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# Calculation of optimal gas retention time using a logarithmic equation applied to a bio-trickling filter reactor for formaldehyde removal from synthetic contaminated air

Mohamad Ali Fulazzaky,*[a] Amirreza Talaiekhozani[ab] and Tony Hadibarata[a]

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Formaldehyde (FA) removal from contaminated air has been extensively studied using a bio-trickling filter reactor (BTFR). However, the effect of different volumetric air flow rates (VAFRs) on FA removal efficiency needs to be verified for better BTFR design with optimal operating conditions. This study uses a laboratory-scale BTFR, operating with the three different VAFRs to remove FA from synthetic contaminated air. Mathematical models to determine the optimal retention time of contaminated air flow through the BTFR system are developed. The effect of different pH values on the FA removal efficiency is evaluated. FA removal efficiencies of 99, 96 and 95% are verified for VAFRs of 90, 291 and 1512 L $h^{-1}$, respectively. Optimal retention times of 141, 50 and 26 s are verified for BTFR experiments operating at 90, 291 and 1512 L $h^{-1}$ VAFR, respectively. The logarithmic models are proposed as a new approach for determining the optimal retention time and hoped to make a significant contribution to future biotechnological developments and air quality improvement analysis.

## 1 Introduction

Although technology has made the world a better place to live, the impact of technology may generate multifarious pollutants if not well planned and controlled. Many pollutants present in wastewater, waste gas and solid waste can negatively affect ecosystems and human health. As the waste gas is very hard to collect and treat, there is still no economically effective method for treating it and therefore air pollution has become local as well as regional in extent. Many volatile organic compounds (VOCs) present in air can travel hundreds of kilometres from their source and can cause multiple human health and environmental problems on the national or international scale. One of the most common air pollutants is formaldehyde (FA), which is one of the VOCs released from *e.g.* solid waste wood-burning sites, chipboard manufacturing plants, synthetic resin industries and several other areas of the chemical industry. FA is an organic compound with formula $CH_2O$ and has a dipolar resonance structure, which makes the molecule a typical electrophile.[1] FA can dissolve easily in water because both these chemicals are polar. FA is a colourless, highly toxic, reactive and flammable gas at room temperature, which is slightly heavier than air. Therefore, FA is one of the most dangerous compounds to ecosystems and human health and has potent mutagenic effects in humans and other organisms, both when acting alone and in combination with other mutagens.[2] Even though determination of global FA emission is quite difficult, a FA emission rate of about 32 million tonnes per year was predicted for the year 2006, while China is the largest producer and consumer of FA in the world.[3]

Different physicochemical and biological methods have been proposed for treating VOCs, including FA from contaminated air, such as activated carbon adsorption, chemical oxidation, and anaerobic and aerobic biological degradation.[4–7] Still, the biological treatment processes are the best methods, and can emerge as a cost-effective and environmentally-friendly technology[8] for treating the high-volume loading rate of gas streams with a relatively low concentration of effluent pollutants.[9] The biodegradation rate coefficients of methanol and toluene have been determined from a study in a biofilter bed.[10] Agro-waste has been used as biofilter medium to remove toluene from an air contaminated effluent.[11] The packing material using the three different inert filter bed materials (*i.e.* lava rock, perlite and activated carbon) had only a small influence on the performance of the biological treatment system to remove FA and methanol.[5] The presence of low concentrations of dimethyl ether in the gaseous mixture did not have a significant effect on the removal of FA or methanol in the specific bioreactor system, although

[a]*Institute of Environmental and Water Resources Management, Water Research Alliance, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia. E-mail: fulazzaky@gmail.com; fulazzaky@utm.my; Fax: +6075531575; Tel: +6075531702*

[b]*Department of Civil and Environmental Engineering, Jami Institute of Technology, Najafabad, Isfahan, Iran*

moderate concentrations of these compounds did negatively affect the biodegradation of dimethyl ether.[12] Removal efficiencies near 100% could be achieved using a biofilter packed with ceramic particles and pure microorganisms to remove trimethylamine from the waste gas when the empty bed residence time was >110 s with 0.30 mg $L^{-1}$ inlet concentration.[6] The use of sewage sludge and yard waste compost as a biofilter medium enabled close to 100% removal of ethanethiol, dimethyl sulfide and dimethyl disulfide.[13] A large number of microorganisms including bacteria, fungi and yeast can grow on supporting materials and can act as a biofilter to degrade any VOCs, including FA.[14–16] A previous study[17] reported that biofilters are usable in a wide range of pH if a mixed culture of suitable microorganisms can be used optimally. Acidophilic and thermophilic bacteria have a low yield coefficient, generating little biomass and having the advantage of reducing the pressure drop of the biofilter.[4,18] Even though each type of research design[19–22] has its own standards for reliability and validity in treating VOCs, the determination of optimal gas retention time for FA removal in terms of the removal efficiency of a bio-trickling filter is not fully understood.

