Removal of *p*-xylene from an air stream in a hybrid biofilter

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Abstract

Biofiltration of an air stream containing *p*-xylene has been studied in a laboratory hybrid biofilter packed with a mixture of mature pig compost, forest soil and the packing material which was made of polyethylene (PE) and used in the moving bed biological reactor (MBBR) in wastewater treatment. Three flow rates, 9.17, 19.87 and 40.66 $m^3\,m^{-2}\,h^{-1}$, were investigated for *p*-xylene inlet concentration ranging from 0.1 to 3.3 $g\,m^{-3}$. A high elimination capacity of 80 $g\,m^{-3}\,h^{-1}$ corresponding to removal efficiency of 96% was obtained at a flow rate of 9.17 $m^3\,m^{-2}\,h^{-1}$ (empty bed residence time of 132 s). At a flow rate of 40.66 $m^3\,m^{-2}\,h^{-1}$ (empty bed residence time of 30 s), the maximum elimination capacity for *p*-xylene was 40 $g\,m^{-3}\,h^{-1}$ and removal efficiencies were in the range of 47–100%. The production of carbon dioxide (P_{CO_2}) is proportional to elimination capacity (EC) and the linear relation was formulated as $P_{CO_2} = 1.65EC + 15.58$. Stable pH values ranging from 6.3 to 7.6 and low pressure drop values less than 0.2 cm H_2O (19.6 Pa) of packing media in compost-based biofilter of hybrid biofilter were observed, which avoided acidification and compaction of packing media and sustained the activity of microorganism populations.
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1. Introduction

The increasing presence of volatile organic compounds (VOCs) in the atmosphere has been one of today's considerable environmental problems such as the depletion of the ozone layer and the greenhouse effect caused by VOCs. VOCs commonly emit from wastewater treatment plants and many industries such as printing and coating facilities, foundries, chemical industries, electronics and paint manufacturing. Conventional VOCs control technologies including incineration, condensation, adsorption, absorption, ozonation, membrane separation technologies have been commonly utilized for the elimination of VOCs from waste gases. However, these technologies suffer from high operating costs or secondary disposal treatments problems. For treating large air volumes and low pollutant concentrations, biofiltration has been considered to be better alternative because of low cost and limited negative environmental effects.

Biofiltration of off-gases is a relatively new application of biological process in waste management. In a typical biofilter, contaminated gas is humidified and passed through a packed bed colonized by microorganisms that biodegrade the contaminants into innocuous products such as carbon dioxide, water and biomass. Biofiltration has proved to be an effective and economical method for eliminating VOCs [1–3].

Xylene is a clear, colorless and hydrophobic liquid that has a characteristic pungent odor. It is an important chemical, and used widely as a solvent in the printing, rubber, leather, painting and varnishing industries. Xylene isomers have been listed as hazardous and toxic atmospheric contaminants under CAAA (Clean Air Act Amendments of 1990, USA). There have been previous studies on removal of xylene and other VOCs by microorganisms in biological process [4–10]. Abumaizar et al. reported biofiltration of benzene, toluene, ethylbenzene and xylene (BTEX) contaminated air streams using compost-activated carbon filter media. With inlet concentrations more than 200 ppm and a gas load rate of 17.6 $m^3\,m^{-2}\,h^{-1}$, removal efficiencies of 90% were achieved [11]. Strauss et al. demonstrated that among overall BTEX compounds, *p*-xylene is more difficult to biodegrade

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under mesophilic and thermophilic conditions in the toluene-acclimatized biofilter [12]. These researchers reported biofiltration of xylene, but the performance of biofilter and removal results were not much satisfied. Furthermore, a limited number of researchers have evaluated the performance of biofiltration in the removal of xylene, especially of *p*-xylene, as a sole contaminant in gas streams [13–16].

The objective of this work is to investigate the biofiltration of an air stream containing *p*-xylene in a hybrid biofilter packed with new packing media and intends to find out a novel and better method and technique improved in biofilteration of VOCs. The present paper describes the effects of various *p*-xylene inlet concentrations and gas flow rates on the hybrid biofilter performance and some operating parameters, such as temperature, carbon dioxide, pH and available nitrogen of packing media.

2. Materials and methods

2.1. Hybrid biofilter system

A downward hybrid biofilter was employed in this study. As shown in Fig. 1, the hybrid biofilter consisted of two biofilters including a compost-based biofilter A and a polyethylene (PE)-based biofilter B. The compost-based biofilter (A) was packed with the mixture of mature pig compost, forest soil and the new packing material which was made of polyethylene and used in the moving bed biological reactor (MBBR) for treating wastewater, and the volume proportion of the mixture was 4:1:2. PE material was made to column with a height of 0.0045 m and an inner diameter of 0.0045 m. The mixture of packing media was sterilized by autoclave before packing. The PE-based biofilter B was only packed with the new packing material made of PE which was the same as that used in biofilter A. Each biofilter was made from a height of 0.33 m cylindrical polymethyl methacrylate column with an inner diameter of 0.05 m, and filled to a height of 0.17 m with the packing media inoculated with activated sludge. The activated sludge was placed for 20 min, then the supernatant liquor was removed. The residual activated sludge suspension was used as inoculum. The volume amount of activated sludge suspension used depended on the

