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High loading toluene treatment in a compost based biofilter using up-flow and down-flow swing operation

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Abstract

A compost/ceramic (1:1, v/v) three section laboratory-scale biofilter inoculated with acclimated activated sludge was examined to treat high loading toluene vapors from a synthetic gas stream. The biofilter was operated continuously at different gas flow rates, 0.108–0.15 $m^3 h^{-1}$, with inlet toluene concentrations ranging 0.5–13 $g m^{-3}$. The overall performance of the biofilter was divided to seven stages according to the mode of operation (down-flow and up-flow) over a period of 102 days. Removal efficiencies ranging from 48 to 100% and elimination capacities ranging from 26 to 180 $g m^{-3} h^{-1}$ were observed depending on the initial loading rates and the mode of operations. A maximum elimination capacity of 180 $g m^{-3} h^{-1}$ was observed in the last period at an inlet toluene concentration of about 13 $g m^{-3}$. The results showed that changing the mode of operation (up-flow and down-flow) periodically will improve the performance of the biofilter under high inlet toluene concentration (higher than 4 $g m^{-3}$). Results obtained in this study provide insight into the possibility of the biofilter to treat high inlet concentrations rather than low concentrations well known in the literature.

Keywords: Biofilter; Compost; Down-flow; Swing operation; Toluene; Up-flow

1. Introduction

Biofilters were first developed more than 40 years ago to control odors originating from agricultural, food processing and wastewater treatment operations. Although originally developed to eliminate odorous contaminants from gases, biofiltration is now used to remove a wide range of volatile organic compounds (VOCs) including petrochemicals solvents [1].

Toluene is a toxic air pollutant and a common constituent emitted from many industrial processes, e.g., chemical manufacturing, painting and petroleum refining. Biofiltration of air emission containing toluene is considered a preferable alternative to other traditional physical and chemical air pollution control methods, e.g., incineration, scrubbing and activated carbon adsorption [2–4]. Advantage of this process include, low investment and operating costs, high removal efficiency and reliable operational stability. Furthermore, high destruction efficiency of the pollutant in the biofilter causes no secondary pollution [5].

In the biofilter, a humid, contaminated air stream is forced to pass through a porous support material on which pollutant degrading cultures are immobilized. Contaminants and also oxygen diffuse from the gas phase to the wet layer of the biofilm and sometimes in the filter medium during a relatively long contact time and then are consumed by the microorganisms communities. Under aerobic atmosphere, these compounds are oxidized to carbon dioxide, water vapors and biomass in the case of organics and to neutral soluble salts in the case of inorganic ones, i.e. ammonium. In this manner, pollutants are removed from the gas phase and converted to inert compounds without need of a secondary pollution control mechanism [1]. Packing material used in biofilter beds can be broadly categorized as either “natural” or “synthetic”. Natural media include soil, peat and compost, with compost by far the most widely used. Synthetic media include activated carbon, ceramic monoliths, ceramic pellets, sintered glass, polystyrene beads, ground tires and polyurethane [1]. When a synthetic support medium is used, nutrients must be added for microbial growth. Nutrient may be mixed with the packing material before biofilter assembly or added in solution sprayed on or mixed with the packing material after construction. In synthetic medium system, nutrient lim-

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Nomenclature

C_{CO_2}	CO_2 concentration in gas stream (g m^{-3})
$C_{CO_2,i}$	inlet CO_2 concentration (g m^{-3})
$C_{CO_2,o}$	exit CO_2 concentration (g m^{-3})
C_g	toluene concentration in gas stream (g m^{-3})
C_{gi}	inlet toluene concentration (g m^{-3})
C_{go}	exit toluene concentration (g m^{-3})
EBRT	empty bed residence time (min)
EC	elimination capacity (g m^{-3} h^{-1})
EC_{max}	maximum elimination capacity (g m^{-3} h^{-1})
H	height of the biofilter (m)
IL	inlet load (g m^{-3} h^{-1})
P_{CO_2}	carbon dioxide production rate (g m^{-3} h^{-1})
Q	gas flow rate (m^3 h^{-1})
RE	removal efficiency (%)
V_b	volume of the filter bed (m^3)
z	distance from the inlet of the biofilter (m)

itations have been reported to cause rapid decrease in performance.