The objectives of this study are: (1) to verify the effect of pH on the performance of the bio-tricking filter reactor (BTFR) system operating at the same volumetric air flow rate (VAFR), (2) to analyse the FA removal efficiencies for laboratory-scale BTFR experiments conducted under the three different VAFRs, and (3) to establish mathematical models capable of determining the optimal retention time of contaminated air flows through the BTFR system.

## 2 Materials and methods

### 2.1 Experimental equipment and procedure

This research was conducted with a laboratory-scale BTFR consisting of a biofilter bed, using fragmented pieces of a polyurethane pipe as supporting material, nutrient solution tank, FA storage tank, compressor, peristaltic pump, flow meter, control air valve and mechanical o'clock switch, as shown in Fig. 1. The BTFR has four sampling ports for monitoring the FA content in the biofilter during the experimental period. Heights of 5, 15, 25 and 40 cm from the bottom of the biofilter bed were set up for ports 1, 2, 3 and 4, respectively. The dimensions of the biofilter are diameter 8 cm, height 66 cm and volume 3.319 L. The percentage of void space in the biofilter was 90%.

The synthetic contaminated air stream (SCAS), which can be ventilated using the air pressure generated by a compressor ''Asian Star AP-1000'' was supplied from the FA storage tank to the biofilter (see Fig. 1). A IF series-DWYER flow meter was used to monitor the air-flow rate. Aerobic granular sludge (AGS) was used as the inoculum for the start-up of the BTFR system coming from a municipal wastewater treatment plant in Isfahan city, Iran. The experiment, conducted at room temperature, examined the effect of pH and VAFR on the performance of the BTFR. In the continuous-flow culture system[23] the nutrient solution regularly flows past the

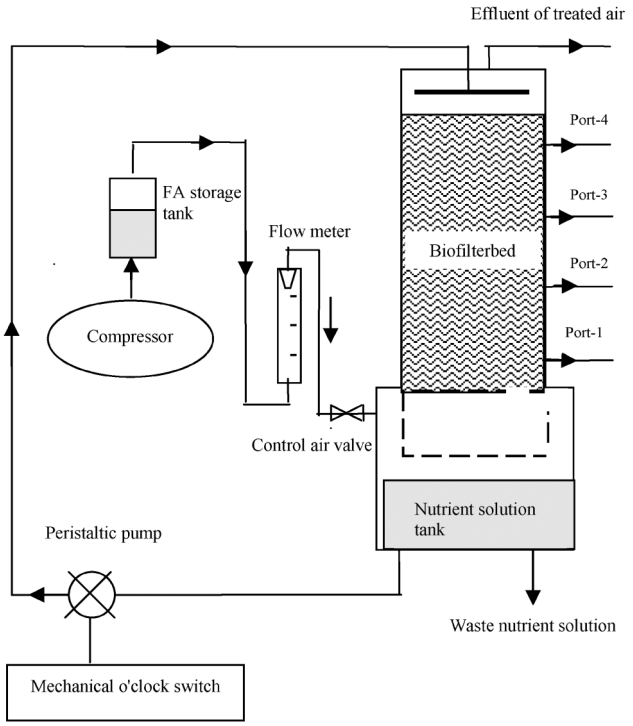


**Fig. 1** Schematic of the BTFR.

biofilter. The mechanical o'clock switch regulates the fed nutrient solution at a flow rate of 50 L $h^{-1}$, and the peristaltic pump circulates the nutrient solution through the top of the biofilter bed during a 15 min period every hour. The experiment was conducted firstly to develop microorganisms on the supporting materials during the adaptation phase of 90 days and continued secondly to collect the data for monitoring the different VAFRs during the experimental period of 80 days. The FA dissolved in water originally from the SCAS was calculated based on the chemical oxygen demand (COD) of the nutrient solution. Different VAFRs of 90, 291 and 1512 L $h^{-1}$ were used to evaluate the FA removal efficiency. The average FA concentration in SCAS was analysed during the experiment; it was about 490 mg $L^{-1}$. To determine the FA concentrations in the biofilter bed at the positions of ports 1, 2, 3 and 4, air samples were collected using the vacuum pump ''Champion Air Pump-AAP Model'' for each day during the experiments. The experimental temperatures were monitored using a digital thermometer at the influent, the middle biofilter bed and the effluent of the BTFR system.