final water content of packing media, and the water content of packing media was generally maintained at about 50%. Prior to packing, the new packing material made of PE was submerged in a mineral medium to absorb water and nutrients for buffering dryness and acidification in packing media. The mineral medium contained: $2.0\,g\,L^{-1}$ $(NH_4)_2SO_4$, $0.8\,g\,L^{-1}$ Na_2HPO_4, $0.068\,g\,L^{-1}$ KH_2PO_4, $0.5\,g\,L^{-1}$ $MgSO_4 \cdot 7H_2O$, $0.002\,g\,L^{-1}$ $CaCl_2$, $0.001\,g\,L^{-1}$ $FeSO_4 \cdot 7H_2O$.

Compressed air was passed first through an activated carbon filtration device to remove moisture, oil and particulate matter. The air filtrated was split into two air fractions. The major portion of air was humidified in a water humidifier to ensure that the air relative humidity was more than 95%. The minor portion of air was allowed to bubble through liquid *p*-xylene container to generate the contaminated air stream. Then these two air streams were mixed in an air mixer, and fed to the top of the hybrid biofilter in downflow mode of operation. The flow rates were controlled by valves and metered by previously calibrated flowmeters to obtain the desired *p*-xylene inlet concentration and gas residence times in the filter bed. Biofilter B was continuously sprayed with about $0.1\,L\,min^{-1}$ identical mineral medium mentioned above for 30 min each day to ensure satisfactory conditions of moisture and nutrients for microorganisms activity. The mineral medium formed laminar flow on surface of packing media, and the pH of the circulating nutrient solution was maintain ranging from 5.8 to 7.3 during experimental operation.

The hybrid biofilter was continuously operated at room temperature in accordance with the following operating conditions, as summarized in Table 1.

2.2. Analytical methods

The gas-phase concentration of *p*-xylene was analyzed by direct injection into a gas chromatography (SHIMADZU GC-14C) unit equipped with a flame ionization detector (FID). Nitrogen was used as carrier gas with a flow of $0.06\,L\,min^{-1}$. The inlet and outlet air streams were sampled using an air sampling apparatus connected to a six-position switching valve (SHIMADZU) with a 1 mL loop. The gas chromatography was operated at
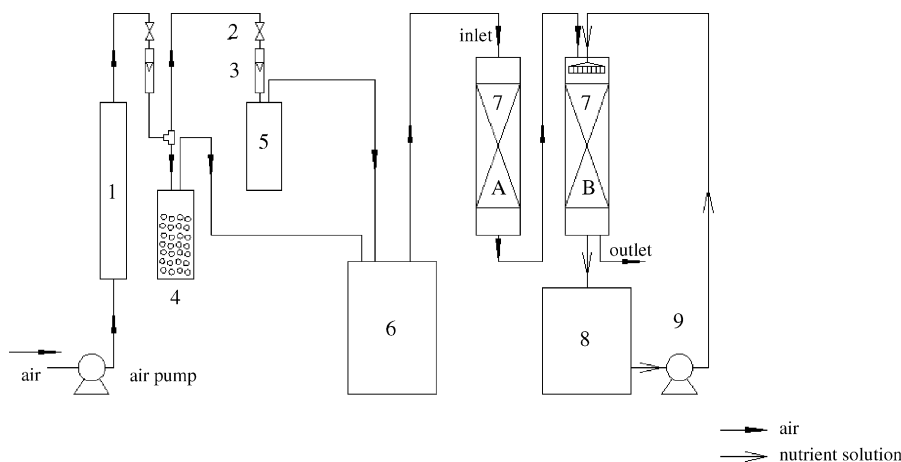

Fig. 1. Schematic diagram of hybrid biofilter system.

Table 1
Hybrid biofilter operating conditions

Packing media	
Biofilter A	The mixture of compost, forest soil and a new packing material made of polyethylene (PE)
Biofilter B	A new packing material made of polyethylene (PE)
Overall bed height	2×0.17 m
Column inner diameter	0.05 m
Initial humidity of packing media	52.6%
Mean diameter of packing media	0.0045 m
p-Xylene concentration	0.1–3.3 g m^{-3}
Gas flow rate	9.17 m^3 m^{-2} h^{-1}, 19.87 m^3 m^{-2} h^{-1} and 40.66 m^3 m^{-2} h^{-1}
Total empty residence time (EBRT)	30 s, 61 s and 132 s

an injection temperature of 160 °C, a detector temperature of 160 °C, and an oven temperature of 120 °C.

The pH values of packing media were measured in the compost-based biofilter during the operation. 5 g packing media were blended with 50 mL deionized water. Then pH values of packing media were determined using a digital pH meter (Sartorius PB-S). The temperature of compost-based biofilter bed was measured by common thermometer with a range from −20 to 110 °C and a scale division of 1 °C.

