Int. J. Environ. Sci. Technol. (2015) 12:1625–1634
DOI 10.1007/s13762-014-0521-3

ORIGINAL PAPER

Performance of packed bed biofilter during transient operating conditions on removal of xylene vapour

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Received: 5 August 2012 / Revised: 27 September 2012 / Accepted: 11 January 2014 / Published online: 31 January 2014

Abstract The performance of two laboratory-scale biofilters packed with pressmud (BF1) and sugarcane bagasse (BF2) was evaluated for gas-phase xylene removal under various operating conditions. Biofilter was inoculated with a mixed culture obtained from pharmaceutical sludge. Experiments were carried out at different flow rates (0.03, 0.06, 0.09 and 0.12 $m^3 h^{-1}$) and inlet xylene concentrations (0.2, 0.4, 0.6 and 1.2 $g m^{-3}$). A maximum removal efficiency of 99 and 95 % were achieved at an inlet concentration of 0.2 $g m^{-3}$ and gas flow rate of 0.03 $m^3 h^{-1}$ for BF1 and BF2, respectively. The dynamic behaviour of the biofilter was tested at different process conditions through vigorous short, medium and long-term shock loads. The biofilter was found to respond apace to rapid changes in loading conditions. The stability of the biomass within the reactor was apparent from the fast response of the biofilter to recuperate and handle intermittent shutdown and restart operations.

Keywords Pressmud · Sugarcane bagasse · Xylene · Shutdown · Shock loading

Introduction

In recent years, biofiltration has been applied to treat gases contaminated by low concentrations of biodegradable volatile organic compounds (VOCs). Conventional biofilters are designed and operated in a manner that limits implementation of engineering decisions that could result in improved performance during transient periods of elevated contaminant loading (i.e. shock loads). These shock loads produce the relatively uncontrolled, unsteady-state conditions commonly encountered in industrial systems. In general, methods which could improve overall biofilter performance by increasing an operator's ability to control the spatial distribution or robustness of the biofilter's microbial consortium have received only limited attention in the literature. Recently, the effects of unsteady-state loading on operating strategies have been applied to biofilters (Rene et al. 2010, 2012).

As knowledge about the hazardous effects of contaminants increases, industry is facing new regulations for contaminated air discharged from different activities. Those regulations are increasingly restrictive, and legal limits on emissions are continuously being lowered. The emission of malodorous chemicals is a public health concern, but it is also related to personal comfort. Numerous technologies are applied to meet new regulations, and of these, biofiltration has significant economic and environmental attractions (Devinny et al. 1999; Miller et al. 1994; Abumaizar et al. 1998). Biofiltration harnesses the efficiency of microorganisms to degrade contaminants to nonhazardous residues. It involves passing chemical-laden gases through a moist, porous medium containing active biomass. The gaseous contaminant is oxidized by the microbes that form a film on the bed material. The end product of these processes is usually sulphate and sulphur solid, but sulphite or polythionates may also accumulate (Paca et al. 2001; Okamoto et al. 2003; Elmrini et al. 2001; Tang et al. 1995). Biofilter performance is highly dependent on the nature of the carrier material, also called

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support or packing material or filter bed (Martin and Loehr 1996). The objective of this work is to study the biofilter behaviour under shock loading and shutdown conditions, which are frequent in industrial operation.

Materials and methods

Biofiltration equipment

In the present work, pressmud (BF1) and sugar cane bagasse (BF2) were used as packing materials. The BF1 and BF2 were obtained from the MRK sugar mill private limited, Sethiaythoppu, Tamilnadu, India. The packing materials were stored in a sealed plastic bag at room temperature to maintain the moisture content. The packing materials were sieved through 1–2-cm screens, washed twice with distilled water, dried in an oven at 80 °C for 2 days and sterilized at 15 psi for 20 min. Both packing materials were mixed with a mineral salt solution prior to addition to the biofilter unit. Initial conditions were kept as follows: pH 7.0 (adjusted with NaOH or HCl), temperature 30 °C and moisture content (wet weight basis) 56.1 %. A nutrient solution contains 10.0 g L^{-1} of $NaNO_3$, 0.7 g L^{-1} of Na_2HPO_4, 0.5 g L^{-1} of KH_2PO_4 and other trace elements. The biofilter was equipped with additional auxiliary units such as flow meters, manometers, nutrient recirculation peristaltic pump, compressor and nutrient storage vessel.

Packed columns

The two columns used in this study were made up of acrylic material. A detailed sketch of the complete assembled packed bed column was shown in Fig. 1. Both columns were 100 cm high with internal diameter of 5 cm.