Some limitations of using the BTFR to remove FA from the air are that: (1) the treatment system is only effective when there is a captured air stream, (2) moisture content in the air affects the BTFR performance, and (3) different types of bacteria that can grow at the supporting materials in the biofilter bed are related to the ability of the media selected to hold the biofilm together and give a specific structure under different culture conditions, if the materials selected of low porosity will not perform satisfactorily.

### 2.2 Nutrient solution

The key to effective BTFR operation is maintaining a healthy environment for microorganisms to thrive at the supporting materials and therefore requires nutrient to support the growth of a variety of microbes. Many bacteria grow with oxygen at the AGS as culture media, designed to provide all the essential nutrients in solution for bacterial growth. Some elements such as carbon, nitrogen, phosphorus, magnesium, potassium, calcium, iron, chloride and manganese are essential for microbial growth. The nutrient solution consists of water containing a sufficient quantity of minerals *i.e.* 0.1 g $L^{-1}$ $MgSO_4$, 0.5 g $L^{-1}$ $KH_2PO_4$, 0.01 g $L^{-1}$ $CaCl_2{\cdot}2H_2O$, 0.001 g $L^{-1}$ $FeSO_4$, 1 g $L^{-1}$ $NH_4Cl$, 0.5 g $L^{-1}$ $K_2HPO_4$ and 0.001 g $L^{-1}$ $MnSO_4$ and has the function of conserving the biofilter in a wet environment during the experiments. Aerobic bacteria living on the supporting materials in the biofilter bed require oxygen for life support which is obtained from the nutrient solution. Different criteria for bioreactor scale-up are considered, affecting the dissolved oxygen (DO) concentration in the real bioprocess.[24] Therefore the nutrient solution was aerated continuously to ensure DO higher than 5 mg $L^{-1}$. The optimum pH of the nutrient solution for all the experiments was set up at $7 \pm 0.5$ and can be adjusted using either sodium hydroxide or hydrochloric acid solution.

### 2.3 Adaptation phase and experimental period

The development of the biofilm on the supporting materials requires the nutrient solution being adapted to support microbial activities. During the adaption phase, a mixture of glucose and FA was added into the nutrient solution as a carbon source. Starting with a low FA level, a high amount of glucose was added into the nutrient solution, giving an organic matter concentration of about 1 g $L^{-1}$ COD. An increased FA concentration decreases the glucose concentration for generation of the product of a similar organic matter fraction in the nutrient solution. After an adaptation phase of 90 days, FA was the sole carbon source used for feeding the BTFR. During the experimental period, air contaminated with FA can be injected into the biofilter to replace FA from the nutrient solution as the carbon source. The operational BTFR system requires air injection to maintain an adequate DO concentration in the nutrient solution. The amounts of FA from the SCAS dissolved in the nutrient solution depend on the temperature of the solution and can react with water to form methanediol or methylene glycol $H_2C(OH)_2$. It is important to identify and regularly review the FA concentration in terms of the COD value. The FA concentration in the treated SCAS was monitored at the outlet of the BTFR. The use of FA as the carbon source for microbial activities—of both gas and liquid origin—can improve the air quality and therefore an increase in biofilm thickness at the supporting materials is expected.

### 2.4 Adjustment of pH in the nutrient solution

An important variable in operating the BTFR is pH, since it influences many biological and chemical processes within the biofilter bed. In this work, the effect of the different values (*i.e.*, 3, 5, 6, 7 and 9) of pH on the performance of the BTFR system was evaluated. If the pH is higher than desired hydrochloric acid solution was added for the adjustment. A pH of 9 can be attained using sodium hydroxide solution. The FA removal efficiencies treated using the BTFR system were evaluated based on data monitoring during a 40-day period for pH 3 and 9 and during a 20-day period for pH 5, 6 and 7.

### 2.5 Analytical methods

Some physicochemical parameters were measured to assess the quality of the nutrient solution such as pH, COD and DO. The measurement of pH of the nutrient solution can be made of using a portable pH-meter (Crison model 507). The FA levels in the nutrient solution can be estimated from COD measurements using a microwave digestion[25] and spectrophotometric method. The DO measurements were made using the DO meter (Cole Parmer model 9070 oxygen meter).