Aqueous extracts of the packing materials in compost-based biofilter were obtained by shaking mechanically with mixture of deionized water and packing media of 10:1 (v/w) for 30 min. The suspensions were centrifuged at 3500 rpm for 15 min and filtered through 0.45 μm membrane filters. The following measurements were carried out on the filtrate: NH_4^+-N by the spectrophotometry method using Nessler reagent [17], NO_3^--N (including NO_2^--N) by the national standard methods (Measure and Analysis Manual of Water and Waste Water of 1995, PR China).

CO_2 concentration was determined by acid–alkali titration method. The air streams containing CO_2 were collected and absorbed by 50 mL NaOH of 0.1 mol L^{-1}. Then the solution absorbed was titrated by HCl of 0.1 mol L^{-1}. The CO_2 concentration was calculated by amounts of NaOH and HCl consumed.

A water-filled manometer with a minimum division length reading of 1-water column was used to measure pressure drop across the compost-based biofilter A.

2.3. Performance evaluation

The performance of the hybrid biofilter was evaluated by the following performance parameters, *p*-xylene inlet load (IL), g m^{-3} h^{-1}, removal efficiency (RE), %, elimination capacity (EC), g m^{-3} h^{-1}. The definitions for these parameters are set out below:

$$IL = \frac{Q \times C_{in}}{V} \tag{1}$$

$$RE = \left(\frac{1 - C_{out}}{C_{in}} \right) \times 100 \tag{2}$$

$$EC = Q \times \frac{C_{in} - C_{out}}{V} \tag{3}$$

where Q is *p*-xylene volumetric gas flow rate (m^3 h^{-1}), V the volume (m^3) of the packing bed and C is the *p*-xylene concentration (g m^{-3}). Subscripts "in" and "out" are referred to the inlet and outlet of the packing bed. EC is usually less than IL and sometimes equal to IL when 100% removal efficiency is achieved.

3. Results and discussion

3.1. Influence of p-xylene inlet concentration

Biofiltration of an air stream containing *p*-xylene was carried out during a period of nearly 5 months at various operating conditions in a laboratory downflow hybrid biofilter. During first 62 days of the experimental study, the performance of hybrid biofilter was studied according to the concentration variations ranging from 0.1 to 3.3 g m^{-3} at the gas rate of 9.17 m^3 m^{-2} h^{-1} (EBRT = 132 s).

At the start-up period of about 10 days, the *p*-xylene contaminated gas with low concentration of about 0.15 g m^{-3}, as a sole carbon source for microorganisms, was fed to the hybrid biofilter. The data during acclimation period of 10 days were not shown here for the fact that the microorganisms acclimatized to the packing media and the biofilm still formed and became thicker which caused fluctuation in the rate of biodegradation for *p*-xylene. Therefore, the experimental results obtained after acclimation period of 10 days were discussed in this study. As shown in Fig. 2, at the steady state, the hybrid biofilter could provide a 100% removal of *p*-xylene for inlet concentration ranging from 0.1 to 1.2 g m^{-3}. When *p*-xylene concentration increased sharply to 1.7 g m^{-3}, a decrease to 85.7% in *p*-xylene removal efficiency was observed, which may be due to kinetic limitation like the transient state induced by high concentration shock to microorganisms and other possible factors such as localized drying of the bed induced by
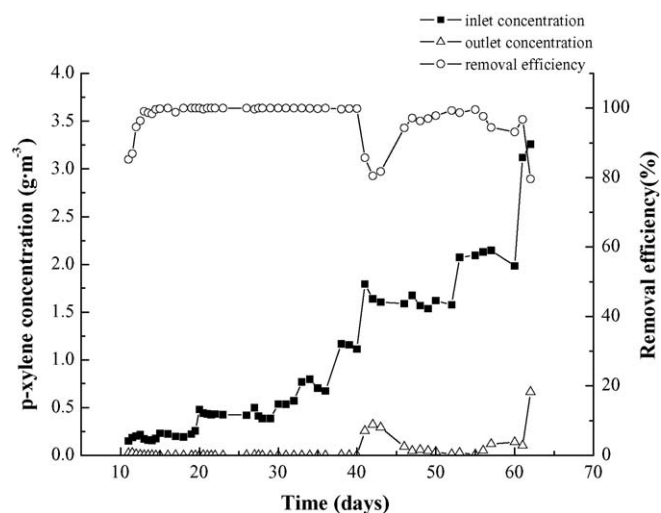

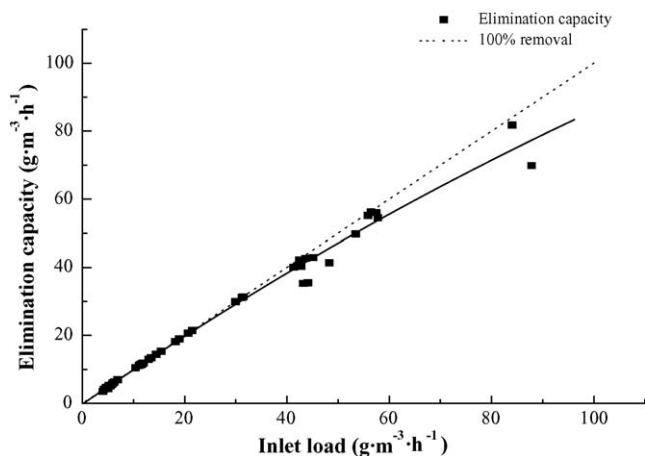Fig. 2. *p*-Xylene concentration and removal efficiency (RE) vs. operation time (gas flow rate = 9.17 m^3 m^{-2} h^{-1}, EBRT = 132 s).