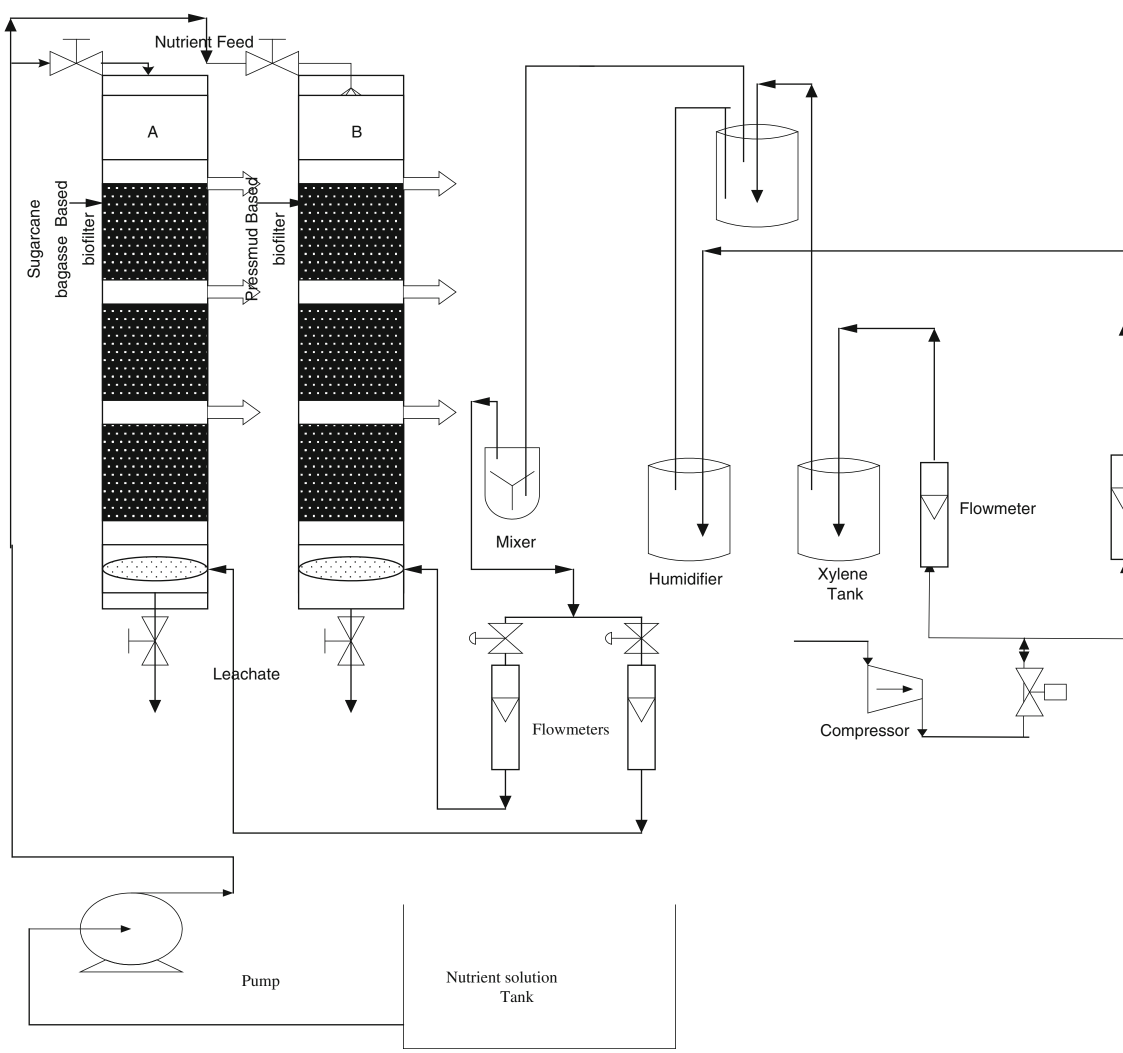

Fig. 1 Schematic diagrams for biofiltration column removing the xylene pollutant using both the packing media

A fully packed column had three sections; a 12.5-cm-high empty space at the bottom (gas distribution section and leachate collection), followed by a 75 cm height of packing medium and a 12.5 cm height of empty space at the top (Nutrient Distribution System and outlet collection). The filter bed had three layers and each layer had a height of 25 cm. The packing material was mixed with Berl saddles, which were packed into the filter bed. The Berl saddles were proved to be very effective to prevent bed compaction for organic packing media (Cox et al. 1993). The volume of packing media is 1.47 L. Each column has three ports for measuring outlet concentration of xylene.

Operating conditions and experimental control

The activated sludge taken from a pharmaceutical industry plant was used as inoculum. The biofilter was operated continuously for more than 160 days. A nutrient solution was added into the filter bed from the top of the biofilter periodically to supply the nutrient for the growth of microorganisms.

The operation of biofilter was divided into four stages, and it was given in Table 1. In each stage, the biofiltration of xylene was performed at different inlet concentrations (0.2–1.2 g m^{-3}) and gas flow rates (0.03–0.12 m^3 h^{-1}). The performance of reactor during transient response to shock loads and periodic shutdowns was studied. The transient behaviour of the biofilter was investigated by subjecting it to short-term shock load (STSL), medium-term shock load (MTSL) and long-term shock load (LTSL). The STSL and MTSL were carried out by increasing the flow rate from 0.03 to 0.12 m^3 h^{-1} for a period of 12 and 17 h, respectively. The effect of LTSLs is investigated for 17 h in four stages by varying the flow rate to 0.03, 0.06, 0.09 and 0.12 m^3 h^{-1}. The transient behaviour of the biofilter was also investigated in the form of intermittent shutdown periods. The biofilter operation was stopped thrice by closing the gas stream during 6th to 10th day (5 days), 21st to 28th day (7 days) and 38th to 50th day (12 days). Samples were collected at regular intervals of time from the inlet and outlet using an airtight syringe and analysed for residual xylene.

Table 1 Operating conditions of each phase for the biofiltration

Phase	Operating days	Average inlet concentration (g m^{-3})	Flow rate (m^3 h^{-1})
I	0–10	0.2	0.03
	11–20		0.06
	21–30		0.09
	31–40		0.12
II	41–50	0.4	0.03
	51–60		0.06
	61–70		0.09
	71–80		0.12
III	81–90	0.8	0.03
	91–100		0.06
	101–110		0.09
	111–120		0.12
VI	121–130	1.2	0.03
	131–140		0.06
	141–150		0.09
	151–160		0.12

Analytical methods

Xylene concentrations were analysed by a gas chromatograph (Nucon5655, Amil Limited, India) with an FID detector. The carrier gas selected was nitrogen and the temperatures of column oven, injector and detector were 150, 250 and 250 °C, respectively. The CO_2 concentrations were analysed by a gas chromatograph (Nucon5655, Amil Limited, India) with a TCD detector and a stainless steel column (3 mm × 2 m). The carrier gas was nitrogen, and the temperatures of the column oven, the injector and the detector were 130, 150 and 100 °C, respectively.

