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Performance evaluation and mathematical modelling of granular activated carbon biofiltration in wastewater treatment

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Abstract−Biological filtration is an effective technique for removing organic matter from wastewater. The performance of a biofilter can be influenced by a range of operational conditions. In this study the performance of biofilters was investigated for the influence of filter media depth, influent concentrations, filtrations rates and backwashing. The results show that performance of GAC filters decreased with shallower filter bed depths. In addition, the GAC performed better at lower influent concentration and lower filtration rates. The daily backwash adopted to avoid the physical clogging of the biofilter did not have any significant effect on the organic removal efficiency of the filter. The concentration, activity and characteristics of the biomass are quantified and described. A mathematical model was developed to simulate the organic removal of the GAC biofiltration system. The performance of the GAC filter under different influent organic concentration levels, filtration rates and filter bed depths was adequately simulated by the mathematical model developed for this study.

Key words: Biofilter, GAC, Organics, Biomass, Mathematical Modelling

INTRODUCTION

Organic matters are present in all kinds of water, particularly in wastewater. In wastewater, organic matters are usually quantified by biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), biodegradable dissolved organic carbon (BDOC) and total organic carbon (TOC) measurement. The presence of organic matters in water, even in a low concentration can directly affect water quality. Organic matters in water are the source of nutrient for aquatic microorganisms including opportunistic pathogens regrowth in the distribution systems. Organics also react with disinfectants such chlorine and ozone to form potential carcinogenic and harmful disinfection by-products. In addition, organic matter can impair the colour, odour and taste of water [1].

Even though organic matter can be removed in a large portion by conventional wastewater treatment processes it is difficult to completely remove. Therefore, organic matter removal is important in advanced water treatment to meet water quality requirements. The use of a biofilter is one of the treatment processes that can effectively remove organic matters that cannot be removed by conventional sewage treatments. Many studies have shown that biofilters can remove the majority of organic matter from water and wastewater with less operational and maintenance requirements [2,3]. The treatment function of the biological filter is based on the activities of microorganism communities that are attached onto filter media. Organic substances in the influent are adsorbed on the biomass and then biodegraded by the microbes.

GAC has an extremely large and irregular surface of the order of several hundred m^2/g of carbon that can provide a large area of available sites for microorganisms to attach onto and grow [3]. The GAC structure also protects microbes from shear loss during its operation. In the initial stage of operating the biofilter, adsorption of substances including microorganisms is the major process while in the later stages organic degradation by microbial activities becomes more important.

Microbes growing onto GAC include bacteria and protozoa [4]. Although there have been many studies on biofilters, the behavior of microbes during filtration has still not been explained clearly due to the variety of microorganisms involved and the number of factors that can influence biofilter performance.

The activities of microbes determine the performance of biological filtration. Microbes oxidize organic matters in water to produce energy and thus the available nutrient source in the feed water is essential for their development. In addition, hydraulic loading rate, backwashing techniques, temperature and pH, can affect the accumulation of biomass onto GAC in the biofilter [5-8]. Most of the studies have been confined to water treatment. Although these parameters were studied by previous authors, there is not enough data with wastewater effluent. More data is required for each of the different parameters to validate the mathematical model outlined in this paper.

Thus, in this study, the long-term performance of the GAC biofilter was evaluated by using synthetic wastewater. The effect of filter bed depth, of backwashing, of influent concentration and of filtration rate on the long-term removal of organic matters was studied. The nature and concentration of biomass was investigated in detail. A mathematical model was developed to simulate the long-term organic removal of the GAC biofiltration system. The performance of the mathematical model was assessed with the experimental data.

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Table 1. Constituents of the synthetic wastewater used

Compounds	Weight (mg/L)
Beef extract	1.8
Peptone	2.7
Humic acid	4.2
Tannic acid	4.2
Sodium lignin sulfonate	2.4
Sodium lauryle sulphate	0.94
Acacia gum powder	4.7
Arabic acid	5.0
$(NH_4)_2SO_4$	7.1
K_2HPO_4	7.0
NH_4HCO_3	18.8
$MgSO_4 \cdot 3H_2O$	0.71

EXPERIMENTAL INVESTIGATION

Long-term column experiments were conducted using a synthetic wastewater. The composition of the synthetic wastewater is shown in Table 1. This wastewater represents the biologically treated sewage effluent [9]. The experiments were run at different bed depth, influent TOC concentration, filtration rates and backwashing. A summary of the conditions for the different column experiments is given in Table 2.

The GAC used in the experiments was washed with distilled water and dried in an oven at 103.5 °C for 24 hours. It was kept in desiccators before being packed into the columns. This ensured the GAC was benign before use. The physical properties of the GAC are shown in Table 3. The filters were backwashed at 30-40% bed expansion for approximately 3-5 minutes every 24 hours of filtration run (see Table 2). Total organic carbon (TOC) was measured on a daily basis by using the UV-persulphate TOC analyzer (Dohrmann, Phoenix 8000). Further details of the experiments are given in Hoang [11].

