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Performance of peat biofilter: impact of the empty bed residence time, temperature and toluene loading

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Abstract

The performance of a pilot-scale peat biofilter in the treatment of air contaminated with toluene has been evaluated in this study. The operational parameters investigated were the empty bed residence time (EBRT), temperature and toluene loading. The EBRT tests were performed at a constant toluene loading of 0.71 kg COD m^{-3} per day and a temperature of 11 °C. Removal efficiencies over 99% were achieved at an EBRT of 12 min. The removal efficiency exhibited a decreasing trend at lower EBRTs, with the efficiency dropping to as low as 75% at an EBRT of 2 min. The performance of the biofilter was found to be sensitive to temperature. For a toluene loading of 0.45 kg COD m^{-3} per day and an EBRT of 2 min, the removal efficiency was 99% at 32.2 °C. The removal efficiency data collected at different temperatures correlated reasonably well with a van't Hoff–Arrhenius-type equation. As the toluene loading was increased at the optimal operational temperature, the removal efficiency decreased to as low as 57% at a toluene loading of 1.57 kg COD m^{-3} per day. An adequate moisture content (55%–60%) and mineral nutrients for microbial activity in organic media were found to contribute significantly in the consistent long-term performance of the biofilter. Published by Elsevier Science B.V.

Keywords: Pilot-scale; Biofilter; Peat; Toluene; Removal efficiency; Temperature; Loading; EBRT

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1. Introduction

As a consequence of the 1990 US Clean Air Act Amendments, the control and removal of volatile organic compounds (VOCs) from contaminated air streams have become major air pollution concerns. Biofiltration is a promising air pollution control technology that consists of contacting the contaminated air with a moist film of microbes attached to stationary synthetic or natural support media. Biofilter systems harness the natural degrading abilities of microorganisms to oxidize organic contaminants biochemically into environmentally benign end-products such as carbon dioxide and water. The simplicity of the biofiltration process has resulted in its emergence as a practical, cost-effective technology for the treatment of large volumes of air contaminated with low concentrations of biologically degradable compounds, as compared with other traditional VOC control technologies, such as incineration and carbon adsorption [1]. The low operating cost results mainly from the utilization of microbial oxidation at ambient conditions instead of oxidation by thermal or chemical means.

Historically, biofilters were first designed as in-ground systems known as soil beds [2,3]. These systems were primarily used for odor control. Soil bed biofilters simply consist of a series of perforated pipes set below the soil, through which a waste gas is blown. The potential ability of soil beds to deodorize gases stems from the adsorptive capacity of the soil as well as from the presence of degrading organisms [4]. Bohn [3], Pomeroy [5] and Hartenstein [6] have provided reviews of soil bed technology for odor and VOC control. Prokop and Bohn [4] investigated the use of soil beds for removing H_2S and other odorous compounds from agricultural and wastewater treatment operations. Kampbell et al. [7] investigated the use of a soil bed for the treatment of volatile aliphatics in a pilot-scale system and were able to achieve 90% removal efficiencies. The major problems encountered in soil biofilters are excessive pressure drops, the large land area required to provide reasonable levels of performance and climatic variations such as temperature, flooding and drying.

These limitations for soil biofilters led to the testing of engineered biofilter systems for VOC control. These systems incorporated self-enclosed packed beds and packing materials that were more effective than soil. Engineered biofilter systems for VOC control primarily depend on the choice of the attachment medium. Ideal attachment media are characterized by high specific surface areas, minimal back pressures and a suitable surface for the attachment of microorganisms. Biofilter media are mainly of two types. The first type is a natural organic medium composed of peat, compost, leaves, wood bark and/or soil [2]. The second type is an inert synthetic medium. A combination of both types is sometimes used. In addition to the above medium types, activated-carbon packing media could be used for supporting biofilms and for providing a buffering treatment capacity [8]. The synthetic media biofilters are beyond the scope of this paper, so will not be discussed.

In organic medium beds, the medium itself is being microbially degraded at rates much higher than the VOC degradation rate [9]. Therefore, the VOC input has only a small effect on the microbial population. Because the VOC loading rates are usually less than the natural decay of the organic medium, the nutrient-supplying capacity of the medium is usually sufficient for the biological oxidation of VOCs. However, lime

Table 1
Some reported elimination capacities for organic media

Compound	Medium	Inlet gas concentration (ppmv)	Elimination capacity ($g\ m^{-3}\ h^{-1}$)	Reference
Toluene	Compost	300	20	[13]
Toluene	Soil	1200–2500	1.73	[16]
Toluene	Compost	50	11.6	[19]
H_2S	Peat	0.04–70.7	18	[20]
Methyl mercaptan	Compost	7–25	2.58	[21]
Acetone	Compost	500–800	40	[22]
H_2S	Compost	8–20	15	[17]
H_2S	Wood bark	10	18	[14,15]

additions may be necessary for buffering the medium against sudden drops in pH, as potentially caused by the release of acidic degradation intermediates or by-products [10]. Nevertheless, mineralization of the packing medium in organic beds has been shown to lead to compaction and pressure build-up [2]. The life span of organic packing material could be lengthened by adding inert lightweight solids such as polystyrene beads to the packing mix to reduce compaction [11].