### 2.6 Model development

Several models have been proposed for explaining the removal of FA from contaminated air.[26,27] The mathematical modelling of bacterial growth and process performance has led to improved design and operation of bioreactor system development.[28,29] The need to operate on a day-to-day basis in practice requires further development of robust, integrated microfluidic systems.[30] In this study, the mass-balance equation for FA removal from SCAS at level of the BTFR system, assuming a combined biofilter bed and nutrient solution tank as black box,[31] is written as:

$$dC/dt = r \quad (1)$$

where $C$ is amount of FA remaining in the biofilter bed originally released from the nutrient solution (in mg $L^{-1}$), $t$ is time (in days), and $r$ is FA removal rate (in mg $L^{-1}$ $day^{-1}$).

In chemical kinetics, the rate of chemical reaction effectively depends on FA reactant and therefore the value of the exponent is one. It is assumed that if $r$ is first order, then rearrangement of eqn (1) gives a continuous equation expressed as:

$$dC/dt = kC \quad (2)$$

where $C$ is amount of FA remaining in the biofilter bed originally released from the nutrient solution (in mg $L^{-1}$), $t$ is time (in day), and $k$ is the biochemical reaction rate coefficient (in $day^{-1}$).

When we separate the variables, eqn (2) can be integrated in the form of:

$$C = C_0\exp(kt) \quad (3)$$

Then eqn (3) can be arranged in form of:

$$\ln(C) = kt + \ln(C_0) \quad (4)$$

where $C$ is amount of FA remaining in the biofilter bed originally released from the nutrient solution (in mg $L^{-1}$), $C_0$ is initial FA concentration in the nutrient solution (in mg $L^{-1}$), $t$

 

is time (in day), and $k$ is the biochemical reaction rate coefficient (in day$^{-1}$).

The following equation can be used to express the BTFR performance to remove FA from the SCAS, such that:

$$E = \frac{C_i - C_e}{C_i} \times 100\% \quad (5)$$

where $E$ is FA removal efficiency (in %), $C_i$ is FA concentration in the SCAS monitored at the inlet of the BTFR system (mg m$^{-3}$); $C_e$ is FA concentration in the SCAS monitored at the outlet of the BTFR system (mg m$^{-3}$).

FA has a high solubility and large amounts can dissolve in the nutrient solution. It is suggested that only a small amount of FA from the SCAS will be used directly by microbial activities on the supporting materials in the biofilter bed. The FA dissolved in the nutrient solution as present in the SCAS may serve as the carbon source for cell growth and respiration. To develop a quantitative model of the BTFR system, one needs to understand the role of each component involved in the BTFR. A systematic approach for developing a conceptual model was based upon the following assumptions: (1) since $C_0$ is the original FA concentration in the nutrient solution, the amount of FA remaining in the biofilter bed for the optimal functioning of the BTFR should be greater than $C_0$; (2) the $E$ levels of aerobic biological treatment processed in the BTFR depend on a number of factors including gas retention time ($\theta$), $C_0$ and VAFR; (3) the tendency toward more rational results requires more monitoring FA concentration at inlet and outlet of the BTFR, and FA in the SCAS moves through the biofilter rapidly; and (4) FA can be removed totally from the SCAS into the BTFR system with an appropriate $\theta$.

The measurement of FA concentration at time $t$ was investigated with multiple-retention times of the SCAS passing the biofilter. Since the value of $C$ is the difference between $C_0$ and the residual FA concentration in the waste nutrient solution, using loading $C$ in the biofilter originally coming from the nutrient solution is analogous to using $E$ in the BTFR system treating the SCAS during the experimental period. To develop a logarithmic model, the following hypotheses were made: (1) $t$ in eqn (4) can be replaced with ln($\theta$), where $\theta$ is defined as gas retention time, (2) ln($C_0$) is a constant and therefore can be replaced with $b$, which is defined as initial removal rate constant which depends on the amount of FA dissolved in the nutrient solution, and (3) ln($C$) can be replaced by $E$ as the FA removal efficiency. Therefore, the logarithmic model of eqn (4) can be arranged in its general form of:

$$E = k\ln(\theta) + b \quad (6)$$

where $E$ is the FA removal efficiency (in %), $k$ is biochemical reaction rate coefficient (in % s$^{-1}$), $\theta$ is the gas retention time (in s), and $b$ is the initial removal rate constant, which depends on the amount of FA dissolved in the nutrient solution (in %).