1. Biomass Measurement-Dry Mass

Dry biomass attached on the GAC was measured in both batch and filtration (column) mode. In batch mode, the same amount of GAC (250 mg) was placed in different beakers with synthetic wastewater. Wastewater was replaced every two days to provide enough nutrients to facilitate biofilm growth onto the GAC surface. Following the period of operation, the whole amount of GAC was extracted from the beaker for dry mass measurement. The GAC was dried in the oven at 103 °C for 24 h and desiccated to eliminate moisture prior to weighing. The difference in mass of the GAC before and after contact with synthetic wastewater is the total adsorbed biomass.

Table 3. Physical properties of GAC

Specification of the GAC	Estimated value
Iodine number, mg/(g·min)	800
Maximum Ash content	5%
Maximum Moisture content	5%
Bulk density, kg/m^3	748
BET surface area, m^2/g	1112
Nominal size, m	3×10^{-4}
Average pore diameter, Å	26.14

Similarly, a series of GAC columns was set up under identical operational conditions such as GAC weight, bed depth, filtration rate and backwashing. After operation, the whole amount of GAC was also taken out of the column for dry mass measurement as described above.

Volatile suspended solid (VSS) was measured by first filtering through a weighed glass-fiber filter paper. Filter paper with retained residue is dried and weighed at 103 °C for at least 1 hour (m1). Sample was then burned at 550 °C for 20 minutes and weighed (m2). VSS was calculated as the following equation:

$$\text{VSS (mg/L)} = \frac{(m1 - m2) \times 1000}{V}$$

where V is volume of sample (mL).

A similar method could not be applied to GAC biomass estimation because GAC burned before the temperature reached 550 °C. Therefore, dry mass was measured by drying at 103 °C. The dry mass data includes not only the biomass but also other materials adhering onto the surface of the filter media although the latter is much smaller in quantity. However, this method gives a simple and practical estimate of the biomass growth in the biofilters.

2. Biological Oxygen Consumption Measurement

Biological oxygen consumption rate gives an estimation of the active rate of aerobic microorganisms in a biological system. In this study, a biological oxygen monitor (Yellow Springs Instrument, YSI probe model 5300) was used to measure the dissolved oxygen consumption rate by microorganisms. The rate of oxygen uptake rate (%) was recorded every minute for 30 minutes. The monitor was calibrated at every measurement with air saturated solution in which

Table 2. Summary of column experiments

Parameter	Experimental Set 1*	Experimental Set 2**	Unit
Filter media	GAC	GAC	
Bed depth	5, 10, 15 and 30	4	cm
Filtration rate	2	1	m/hr
Average TOC of influent	11.6	3.5	mg/L
Column diameter	2	2	cm
Backwashing expansion	40%	30%	
Backwashing duration and frequency	3 minutes every 24 hours	5 minutes every 24 hours	

*Hoang [10]

**Chaudary [11]

dissolved oxygen content was set at 100%.

3. Viable Counts of Bacteria

The amount of bacteria presented in water samples and on GAC surface was analyzed by using a spread plate technique.

4. Total Coliforms

A total coliform count was conducted by using a spread plate technique. The procedure of total coliforms test is similar to the viable counts test presented earlier except the MacConkey medium was the nutrient medium used for the enumeration of total coliforms.

5. Faecal Coliforms

Faecal coliform content in water samples was detected by using membrane filtration technique.

6. Microbial Identification

Microbes in the biofilter were identified by using a BIOLOG system (Biolog Inc. California, USA, 1993). *Providencia stuartii* was used as a quality control strain of the test [12].

EXPERIMENTAL RESULTS

1. Effect of Filter Bed Depth

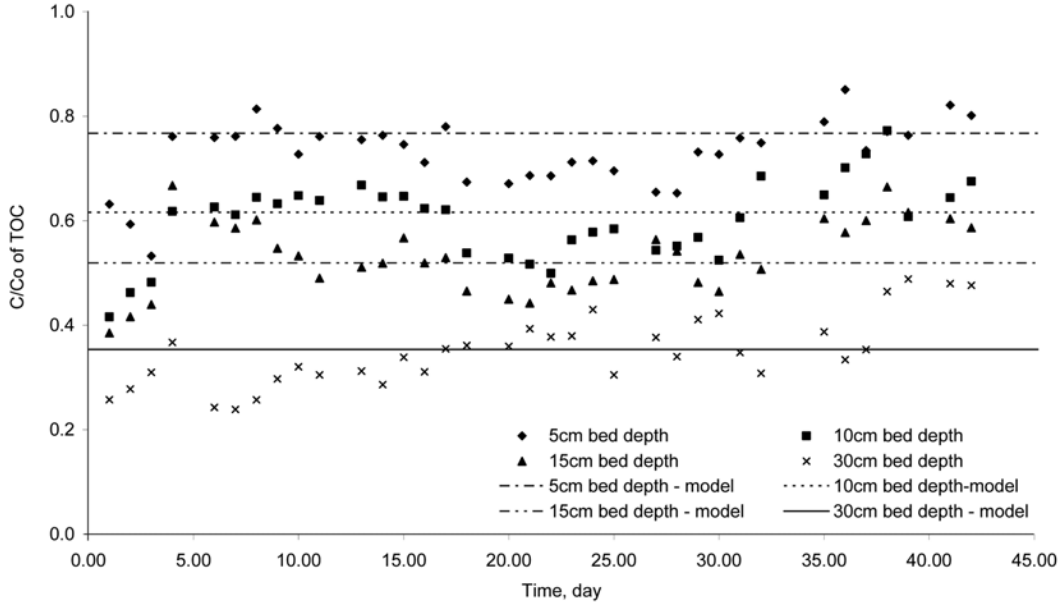

Fig. 1. Variation of C/Co of the GAC biofilter for various filter bed depths. Also shown is the fit between experimental data and model simulation in the long term for variation in bed depth (Filtration rate=2 m/hr, Average influent TOC=11.6 mg/L).