The single most important operating parameter for these media is the bed moisture content. The optimum values range between 50% and 60% for peat beds. If the bed becomes dry, then the medium will repel water, because of its hydrophobicity [9,11]. Applications for these organic medium systems have been limited to the treatment of air streams that contain relatively low concentrations of VOCs [1,12–22]. Some reported elimination capacities are shown in Table 1.

The objective of this research was to evaluate the limitations of a peat mixture biofilter with respect to its performance for the removal of toluene from contaminated air. The main focus was to determine the optimal operating conditions. Toluene was chosen as the target contaminant, because of its presence in the concentration range of 20–200 ppmv in the effluent air from paint industries. The operational parameters evaluated in this study were the empty bed residence time (EBRT), temperature and toluene loading.

2. Materials and methods

2.1. Experimental apparatus

The biofilter is constructed from 304 stainless steel and contains 1.2 m of biological attachment medium (Clairtech Bioton® proprietary peat mixture). The biofilter has a circular cross-section with an internal diameter of 14.6 cm and consists of the following sections from top to bottom:

1. a heat exchanger for heating or cooling the water feed;
2. an inner heating or cooling coil (placed in the head space section) for controlling the inlet air temperature;

3. a head space of 40.6 cm for the air inlet and for housing the water spray nozzle;
4. four modules 30.5 cm that contain the biological attachment medium;
5. a disengagement module 10.2 cm for an air outlet.

To maintain a constant operating temperature, the biofilter is insulated and temperature controlled with external coils for heating or cooling.

The air supply to the biofilter is purified with the complete removal of water, oil, CO_2, VOCs and particulates. After purification and pressure letdown, the air flow to the biofilter is mass flow controlled. The air stream is then humidified, externally heated to assist in vaporizing the injected VOC into the air stream via a syringe pump, and finally fed to the biofilter. A schematic diagram of the experimental apparatus is shown in Fig. 1.

2.2. Materials

Reagent-grade toluene (99.9%, Fisher Scientific, Fair Lawn, NJ) was used as the sole VOC contaminant in this study.

A peat mixture of 50:50 peat:expanded styrofoam beads (Clairtech Bioton®, Matawan, NJ) was used as the biological attachment medium. For the first reported run in this study, the moisture content of the peat mixture supplied was measured to determine the additional water required to reach the optimum level of 55%–60%. The freeze-dried bacterial seed provided by the supplier was soaked in deionized water and mixed for 2 h. The volume of peat, which was equal to about 120% of the volume of the reactor, was

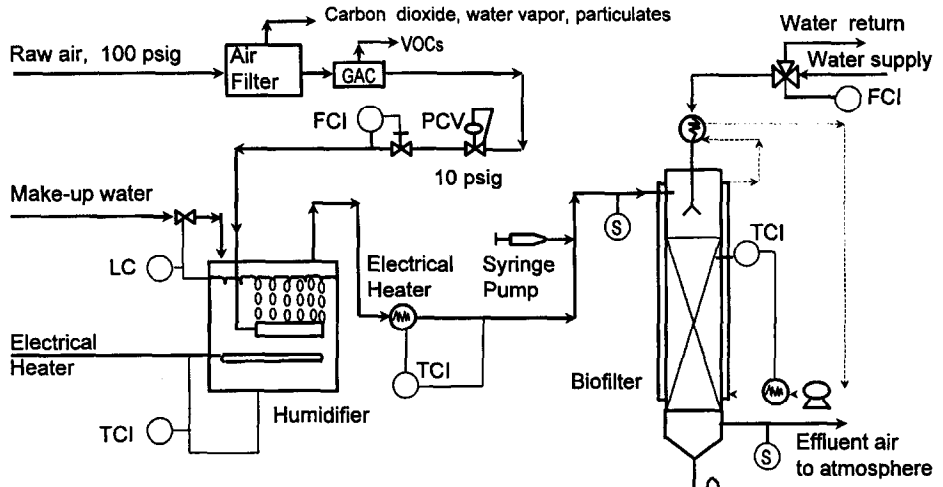

Fig. 1. Schematic diagram of the experimental set-up.

placed on a plastic sheet on the floor in an even layer about 7.5 cm thick. The seed bacteria was carefully distributed by hand over this layer of peat. The remaining water necessary to reach the optimum moisture content was then added to the peat, again carefully distributed by hand. The peat was then gently blended by hand to distribute the bacteria and water evenly throughout the peat. The medium was then slowly and gently poured into the reactor to avoid compaction. For the second run, the peat medium was received from the vendor ready for use, i.e. already mixed with the bacterial seed and containing the required optimum moisture level.