Fig. 3. *p*-Xylene elimination capacity (EC) vs. *p*-xylene inlet load (gas flow rate = 9.17 m³ m⁻² h⁻¹, EBRT = 132 s).

deteriorating media bed, air-stream channeling brought on by biomass accumulation, nutrient limitation, toxicity of degradation products. However, after microorganisms acclimatized to this high concentration, the mean removal efficiency raised gradually to more than 96%, which is higher compared with the results observed in the previously reported study [16]. Above $2.1\,g\,m^{-3}$ of *p*-xylene concentration, the removal efficiency declined gradually, reaching less than 80% for $3\,g\,m^{-3}$ of *p*-xylene inlet concentration. The results suggest that it was difficult that high removal efficiency like 96% for low inlet concentration $1.7\,g\,m^{-3}$ could be obtained for inlet concentration above $3\,g\,m^{-3}$ at this flow rate. That is, *p*-xylene inlet concentration of above $3\,g\,m^{-3}$ exceeds the biodegradation capacity of microorganisms for achieving high removal efficiency at this gas flow rate.

Fig. 3 shows the elimination capacity of *p*-xylene as a function of the *p*-xylene inlet load at a constant gas flow rate of $9.17\,m^3\,m^{-2}\,h^{-1}$. The elimination capacity increased with the increasing of *p*-xylene inlet load ranging from 4.08 to $87.8\,g\,m^{-3}\,h^{-1}$. The results reveal that the elimination capacity increases obviously with the increase of inlet load for this inlet load range. And the elimination capacity of about $80\,g\,m^{-3}\,h^{-1}$ for *p*-xylene was obtained for inlet load of about $84\,g\,m^{-3}\,h^{-1}$, corresponding to removal efficiency of 96%. These results were higher than the elimination capacity obtained by Jorio et al. in the previously reported work under similar operating conditions [13].

3.2. Influence of gas flow rate

The gas flow rate is an important parameter in biofiltration process. In present study, three levels of gas rate, i.e. 9.17, 19.87 and $40.66\,m^3\,m^{-2}\,h^{-1}$, were investigated. Figs. 1, 4 and 5 describe the removal efficiency and elimination capacity of *p*-xylene versus operation time, respectively. As shown in Fig. 4, at a gas flow rate of $40.66\,m^3\,m^{-2}\,h^{-1}$ (EBRT = 30 s), the removal efficiency was approximate 100% for *p*-xylene inlet concentration ranging from 0.1 to $0.3\,g\,m^{-3}$ and decreased from 100 to 47% for load shock of the sudden increasing of *p*-xylene inlet
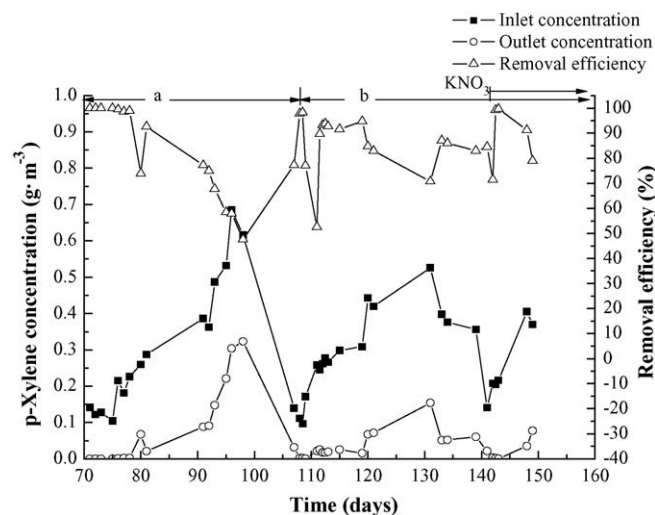

Fig. 4. *p*-Xylene concentration and removal efficiency (RE) vs. operation time at various gas flow rates ($a = 40.66\,m^3\,m^{-2}\,h^{-1}$, EBRT = 30 s; $b = 19.87\,m^3\,m^{-2}\,h^{-1}$, EBRT = 61 s).