Although high removal capacities have been achieved in many studies, long-term operation is often unstable at high pollutant loadings due to biomass accumulation and drying of the packing medium. Excess biomass accumulation creates a high pressure drop across a bioreactor column and hinders the reliable long-term operation of vapor phase bioreactors. In bioreactors equipped with a unidirectional feed system, clogging problems are most severe in the inlet section of the reactor column where the carbon supply is the most abundant [6]. Smith et al. [7] demonstrated in a mixed culture bioreactor degrading toluene that the toluene degrading fraction of the total microbial population declines significantly along the length of the bioreactor column, resulting in poor pollutant removal efficiencies. Therefore, clogging is problematic in biofiltration systems subjected to high pollutant loadings, leading to increased pressure drop and channeling of the gas flow through the filter bed.

To avoid clogging, many different approaches to biofilter operation have been proposed, including chemical rinsing, backwashing and nutrient limitation [7–10]. The use of various packing media and the predation of bacterial biofilms by protozoa also have been suggested for controlling clogging problems in highly loaded biofilters [11–13]. However, these methods often fail to consistently maintain high pollutant removal efficiencies over extended periods of operation under high inlet loading conditions and may not be feasible for full-scale applications. One potential useful biomass control technique is directionally switching operation. In which the air stream direction through the reactor column is periodically reversed. Song and Kinney [14] demonstrated that directionally switching operation is more stable than unidirectional operation because it distributes the biomass and pollutant degrading microbial populations more evenly along the biofilter. However, little work has been done to investigate the highly loaded biofilters and according to the authors' knowledge no study published dealing

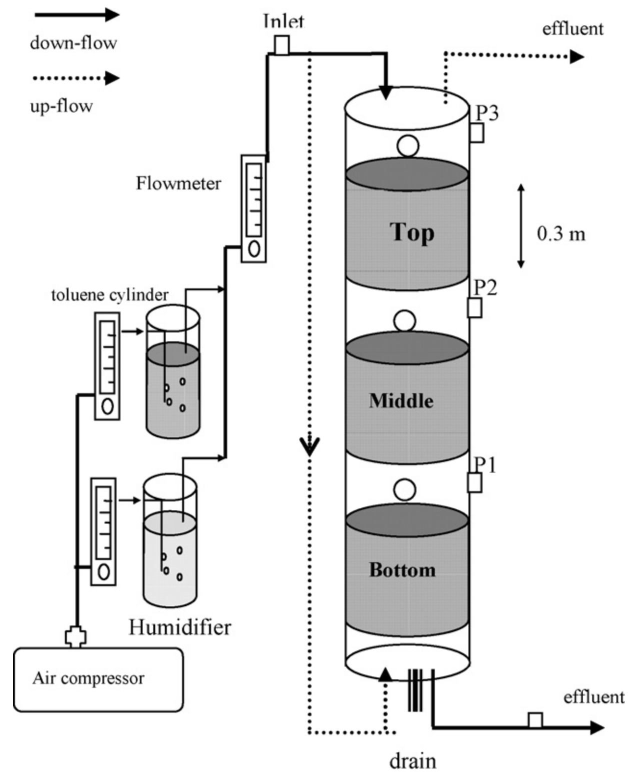

Fig. 1. Experimental setup of three sections compost based biofilter.

with high inlet load biofilter operating with periodically reversed mode.

The objective of this study was to investigate the performance of the highly loaded biofilter using different operation modes (up-flow and down-flow) with and without remixing the filter bed. Continuous experiments were conducted in a laboratory-scale ceramic/compost biofilter.

2. Material and methods

2.1. Biofilter setup

The experimental apparatus used in this study is shown in Fig. 1. The biofilter had an inner diameter of 10.3 cm and an overall height of 1.5 m. The column consisted of three 40 cm height sections. Each section was filled with 30 cm of biofilter medium to provide a total bed depth of 90 cm and a total bed volume of approximately 7.2 l, the bed porosity was 0.42. Each of the biofilter section was provided with a stainless-steel mesh to maintain the filtering material in position and also to enhance the radial distribution of gas between adjacent filter sections. Gas sampling ports, located at heights of 0, 20, 40 and 70 cm from the influent. Air fed to the biofilter was divided in two streams. The main one passed through a saturated cylinder to attain high humidity content. The secondary stream was bubbled through pure liquid toluene. Both streams were independently controlled and measured by two flow meters before mixing. The configured biofilter was in down-flow (solid line) and up-flow mode (dashed line) (Fig. 1). Inlet toluene concentrations and flow rates were varied independently.