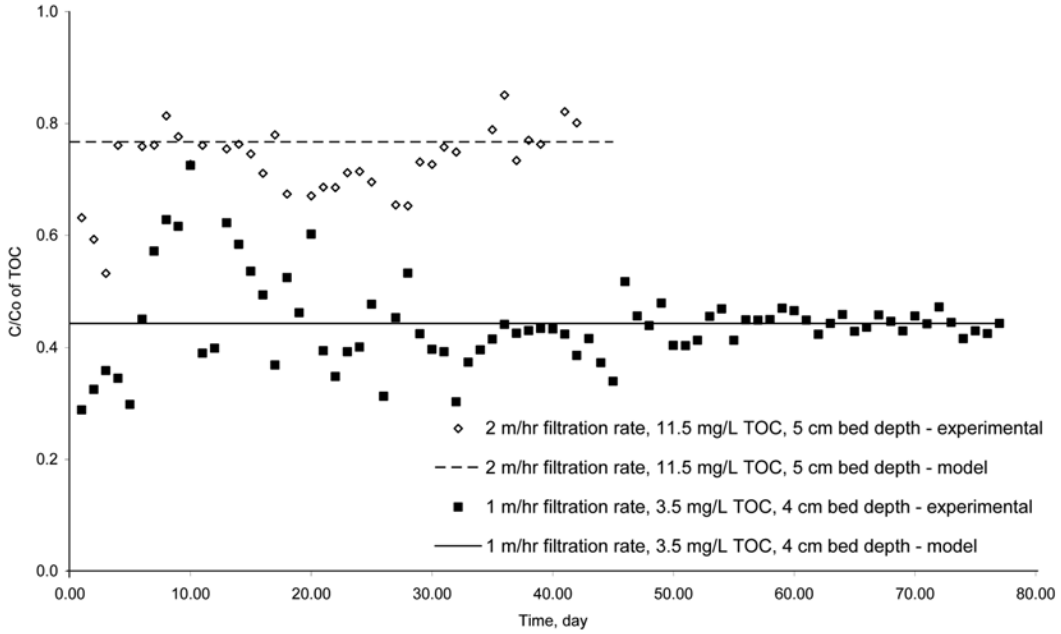

Fig. 2. Comparison of the removal efficiency of GAC filter for different influent concentrations. Also shown is the fit between experimental data and model simulation in the long term for variation in influent concentration.

The experimental columns packed with GAC to different bed depths were operated for a period exceeding six weeks. The columns were fed by synthetic wastewater at the filtration rate 2 m/h. The filtration rate was kept low as the GAC bed depths were shallow at between 5 cm to 30 cm. The organic removal capacity of the biofilters in terms of the ratio of the concentration of TOC in the effluent to the concentration of TOC in the influent is presented in Fig. 1.

These results show that the GAC biofilters led to a consistent TOC removal even after a long period of operation without the regeneration of the activated carbon. Even after 42 days of continuous running, the effluent from the 15 cm bed depth GAC biofilter was between 45 to 60% of the influent quality, while the effluent from the 30 cm bed depth GAC biofilter was between 25 to 40% of the influent quality. A deeper bed led to a better organic removal and TOC removal was significantly higher than the shallow bed. The computer model results are discussed in a later section.

2. Effect of TOC Influent Concentration and Filtration Rate

Long-term biofilter experiments were conducted at an influent concentration of 3.5 mg/L and filtration rate of 1 m/hr with GAC filter medium of 4 cm bed depth. The column was operated for more than 10 weeks with synthetic wastewater.

The result of this run is presented in Fig. 2. It was compared with the experiment run with an influent concentration of 11.5 mg/*l*, a filtration rate of 2 m/hr and a GAC filter bed depth of 5 cm. The removal efficiency shown is the ratio of organic material removed from that originally present in the influent wastewater, expressed as a percentage. Fig. 2 shows that with increased influent concentration and filtration rate, the effluent quality was inferior. However, the pattern of organic removal was not affected by changing variables such as influent concentrations, filtration rates and filter bed depths. A steady fluctuation pattern was quickly achieved and it remained unchanged with time. The computer model results are discussed in a later section.

3. Effect of Backwashing

The daily backwash adopted to avoid the physical clogging of the biofilter did not have any significant effect on the organic removal efficiency of the filter. Some of the biomass was lost during the backwashing of the filter, but loss of biomass created more sites on the GAC for adsorption of microorganisms and organics and thus the impairment was balanced [13]. This process, however, created a fluctuation pattern observed in the experimental data in Fig. 1 and 2.

BIOMASS in GAC BIOFILTER

The accumulation of microorganisms onto GAC filter media plays an important role in determining the effectiveness of a biofilter. The concentration, activity and characteristics of the biomass are quantified and described in the following sections.