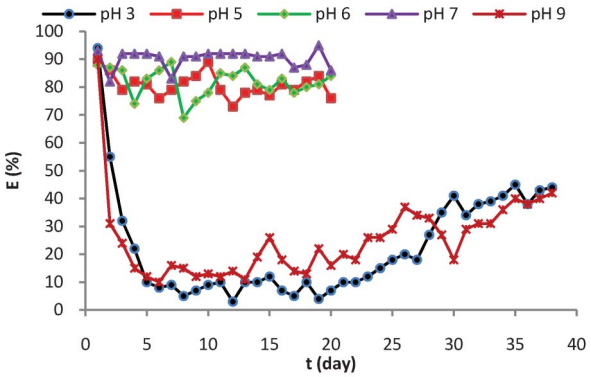


**Fig. 2** Effect of different values of pH on the FA removal efficiency.

## 3 Results and discussion

### 3.1 Effect of pH on FA removal efficiency

Many studies support the supposition that a change in pH can effect the microbial growth and efficiency of the BTFR to remove FA from the air.[32,33] Accurate volume growth measurements are important for the applications of biological treatment systems for modelling and simulation.[34] An efficient approach for producing specific growth with various morphologies can be generated by dynamically controlling and stabilising the phase separation.[35] A large number of bacteria were found if the pH of the biofiltration media was kept between 6.6 and 8.7.[36] A previous study[5] reported that FA removal efficiency using the biofilter can be partially inhibited if the pH is below 4.2. In this work, the influence of environmental pH on the efficiency of the BTFR system to remove FA from the air was evaluated based on the experiments conducted at five different values of pH *i.e.*, 3, 5, 6, 7 and 9 with the same VAFR of 90 L h$^{-1}$. The best environmental pH was assessed to enable selection of the appropriate conditions for further experiments using the different VAFRs. Fig. 2 shows that the neutral pH 7 of the nutrient solution is the best condition of the BTFR system to remove FA from SCAS. Even for BTFR operated at low VAFR (90 L h$^{-1}$), still 95% of the maximum possible FA removal efficiency, as assessed on the 19th day of the experiment, can be achieved at pH 7. In this case, bacterial growth response to biochemical reaction rate slightly lower for two consecutive days of the treatment (see Fig. 2) can create physiological conditions of the biofilter conducive to high demand for organic carbon and then suddenly accelerates the consumption of FA as a sole source of carbon and energy for bacterial growth to reach the peak performance. The experiments conducted with slightly acidic nutrient solution of pH 5 and 6 affected the efficiency of the BTFR, with this varying between 70 and 90%. Experiments conducted at acidic pH 3 or alkaline pH 9 of the nutrient solution reduces the FA removal efficiency to $<$20%, even though microbes possess the ability to adapt naturally to their environment, which improves the efficiency of the BTFR system with time on stream after 20 days. A neutral pH of 7 was subsequently used to study the

**Table 1** Values of $\theta$ and $E_g$ for the three experimental runs

| | Experiment 1[a] | | Experiment 2[b] | | Experiment 3[c] | |
|---|---|---|---|---|---|---|
| Sampling position | $\theta$/s | $E_g$ (%) | $\theta$/s | $E_g$ (%) | $\theta$/s | $E_g$ (%) |
| Port 1 | 10 | 51 | 3 | 74 | 0.6 | 86 |
| Port 2 | 30 | 66 | 9 | 82 | 1.8 | 90 |
| Port 3 | 50 | 76 | 15 | 89 | 3.0 | 92 |
| Port 4 | 80 | 87 | 25 | 95 | 4.8 | 94 |
| Effluent | 132 | 99 | 41 | 96 | 8.0 | 95 |

[a] VAFR = 90 L $h^{-1}$. [b] VAFR = 291 L $h^{-1}$. [c] VAFR = 1512 L $h^{-1}$.

effect of the different VAFRs on the FA removal efficiency and to maximise the effectiveness of the trickling biofilter system.