concentration from 0.3 to $0.685\,g\,m^{-3}$. At this gas rate, elimination capacity of about $45\,g\,m^{-3}\,h^{-1}$ was observed for inlet load of $82\,g\,m^{-3}\,h^{-1}$, corresponding to inlet concentration of $0.685\,g\,m^{-3}$ (in Fig. 5). At a gas flow rate of $19.87\,m^3\,m^{-2}\,h^{-1}$ (EBRT = 61 s), the average removal efficiency was 90% when inlet concentration ranged from 0.096 to $0.53\,g\,m^{-3}$. Compared with the results at a gas flow rate of $9.17\,m^3\,m^{-2}\,h^{-1}$ (EBRT = 132 s) in Fig. 2, the removal efficiency and elimination capacity at this gas flow rate were lower for the same *p*-xylene inlet concentration. For a gas flow rate of $9.17\,m^3\,m^{-2}\,h^{-1}$ (EBRT = 132 s), approximately 100% removal efficiency can be observed for inlet concentration from 0.1 to $1.2\,g\,m^{-3}$ (in Fig. 2). Thus low values of gas flow rates (i.e. high values of EBRT) were favorable for degradation because the contact time between the microorganisms and *p*-xylene was increased. For high values of gas flow rates corresponding low values of EBRT (in Fig. 4), the contact time between the microorganisms and *p*-xylene was too
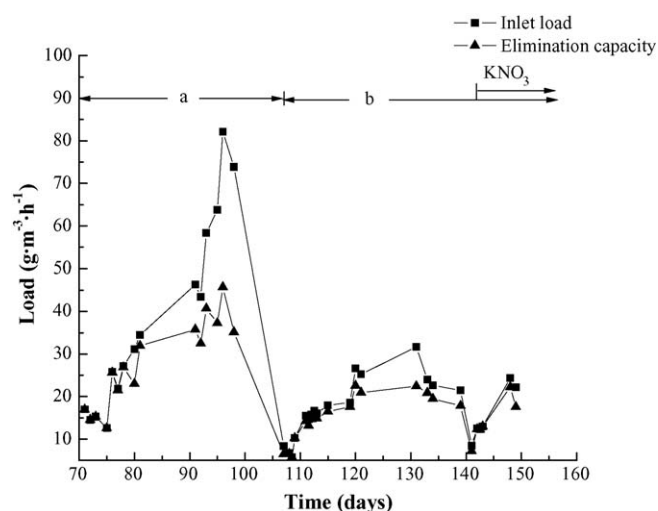

Fig. 5. *p*-Xylene elimination capacity (EC) vs. operation time ($a = 40.66\,m^3\,m^{-2}\,h^{-1}$, EBRT = 30 s; $b = 19.87\,m^3\,m^{-2}\,h^{-1}$, EBRT = 61 s).
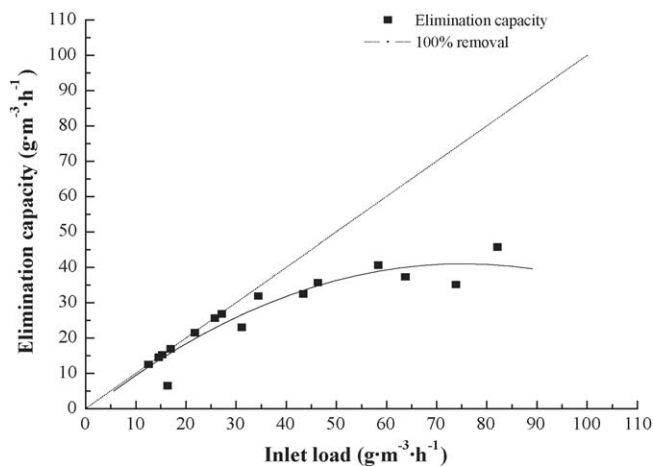
Fig. 6. p-Xylene elimination capacity vs. inlet load at a gas flow rate of $40.66 \, m^3 \, m^{-2} \, h^{-1}$ (EBRT = 30 s).

short and microorganisms ha insufficient time to perform the required degradation on the available amount of p-xylene. At whiles, the poor performance of biofilter may be caused by the insufficiency of nutrient and moisture content of packing media for microorganism metabolic reactions of degrading p-xylene. Fifteen millilitre KNO_3 of $10 \, g \, L^{-1}$ was added in compost-based biofilter A to provide nutrient and moisture content. After adding KNO_3 solution, the removal efficiency increased up to approximate 100% for inlet concentration of $0.22 \, g \, m^{-3}$. However, the removal efficiency reduced to 80% with increasing of inlet concentration, which indicated that KNO_3 nutrient solution was possibly not enough for achieving complete removal efficiency for microorganism populations degrading p-xylene. It is necessary that the more nutrient solution could be added for high performance of biofilter in long-term operation. Gribbins and Loehr reported that soluble nitrogen concentration in the medium could limit biofilter performance after long periods of operation [18].