1. Biomass in the Influent, Effluent and on GAC Biofilter

A GAC column with a bed depth of 15 cm was fed with synthetic wastewater and operated at the filtration rate of 2 m/h. The microbial population in the influent, effluent and on the GAC was estimated by using the viable cell count technique by plate count of colony forming units (CFU). With GAC samples taken from filters, microorganisms were detached by agitating GAC in a pre-determined amount of distilled water and then enumerated by the viable cell count analysis process. Fig. 3 shows the results of viable cell number in GAC the biofilter. The results show that the amount of viable bacteria attached on the GAC generally increased with time. The quantity of biomass in the effluent was small in comparison and relatively constant. In this study, the amount of organisms attached on GAC was difficult to accurately measure due to the difficulty in detaching all the biofilm from GAC.

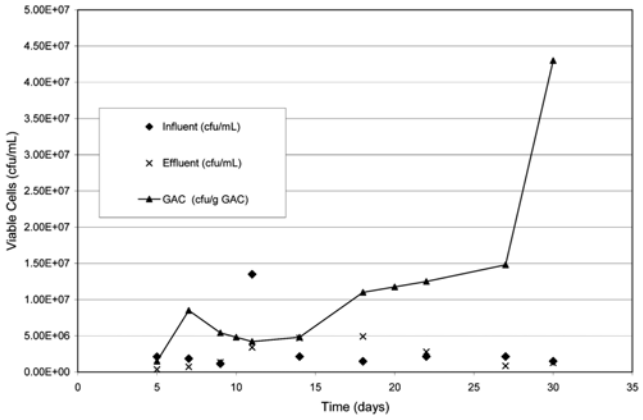

Fig. 3. A comparison of viable cell count in the influent, effluent, on the GAC filter and the amount of mass detached by backwashing (GAC bed depth=15 cm, filtration rate=2 m/h, average influent TOC=10 mg/L).

2. Biomass Detachment by Backwashing

The biomass loss by backwashing was investigated by determining the dry mass. Daily backwash was applied to avoid filter clogging. Backwashing was performed daily by using fresh tap water in an up-flow direction for a period of 3 minutes. The bed of the GAC column was expanded about 40% during backwashing. Biomass removal during backwashing is shown in Fig. 4. It was less than 5% of the total accumulated dry mass in the biofilter. There was no significant difference in the TOC value of effluent before and after backwashing and is in accordance with previous studies [7,14].

3. Relationship Between Oxygen Uptake Rate and Dry Mass

There is a relation between fixed biofilm on GAC and its respira-

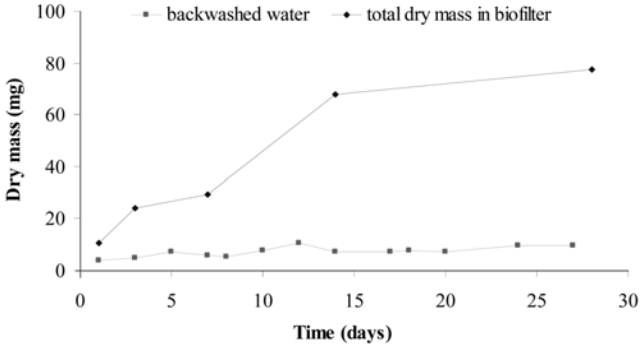

Fig. 4. A comparison of total dry mass accumulation and the amount of mass detached by backwashing in GAC biofilter (GAC bed depth=5 cm, filtration rate=2 m/h, influent =synthetic wastewater, average influent TOC=10 mg/L, backwashing expansion=60%, backwash duration=2 minutes).

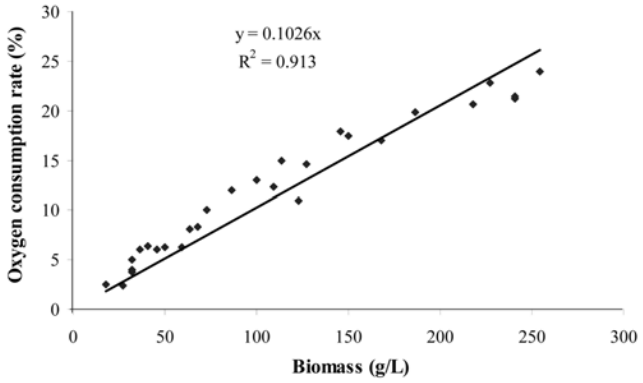

Fig. 5. Relationship between biomass and oxygen consumption rate of fixed biofilm (oxygen consumption rate was measured in 30 minutes).

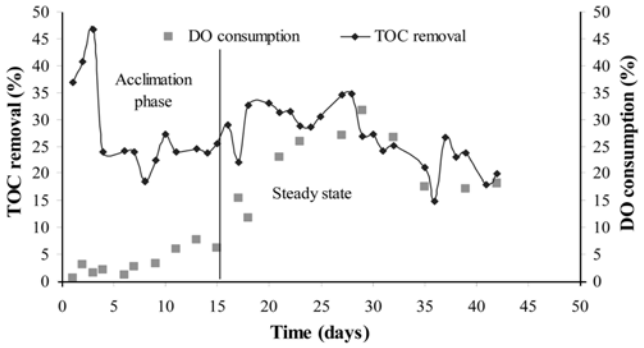

Fig. 7. Relation between dissolved oxygen consumption rate and TOC removal by GAC biofilter (diameter=2 cm, bed depth =5 cm, filtration rate=2 m/h, TOC influent=10 mg/L; DO consumption in 30 minutes).

tory rate in the biofilter. The oxygen consumption rate in the biofilter is the result of microbial metabolism. Thus, a direct link is expected between the amount of microorganisms and the oxygen uptake rate. It was found that not only microbial growth but also substrate removal correlated with the respiration rate [15].