2.2. Filter material

Filter material used consist of equal volume of compost and ceramic bed. The composition of the compost was: nitrogen (1.36%), phosphorus (1%), calcium (1.8%) with C/N ratio and water content of 26 and 51.3%, respectively. The ceramic bed (0.59 g weight and 0.4 cm^3 volume per one bed, 46.6% porosity) serves to increase the bed porosity and to ensure more homogeneous gas distribution across the filter bed. Although the inert material contributes very little to the biodegradation of air pollutants, it adsorbs a substantial amount of gas pollutants, which will gradually be degraded by microorganisms within the biofilm over time. The filter material is inoculated with activated sludge obtained from Kawagoe wastewater treatment plant, Saitama, Japan. Microorganisms in the activated sludge are acclimated to the pollutant (toluene), before using in the biofilter for two months, thereby reducing or neglecting the required adaptation time for the microorganisms in the biofilter. The nutrient solution used has the following compositions ($g\,l^{-1}$ of distilled water): 0.8 K_2HPO_4, 0.2 KH_2PO_4, 0.05 $CaSO_4$, 0.5 $MgSO_4$, 0.01 $FeSO_4$, 1 $(NH_4)\,SO_4$. The water content of the filter material is controlled at about 50% (w/w) by humidification of the inlet gas stream and addition of nutrient solution (20 ml daily).

2.3. Analytical techniques

Toluene concentration and carbon dioxide profiles in the gas phase along the biofilter column and overall efficiencies were determined on a daily basis. Gas phase toluene was measured using a gas chromatograph (SHIMADZU, GC 18-A, Japan) equipped with 60 m capillary column and a flame ionization detector (FID). Operating conditions were: column 40 °C; oven 250 °C; detector 250 °C. Helium was used as the carrier gas and its flow rate was 12 $ml\,min^{-1}$. The retention time of toluene was approximately 2.73 min under these conditions. A 5 μl of the gas sample from the biofilter was collected into a gas-tight syringe and immediately injected into the gas chromatograph. The sample volume injected into the gas chromatograph was 1 μl. The average concentrations of the three injections were used for data analysis.

The standard curve for toluene was prepared by injecting known amounts of toluene into a sealed flask equipped with Teflon septum according to a standard procedure [15]. The injected solvent was allowed to evaporate in the air space within the flask at room temperature. The air sample from the flask were drawn by a gas-tight syringe (Hamilton Co. Reno, Nev.) and analyzed by gas chromatography. Carbon dioxide evolution from the biofilter was monitored with a CO_2 meter (Testo 535, Germany). Gas sampling ports along the column were directly connected to the CO_2 meter with Teflon tubing. The pressure drop across the biofilter was measured periodically by connecting U-tube manometer to the sampling ports located on the top and the bottom of the bioreactor.

The pressure difference was measured in mm of H_2O. Water content of the biofilter was determined by drying the filter material at 100 °C for 24 h. The pH of the filter material was obtained by mixing 1 g of the filter material with 10 ml distilled water and the resultant solution was then measured by a pH meter (Shindengen, ISFET, KS723, Japan).

3. Results and discussion

3.1. General evaluation for the compost based biofilter performance

The performance of the biofilter was evaluated in terms of the removal efficiency (%), elimination capacity, inlet load and carbon dioxide production rate (P_{CO_2}), which were estimated by the following equations:

Inlet load ($g\,m^{-3}\,h^{-1}$):

$$\mathrm{IL} = \frac{QC_{gi}}{V_b} \tag{1}$$

Elimination capacity ($g\,m^{-3}\,h^{-1}$):

$$\mathrm{EC} = \frac{Q(C_{gi} - C_{go})}{V_b} \tag{2}$$

Removal efficiency (%):

$$\mathrm{RE} = \frac{C_{gi} - C_{go}}{C_{gi}} \times 100 \tag{3}$$

CO_2 production rate ($g\,m^{-3}\,h^{-1}$):

$$P_{CO_2} = \frac{Q(C_{CO_2,i} - C_{CO_2,o})}{V_b} \tag{4}$$

where Q is the gas flow rate ($m^3\,h^{-1}$), V_b the volume of the filter bed (m^3), C_{gi} and C_{go} are the inlet and exit toluene concentration ($g\,m^{-3}$) and $C_{CO_2,i}$ and $C_{CO_2,o}$ are the inlet and exit CO_2 concentration ($g\,m^{-3}$). The overall performance of compost based

Table 1
Experimental scheme for continuous toluene biodegradation experiments

Operation (days)	Operation mode	Inlet concentration range, C_{gi} ($g\,m^{-3}$)	EBRT (min)	Average RE (%)	Homogenization conditions	Average pressure drop (mm H_2O)
1–34	Down-flow (I)	0.5–3.8	3.9	100	Remixing	5
35–45	Up-flow (II)	3.2–6.3	3.1	95	No remixing	7
46–51	Down-flow (III)	6	3.1	68	No remixing	7
52–69	Up-flow (IV)	3.5–8.5	3.1	75	Remixing	5
70–80	Down-flow (V)	3.8–4.5	3.1	70	Remixing	5
81–85	Up-flow (VI)	3.5	3.1	94	No remixing	10
86–102	Up-flow (VII)	4–13	4.3	95	No remixing	20

