TECHNICAL PAPER

ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **56**:1567–1575

Comparison of Different Packing Materials for the Biofiltration of Air Toxics

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ABSTRACT

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Four different biofilter packing materials (two porous ceramics, perlite, and open pore polyurethane foam) were compared for the removal of toluene vapors. The focus was on evaluating performance at relatively short gas retention time (13.5 and 27 sec). The reactors were initially operated as biotrickling filters with continuous feeding and trickling of a nutrient solution. After significant plugging of the biotrickling filter beds with biomass was observed, the operation mode was switched to biofiltration with only periodic supply of mineral nutrients. This resulted in stable conditions, which allowed detailed investigations over >6 months. The reactor packed with cattle bone Porcelite (CBP), a ceramic material containing some macronutrients and micronutrients, exhibited the highest performance. The critical load (i.e., load at which 95% removal occurred) was 29 g m^{-3} hr^{-1} at a gas retention time of 13.5 sec and 66 g m^{-3} hr^{-1} at a gas retention time of 27 sec. After the long-term experiment, the packing materials were taken from the reactors and examined. The reactors were divided into three sections, top, middle, and bottom, to determine whether spatial differentiation of biomass occurred. The assays included a double-staining technique to count total and live microorganisms and determination of moisture, protein, and dry weight contents. Microbial community analysis was also conducted by denaturing gradient gel electrophoresis. The results showed that most reactors had a significant fraction of inactive biomass. Comparatively, the CBP biofilter held significantly higher densities of active biomass, which may be the reason for the higher toluene removal performance. The analyses suggest that favorable material properties and the nutrients slowly released by the CBP provided better environmental conditions for the process culture.

IMPLICATIONS

As biological methods for air pollution control are becoming more popular, end-users are facing many choices. Will a biofilter reach the desired treatment? Should a biotrickling filter be considered? What packing will provide the best treatment? Researchers in the field are trying to find sound explanations to support answers to the questions above. The present study investigated the removal of toluene vapors as a model pollutant in biofilters and biotrickling filters. Four different packings were used, and the long-term performance was compared. At the end of the experiment, the reactors were subjected to a detailed analysis to determine the reasons for the differences in performance that were observed. The results suggest that the choice of the packing and of the mode of operation have profound implications on the treatment performance.

INTRODUCTION

Biological treatment is an increasingly accepted method for the control of gaseous volatile organic compound (VOC) emissions. Biofilters and biotrickling filters offer a cost-effective and environmentally friendly alternative to physical and chemical air pollution control methods.[1] Biofilters work by passing humidified polluted air through a bed on which a pollutant degrading biofilm develops. On the packing material, microorganisms are naturally immobilized and biodegrade the absorbed pollutants. Under optimum conditions, biodegradable contaminants are rapidly converted to CO_2 and water.[1] In biotrickling filters, a free water phase exists, which usually contains nutrients. Biotrickling filters are often more efficient than biofilters, but the feeding of nutrients stimulates biomass growth. Clogging by excessive growth of biomass is one of the main obstacles to the implementation of high-performance biotrickling filtration, and several clogging control methods have been suggested by researchers.[2–6] In both biofilters and biotrickling filters, the selection of packing materials is an important factor in establishing a high removal efficiency and maintaining performance over the long term. Four inorganic packing materials were compared previously for the removal of H_2S or NH_3.[7,8] Both reports showed that porous ceramic was the best material, providing the highest pollutant removal rates. A porous ceramic packing was also tested and compared with previously published data for toluene vapor removal in a biofilter.[4] However, parallel operation and comparison of different packing materials has rarely been done. In addition, most previous studies on the biotreatment of toluene considered retention times ranging from 40 sec to 2 min and relatively high concentrations, that is, conditions that may not be representative of a real industrial application.[6,9–12] In this paper, four packing materials were compared for their ability to sustain toluene vapor removal at gas retention times of 13.5 sec and 27 sec. The focus was on determining the performance of toluene removal and the long-term stability of the reactors, as well

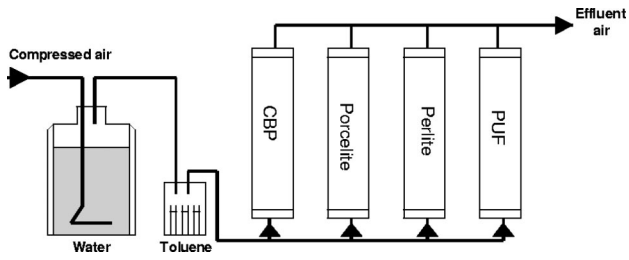

Figure 1. Schematic diagram of the experimental system.

as conducting quantitative process culture analyses to better understand the relationships between packing properties and reactor performance.