In order to estimate the fixed biofilm on GAC more accurately, a simple mathematical equation between the oxygen uptake rate and dry mass was established. Fig. 5 presents the experimental data and mathematically fitted curves for dry mass and dissolved oxygen consumption. Here the biomass was determined as volatile suspended solid (VSS). The relationship between oxygen consumption rate and biomass is mathematically expressed in Eq. (1).

$$\text{Oxygen consumption rate (\%)} = 0.1026 \times \text{amount of biomass (mg/L)} \quad (1)$$

The linear relationship between the oxygen consumption rate and biomass was obtained during the exponential phase of microbial growth. The result showed that the oxygen consumption rate could be used as a practical tool to evaluate biological activity in the biofilter. The relationship between biomass and the oxygen consumption rate allows an estimate of the fixed biomass in the biofilter.

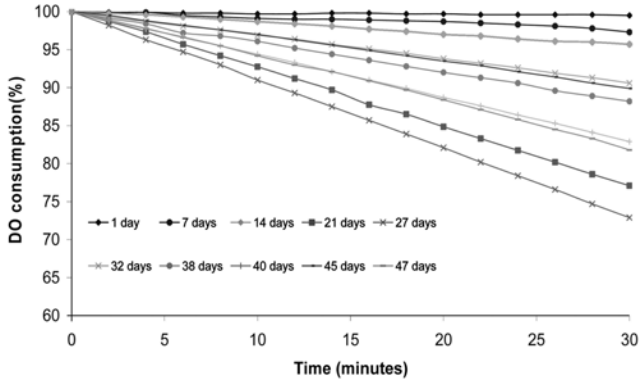

Fig. 6. The changes in dissolved oxygen content of samples during 30 minutes of respiratory measurement (the days in the Figure caption refers to the number of the day of operation by the biofilter) (diameter=2 cm, bed depth=5 cm, filtration rate=2 m/h, TOC influent=10 mg/L; DO consumption in 30 minutes).

4. Microbiological Activity in Biofilter

The biological activity of microbes in the biofilter was estimated by measuring their oxygen utilisation. Figs. 6 and 7 illustrate the DO consumption of microbes on GAC in biofilter for 30 minutes at varying stages during its operation. In this experiment, a GAC column was operated with synthetic wastewater at a filtration rate of 2 m/h and shallow bed depth of 5 cm to shorten the biofilter acclimation time. Samples of GAC with retained biomass were taken from the top layer of biofilter where the microbial community is most active and well developed [16].

During oxygen consumption measurement, oxygen content in the sample steadily decreased with time. The higher rate of oxygen consumption or metabolic rate of microorganisms led to steeper slope of dissolved oxygen content. It can also be seen from Fig. 6 that the oxygen consumption rate has a linear relationship with time. This indicated constant rate oxygen of consumption by microorganisms in GAC biofilter.

Fig. 7 shows the pattern of microbiological activities through the oxygen consumption rate in the GAC biofilter. Overlaid is the TOC removal which shows how the activity of microorganisms on the GAC is related to TOC removal. During the first 20 days, the rate of oxygen consumption increased gradually due to the build-up of the microorganism community. This period was the acclimation stage of the biofilter or the lag phase of microbial growth. The highest microbial activity was observed from 25-35 days of biofilter operational period. This corresponds to the period where the biofilter exhibited the highest TOC removal (Fig. 7). Except for the acclimation time (the first 20 days), the TOC removal rate and respiration rate followed the same pattern. They both reached a peak after about 30 days of filter operation with 35% TOC removal and 30% oxygen consumption in 30 minutes. Servais et al. [17] observed the same kind of evolution of biological activity.

5. Microbiological Assessment of a GAC Biofilter

Microbiological safety is a significant criterion in assessing water quality. In drinking water treatment, biological quality is strictly controlled because it directly affects public health. The reduction of microorganisms in wastewater treatment contributes to better performance in the subsequent steps. It helps to decrease doses of disinfectants and membrane fouling. Among several indicators of bio-

Table 4. Total faecal coliforms of influent and effluent of GAC biofilters for synthetic wastewater

Biofilter	Sample	Average total fecal coliforms (cfu/100 mL)
GAC biofilter with synthetic wastewater	Synthetic wastewater	13.73
	Effluent 1*	0
	Effluent 2*	4.27
	Effluent 3*	0

*1, 2 and 3 are the 5, 15 and 30 cm GAC bed depth column for synthetic wastewater.

Table 5. Microbial identification on GAC in biofilter

Column	Predominant microbal genera
Synthetic wastewater	• *Pseudomonas Aeruginosa* • *Pseudomonas Alcaligenes* • *Streptococcus oralis*

logical quality, total coliforms are the most common indicator for evaluating faecal contamination. In this study, a total coliform indicator was used to evaluate the biological quality of water treated by GAC biofilter. The evaluation was conducted when a GAC biofilter was at steady state (Fig. 7). The results of this measurement are shown in Table 4.