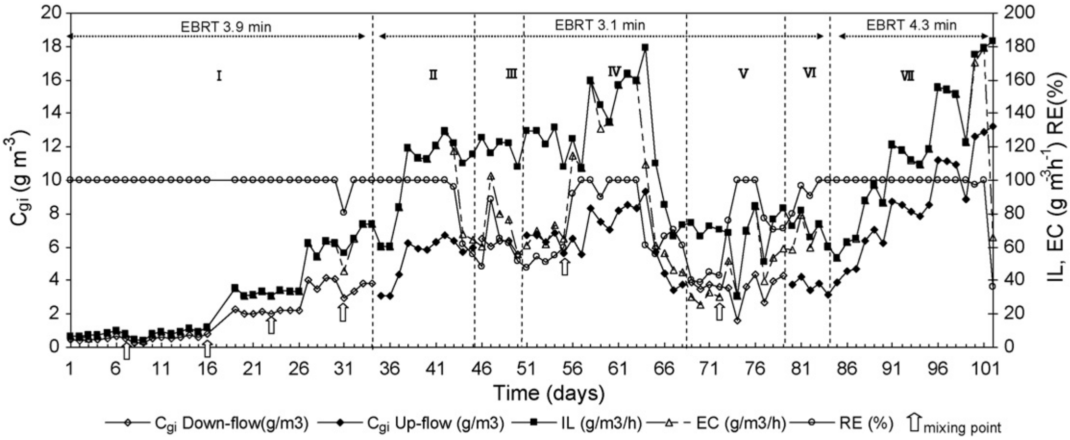

Fig. 2. Overall performance of compost based biofilter.

biofilter over a period of 101 days was investigated in seven successive stages according to the mode of operation, as described in Table 1 and the results are shown in Fig. 2.

During the first 16 days of stage I, the biofilter switched on at low concentrations (0.25–0.5 g m^{-3}) and low gas flow rate of 0.12 m^3 h^{-1} which was necessary to obtain sufficient biomass concentration in the filter bed and to ensure steady state operation. During stage I (32 days, down-flow mode operation), the gas flow rate was kept constant at 0.12 m^3 h^{-1} corresponding to EBRT of 3.9 min, the toluene inlet concentration increased gradually from 0.5 to 3.75 g m^{-3} and maintained constant for at least 3 days to stabilize a new steady state. The removal efficiency was almost 100%, this is can be attributed to good acclimation for the filter material (outside the biofilter) and remixing the filter material four times periodically, on days 7, 16, 23 and 31, respectively. During stage I both the EC_{max} and the IL was 74 g m^{-3} h^{-1}. However, the rehomogenization is not a practical solution for a large-scale biofilter, therefore changing the operation mode periodically could be a good solution to neglect or reduce the mixing and rehomogenization.

On day 34 the mode of operation was changed from down-flow to up-flow (stage II). During stage II (10 days) the toluene inlet concentration increased from 3.2 to 6.3 g m^{-3} gradually without any remixing however the RE reduced from 100 to 61% at 6.3 g m^{-3} inlet toluene concentration. The EC_{max} was about 120 g m^{-3} h^{-1} and the critical IL was about 117 g m^{-3} h^{-1}, at which the RE deviated from 100%. Changing the mode operation to down-flow for 5 days at the same inlet toluene concentration, about 6.3 g m^{-3} (stage III) have improved the RE for 2 days then decreased to 47%. This is probably associated with the development of dried and/or clogged zones, therefore the bioifilter switched on to the up-flow mode (stage IV) for 2 weeks, during the first 5 days the RE increased but very slowly at C_{in} of 6.6 g m^{-3} and after remixing the compost on day 55 the RE increased rapidly to 100%, this is a confirmation that the biomass should be redistributed homogenously through the filter material in order to improve the performance of the compost based biofilter under high loading. On day 57 the C_{gi} increased to 8 g m^{-3} and RE remained higher than 95% however after the RE reduced to 55%, due to high loading, the C_{gi} reduced to 4 g m^{-3} gradually and the mode operation again changed to down-flow (stage V) to redistribute the biomass and to improve the performance of the biofilter, during that stage the worst behavior was observed and the RE improved only for a short period of 2–3 days, after remixing of the filter material on day 72. However, during the last two stages (VI and VII), the best performance was observed and the microorganism recovered their ability to degrade high inlet toluene concentration with a high RE (almost 100%) for about 20 days without any remixing. During that period the resident time was increased to 4.3 min due to reducing the inlet gas velocity, and this gave the microorganism enough time to degrade as much toluene as possible, and the higher CO_2 produced confirm this fact. When the inlet toluene concentration was further increased to 13 g m^{-3}, the RE decreased rapidly to lower than 40%, providing evidence of an inhibiting effect likely due to excess toluene mass loading. According to the authors knowledge no study has been reported at high inlet toluene loading. A previous study of active compost biofiltration had shown that the toluene biodegradation rate under mesophilic conditions reached a maximum of 80 g m^{-3} h^{-1} at an inlet concentration of about 4 g m^{-3} [16]. Hsiu-Mu et al. [5] showed that GAC/compost biofilter has EC_{max} of 97 g m^{-3} h^{-1} at an inlet toluene concentration of 5.32 g m^{-3} (RE about 70%). Matteau and Ramsay [16] reported during the thermophilic biofiltration of toluene (45–55 °C), toluene biodegradation rates of 110 g m^{-3} h^{-1} at an inlet concentration of about 5 g m^{-3} and a gas residence time of 90 s.