EXPERIMENTAL WORK

Biofiltration Experiments

Biofilter and Packing Materials. Four identical biofilters were used this study. The biofilters were constructed from clear polyvinyl chloride pipes and were 1.2 m in length and 10 cm in i.d. Figure 1 provides a schematic of the setup. The biofilters were filled to a bed depth of 60 cm. The four reactors were operated in parallel in an identical manner, and the only difference was the packing material. Cattle bone Porcelite (CBP), a composite ceramic (Aisin Takaoka Co., Ltd.), Porcelite, a porous ceramic (Aisin Takaoka Co., Ltd.), horticultural perlite ([Perlite] Aztec Escondido), and open-pore polyurethane foam ([PUF] EDT) were used in this study. CBP is manufactured with 80% vol. of the same raw material used in the making of Porcelite and 20% volume of cattle bone powder. Cattle bone mainly consists of hydroxyapatite and organic matter. During the making of the ceramics, part of the cattle bone may burn, leaving pore space and ashes, whereas the remainder of the cattle bone acts as a slow release nutrient source for microorganisms. The properties of four packing materials are shown in Table 1. PUF was selected for the study, because it had shown superior performance for the treatment of H_2S.[13] Perlite was selected because it had been used in many successful biofiltration studies.[1] CBP and Porcelite were selected for the study because their hydrophilic surface properties, as well as nutrient release properties (for CBP), were thought to possibly enhance biofiltration performance. The biofilters were inoculated with several mixed cultures of toluene-degrading microorganisms maintained in the laboratory.

Setup and Operating Conditions. Compressed air was passed through a humidifier and was then mixed with concentrated toluene vapors in a mixing chamber. The synthetic contaminated airstream was supplied to the bottom of the biofilters (i.e., upflow mode). In most experiments, the airflow rate was 20 L min^{-1}, corresponding with an empty bed residence time (EBRT) of 13.5 sec. The toluene concentration in the influent gas stream was in the range of 0.01–0.44 g m^{-3}, resulting in a loading to the biofilters of 2.8–116 g m^{-3} hr^{-1}. From day 90 and day 127, the airflow was 10 L min^{-1}, corresponding with an empty bed gas residence time of 27 sec, and the influent toluene concentration ranged from 0.44 to 0.86 g m^{-3} resulting in a loading to the biofilters of 58–114 g m^{-3} hr^{-1}. These inlet toluene concentrations are on the low end of concentrations usually used for laboratory-scale biofiltration studies. Even so, they correspond better with the needs of the air pollution control systems, for example, for paint spray booths. The inlet air had a relative humidity of ~70%, and all of the experiments were carried out at a room temperature (21–24 °C). Mineral medium (120 mL) was manually supplied to the columns twice per week for the first 20 day, and 60 mL of mineral medium were manually added to the filter bed twice a week thereafter. The mineral medium contained 2 g L^{-1} of KH_2PO_4, 2 g L^{-1} of K_2HPO_4, 2 g L^{-1} of KNO_3, 2 g L^{-1} of NaCl, 0.04 g L^{-1} of $MgSO_4$, 0.04 g L^{-1} of $CaCl_2$, and 2 mL L^{-1} of a trace-elements solution. The trace element solution contained 1.5 g L^{-1} of $FeCl_2 \cdot 4\ Hr_2O$, 0.06 g L^{-1} of H_3BO_3, 0.1 g L^{-1} of $MnCl_2 \cdot 4\ Hr_2O$, 0.12 g L^{-1} of $CoCl_2 \cdot 6\ Hr_2O$, 0.04 g L^{-1} of $ZnCl_2$, 0.025 g L^{-1} of $NiCl_2 \cdot 6\ Hr_2O$, 0.015 g L^{-1} of $CuCl_2 \cdot 2\ Hr_2O$, 0.025 g L^{-1} of $NaMoO_4 \cdot 2\ Hr_2O$, 18.27 mL L^{-1} 37% HCl, and 5.2 g L^{-1} of EDTA $Na_4 \cdot 4\ H_2O$.

Analysis. Gaseous toluene concentrations were measured by gas chromatography (HP 5890) using a flame-ionization detector. Online monitoring of CO_2 in the reactor influent and effluent air was performed using a nondispersive infrared probe and a data logger from Vernier Instruments.

Biomass Assay

At the end of the long-term biofilter test, the content of 3 bioreactors (CBP, Porcelite, and Perlite) was gently removed (the results of the PUF were poor and did not warrant further investigations), and the packing was split into three sections of equal volume (top third, middle, and bottom third of each reactor). Each section was independently mixed, and subsamples were taken for measurements. For dry biomass weight, ~30 cm^3 of packing was placed in an oven at 80 °C for 48 hr to reach a constant weight. The moisture content in the packing material was determined by measuring the weight loss

Table 1. Properties of the packing materials.

Variable	CBP	Porcelite	Perlite	PUF
Particle size (mm)	3	4	4	NA (~20 pores/in.)
Dry packed bed density (g/cm^3)	0.81	0.85	0.15	0.035
Packed bed porosity (%)	35	35	40	95%
Micropore porosity (%)	37	47	ND	Nonporous
Crushing strength	Medium	High	Medium-low	Very low

Notes: NA = not applicable.

Table 2. Summary of performance during the various operating modes.