As can be seen in Table 4, all the GAC columns in this experiment resulted in a good removal rate of total coliforms. GAC columns eliminated 66-73% of coliforms from synthetic wastewater with the bed depth only 5-30 cm. The results were in accordance with the previous studies on biofilter in removing pathogens. It was found that a biofilter could remove from 20 to more than 90% of bacteria depending on operational conditions [18].

6. Microbiological Identification in GAC Biofilter

After the GAC biofilter reached its steady state, microorganisms were isolated for bacterial identification. The results of microbial identification in biofilter fed by synthetic wastewater are shown in Table 5. *Pseudomonas* was present on the GAC in the biofilter for synthetic wastewater. These bacteria are Gram-negative, aerobic, and non-fermentative. Previous studies indicated that *Pseudomonas aeruginosa* was frequently found in water, wastewater, soils and the biofilm of biofilter and drinking water distribution systems [18]. *Pseudomonas Aeruginosa* and *Pseudomonas Alcaligenes* are among the common opportunistic pathogens of humans and exposed to faecal pollution [18]. Therefore, disinfection is necessary as a post-treatment to eliminate those pathogens.

MATHEMATICAL MODEL

A mathematical model was developed to simulate the organic removal efficiency of the GAC biofiltration system. In this simulation model, the performance can be described in two stages: adsorption during the initial stage and biodegradation in the latter stage. In practice, the prediction of the performance of a biofilter during the biological phase or steady phase is more important because the initial stage only lasts for a short duration of less than a day at the beginning of a run. Therefore, the simulation of the adsorption processed was simplified.

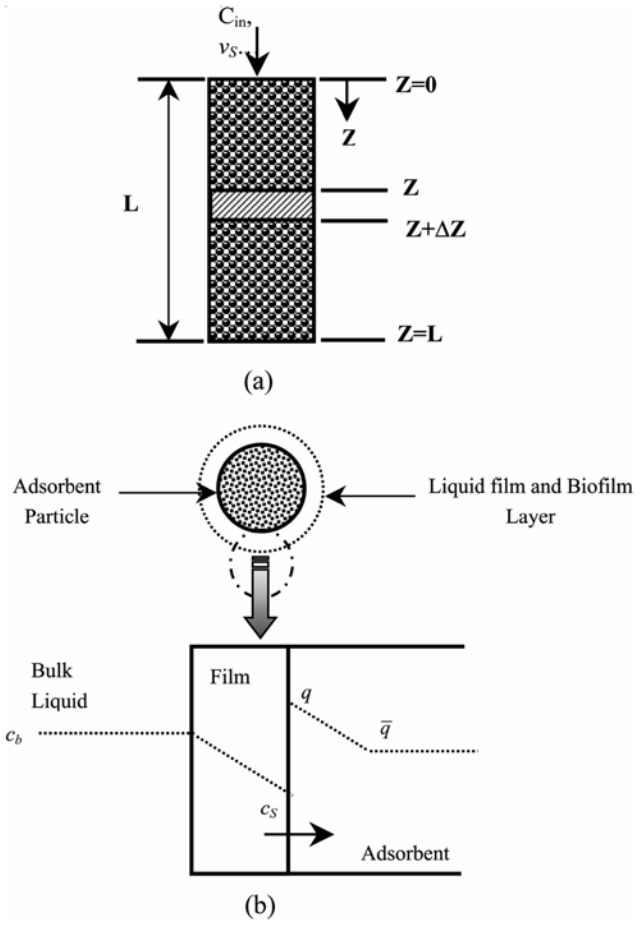

Fig. 8. (a) Schematic representation of the mass balance in a bioactive GAC (b) and the biofilm on an adsorbent surface.

A systematic representation of the mass balance in a biologically activated carbon system and the biofilm on the activated carbon is shown in Fig. 8. The model is based on the fundamental mechanisms of transport of substrate in the bulk liquid, biofilm growth, transport and biodegradation within the biofilm, and adsorption on activated carbon. The following additional assumptions are made in relation to the modelling work.

(1) The adsorbent particles are assumed to be spherical and uniform in size, and the curvature effect of the adsorbent surface can be ignored. No biological reaction occurs inside the adsorbent particle.

(2) The biofilm is thin relative to the radius of the adsorbent particle and can be modelled as a flat plate. The biofilm is homogeneous with respect to thickness, porosity, composition, and density. The specific surface area and bed porosity are constant with biofilm growth. Any increase in biofilm thickness is due to the growth of biofilm.

(3) The biological activity is assumed to be substrate limiting and can be represented by the Monod equation.

(4) The Glueckauf approximation may be used to describe intrapellet diffusion.

1. Substrate in the Bulk Liquid

The rates of removal of the substrate from the liquid phase by adsorption (γ_{ADS}) and biodegradation (γ_{BIO}) are given by:

$$\gamma_{BIO} = k_{max} \cdot \frac{C \cdot X_S}{K_S + C}, \qquad \gamma_{ADS} = (1-\varepsilon_b) \cdot \frac{3N}{4\pi R_p^3} \tag{2}$$

where N is the adsorbate uptake rate per pellet, ε_b is the bed porosity, R_P is the pellet radius, k_{max} is the maximum rate of substrate utilization, K_S is the Monod half velocity coefficient, X_S is the suspended cell concentration, and C is the liquid phase concentration [19].