Performance evaluation

The performance of the biofilter was evaluated by the following parameters, inlet loading rate (IL), g m^{-3} h^{-1}, removal efficiency (RE) % and elimination capacity (EC), g m^{-3} h^{-1}. Empty bed residence time (EBRT), s.

$$\mathrm{RE} = \frac{C_\mathrm{i} - C_\mathrm{o}}{C_\mathrm{i}} \times 100\ \% \tag{1}$$

$$\mathrm{IL} = \frac{F(C_\mathrm{i})}{V}\left(\mathrm{g\,m^{-3}\,h^{-1}}\right) \tag{2}$$

$$\mathrm{EC} = \frac{F(C_\mathrm{i} - C_\mathrm{o})}{V}\left(\mathrm{g\,m^{-3}h^{-1}}\right) \tag{3}$$

$$\mathrm{EBRT} = \frac{V}{F}(\mathrm{s}) \tag{4}$$

where V is the volume of the reactor in m^3, F is the flow rate of the gas in m^{-3} h^{-1}, C_i is the inlet xylene concentration in g m^{-3}, C_o is the outlet xylene concentration in g m^{-3}.

Results and discussion

Biofiltration of air contaminated with xylene using pressmud- and sugarcane bagasse-based biofilters

The biofiltration of gas stream containing xylene was carried out for 160 days at various operating conditions in

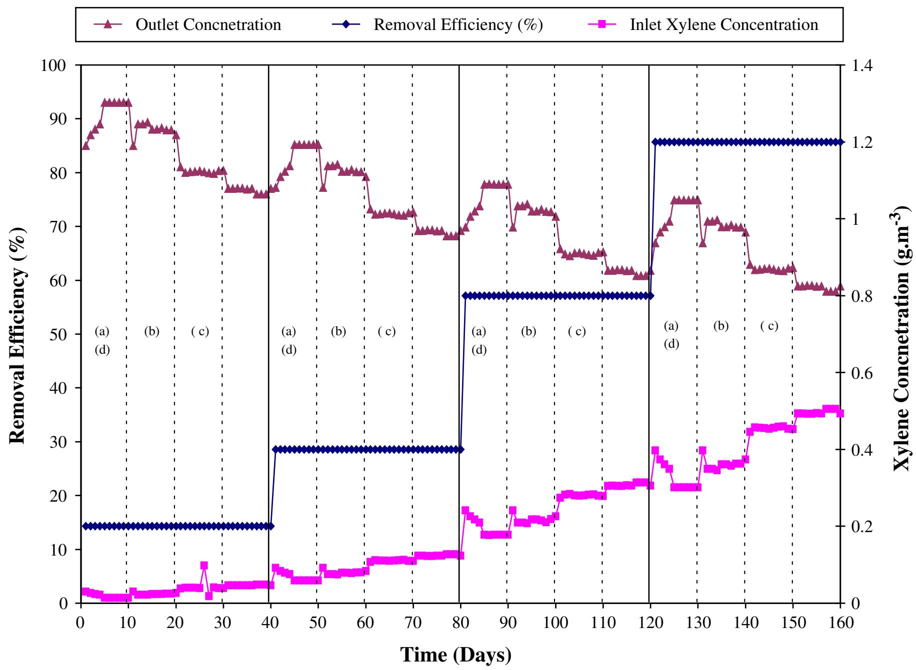

Fig. 2 Experimental results of continuous tests of xylene removal from air stream using pressmud as packing material for gas flow rate of **a** 0.03 $m^3\ h^{-1}$ **b** 0.06 $m^3\ h^{-1}$ **c** 0.09 $m^3\ h^{-1}$ and **d** 0.12 $m^3\ h^{-1}$