Variable	Period (days)	CBP	Porcelite	Perlite	PUF
BTF with nutrient supply	78	Removal: high ΔP: high	Removal: medium ΔP: high	Removal: high ΔP: high	Removal: low ΔP: low
BF without nutrient supply	21	Removal: low-medium ΔP: medium	Removal: low-medium ΔP: low	Removal: low ΔP: low	Removal: low ΔP: low
BF with nutrient supply	198	Removal: high ΔP: low-medium	Removal: medium ΔP: low-medium	Removal: low-medium ΔP: low	Removal: low ΔP: low

Notes: BTF = biotrickling filter; BF = biofilter; ΔP = pressure drop.

after drying. The dried samples were then placed in a furnace at 800 °C for 4 hr, and the dry biomass content per volume of packing material was determined by measuring the weight loss. For protein analysis and microscopy observation, ~60 cm^3 of packing was mixed with 180 mL of double-concentrated mineral medium (i.e., twice the concentrations listed above) and shaken on a rotary shaker at 300 rpm for 10 min, and the suspension was used as is. Protein analysis was performed using the BCA Protein Assay kit from Pierce following the manufacturer's instructions. 5-Cyano-2,3,-ditolyl tetrazolium chloride (CLC)/4′,6-diamidino-2-phenylindole, dihydrochloride (DAPI) staining was performed using a procedure modified from Bhupathiraju et al.[14] and Rodriguez et al.[15] Staining was performed in 2-mL microcentrifuge tubes containing 0.4 mL of suspended sample as described above. CTC was added to achieve a final concentration of 5 mM from a stock solution (50 mM) prepared in deionized water. Samples (wrapped in aluminum foil to protect from light) were incubated for 4 hr in the dark at room temperature before counterstaining. All of the staining assays were performed in duplicate. Sodium azide-treated (3.2% final concentration, treated 15 min) cultures were used as killed controls. After CTC incubation, DAPI was added to a final concentration of 0.01%. Samples were first mixed for 3 min, then one drop of the samples was transferred to a clean microscope slide, and a coverslip was immediately laid on the slide. Fluorescence microscopy was performed with an Olympus BX51 microscope at ×400 magnification. Two different excitation and barrier filters were used to simultaneously observe CTC and DAPI fluorescence. A total of three fields per slide were counted. The ratio of active bacteria was determined by:

$$Ac = N_{act}/N_{tot} \times 100 \quad (1)$$

where Ac is the ratio of active bacteria (%); N_{act} is the number of active bacteria per field determined by CTC staining, and N_{tot} is the total number of bacteria per field determined by DAPI staining.

For denaturing gradient gel electrophoresis (DGGE), DNA from the cell suspension prepared as described above was extracted with a Bio101 kit (Bio-Rad). DNA concentration was determined with a spectrophotometer SmartSpec3000 (Bio-Rad) and kept frozen at −20 °C until used. The genomic DNA was PCR amplified using the primers PRBA338F and PRUN518,[16] which amplify the V3 region of the 16 S ribosomal DNA. The PCR amplification was performed with a PCR HotMasterMix (Eppendorf), to which 5 pmol of each primer, 250 ng DNA template, and sterile water were added for a total reaction volume of 25 μl. The DNA was amplified in a PTC-200 Peltier Thermal Cycler (MJ Research Inc.) with the following program: 95 °C for 2 min followed by 35 cycles of 92 °C for 1 min, 55 °C for 30 sec, and 72 °C for 1 min and a single final extension step consisting of 72 °C for 6 min. DGGE was performed with 8% (weight/volume) acrylamide gels in a perpendicular gradient from 20% to 70% denaturant (7 M urea plus 40% [volume/volume] formamide) and the gels were electrophoresed for 8 hr at 60 °C and 80V in a DCode universal mutation detection system (Bio-Rad). The gels

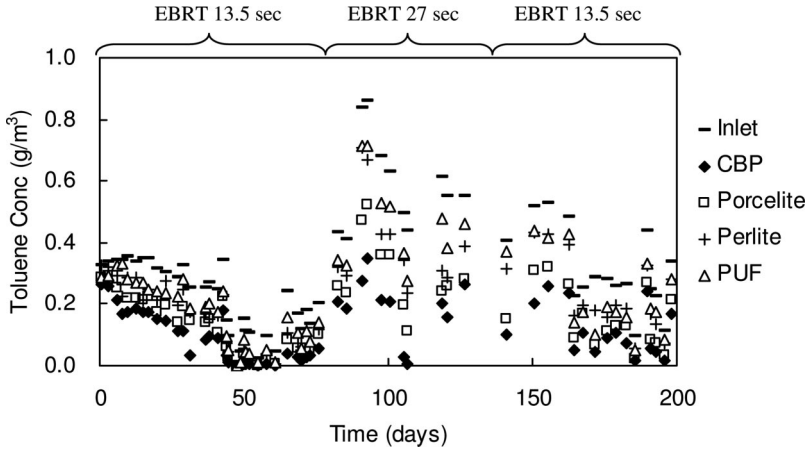

Figure 2. Toluene inlet and outlet concentrations during the operation as biofilter with periodic nutrient addition. Day 0 corresponds with the first day of operation of the reactors as biofilter with periodic nutrient addition. EBRT = empty bed gas residence time.

were stained with ethidium bromide and analyzed in a Quantity One photo documentation system (Bio-Rad).