### 3.2 Analysis of FA removal efficiency for the different experiments

FA is recognized as one of the most common air pollutants and is a ubiquitous chemical found in garments, food, indoor air, gasoline and diesel exhausts.[5] Even though many methods have been attempted to decompose and remove FA from air, some biological methods today still have a larger practical importance due to that these environmentally friendly methods have the advantages of low operational and maintenance costs. This work examines FA removal in an aerobic BTFR. Table 1 shows that the retention times of FA flow were 132, 41 and 8 s for the BTFR system for injections of the VAFR of 90, 291 and 1512 L $h^{-1}$, respectively. An increase in retention time from 10 to 30 to 50 to 80 s with increasing of the biofilter bed height from 5 to 15 to 25 to 40 cm enhances the increase of FA removal efficiency from 51 to 66 to 76 to 87%, respectively, for the experiment with a VAFR of 90 L $h^{-1}$. The increase in retention time from 3 to 9 to 15 to 25 s enhances the increase of FA removal efficiency from 74 to 82 to 89 to 95%, respectively, for a VAFR of 291 L $h^{-1}$. The increase in retention time from 0.6 to 1.8 to 3.0 to 4.8 s enhances the increase of FA removal efficiency from 86 to 90 to 92 to 94%, respectively, for a VAFR of 1512 L $h^{-1}$. The effect of an increased pressure air compressor on the VAFR can increase concentration of FA in the SCAS and speeds up the removal efficiency. It seems that retention time is a critical factor for the development of an empirical model designed to predict the BTFR optimal functional criteria.

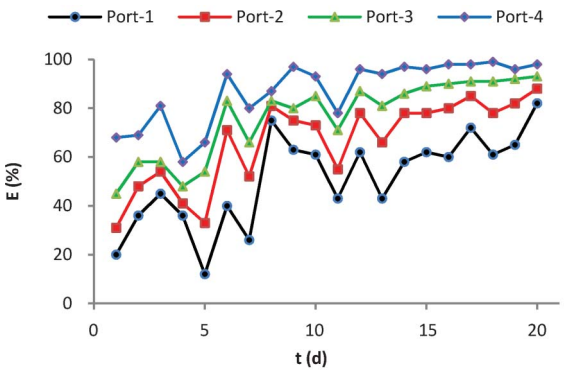


**Fig. 3** Curve of *E vs. t* for experiment 1 with a VAFR of 90 L $h^{-1}$.

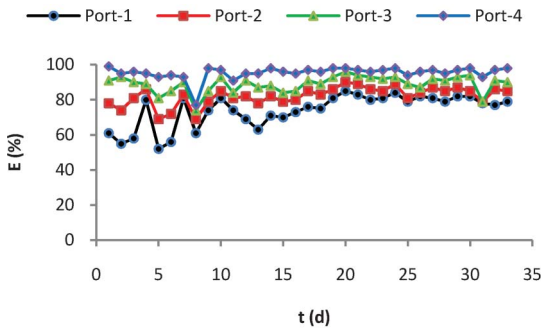


**Fig. 4** Curve of *E vs. t* for experiment 2 with a VAFR of 291 L $h^{-1}$.

Fig. 3, 4 and 5 show the resulting plots of $E$ as function of $t$. The nature of the curves shows an increasing trend in the percent FA removal as a function of biofilter bed height from 5 cm (port 1) to 15 cm (port 2) to 25 cm (port 3) to 40 cm (port 4), showing that the performance of the BTFR system increases with increasing of retention time. Flow parameters such as the characteristic flow time and length-scale may provide an introduction to the area of fluid dynamics with emphasis on both theory and experiments.[37] Increasing the VAFR from 90 L $h^{-1}$ (Fig. 3) to 291 L $h^{-1}$ (Fig. 4) to 1512 L $h^{-1}$ (Fig. 5) makes the increase in $E$ value more effective to remove FA as a high FA concentration of the SCAS can dissolve faster in the nutrient solution due to its increased mass transfer driving force.[31,38] The variations in percentage of FA removal might be more sensitive for the operational BTFR system at a low VAFR of 90 L $h^{-1}$ because of it takes a long $\theta$ period to travel through every port of the biofilter bed for experiment 1 (Fig. 3). Moisture content and VAFR in the biofilter bed affect drying-out of the packaged biological treatment system. In the presence of moisture in the SCAS, FA can react with water to form methylene glycol and this affects the BTFR performance. A moisture content of about 70% has reported in a previous study[39] to be optimal for an effective biofiltration process and plays an important role in reaching high values of VOC removal efficiency.