3.2. *Effect of remixing*

Remixing is known to improve operating conditions (reduced channeling effect and bed drying or clogging and improved particle homogenization) and environmental conditions (nutrients, water, oxygen and redistribution of biofilm), resulting in better biofilter performance [17]. Long-term operation is often unstable at high pollutant loading due to biomass accumulation and drying of the packed medium. To improve the performance of the compost based biofilter under these conditions, the biofilter was shut down (for 2–3 h, in the present experiments) and the compost manually remixed. After each mixing (after days 7, 16, 23, 31, 55 and 72), a high RE of toluene was observed, as shown in Fig. 2. Matteau and Ramsay [16,18] during their experiments dealing with high loading toluene biofiltration, the mesophilic and thermophilic compost was mixed manually every 24–48 and 24–72 h, respectively, to prevent channeling and drying of the bed and to add fresh substrate. However, unpacking the biofilter and manually mixing the packing material would probably not be viable in large-scale biofilters. It is not clear how often the compost should be mixed and homogenized. During the course of the present experiments the compost was remixed to keep the RE closer to 100%, and not every fixed period (48 or 72 h). Furthermore, the results showed that changing the mode of operation reduced both occurrences and time needed for mixing of the biofilter matrix. Additionally the pressure drop across the biofilter was reduced during these experiments ranging from 5 to 20 mm H_2O. The highest pressure (about 20 mm H_2O) drop was detected during the last 5 days of stage VII. However, this range of pressure drop did not affect the performance of the biofilter negatively. Therefore, another technique can be applied to improve the performance of the biofilter, by changing the mode of operation, up-flow and down-flow periodically whenever the removal efficiency of the biofilter reduced.

3.3. *Effect of mode operation*

A potential method to improve biomass distribution and the stability of vapor-phase bioreactors is to operate them in a directionally switching mode such that the contaminant air stream direction is periodically reversed through the biofilter [19]. All the toluene removal during the study period (up-flow or down-flow) occurred in the section closest to the inlet. In the down-flow mode the top section is the nearest to the inlet, while in the up-flow mode the bottom section is the nearest. A visual inspection revealed brown biomass in section nearest to the inlet and no observable growth in the section nearest to the outlet. The higher biomass concentration at the section nearest to the inlet is due to the higher toluene concentration in the inlet zone that stimulated the pollutant bio-oxidation and cell development. During the last stages of the up-flow mode (VI and VII) the bottom and the middle sections were very active, no toluene was detect out from the middle section (100% RE), this is could be harmful to the microorganisms in the top section which use the toluene as the only source of carbon as food and energy. Therefore, changing the mode of operation should be as short as possible to avoid the disability of the microorganism to degrade the pollutant. The progressive growth of biomass at the nearest section to the inlet did not in fact lead to a relatively uniform distribution of biomass throughout the biofilter without changing the mode of operation periodically, contrary to Zilli et al. [20] who pointed a uniform biomass distribution due to the progressive growth of biomass at the nearest section to the inlet in their single section compost based biofilter.

Figs. 3 and 4 show the typical profiles of the toluene and CO_2 along the height of the biofilter for the down-flow and up-flow operations mode, respectively.