Figs. 3, 6 and 7 show that the elimination capacity of p-xylene was as a function of inlet load. The maximum elimination capacity of p-xylene was $40 \, g \, m^{-3} \, h^{-1}$ for the gas flow rate of $40.66 \, m^3 \, m^{-2} \, h^{-1}$ (EBRT = 30 s), and the removal efficiency varied from 47 to 100%. In these figures, results for a gas flow rate of 9.17 and $19.87 \, m^3 \, m^{-2} \, h^{-1}$ and when p-xylene inlet load was less than $55 \, g \, m^{-3} \, h^{-1}$ at a gas flow rate of $40.66 \, m^3 \, m^{-2} \, h^{-1}$, a trend was observed that the elimination capacity of p-xylene increased with the increase of the inlet load. It suggests that the increasing of inlet load enhanced the transfer rate of p-xylene to the biofilm at a constant gas flow rate so that, in range of inlet load mentioned above, more p-xylene were degraded by microorganisms involved and the elimination capacity for p-xylene increased in the biodegradation capacity of microorganisms. However, when inlet load was more increasing, the elimination capacity curve deviated markedly from the 100% removal curve till the elimination capacity did not increase and even decreased finally with the increase of inlet load. It can be explained that at these gas flow rates, the biodegradation rate for p-xylene by microorganisms involved reduced gradually and ultimately is less than the input load rate of pollutant (p-xylene).
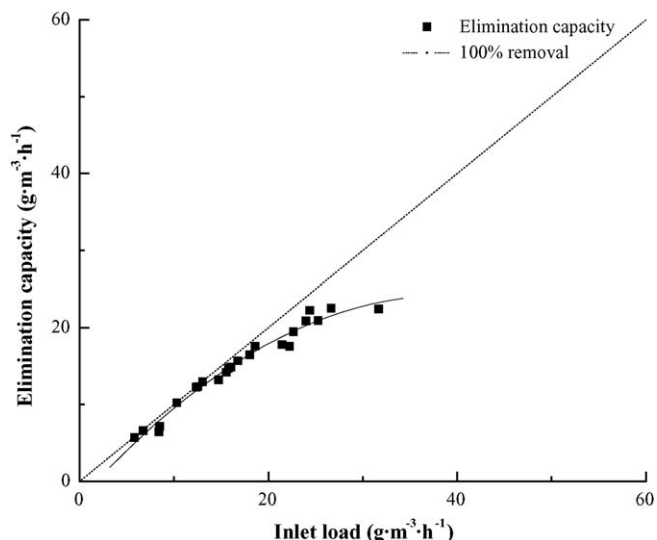

Fig. 7. p-Xylene elimination capacity vs. inlet load at a gas flow rate of $19.87 \, m^3 \, m^{-2} \, h^{-1}$ (EBRT = 61 s).

This suggests that this inlet load range reaches inhibition levels for biodegradation of p-xylene.

3.3. Variation of bed temperature

In this study, the mean bed temperature of compost-based biofilter A was monitored. As shown in Fig. 8, in compost-based biofilter A, the elimination capacity of p-xylene and the average bed temperature had the similar trend of variation. When the elimination capacity of p-xylene increased, the average bed temperature rose. As trend value of the bed average temperature rose from 20 to 27 °C, the trend value of elimination capacity increased from 2 to $62 \, g \, m^{-3} \, h^{-1}$. The water content changed from 47 to 53% during this experiment. The increase of elimination capacity suggested that it was possible that more microorganisms grew and were involved in the biodegradation of the greater quantity of contaminants, so that the filter bed
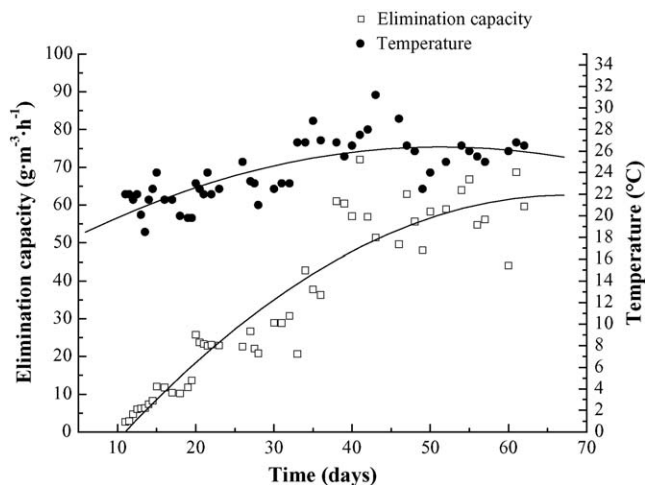

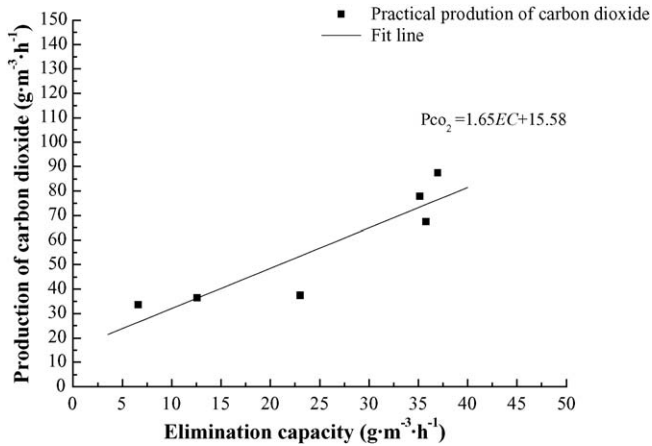Fig. 8. Average bed temperature and elimination capacity in compost-based biofilter A vs. operation time (gas flow rate = $9.17 \, m^3 \, m^{-2} \, h^{-1}$, EBRT = 132 s).