Several methods for the determination of immobilised biomass on the supporting materials in the biofilter bed were

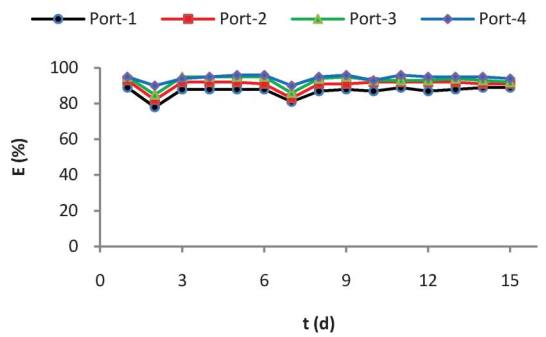


**Fig. 5** Curve of *E vs. t* for experiment 3 with a VAFR of 1512 L $h^{-1}$.

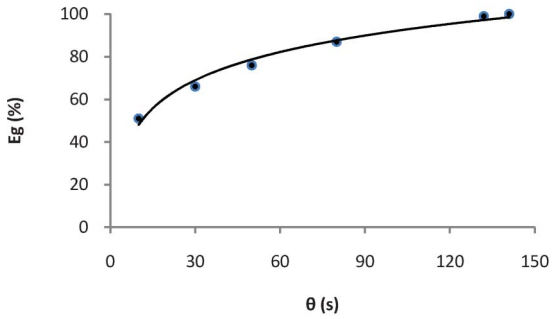


**Fig. 6** Logarithmic model for experiment 1 with a VAFR of 90 L $h^{-1}$.

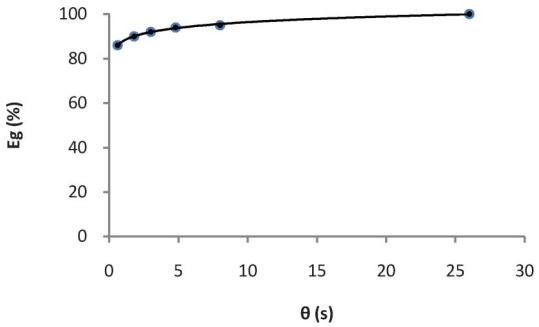


**Fig. 8** Logarithmic model for experiment 3 with a VAFR of 1512 L $h^{-1}$.

performed based on analysis of bacterial identification tests. Although the BTFR houses a wide variety of microorganisms at any biofilter bed depth, the diversity of bacteria occurs predominantly at the supporting materials. Morphological characteristics of colony development in the biofilter bed show rod-shaped bacteria were observed with the aid of a compound microscope (Olympus CH40) using a 100× oil immersion objective. Five strains of dominant bacteria were identified with *Salmonella bongori* being more dominant in port 1, *Salmonella choleraesuis subsp. arizonae* in port 2, and *Salmonella typhimurium*, *Serratia entomophila* and *Serratia ficaria* in ports 3 and 4. The BTFR system demonstrated a high performance of the bottom part of the biofilter bed (see port 1) to remove FA from the air, of the order of 51, 74 and 86% for experiments 1, 2 and 3, respectively (see Table 1). The results showed that maintaining the dominant strains of bacteria is critical to the success of the BTFR system and that this factor is more important than the residence time.

### 3.3 Calculating the optimal $\theta$

Calculating the average $E$ for each port of the biofilter bed over a period of 20 days for experiment 1, 33 days for experiment 2 and 15 days for experiment 3, we can generate the general $E$ ($E_g$) as a function of $\theta$. Fig. 6, 7 and 8 that show the resulting $E_g$ plotted over $\theta$ can determine the logarithmic regression model equation to represent the experimental data. The figure shows a good correlation between $E_g$ and $\theta$, both fit a logarithmic line with a correlation greater than 97.9% ($R^2$ = 0.979; Table 2). This signifies that both the "coefficient $k$" and "constant $b$" of eqn (6) have physical interpretation and can be used to determine the optimal $\theta$. As a conclusion, in this study of the bio-tricking filter for FA removal, we can develop reasonable models for the prediction of optimal $\theta$, and the use of eqn (6) is well validated for the assessment of the performance of the BTFR.