RESULTS AND DISCUSSION

Operating Modes of Biotreatment: Biotrickling Filters

The four bioreactors were operated in parallel for a period of >8 months. During this time, three different modes of operation were investigated. These included operation of the reactors as biotrickling filters with continuous trickling and nutrient supply, as biofilters without nutrient supply, and as biofilters with periodic nutrient supply. Table 2 summarizes qualitatively the results in terms of toluene treatment performance and pressure drop. As described in Experimental Work, experiments started in the biotrickling filtration mode, with ample supply of nutrients and continuous trickling. This resulted in high toluene removal rates but also rapid accumulation of biomass, which ultimately led to excessive pressure drop and unstable operation. This was not expected, because the concentration of toluene was relatively low, which is known to be unfavorable for biomass growth.[17] On the other hand, CBP, Porcelite, and Perlite packings beds have a relatively low void volume and are more susceptible to plugging by biomass than random dump plastic packings. This suggests that packing designs with greater voids may be desirable. After excessive pressure drop was observed, the nutrient supply was halted for 21 days, and the systems were operated as biofilters without any nutrient supply. Water was added as needed to the reactors to prevent drying of the bed. This mode of operation significantly reduced the pressure drop (data not shown), but also resulted in lower pollutant removal because of nutrient starvation. Quasi-steady state with respect to biomass content and pressure drop and effective removal of toluene were achieved when nutrients were periodically supplied as described in Experimental Work. Results obtained during that phase are presented and discussed below.

AQ: A T2

Operation as Biofilters with Periodic Nutrient Supply

F2 F3

Toluene Degradation. In Figures 2 and 3, the results of continuous operation of the biofilters with periodic supply of nutrients are reported. Day zero corresponded with a shift from operation as a biofilter without any nutrient supply. The inlet concentrations ranged from 0.01 to 0.44 g m^{-3} at an empty bed residence time of 13.5 sec (days 0–90 and days 127–198) and inlet concentrations ranging from 0.44 to 0.86 g m^{-3} at an empty bed residence time of 27 sec (days 90–127). During the initial 40 days of operation, the inlet concentration of toluene slowly decreased from 0.35 to 0.25 g m^{-3} (see Figure 2), which resulted in increased removal efficiency for all of the packing materials (Figure 3). Throughout this phase, the highest removal was obtained for the reactor packed with CBP. Still, the removal was at most 65%, which would not be acceptable for practical application; hence, the inlet concentration was further decreased to 0.05–0.15 g m^{-3}. Monitoring of toluene removal at lower concentrations allowed for determining the critical load, which is defined as the maximum load at which 95% removal occurred. Plots of the toluene elimination capacity versus loading with empty bed residence time of 13.5 sec and 27 sec are shown in Figures 4 and 5, respectively, whereas maximum elimination capacities and critical loadings are summarized in Table 3. At an empty bed residence time of 13.5 sec, the critical load for CBP was 29 g m^{-3} hr^{-1} and that of Porcelite was 12 g m^{-3} hr^{-1}. The reactors packed with Perlite and PUF never reached a removal of 95% under these conditions. A comparison of the maximum elimination capacity of the reactor packed with CBP shows that it was about twice that of Perlite and PUF and ~20% higher than the maximum elimination capacity obtained with Porcelite. In addition, a critical load of 62 g m^{-3} hr^{-1} at gas retention time of 27 sec was obtained with the biofilter packed with CBP. The higher critical elimination capacity obtained at a longer residence time (i.e., at a

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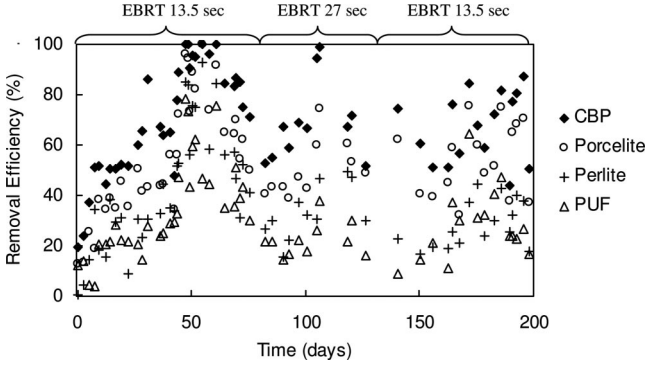

Figure 3. Toluene removal over time during operation as a biofilter. Day zero corresponds to the first day of operation of the reactors as biofilter with periodic nutrient addition.

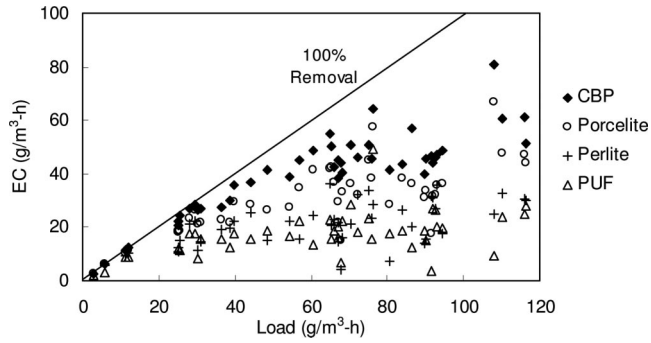

Figure 4. Elimination capacity vs. load during operation as a biofilter (gas retention time = 13.5 sec).