Fig. 3 shows the concentration profiles of the toluene and CO_2 in the down-flow mode operation. Two different inlet toluene

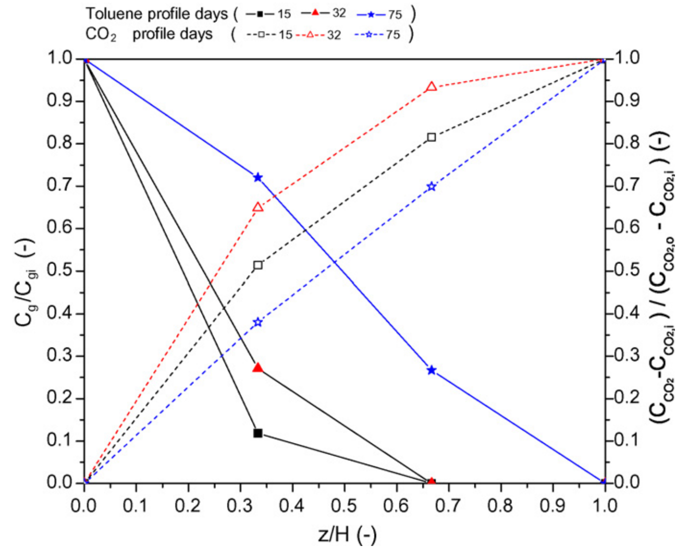

Fig. 3. Toluene and CO_2 profile along the biofilter under down-flow mode operation.

concentrations, 0.59 g m^{-3} (day 15) and 3.8 g m^{-3} (day 32) at constant EBRT of 3.9 min and one inlet toluene concentration 3.8 g m^{-3} (day 75) at EBRT of 3.1 were presented. At EBRT of 3.8 min it is clearly shown that the top section is more active than the middle and bottom sections, about 80% of the 0.59 g m^{-3} and 75% of the 3.8 g m^{-3} have been degraded in the top section, respectively, while in both the middle and bottom sections about 20 and 25% was degraded, respectively. Indicating that most biological reactions occurred within the top section of the biofilter. This could be explained by the presence of more carbon source (toluene), moisture contents (about 56%) and nutrients (20 ml daily), which caused a higher metabolic reaction and thus led to a faster biodegradable rate of toluene. Comparing the profiles of days 32 and 75 under the same inlet toluene concentration (3.8 g m^{-3}) and different EBRT (3.9 and 3.1 min), shows that at longer EBRT (3.9 min) complete toluene biodegradation was

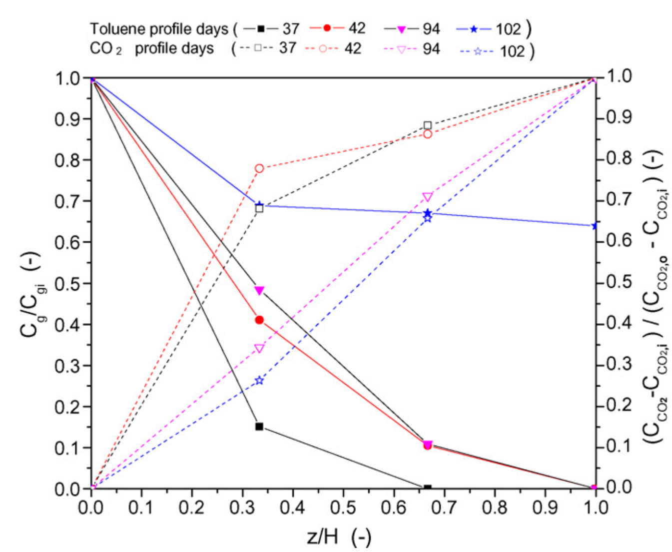

Fig. 4. Toluene and CO_2 profile along the biofilter under up-flow mode operation.