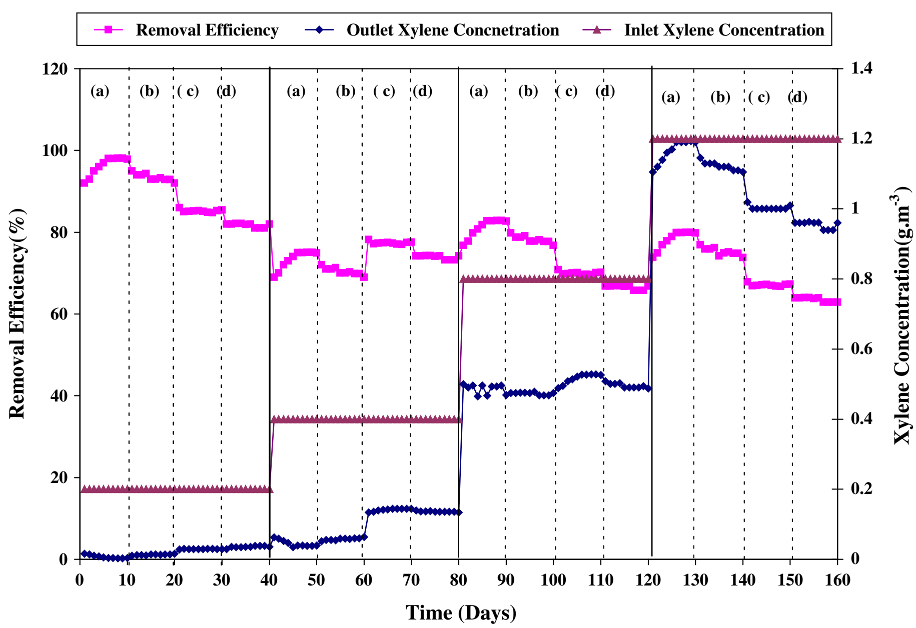

Fig. 3 Experimental results of continuous tests of xylene removal from air stream using sugarcane bagasse as packing material for gas flow rate of **a** 0.03 $m^3\ h^{-1}$ **b** 0.06 $m^3\ h^{-1}$ **c** 0.09 $m^3\ h^{-1}$ and **d** 0.12 $m^3\ h^{-1}$

BF1 and BF2 biofilters. Each biofilter had been operated in four stages. The performance of the biofilter was studied at various loading rate by changing the flow rate and inlet xylene concentration.

The first stage of the biofiltration was carried out at an inlet xylene concentration of 0.2 g m^{-3} for 40 days. During the first 10 days of operation, the flow rate was maintained at 0.03 $m^3\ h^{-1}$. At this condition, the corresponding loading rate and EBRT was 4.08 g $m^{-3}\ h^{-1}$ 2.8 min, respectively. From Figs. 2 and 3, it was observed that the RE increases gradually and reaches steady state after 8 days of operation. At steady state, a RE of more than 99.5 and 95 % was obtained in BF1 and BF2, respectively. The results showed that the RE of BF1 is greater than BF2. After 10 days of operation, the loading rate has been increased twice from 4.08 to 8.16 g $m^{-3}\ h^{-1}$ by increasing the flow rate to 0.06 $m^3\ h^{-1}$. The EBRT was 1.47 min. During the initial stage, the RE of xylene decreased from 99 to 85 % and 95 to 80 % in BF1 and BF2, respectively, due to sudden increase in the flow rate. After 1 day of operation, the biofilters recover and reach the steady state. At this stage, the RE was found to be 95 and 91 % for BF1 and BF2, respectively.

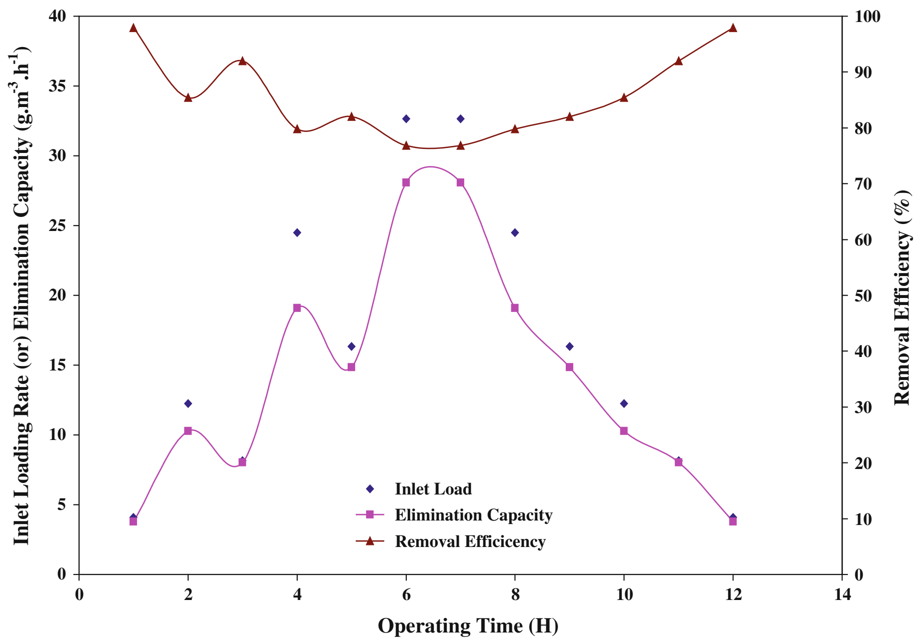

Fig. 4 Effect of short-term medium shock load on the removal efficiency of the xylene vapour using pressmud-based biofilter