Fig. 9. Production of carbon dioxide (P_{CO_2}) vs. elimination capacity for *p*-xylene.

Fig. 10. Production of carbon dioxide.

3.4. Carbon dioxide production

Production of carbon dioxide (P_{CO_2}) is an important indicator for degree of VOCs mineralized completely, because VOCs are finally biodegraded to water and carbon dioxide and utilized as carbon source to format biomass for microbial growth. The production of carbon dioxide was measured in this study for evaluating the degree of *p*-xylene mineralization. The reaction of biological oxidation of *p*-xylene to water, carbon dioxide and biomass can be written as follows:

$$C_8H_{10} + xO_2 = yCO_2 + zH_2O + w \text{ biomass} \tag{4}$$
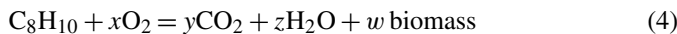
Assuming that a complete oxidation and "mineralisation" of *p*-xylene took place, i.e. ignoring the biomass generated, and with $w = 0$, $x = 10.5$, $y = 8$, $z = 4$, the mass ratio of carbon dioxide produced/*p*-xylene consumed (i.e. P_{CO_2}/EC) was 3.3.

The experimental data are plotted in Figs. 9 and 10. The production of carbon dioxide as a function of elimination capacity during the whole experimental period is presented in Fig. 9. And the practical production of carbon dioxide versus the theoretical production is depicted in Fig. 10. Elmrini et al. [16] and Delhomenje et al. [19] reported biofiltration of *p*-xylene and toluene, respectively. In their studies, variation of P_{CO_2} versus EC was linearly. According to literatures, a linear fit to these experimental data was made. The linear equation obtained from the data point was formulated as $P_{CO_2} = 1.65 \text{EC} + 15.58$. When the value of EC was zero (i.e. no carbon source was introduced into the biofilter), the P_{CO_2} value was 15.58 g m^{-3} h^{-1}. This P_{CO_2} produced was likely due to endogenous respiration of microorganism populations that do not utilized *p*-xylene as carbon source and the desorption of CO_2 generated by *p*-xylene biodegradation from the packing media. The mass ratio of the practical P_{CO_2} was approximately 1.65 that was lower than the
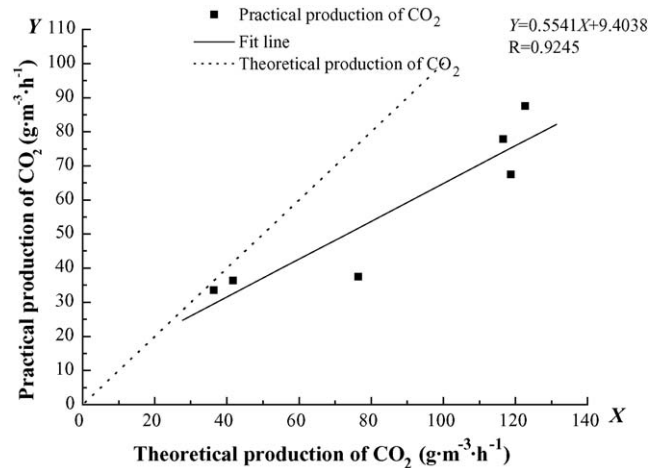
theoretical value of 3.3 estimated from Eq. (4). In other words, the observed production of carbon dioxide was lower than the theoretical production of carbon dioxide in the gas phase, as shown in Fig. 10. The possible reasons of discrepancy between these two values were that some of biodegraded *p*-xylene was converted into the biomass for microbial growth and/or the CO_2 produced may have accumulated in the aqueous biolayer as some forms, such as HCO_3^-, H_2CO_3, CO_3^{2-}. On the other hand, the reduced fraction of P_{CO_2} suggested that the removal of *p*-xylene was possibly due to biodegradation by microorganisms.

3.5. The variations of pH and nitrogen content of packing media

Acidification of the packing media in biofiltration process may cause deterioration of biofilter performance, especially in high concentration load run for bacterial biofilteration system. Extreme acidity may cause low removal efficiency of pollutants. In the present study, the variation of pH of the packing media in compost-based biofilter A was recorded and plotted in Fig. 11. During the experimental period, no sudden change of pH occurred in packing media and the value of pH maintained a steady range from 6.3 to 7.6, which demonstrates that an acidification did not occur in packing media.

Nitrogen is the essential nutrient for microbial metabolism and activity because nitrogen is a major constituent of microorganism proteins and nucleic acids and makes up to 15% of the microbial cell dry weight. Hence, nitrogen has been the crucial limiting factor for a long operation for biofilter if adequate nutrient are not available. Generally, available nitrogen utilized by microorganism populations is present in inorganic forms such as ammonia and nitrate. During VOCs degradation, the various forms and content of nitrogen are presence. However transforming of various forms and content of nitrogen do not achieve equilibrium due to denitrification, leaching. Nitrogen can eventually be removed from packing media along with the long-term run of biofilter.