The unsteady-state material balances on the substrate in the bulk liquid can be represented by the advection-diffusion equation with the inclusion of adsorption and reaction terms as follows:

$$\frac{\partial C}{\partial t} = D_{ax} \cdot \frac{\partial^2 C}{\partial z^2} - u \cdot \frac{\partial C}{\partial z} - \gamma_{BIO} - \gamma_{ads} \tag{3}$$

where D_{ax} is the axial dispersion coefficient and u is the interstitial velocity. The initial and boundary conditions are:

Initial condition, C=0

Boundary condition at z=0 is $C=C_0$ and at z=L is dC/dz=0

2. Biomass Suspended in the Bulk Liquid

Suspended biomass accumulates on the adsorbent due to deposition, growth, decay, and shear loss. The equation for suspended biomass in the bulk liquid is as follows:

$$\frac{\partial X_S}{\partial t} = \left(Y \cdot \frac{k_{max} \cdot C}{K_S + C} - K_d \frac{\beta}{\theta \cdot \varepsilon_b} \right) \cdot X_S + \frac{1-\varepsilon_b}{\varepsilon_b} \cdot a_f \cdot X_f \cdot \sigma \tag{4}$$

where Y is the yield coefficient, K_d is the decay constant, β is the filtration efficiency, θ is the empty bed contact time, X_f is the cell density of biofilm, a_f is the specific surface area and σ is the biofilm shear loss coefficient.

The associated initial and boundary conditions are

Initial condition, $X_s = X_{so}$

Boundary condition at z=0 is $X_s = X_{so}$, and at z=L is $dX_S/dz = 0$. Z and L are defined in Fig. 8.

3. Biofilm Diffusion and Biodegradation

Andrews and Tien [20] proposed a conceptual model of bio-film and its growth in which they assumed that the substrate diffuses through and is taken up by the biofilm. The diffusion of the substrate across the biofilm is accompanied by its biodegradation. The model equation for biofilm diffusion with Monod type is given by:

$$\frac{\partial S}{\partial t} = D_f \cdot \frac{\partial^2 S}{\partial x^2} - X_f \cdot \frac{k_{max} \cdot S}{K_S + S} \tag{5}$$

where, D_f is the molecular diffusivity within biofilm and S is the concentration of substrate in the biofilm. However it is assumed that the amount adsorbed into the particles is small and can be ignored. Furthermore, it is assumed that no biological reaction occurs inside the adsorbent particle. The associated initial and boundary conditions are:

Initial condition, $S=S_o$

Boundary condition at x=0 is $S=0$

at $x=L_f$ is $D_f \cdot \frac{\partial S}{\partial x} = k_f \cdot (C - S)$

where k_f is the interphase mass-transfer coefficient from liquid to biofilm.

4. Bed Porosity and Specific Surface Area

The growth of biofilm outside an adsorbent results in a change in the bed porosity and specific surface area. Alonso et al. [21,22] showed that the specific surface area could be calculated based on the consideration of the area and volume of biofilm lost in each contact point as compared with no contact point between solids. Then the specific area is given by:

$$a_f = \frac{3 \cdot (1-\varepsilon_{b0})}{2 \cdot R_p} \cdot \left(1 + \frac{L_f}{R_p}\right) \cdot \left[(2 - P_n) \cdot \frac{L_f}{R_p} + 2 \right]$$

where, P_n is the number of characteristic packing spheres. Assuming L_f is small in relation to R_p then

$$a_f = \frac{3 \cdot (1-\varepsilon_{b0})}{R_p}$$

The bed porosity with biofilm, ε_b, is given by:

$$\varepsilon_b = 1 - (1-\varepsilon_{b0}) \cdot \left[\left(1 + \frac{L_f}{R_p}\right)^3 - \frac{P_n}{4} \cdot \left(\frac{L_f}{R_p}\right)^2 \cdot \left(2 \cdot \frac{L_f}{R_p} + 3\right) \right]$$

Assuming L_f is small in relation to R_p then

$$\varepsilon_b = \varepsilon_{b0}$$

5. Backwashing System

The daily backwash adopted in the experimental study to avoid the physical clogging of the biofilter was found not to have any significant effect on the organic removal efficiency of the filter. Furthermore, several investigators examined the bed expansion due to filter backwash [23,24]. They found no major loss of biomass during backwash of the biofilter. Servais et al. [17] backwashed the GAC biofilter with air scour and water routinely every 50-100 hours of continuous run, but observed no significant difference in vertical biomass profiles before and after backwash. Shim et al. [19] showed there is no significant difference in concentration profile before and after backwash. The organic removal efficiency of the system remained constant. In this study backwashing was not implemented in the model as it did not affect the filter performance based on the experiments carried out in this study.

6. Finite Difference Model

The set of coupled parabolic second-order partial differential equations, Eqs. (2) to (5), cannot be solved analytically. Therefore, the preferred means of numerically solving this set of partial difference equations is the finite difference method using the prescribed boundary conditions. A model was developed to undertake this.