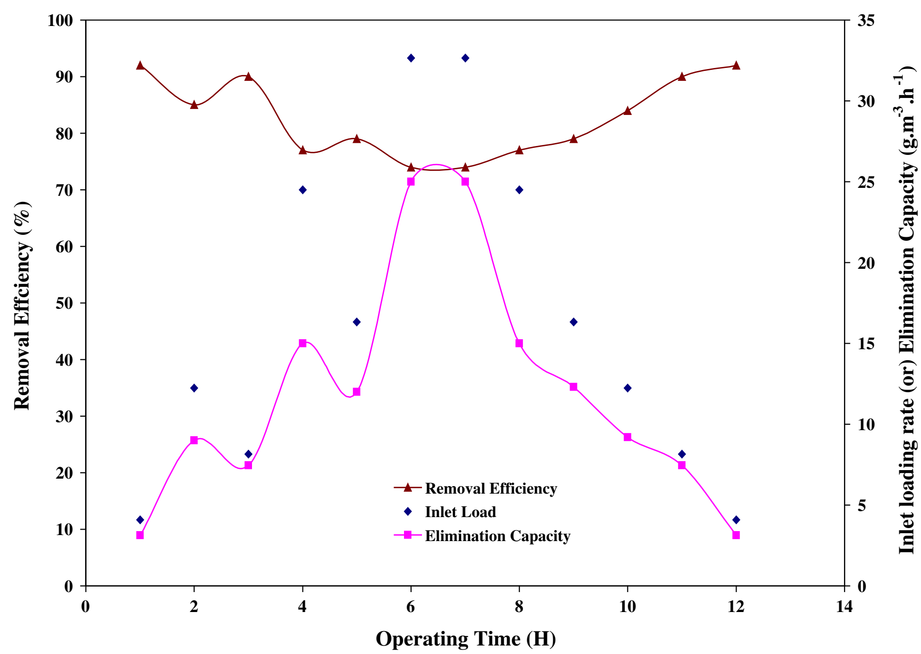

Fig. 5 Effect of short-term medium shock load on the removal efficiency of the xylene vapour using sugarcane bagasse-based biofilter

On 21st day, the loading rate was increased from 8.16 to 12.14 g m^{-3} h^{-1} by increasing the flow rate to 0.09 m^3 h^{-1}. The EBRT was 0.7 min. With the sudden increase in the loading rate, the RE of BFI and BF2 decreased to 70 and 65 %, respectively. After 2 days of operation, the biofilters recover and reach a maximum RE of 90 and 88 % in BF1 and BF2, respectively. After 30 days, the loading rate has been increased from 12.14 to 16.33 g m^{-3} h^{-1} by increasing the flow rate of gas stream to 0.12 m^3 h^{-1}. The EBRT was 0.45 min. Due to this shock load, there was a fall in the RE from 90 to 61 % in BF1 and 55 % in BF2, and it took 3 days to recover. It recovered gradually from this shock loading to 88 % in both the biofilters.

The second, third and fourth stages of experiment were performed for different inlet concentration of 0.4, 0.8 and 1.2 g m^{-3}, respectively. During the operation, the performance of both the biofilters were similar to the first stage. The RE of both the biofilters was found to be satisfactory and the system proved very stable during the whole experimental investigation. It shows high capacity of the cells to withstand a wide variation in pollutant

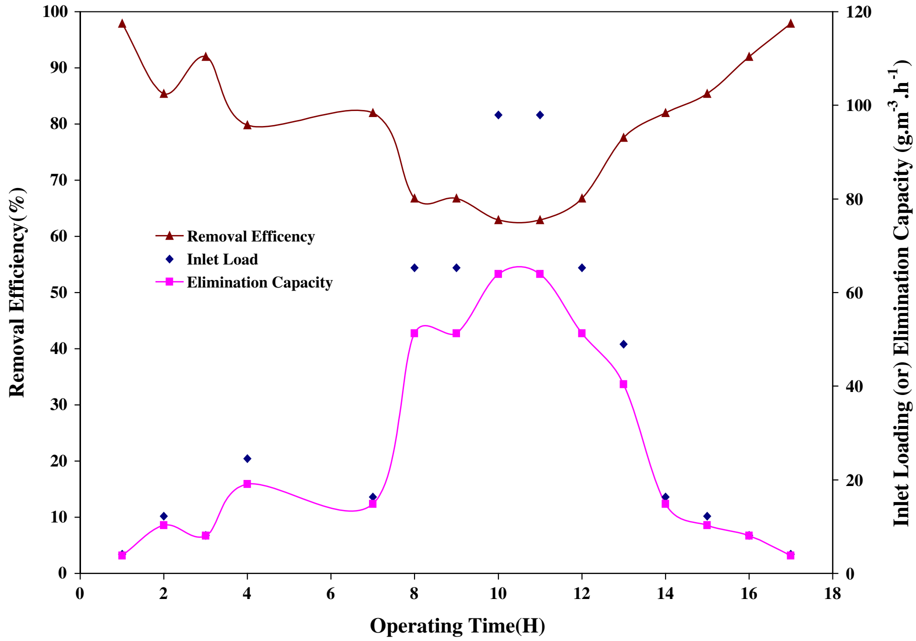

Fig. 6 Effect of medium-term shock load on the removal efficiency of the xylene vapour using pressmud-based biofilter

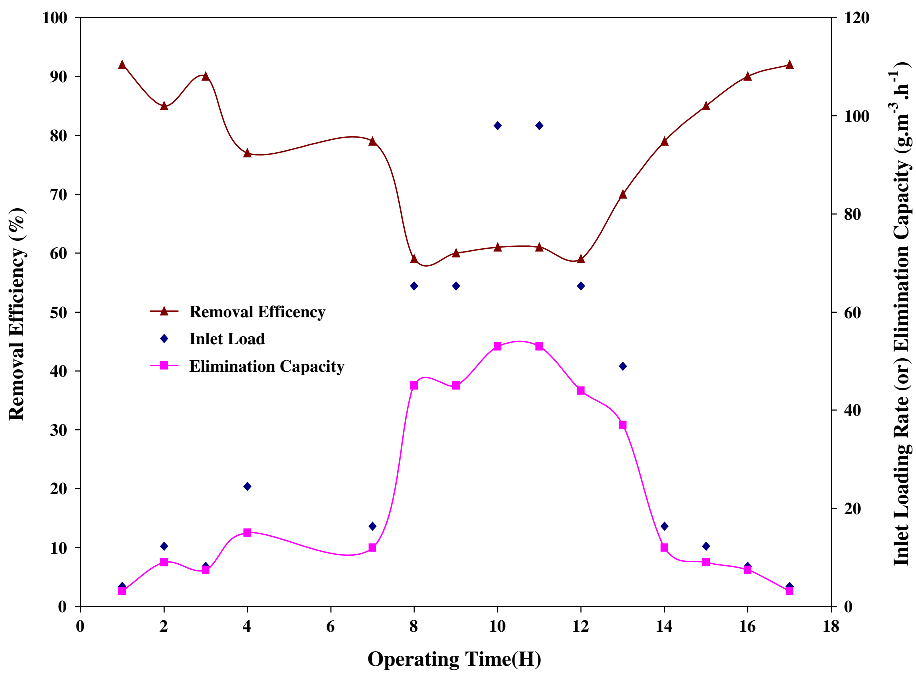

Fig. 7 Effect of medium-term shock load on the removal efficiency of the xylene vapour using sugarcane bagasse-based biofilter