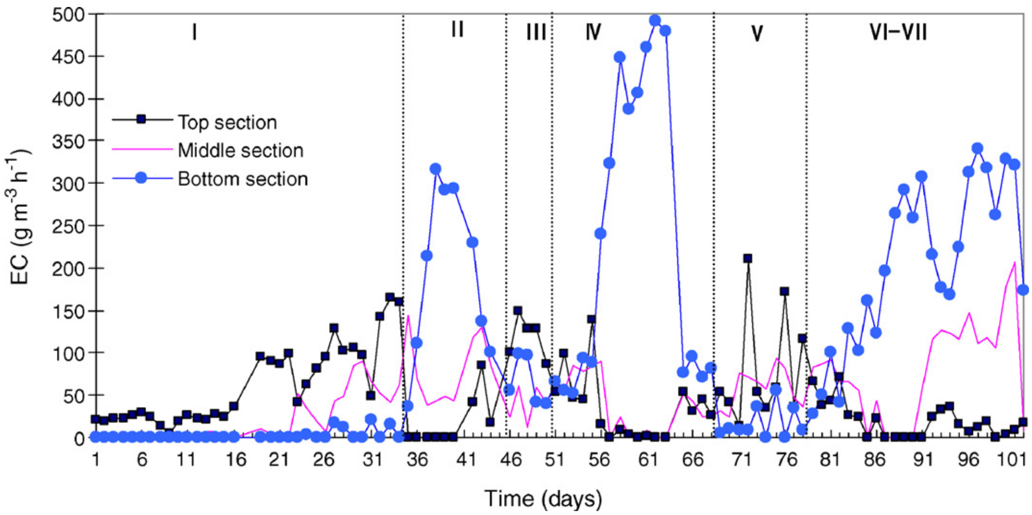

Fig. 5. Variation of the individual elimination capacities (bottom, middle and top) with time.

occurred in two sections (top and middle) and the concentration profile was lower than that at EBRT of 3.1 min, this is can be attributed to the fact that the attached microorganisms had more time to decompose more toluene. The CO_2 concentration in the polluted air entering the biofilter was not zero or negligible, as many studies assumed [21]. In the present study the inlet CO_2 concentration was higher than 400 ppm, therefore to avoid the intersection with the CO_2 produced in the biofilter the inlet CO_2 was excluded. Fig. 3 shows smooth increase of CO_2 in the gas phase along the biofilter. At the same EBRT of 3.9 min (days 15 and 32) the CO_2 concentration profile significantly increased with increased inlet toluene concentration, where the CO_2 is the end product of microbial metabolism.

Fig. 4 shows the toluene and CO_2 concentrations profiles along the biofilter in the up-flow mode operation. Four different inlet toluene concentrations, 4.5 g m^{-3} (day 37), 6 g m^{-3} (day 42), 8 g m^{-3} (day 94) and 13 g m^{-3} (day 102) were presented. It was very interesting to note that the most active section is the bottom section (the nearest to the inlet). Regardless the value of the removal efficiency (100% or less) comparing two different concentrations (days 37 and 102) show that about 85% of 4.5 g m^{-3} and 30% of the 13 g m^{-3} have been degraded in the bottom section, while in both the middle and bottom sections about 15 and 3% was degraded, respectively. The CO_2 concentration profile on day 102 was the lowest this is probably due to the inhibiting effect of the microorganisms to degrade toluene and produce CO_2, likely due to excess toluene mass loading as the RE was lower than 40%.

Fig. 5 shows the variation of the elimination capacity with time in different sections of the biofilter. The elimination capacity has the highest value at the top section and the lowest at the bottom section (in the case of down-flow, I, III and V) of the biofilter. It is mainly due to the higher water content of packing in the bottom section. The optimum water content for biofilters depends on the media composition and the physical characteristic of the pollutants. With typical natural biofilter media (compost) operators have found that water content should be maintained in the range of 40–60% [22]. In the down-flow mode operation the moisture content was the highest in the bottom section (about 65%), consequently reducing the performance of that section which has the lowest EC. Excessively high water content can cause a variety of problems. Air pressure drop across the biofilter increases as water displaces air in the space between the particles, thereby restricting the flow of air.

However, in the case of up-flow mode (II, IV, VI and VII) the elimination capacity has the highest value at the bottom section and the lowest at the top section of the biofilter. The highest water content was observed in the top and middle sections and the lowest was in the bottom section, in this case the inlet air has significantly reduced the water content in the bottom section. Another reason can be mentioned here that high toluene concentration in the section nearest to the inlet (top section in down-flow mode and bottom section in up-flow mode) can increase the elimination capacity.

3.4. Carbon dioxide production

The degree of toluene biodegradation can be assessed by the increment of CO_2 concentration in the effluent gas streams. According to the stoichiometry, 7 mol of CO_2 can be obtained by the complete biooxidation of 1 mol of toluene or on a weight basis, 3.35 mg of CO_2 are generated per mg of toluene degraded [23]. Fig. 6 shows the carbon dioxide production rate (P_{CO_2}) as a function of the elimination capacity (EC). The alignment of the data series shows that the quantity of carbon dioxide released strongly correlated with the quantity of toluene oxidized.