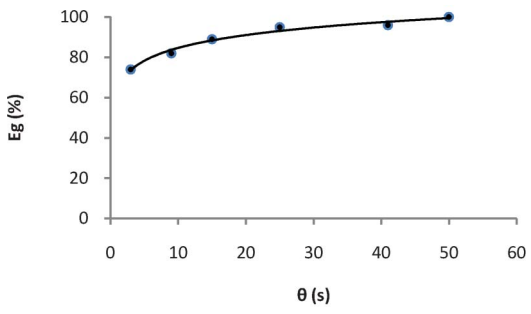


**Fig. 7** Logarithmic model for experiment 2 with a VAFR of 291 L $h^{-1}$.

**Table 2** Logarithmic model analysis for the three experimental runs

| Experimental run | VAFR/L $h^{-1}$ | $k$ (% $s^{-1}$) | $b$ (%) | $R^2$ |
|---|---|---|---|---|
| Experiment 1 | 90 | 19.0 | 4.3 | 0.9833 |
| Experiment 2 | 291 | 9.2 | 63.4 | 0.9791 |
| Experiment 3 | 1512 | 3.7 | 87.9 | 0.9961 |

The curves (see Fig. 6, 7 and 8) of $E_g$ *vs.* $\theta$ show that the logarithmic trend line is a best-fit curved line to predict the optimal $\theta$ ($R^2$ = 0.979, see Table 2). Better knowledge of $k$ and $b$ in the logarithmic model of eqn (6) may give accurate calculation of the optimal $\theta$ to remove FA from air. The respective $k$ coefficients (Table 2) are 19.0, 9.2, 3.7 % $s^{-1}$ with values of constant $b$ of 4.3, 63.4, 87.9% and VAFR of 90, 291, 1512 L $h^{-1}$, for experiments 1–3, respectively. The decrease in $k$ value with increasing of the VAFR would be due to that the ability of aerobic bacteria to break down organic matter reduces with increasing FA concentration. A delay in the biodegradation occurs because of the time required to obtain the optimal growth rate for bacterial population is too short. FA is used as an intermediate in bacterial metabolism of one-carbon growth substrates and is also well-known as a highly toxic chemical common in industrial effluents.[40] Chemical tools to study biology at the molecular level, with a particular focus on the unusual structures of bacterial glycans and their link to pathogenesis, can lead to the discovery and targeting of bacterial glycoproteins.[41] Higher loading rate indicates higher level of FA in the SCAS. Consequently, the increase in $b$ value with increasing of the VAFR was verified through the increasing FA concentration in the nutrient solution as monitored in terms of the COD values. Biomass concentrations of 210, 40 and 30 mg of dry solids $L^{-1}$ (see Table 3) were verified for experiment 1 with an effluent $\theta$ of 132 s, experiment 2 with an effluent $\theta$ of 41 s and experiment 3 with an effluent $\theta$ of 8 s, respectively. The concentration of biomass at the surface of the supporting materials for experiment 1 was much higher than that for experiments 2 and 3 because it takes a long contact time between the SCAS and supporting

**Table 3** Biomass concentration for three different VAFRs

| BTFR operation | VAFR/L $h^{-1}$ | Effluent $\theta$/s | BC[a]/mg $L^{-1}$ |
|---|---|---|---|
| Experiment 1 | 90 | 132 | 210 |
| Experiment 2 | 291 | 41 | 40 |
| Experiment 3 | 1512 | 8 | 30 |

[a] BC is biomass concentration in terms of dried solids.

materials to develop biomass. The elevated biomass concentration in the BTFR process increases the effectiveness in the removal of FA from the SCAS (see Table 1). The design parameters of the BTFR system can be quantitatively specified, because it is possible to calculate the optimal $\theta$ for a contaminated air flow into the biofilter bed. In this study, optimal $\theta$ of 141, 50 and 26 s to have 100% FA removal efficiency were verified for the BTFR experiments operated at 90, 291 and 1512 L $h^{-1}$ VAFR, respectively.

Through development and operation of a trickling biofilter system to remove FA from the air it is possible to approach 100% efficiency if the BTFR module is designed based on optimising $\theta$ of eqn (6). The results obtained from the three different VAFRs have proved the bio-trickling filter method to be thoroughly practical and to have definite advantages over other methods of such as combination of sorption- and decomposition-type air filters,[42] rotating adsorbent coupled with a photocatalytic reactor[43] and passive type air-cleaning materials.[44]

## 4 Conclusions

This study used a BTFR to remove FA from SCAS. Mathematical models were developed to determine the optimal $\theta$ of SCAS to pass through the biofilter bed. Functional logarithmic equations accounting for biochemical reaction rate, $\theta$, FA dissolved in water and biofilter bed height were presented. All the parameters in equations have physical interpretation. The models tested the data monitoring $E$ levels using the three different VAFRs are sufficiently accurate. The optimal $\theta$ values of BTFR systems to remove FA from the SCAS were verified. A new method for determining the optimal $\theta$ is proposed to contribute to air quality improvement analysis and advanced biotechnology studies.

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