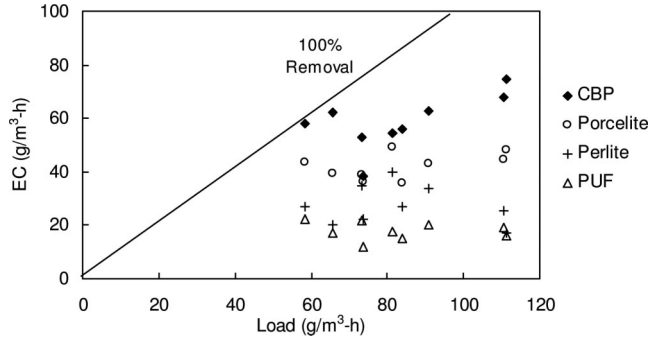

Figure 5. Elimination capacity vs. load during operation as a biofilter (gas retention time = 27 sec).

Table 3. Summary of EC_{max} and critical load (biofilter operation).

Variable	CBP		Porcelite		Perlite		PUF	
Retention time (sec)	**13.5**	**27**	**13.5**	**27**	**13.5**	**27**	**13.5**	**27**
EC_{max} (g m^{-3} hr^{-1})	81	75	67	49	36	40	30	22
Critical load (g m^{-3} hr^{-1})	29	66	12	N/A	N/A	N/A	N/A	N/A

Notes: EC_{max} = maximal elimination capacity; N/A = not applicable.

higher toluene concentration) indicates that a significant degree of kinetic limitation occurred in the biofilm. This trend is consistent with the slower degradation rates that result from essentially first-order biological kinetics, when the toluene concentration in the biofilm falls below the half-saturation rate constant. This had been discussed by Strauss et al.[18] for an extensive set of data on toluene removal at various concentrations and gas residence times. Overall, the toluene elimination capacities of the different biofilters ranked as follows: CBP ≫ Porcelite > Perlite > PUF. The PUF turned out to be poor packing when operated as described, most probably because of its low water holding capacity.

CO_2 Production. CO_2 production data are shown in Figure 6 and summarized in Table 4. In all of the cases, <100% of the degraded toluene was recovered as CO_2, indicating that some of the toluene was used for biomass growth and/or that toluene was only partially degraded, although no metabolites were ever detected. Others have found CO_2 recovery values ranging from 60% to 90%, with increasing values as the concentration of pollutant decreases.[1,17,19] This is because as pollutant concentration decreases, an increasing fraction of the pollutant is used to satisfy the maintenance requirements of the cell. The CO_2 recovery observed here (44–60%) is slightly lower than usually observed values, and no trend could be detected with the toluene concentration (Figure 6). However, the lowest mineralization was found for the reactor packed with CBP, which is consistent with the observation that this reactor had the largest amount of biomass buildup. Often, reactors with substantial growth perform better in terms of pollutant removal. However, it implies that more biomass will be formed over time and that it may result in plugging.

Pressure Drop. In Figure 7, the evolution of the pressure drop is reported over time. The pressure drop of CBP and

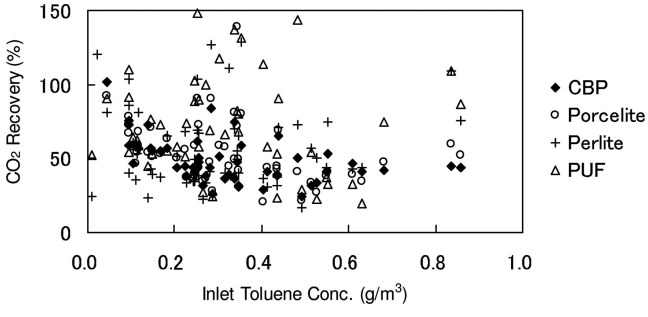

Figure 6. Recovery of the C-toluene degraded into C-CO_2 vs. inlet toluene concentration during operation as a biofilter.

Table 4. Average C-CO_2 recovery of the C-toluene degraded and standard deviation (day 0–198).

Variable	CBP	Porcelite	Perlite	PUF
CO_2 conversion (%)	55	58	61	82
Standard deviation	36	30	37	56

Porcelite beds was high (4–9 cm water column) during the first 20 days because of the initial higher biomass content. Hence, additions of mineral medium were reduced by half after 20 days. It was obvious that reducing nutrient supply had a direct effect on pressure drop, as other researchers have suggested.[2,5] Table 5 summarizes the average value of the pressure drop between days 30 and 170, that is, after the biomass content and pressured drop had decreased to reach quasi-steady state. The reactor packed with CBP had the highest pressure drop; it was also the reactor with the most biomass. However, with periodic mineral medium supply, all of the reactors were successfully operated for >5 months without excessive buildup of biomass.

Detailed Packing Analysis

The differences in toluene removal performance stimulated further analysis of the packing and of the attached microbial culture. The results are presented in Figures 8–11. All of the analyses were conducted at the end of the experiment (day 198). No data are reported for the PUF, because the performance of the reactor with this packing was too low.