concentration as well the relative resistance of the selected sludge to toxic xylene. Steady state was assumed to be achieved when the RE under given operating conditions kept nearly constant for at least 3 days. The result obtained during the overall experimental study showed that xylene RE was high in BF1-based biofilter. This may be due to the property of the packing material used. The BF1 contains high water-holding capacity (Gupta et al. 2011), adequate structure for biomass development (Sene et al. 2002) and some macro and micro nutrients when compared with bagasse (Gupta et al. 2011). Similar observations were reported for benzene removal (Abumaizar et al. 1998). The maximum RE (99.5 %) obtained in this work is higher than the values reported earlier (Abumaizar et al. 1998) using mixed compost and activated carbon as packing material.

Biofilter response to shock load

The transient behaviour of the BF1 and BF2 was investigated by subjecting it to different types of shock loads, viz, STSL, MTSL and LTSL. The STSL was carried out by increasing the flow rate from 0.03 to 0.12 m^3 h^{-1}. During

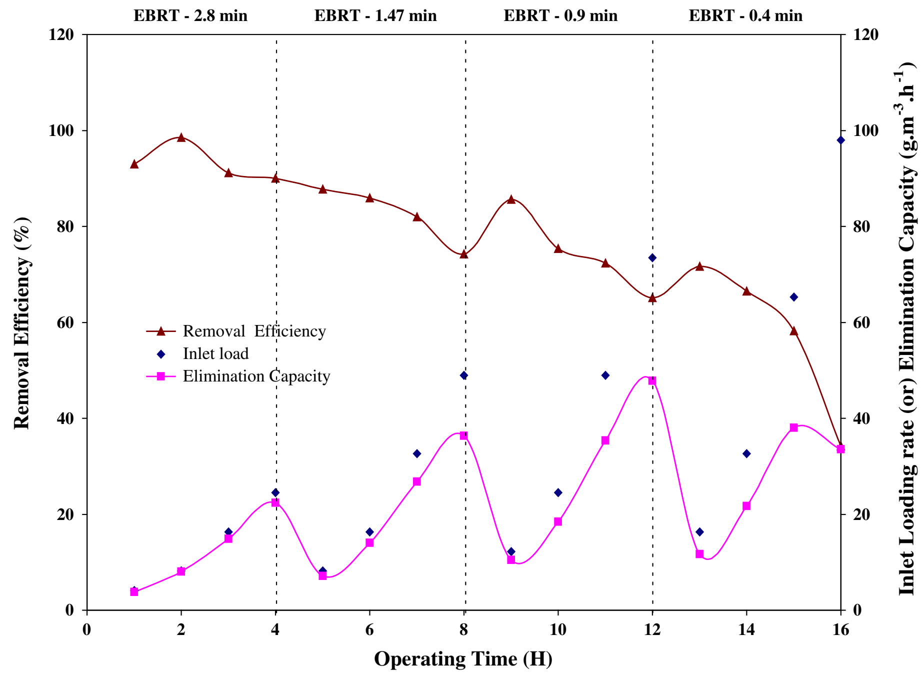

Fig. 8 Effect of long-term shock loads on the removal efficiency of xylene vapour using pressmud-based biofilter

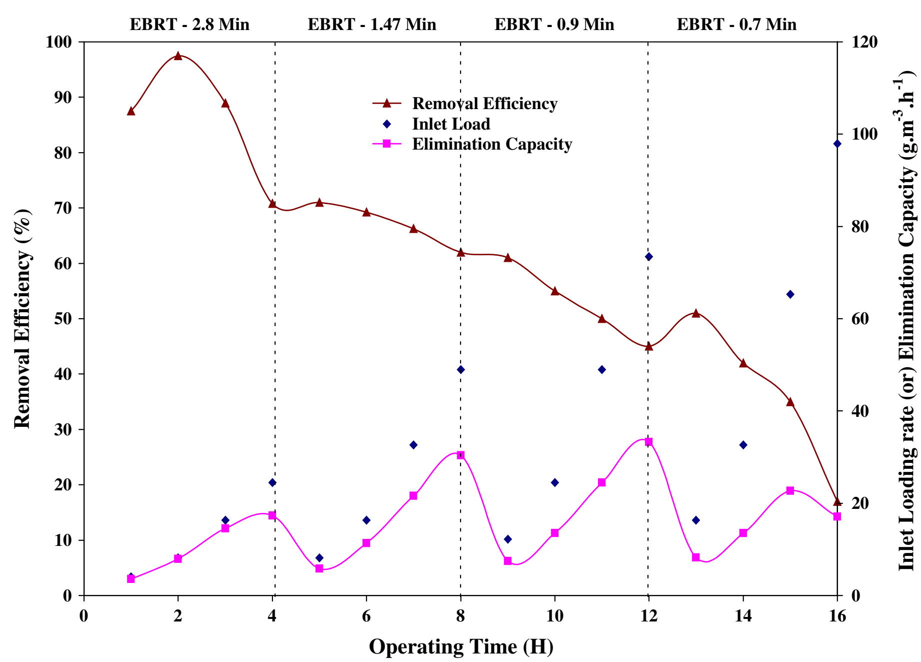

Fig. 9 Effect of long-term high shock loads on the removal efficiency of xylene vapour using sugarcane bagasse-based biofilter