Fig. 12 describes the variation of nitrogen (NO_3^--N and NH_4^+-N) along with the operation time in compost-based biofil-
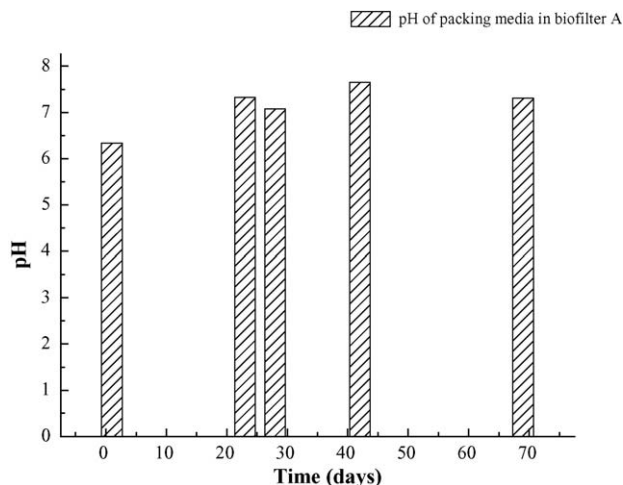
Fig. 11. The variation of pH in compost-based biofilter A of hybrid biofilter vs. operation time.

ter A. It could be seen that the longer operation time, the lower nitrogen content. When it decreased to some value, nitrogen content would likely become a limiting factor for the performance of biofilter. Therefore, the further research should be carried out to attain the optimal nitrogen content for the long-term of biofilter in the future.

Pressure drop cross the filter bed is an important evaluation parameter because it can indicate the compaction state of the filter bed and the excess biomass accumulation. Moreover, increase of the pressure drop cross the filter bed not only disturbs the homogeneous flow distribution to impact adversely performance of biofilter, but also results in higher energy requirements to maintain the good performance in practical biofiltration process. In this study, pressure drop through the compost-based biofilter A bed was measured. A relatively low value in pressure drop (less than 0.2 cm H$_2$O, i.e.19.6 Pa) was obtained. This indicates that this packing media has a good mechanical strength that leads
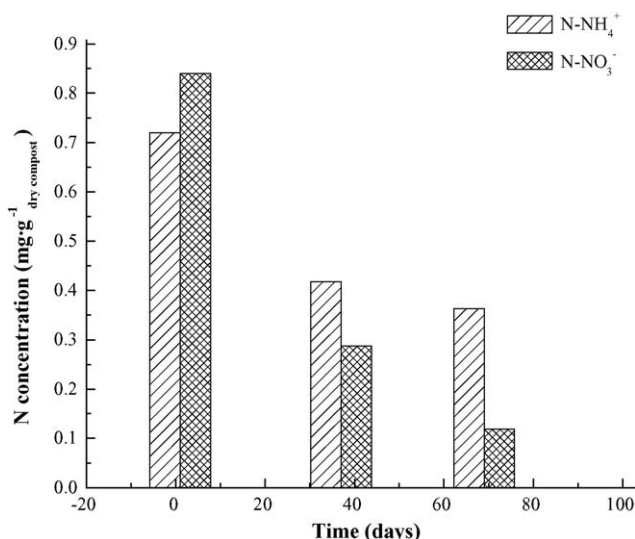
to negligible bed compaction and was favorable for practical application of biofiltration process for low energy requirements.

4. Conclusion

Biofiltration of an air stream containing *p*-xylene was carried out in a laboratory downflow hybrid biofilter packed with a mixture of compost, soil and the packing material which was made of polyethylene and used in the moving bed biological reactor. The *p*-xylene inlet concentration ranged from 0.1 to 3.3 g m^{-3}. The high elimination capacity of 80 g m^{-3} h^{-1} for *p*-xylene was obtained, corresponding to removal efficiency of more than 96% at an EBRT of 132 s. At a gas flow rate of 40.66 m^3 m^{-2} h^{-1} (EBRT = 30 s), the maximum elimination capacity for *p*-xylene was 40 g m^{-3} h^{-1}.

The production of carbon dioxide was measured for evaluating the degree of *p*-xylene mineralization. The mass ratio of the practical P_{CO_2} was 1.65 that was lower than the theoretical mass ratio of 3.3 in the case of complete oxidation of *p*-xylene. The reduced fraction of P_{CO_2} suggested that the removal of *p*-xylene was possibly due to biodegradation by microorganisms.

Acidification and compaction of packing media may cause deterioration of biofilter performance. In the present work, the fluctuation of pH of packing media was not obvious. This reveals that an acidification does not occur in packing media. Pressure drop of packing bed was a relatively low value (less than 0.2 cm H$_2$O, i.e. 19.6 Pa), which led to negligible bed compaction and was favorable for practical application of biofiltration process for low energy requirements.

The content of the soluble nitrogen (NH_4^+-N and NO_3^--N) in packing media of compost-based biofilter in hybrid biofilter decreased gradually. The nitrogen limitation would be the limiting nutrient ultimately if no additional nitrogen source were introduced into biofilter.

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Fig. 12. Nitrogen content in packing media of compost-based biofilter A in hybrid biofilter during different operation time.

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