In Figure 8, the dry biomass, protein, and moisture contents of the beds are reported. The moisture data show that the upper segments all had higher water contents, consistent with the fact that watering was applied at the top of the beds and that partial drying was occurring at the air inlet ports, that is, at the bottom of the reactor. CBP seems to have the highest water content. When dry biomass content was analyzed, the CBP clearly showed a two- to three-fold superior biomass content, compared with the other packings. Interestingly, biomass content of the top of the bed was higher than the bottom, which is opposite to what is usually seen by others. Most other authors have found that biomass concentration was the highest at the inlet port of the biofilter (here, the bottom

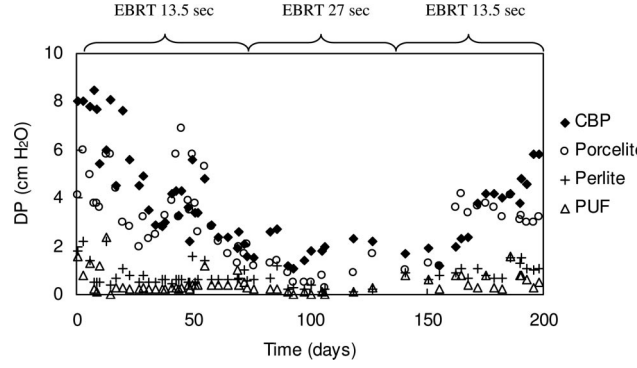

Figure 7. Pressure drop during operation as a biofilter.

Table 5. Average pressure drop (ΔP) across the bed as a function of gas residence time.

Variable	CBP	Porcelite	Perlite	PUF
Average ΔP (mm H_2O) at 13.5 sec gas residence time	41	33	9	5
Average ΔP (mm H_2O) at 27 sec gas residence time	17	8	2	1

section), where the highest concentration of pollutant exists. The dry biomass determinations were confirmed by protein analyses (Figure 8), which showed a much higher value for the CBP top segment and slightly higher values for the other two segments compared with regular Porcelite and perlite packings. The high values observed for the CBP packing could be the result of additional growth, stimulated or supported by the nutrients slowly released by the CBP. It is reasonable to speculate that the additional biomass amount in the CBP reactor contributed to or caused the higher performance by this reactor. As discussed earlier, the toluene removal of the biofilter packed with PUF was low. Extraction of biomass from that packing did not result in a sufficient amount for analysis. A possible reason for low biomass and poor performance in that reactor could be similar to the one advanced by Qi et al.[20] They found that poor VOC removal performance in biofilters packed with PUF was because of incomplete humidification of the influent air, which caused partial drying of the packing material and high salinity at the inlet port of the reactor. This effect, although minimized by the higher water holding capacity of the porous packings, could have influenced the axial distribution patterns in the other biofilters shown in Figure 8.

In Figure 9, typical images of DAPI- and CTC-stained biomass extracted from the biofilters are shown, whereas the results of the normalized counts of the total and alive bacteria are summarized in Figure 10. Detailed examination of the images of Figure 9 and the corresponding ones for Porcelite and Perlite-packed biofilters (data not shown) reveals subtle differences between the reactors and along the axial direction within the reactors. Some segments exhibit marked differences between DAPI- and CTC-stained images indicating that most bacteria were inactive, whereas other segments had virtually no difference between the DAPI- and CTC-stained images, indicating a high ratio of active cells. Quantitative image analysis (Figure 10) revealed that the CBP reactor had the highest counts and ratio of live cells, with up to 98% of the total count in the top section. This is remarkable, because the CBP top section was exposed to relatively low concentrations of toluene, because most of the toluene was treated before reaching that segment. It should be mentioned that the cell counts reported by CTC staining are not necessarily toluene-degrading cells but merely actively respiring cells. Whatever their role was, they probably contributed to the high metabolic activity in that segment of the CBP reactor.

Further examination of the bacterial cultures in the reactors was conducted using DGGE. The results of the DGGE gel (Figure 11) are not easy to interpret. Here, attention should be placed to: (1) the number of bands and (2) matching bands between the different lanes (i.e., bands that are at the same height). Examination of the gel reveals that the pattern of bands in the CBP reactor is significantly different than the patterns in the other reactors. In other words, some bands present in the CBP reactor are not present in the other reactors and vice versa. A plausible explanation is that the CBP biofilter developed a different consortium of microorganisms, which was able to degrade toluene faster than the populations in the other reactors. This is consistent with the observations of Li and Moe,[21] who found differences in DGGE band patterns along the axial direction and between reactors depending on their operating modes, as well as those of Khammar et al.,[22] who used single-strand conformation polymorphism analyses and found that different communities developed in two parallel biofilters. They further showed that the distribution of the biodegradation activity correlated with the local microbial density and diversity. Although most of the effects seen in the latter study are probably because of the fact that mixtures of VOCs were treated, the study nicely illustrates the link between the makeup of the culture and reactor performance. In the current case, because the only difference between the four reactor systems was the packing, one can reasonably conclude that the changes in the bacterial population were because of the nature of the packing.