this shock load, the loading rate was increased from 4.08 to 24 g m^{-3} h^{-1}. The results obtained were shown in Figs. 4 and 5 for BF1 and BF2, respectively. From the figures, it was observed that the biofilters were able to maintain a high performance close to 100 % RE. The response of the biofilter was fast as seen from the immediate decrease in removal profile during STSL. The biofilter recovered almost instantaneously after both the shock loads. The results obtained in this study are inconsistent with the literature reported by Barona et al. (2004) and Jin et al. (2007).

The effect of MTSL was investigated for 17 h by varying the flow rate from 0.06 to 0.12 m^3 h^{-1}. The corresponding loading rate ranges from 12 to 97 g m^{-3} h^{-1}. The results were depicted in Figs. 6 and 7. At loading rates lesser than 20 g m^{-3} h^{-1}, the removal efficiencies were more than 80 % during 0–7 h. However, these values of RE gradually declined when the flow rate were changed in the subsequent shock loads during 7–12 h. At a loading rate of 65 g m^{-3} h^{-1}, the RE was 66.8 and 65 %, for BF1 and BF2, respectively. When the loading rate was increased to 97 g m^{-3} h^{-1}, the RE dropped by 6 and 1 %

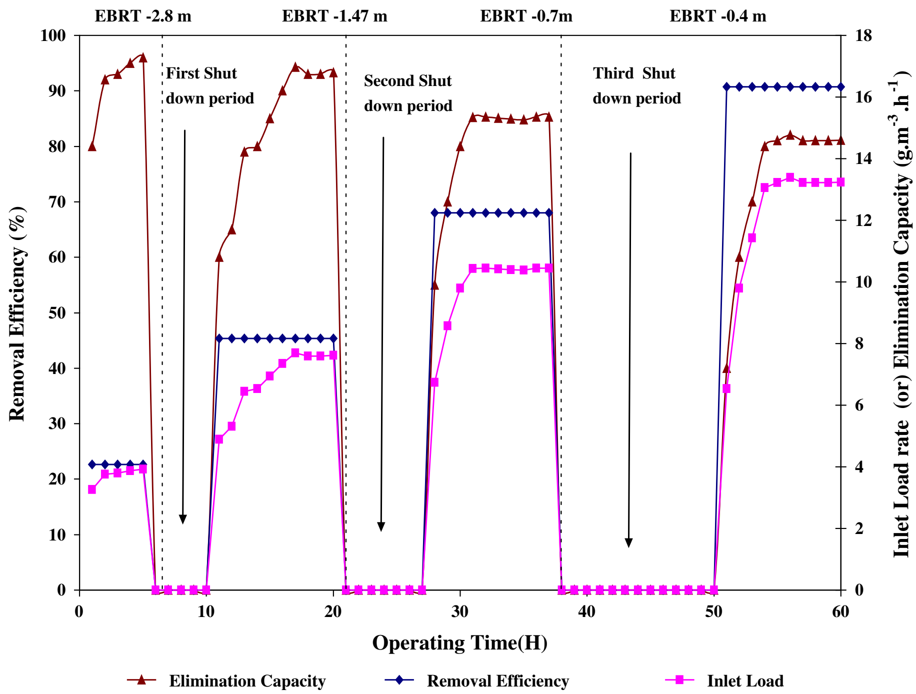

Fig. 10 Response of biofilter to intermittent shutdown and restart for xylene vapour using pressmud-based biofilter

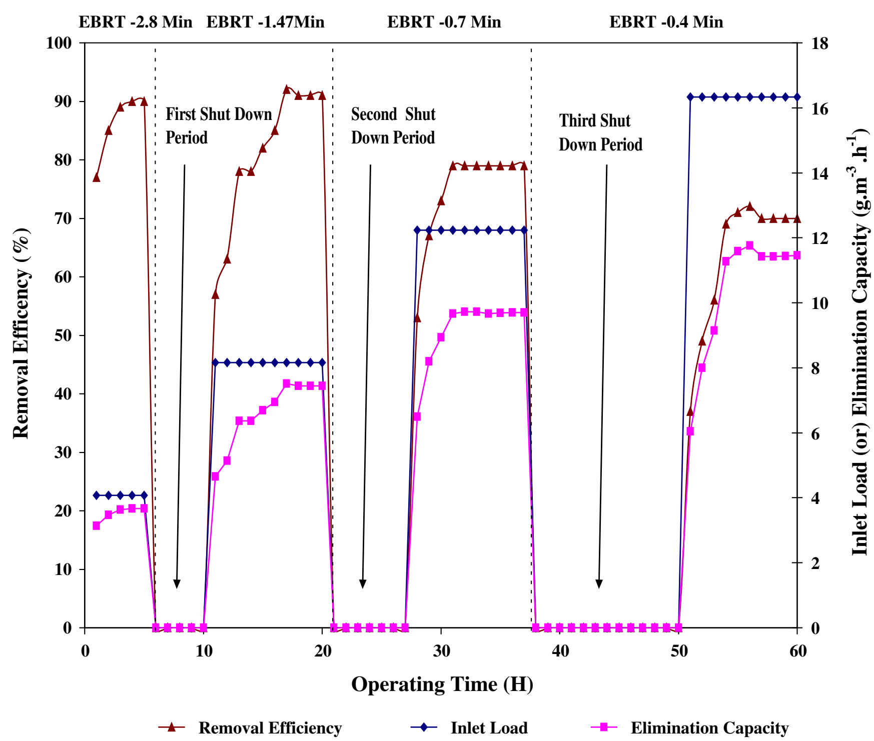

Fig. 11 Response of biofilter to intermittent shutdown and restart for xylene vapour using sugarcane bagasse-based biofilter

