefficient from air to biofilm (m/d)

For Eq. (2): As defined by Hyrdomantis (2013)

A	Area of attached microorganisms (m^2)
D_S	State variable diffusion coefficient (m^2/d)
Q_B	Volumetric flowrate of attached biofilm layer (L/d)
R_S	Substrate utilization rate (mg/L/d)
S	State variable concentration in layer (mg/L)
S_j^B	State variable concentration in attached biofilm layer j (mg/L)
t	Time (days)
y	Thickness of biofilm layer (m)
δ_L	Attached biofilm thickness in layer (m)
TSS	Total suspended solids
COD	Chemical oxygen demand
BOD_5	Biological oxygen demand
TKN	Total Kjeldahl nitrogen
TP	Total phospherous
BAF	Biological aerated filter
UASB	Upflow anaerobic sludge blanket reactor
1/m	Area of the media (equivalent to m^2/m^3)
ASM	Activated sludge model No.1
ASM3	Activated sludge model No.3
Mantis	Mantis Model
ASM2d	Activated Sludge Model No. 2d

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