Overall, the combined results of Figures 8–11 provide a relatively strong explanation as to why the biofilter

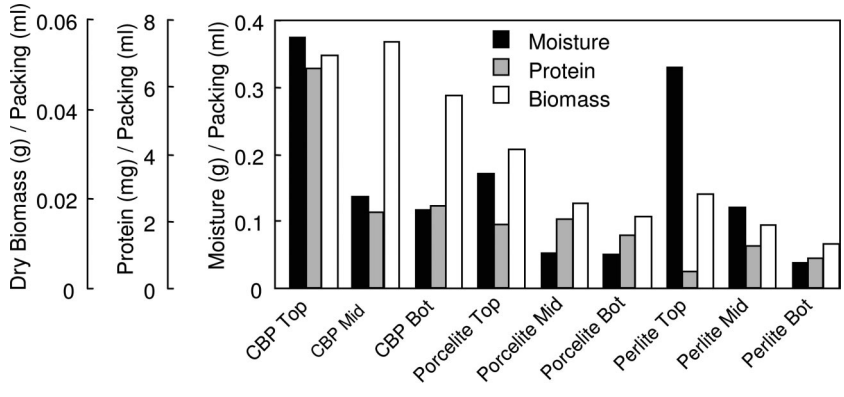

Figure 8. Volumetric moisture, protein, and dry biomass contents of the different sections of the three tested biofilters.

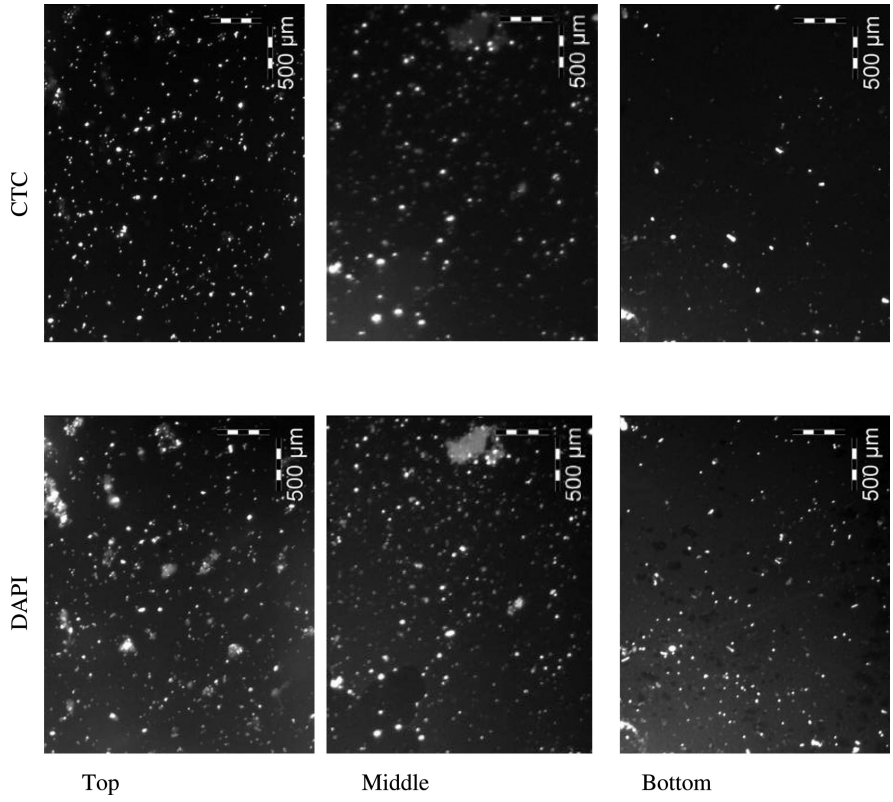

Figure 9. Pictures of DAPI (all bacteria) and CTC (live bacteria) stained suspensions of bacteria extracted from the various sections of the biofilter packed with CBP. The DAPI and CTC pictures show the same fields of view.

packed with CBP exhibited better performance. CBP was able to provide better environmental conditions for the process culture; hence, a higher cell density and a higher fraction of viable cells, as well as a different process culture makeup, were able to develop. Such development is consistent with the hypothesis that nutrients released by CBP would be able to be used by microorganisms and would then result in enhanced process performance.

The present study demonstrates that the packing plays an important role in biofilter performance. Packing factors expected to affect biofilter performance include the packing chemical composition, surface chemistry, micropore structure, macropore and mesopore structure and distribution.[1] In the case of CBP, Porcelite, and Perlite, the main ingredient is silica. CBP and Porcelite contain ~5–7 weight percent (wt %) of iron, whereas Perlite contains only 2–3 wt % of iron. Moreover, CBP contains ~20 wt % of calcium phosphate, which is purposely added in the making of the packing to serve as slow release nutrient and to allow a more vigorous culture to develop. Qualitative crush tests were conducted to compare the compression strength of CBP before and after the experiment. No obvious differences were observed, suggesting that the release of nutrients from the CBP did not markedly affect its mechanical strength. Another possible reason for the difference in biofilter performance is the absorption capacity of the packing material and surface properties. Hydroxyapatite, the main component of CBP, is well known for its absorption capacity of protein, water, and amino acids. This may be another factor leading to better