A linear regression calculated according to the least-squares method, provides the following equations, for the down-flow and up-flow mode operation:

$$\text{Down-flow experiments} \quad P_{CO_2} = 2.72\text{EC} + 73 \tag{5}$$

$$\text{Up-flow experiments} \quad P_{CO_2} = 2.36\text{EC} + 76 \tag{6}$$

Eqs. (5) and (6), show that a proportionality ratio exists between toluene elimination capacity and CO_2 production rate. A 100% toluene conversion to CO_2 can be obtained with a slope of 3.36

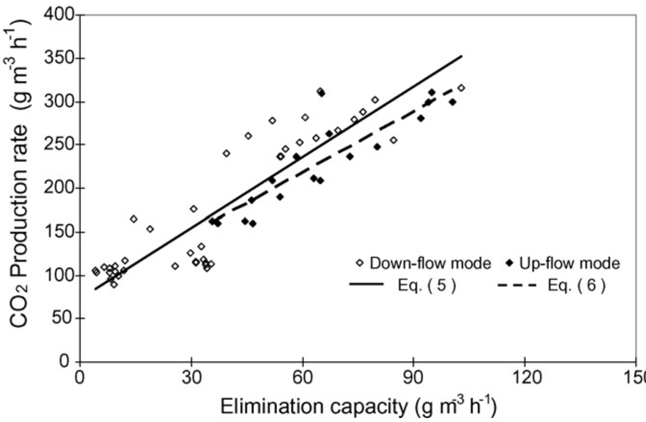

Fig. 6. Relationship between the CO_2 production rate (P_{CO_2}) and toluene elimination capacity (EC) for down-flow and up-flow operations mode.

according to stoichiometry [23,24]. Accordingly, in this experiment, the values of the slopes for Eqs. (5) and (6) show that about 81 and 70% of the loaded toluene was converted to CO_2 in the down-flow and up-flow mode operations, respectively. The high conversion ratio of toluene to CO_2 in the biofilter with down-flow mode operation suggests that a relatively smaller biomass production and high CO_2 production in toluene degradation were effective to minimize clogging during operation [25]. However, the smaller biomass production reduces the ability of the biofilter to degrade high load toluene due to decreasing in the microorganisms responsible for degrading the toluene, therefore changing the mode of operation and remixing occasionally without removing the produced biomass could be helpful to make the biofilter working efficiently at high inlet loading. Because the CO_2 is the end product of microbial metabolism, the CO_2 significantly increased with increased influent toluene concentration, higher loading and elimination capacities of toluene, leading to more biodegraded toluene and consequently releasing more CO_2. Therefore, the CO_2 production should be directly related to toluene elimination capacity. Delhoménie et al. [26] found that the slopes of P_{CO_2} versus EC for three different biofilters treating toluene are in the same order (2.4 and 2.8) and they concluded that microbial behavior was independent on the physical characteristics of the particles used in these biofilters.

4. Conclusions

In this study a new operation strategy was applied to improve the performance of the compost based biofilter, treating high inlet toluene concentration. The biofilter was operated continuously at different gas flow rates, 0.108–0.15 $m^3\,h^{-1}$, with inlet toluene concentrations ranging 0.5–13 $g\,m^{-3}$. The overall performance of the biofilter was divided to seven stages according to the mode of operation (down and up-flow) over a period of 102 days. Removal efficiencies ranging from 48 to 100% and elimination capacities ranging from 26 to 180 $g\,m^{-3}\,h^{-1}$ were observed depending on the initial loading rates and the mode of operations. A maximum elimination capacity of 180 $g\,m^{-3}\,h^{-1}$ was observed in the last period at an inlet toluene concentration of about 13 $g\,m^{-3}$. Correlations for the CO_2 production rate with toluene elimination capacity were proposed for the up-flow and down-flow mode. The results showed that changing the mode of operation (up-flow and down-flow) periodically will improve the performance of the biofilter under high inlet toluene concentration. Several factors can contribute to our high EC_{max} value: the uniformity of the gas distribution by changing the mode operation, keeping and redistributing the accumulated biomass inside the biofilter by remixing rather than removing the excess biomass by washing, consequently keeping the pressure drop across the biofilter within a reasonable range (3–25 mm H_2O) and increasing the ability of the microorganusms to degrade toluene, the nutrient solution (20 ml added daily), the control of the moisture of the filter bed (around 60%). All these factors are the reasons to make the biofilter treat high inlet load toluene efficiently. The mixed composed—ceramic bed provide an excellent filtering medium with a negligible pressure drop and optimum water retention. The results obtained in this study provide insight into the possibility of the biofilter to treat high inlet concentrations (greater than 4 $g\,m^{-3}$) rather than low concentrations (in ppms) well known in the literature.

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