in BF1 and BF2, respectively. During 12–17 h, the loading rate was decreased to 12 g m^{-3} h^{-1}. However, the original removal profile was almost restored when the loading rate was reduced. It is evident from the Figs. 6 and 7 for BF1 and BF2, respectively. These results clearly show the sensitivity of the biofilter to changes in loading rate due to variations in loading rate.

The effect of LTSL was investigated for 15 h in four stages by varying the flow rates viz. 0.03, 0.06, 0.09 and 0.12 m^3 h^{-1}. Corresponding loading rate varies between 4.08 and 97 g m^{-3} h^{-1} for these flow rates, and the results were shown in Figs. 8 and 9. At a flow rate of 0.03 m^3 h^{-1}, which corresponds to a loading rate lesser than 24.49 g m^{-3} h^{-1}, the RE was higher than 90 % for BF1 and 71 % for BF2 during 0–4 h. However, these values of RE gradually declined when both the flow rate and xylene concentration were changed in the subsequent shock loads during 5–8 h. At a loading rate of 8.16 g m^{-3} h^{-1}, the RE was 87.75 % for BF1 and 71 % for BF2. When the loading rate was increased gradually to 48.98 g m^{-3} h^{-1}, the RE dropped to 74.5 % in BF1 and 60 % in BF2. In the next step of 9–12 h, the gas flow rate was increased to 0.09 g m^{-3} corresponding to shock loads varying between 12.24 and 73.47 g m^{-3} h^{-1}. It was observed that the RE dropped to 65.1 % in BF1 and 45 % in BF2. In the last step, the gas flow rate was increased to 0.12 m^3 h^{-1} during 13–16 h. At a loading rate of 16.33 g m^{-3} h^{-1}, the RE was 71.65 % for BF1 and 51 % for BF2. But after shock loads, of 97.96 g m^{-3} h^{-1}, the RE dropped to just 35.5 % in BF1 and 20 % in BF2. However, the original removal profile was almost restored when the concentration of xylene was reduced. These results clearly show the sensitivity of the biofilter to changes in loading rate due to variations in concentration and flow rate. Furthermore, it was also evident that a maximum EC of 78 g m^{-3} h^{-1} was achieved with 76 % removal during different shock loading studies, and the critical load for 100 % removal was found to be 24 g m^{-3} h^{-1}.

Biofilter response to intermittent operations

The effect of shutdown was investigated after about 2 months of steady removal operation under non-sterile conditions. Removal pattern and RE during the three kinds of shutdown experiments were shown in Figs. 10 and 11 for BF1 and BF2, respectively. From day 1 to 5, the experiment was carried out at an inlet concentration of 0.2 g m^{-3} with a gas flow rate of 0.03 m^3 h^{-1}. During this stage of biofiltration, a maximum RE of 96 % for BF1 and 90 % for BF2 was obtained. From 6th to 10th day, the biofilter was shut down. After shutdown period (11th day), 0.2 g m^{-3} of xylene was resupplied to the biofilter at a rate of 0.06 m^3 h^{-1}. Xylene RE was restored quickly and a RE of 60 and 57 % was observed in 1 h after resupply of xylene. After 6 days of operation, the biofilters recovered to reach a maximum RE of 94 and 91 % in BF1 and BF2, respectively. Again from 21st to 27th day, the biofilters were shut down. On 28th day, the gas containing xylene was passed at the rate of 0.09 m^3 h^{-1} into the biofilters. A RE of 55 and 50 % in BF1 and BF2, respectively, was achieved on the first day of operation. After 6 days of operation, the biofilters reach the maximum RE of 85 and 80 % in BF1 and BF2, respectively. The third shutdown was performed from 39th to 50th day. After 1 day of operation in a third shutdown period, a maximum RE of 58 and 55 % was obtained in BF1 and BF2, respectively. After 6 days of operation, the biofilters reach its maximum RE of more than 81 and 71 % in BF1 and BF2, respectively. After the first shutdown period, xylene RE was completely recovered within 6 days, when the load was carefully controlled. However, after the second and third shutdown experiments, the RE of xylene decreases. Similar results were reported by Juneson et al. 2001.

Conclusion

This work shows promising results for the treatment of high concentrations of gas emissions containing xylene by means of two biofilters packed with BF1 and sugarcane bagasse. From the results, it was found that the complete xylene removal was possible at inlet concentration of 0.2 g m^{-3}, irrespective of the gas residence time. Also, it was observed that the performance of biofilter depends on gas flow rate and inlet concentration. The response of the biofilter to various shock loads was found to be sensitive, as seen from the immediate decrease in RE at high loads. The restoration of RE is found to be good under low-shock loading conditions. Short-term intermittent shutdown (5 and 7 days) apparently had no effect on the biofilter performance during restart, while a 12-day shutdown period had reduced the removal by 10 %.

Acknowledgments The authors would like to gratefully thank the Department of chemical Engineering, Annamalai University, for providing the Environmental Engineering laboratory for carrying out this research.

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