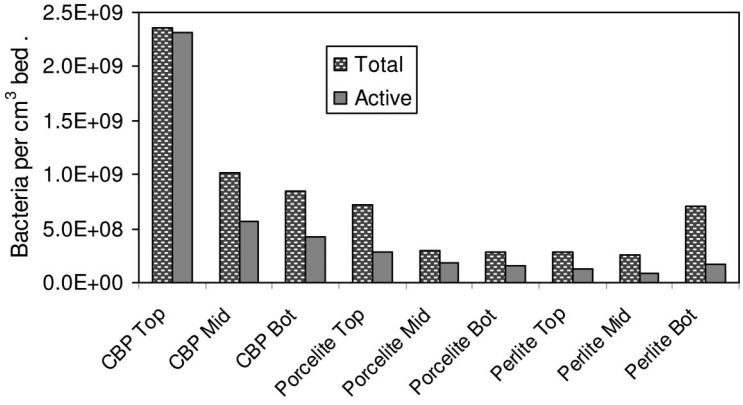

Figure 10. Summary of the total (DAPI) and active cell (CTC) counts of the bacteria in the different sections of the three test biofilters.

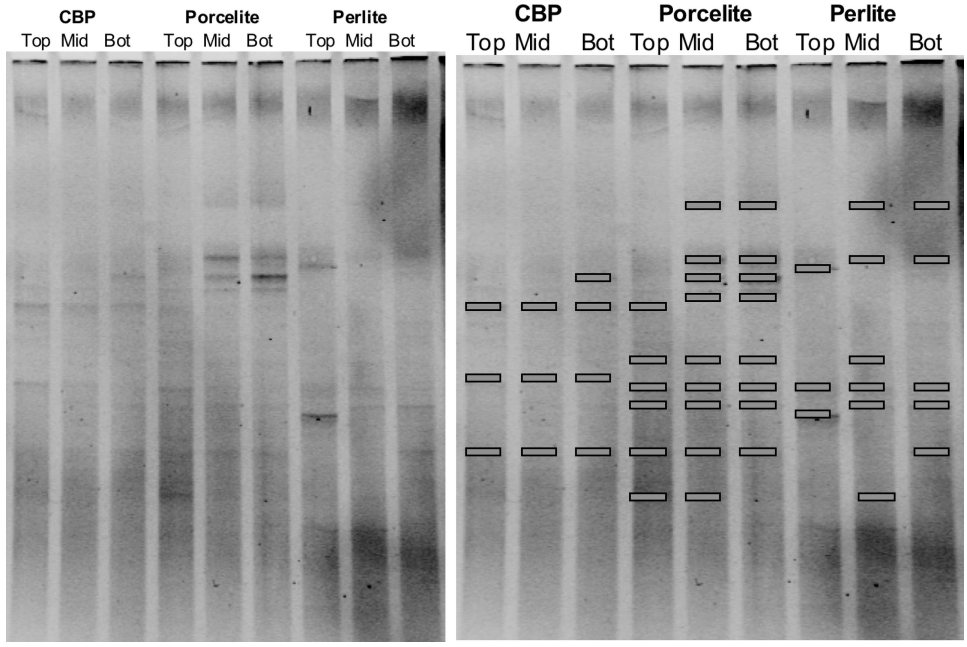

Figure 11. DGGE of the bacteria in the different sections of the CBP, Porcelite, and Perlite biofilters (left: gel; right: same gel with dominant bands highlighted).

growth conditions for the bacteria, because the packing material works as a reservoir of nutrients for the microorganisms.[5,19] Overall, the results suggest that CBP is a very suitable biofilter packing, because it has many of the advantages of organic biofilters packings without many of their disadvantages.

CONCLUSIONS

Overall, the results demonstrate that toluene vapors can be efficiently removed in biofilters at a gas retention time as low as 13.5 sec, if a proper packing material is used. In the current case, from the four packing materials that were tested, CBP exhibited the best toluene elimination performance. The critical load was 29 g m^{-3} hr^{-1} at a gas contact time of 13.5 sec and 66 g m^{-3} hr^{-1} at a gas contact time of 27 sec. The maximum elimination capacity was ~75–80 g m^{-3} hr^{-1}. These performances are high compared with the average elimination capacity reported in other biofiltration studies. Most reports range between 5 and 20 g m^{-3} hr^{-1} for the critical loading and between 10 and 40 g m^{-3} hr^{-1} for the maximum elimination capacity.[1,23] There are several reports of maximum elimination capacities in the range of 80–120 g m^{-3} hr^{-1}, although many of the studies reporting such elimination capacities were obtained at higher concentrations and longer gas contact time, which favors high elimination capacities. Also, these studies were often short term, which means that biomass plugging problems may have been overlooked. In the current case, with intermittent mineral medium supply, the biofilters packed with CBP maintained high toluene removal performance without increases of pressure drop for 5 months. The detailed analysis of the packing and of the attached culture at the completion of the experiment revealed marked differences between the reactors. These were consistent with the differences in treatment that were observed. Biofiltration performance was related to the total mass and total number of live bacteria in the systems. Such knowledge should enable better design of biofilter packings in the future.

ACKNOWLEDGMENTS

The financial support of Aisin Takaoka Co., Ltd., who funded this study, is greatly acknowledged.

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