MODEL RESULTS AND DISCUSSION

The model developed in this study incorporates the mechanisms such as bulk transport, utilization and biofilm degradation. Tables 6 and 7 present the estimated value of physical and biological parameters, which were used in the modelling the GAC biofilter. Some of biological parameters such as biofilm thickness, maximum growth rate, suspended cell concentration, etc. were obtained from previous studies of Hozalski and Bouwer [25] and Alonso et al. [22]. The diffusion coefficient, D_s, and axial dispersion coefficient, D_{ax} were based on values in Shim et al. [19] and Chang and Rittman

Table 6. Physical parameters used for model simulation of GAC biofilter

Parameter	Value				
Bed depth (cm)	4	5	10	15	30
Velocity (m/hr)	1		2		
TOC of influent (mg/L)	3.5		11.6		
Diffusion coefficient D_f ($\times 10^{-10}$) (m^2/s)			6.8		
Film mass transfer coefficient K_f ($\times 10^{-6}$) (m/s)	2.75	1.3	1.15	1	0.7
Axial dispersion coefficient D_{ax} ($\times 10^{-7}$) (m^2/s)			1		

Table 7. Biological parameters used for model simulation of GAC biofilter. The same parameters were used for all runs

Biological parameter	Value	Unit
Biomass density (X_f)	6.4×10^{3}	mg/L
Yield coefficient (Y)	0.34	mg/mg
Decay coefficient (K_d)	7.9×10^{-07}	s^{-1}
Total biofilm loss efficient (b_{tot})	1.9×10^{-06}	s^{-1}
Biofilm thickness (L_{f0})	1.0×10^{-06}	m
Suspended cell concentration (X_s)	1.0×10^{-08}	mg/L
Shear Loss (σ)	1.16×10^{-06}	s^{-1}
Maximum rate of substrate utilization (K_{max})	3.5×10^{-06}	s^{-1}
Monod half velocity coefficient (K_S)	0.24	mg/L

[26,27]. All biological parameters were maintained the same for all model simulations. Physical parameters such as D_s, and D_{ax} were kept constant, while the filter bed depth, TOC influent concentration and filtration rate were varied to match the experimental conditions (see Table 2). The only exception was the film mass transfer coefficient, K_f, which was obtained from the fitting of simulated model values with the experimental data and was varied within a small range of between 0.7 to 2.75×10^{-7} m/s. The values of K_f used for each model simulation run are shown in Table 6.

In this simulation model adsorption during the initial stage was simplified because it only lasted for a short duration, for less than a day, and the principal pollutant removal mechanism was by biodegradation. In practice, the prediction of the performance of a biofilter during the biological phase or steady fluctuating phase is more important because the initial stage only lasts for short duration at the beginning of a run. The duration of steady state can be for a few months or even a year. The fit of the model simulation with experimental results is largely determined by its ability to simulate the biological phase.

Fig. 1 shows the fit with experimental data with different filter depths where the influent concentration and filtration rates were held constant. The model is able to predict the average long-term experimental results in the biological phase.

Fig. 2 shows the fit with experimental data where the influent concentration, filter bed depths and filtration rates were all different. Even in these varied experimental conditions the simulated performance of the biofilter shown in Fig. 2 fitted rather well with the average long-term experimental results in the biological phase.

CONCLUSIONS

GAC biofilter can be used as a cost-effective treatment in removing organic matters from biologically treated sewage effluent. The advantages of the GAC biofilter are the consistency of TOC removal, long operational life, and simplicity in operation. The biomass in the GAC biofilter remains in a consistent concentration over a long time and can keep the biofilter working properly for a long period of operation. The performance of the GAC biofilter can be improved by increasing the filter bed depth. With increased influent concentration and filtration rate, the effluent quality became inferior to that with lower concentration but the organic removal pattern remained unchanged with time. The daily backwash adopted in the experimental study to avoid the physical clogging of the biofilter was found not to have any significant effect on the organic removal efficiency of the filter. The concentration, microbial activity and characteristics of the biomass were quantified and described. The performance of GAC filter was adequately simulated by a mathematical model developed for this study.

NOMENCLATURE

a_f : specific surface area [m2]
C : liquid phase concentration [mg/L]
C_0 : initial concentration [mg/L]
D_{ax} : axial dispersion coefficient [m2/s]
D_f : molecular diffusivity within biofilm [m2/s]
k_f : interphase mass-transfer coefficient from liquid to biofilm [m/s]
k_{max} : maximum rate of substrate utilization [s^{-1}]
K_d : decay constant [s^{-1}]
K_S : monod half velocity coefficient [mg/L]
L_f : biofilm thickness [m]
N : substrate uptake rate by pellet [g/s]
R_P : pellet radius [m]
S : concentration of the substrate in the biofilm [mg/L]
t : time [s]
u : interstitial velocity [m/s]
x : radial distance [m]
X_f : cell density of biofilm [mg/L]
X_S : suspended cell concentration [mg/L]
Y : yield
β : filtration efficiency [-]
ε_b : bed porosity [-]
γ_{ADS} : rate of removal of the substrate from the liquid phase by adsorption defined by Eq. (3)
γ_{BIO} : rate of removal of the substrate from the liquid phase by biodegradation defined by Eq. (3)
θ : empty bed contact time [s]
ρ_p : solid density [kg/m3]
σ : biofilm shear loss coefficient [s^{-1}]

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