2.3. Analytical methods

The concentrations of toluene were measured using chromatographic separation with a 30 m megabore column (DB 624, J and W Scientific, Folsom, CA), using a gas chromatograph (HP 5890, Series II, Hewlett-Packard, Palo Alto, CA) equipped with a liquid sample concentrator (LSC 2000, Tekmar, Cincinnati, OH) and a photo-ionization detector (PID) (Model 4430, OI Corp., College Station, TX). The liquid sample concentrator was programmed according to US Environmental Protection Agency (EPA) method 601, and a Tenax trap was used with a helium (He) purge flow of 40 ml min^{-1}.

The gas chromatograph oven temperature was programmed from 40 to 120 °C in increments of 5 °C min^{-1} with a hold of 4 min at 40 °C and a hold of 6 min at 120 °C. The carrier gas (He) flow rate was set at 8 ml min^{-1} and the PID detector was used with He make-up gas at a flow rate of 20 ml min^{-1}, a sweep gas (H_2) flow rate of 100 ml min^{-1} and a base temperature of 250 °C. The detection limit of this procedure was 0.2 $\mu g\ l^{-1}$ (0.05 ppmv) toluene. Calibration curves for toluene were developed using prepared standard solutions of toluene in methanol.

Gas-phase samples for VOC analysis were taken using gas-tight syringes through low-bleed, high-puncture-tolerance silicone gas chromatograph septa (replaced every week) installed in the sampling ports in the biofilter gas inlet and outlet. The samples were introduced into the gas chromatograph through the liquid sample concentrator accessory. 5 ml of purged distilled deionized water was introduced into the purge vessel of the liquid sample concentrator prior to the injection of the gas sample.

Effluent gas-phase samples for carbon dioxide (CO_2) analysis were also taken using gas-tight syringes through effluent sampling ports in the biofilter. A gas chromatograph equipped with a thermal conductivity detector (TCD) was used for determining the CO_2 concentrations in the effluent gas phase. The gas chromatograph oven temperature was programmed from 50 to 80 °C in increments of 10 °C min^{-1} with a hold of 3.2 min at 50 °C and a hold of 1.5 min at 80 °C. The carrier gas (He) flow rate was set at 30 ml min^{-1} and the TCD detector was used with He make-up gas at a flow rate of 35 ml min^{-1}. The detection limit for this method was 50 $\mu g\ l^{-1}$ (28.2 ppmv) CO_2.

3. Results and discussion

Two experimental runs were carried out. The first run was conducted at a temperature of 11 ± 1 °C to simulate soil venting temperatures. In this run, the impact of the EBRT

(at a constant toluene loading) on the biofilter performance was studied. The second run was conducted to evaluate the impact of the temperature and toluene loading on the biofilter performance at an EBRT of 2 min.

3.1. Run no. 1

The biofilter was started up with 50 ppmv toluene (0.09 kg COD m^{-3} per day) at an EBRT of 12 min and maintained at a constant temperature of 11 ± 1 °C. By day 12, the removal efficiency was 99 + %. The mass flow rate of toluene was then increased steadily to achieve an inlet concentration of 500 ppmv (0.71 kg COD m^{-3} per day) at an EBRT of 12 min. The percentage removal of toluene reached 99% on day 39. The biofilter was then maintained at an EBRT of 12 min for 9 days to ensure stability of the effluent gas concentration. The biofilter performance during this period is shown in Fig. 2.

On day 48, a residence time test was begun, with the EBRT being varied from 12 to 2 min. This was carried out while holding constant the total mass of toluene fed per day. The biofilter was maintained at each EBRT for 5 days to ensure stability of the outlet gas concentration. At an EBRT of 8 min, the removal efficiency dropped to about 97%, and the performance further dropped to 88% at an EBRT of 4 min and to 75% at an EBRT of 2 min. Fig. 3 shows the biofilter performance during the residence time cycle test. Each data point represents the average of 10 samples collected during the period of

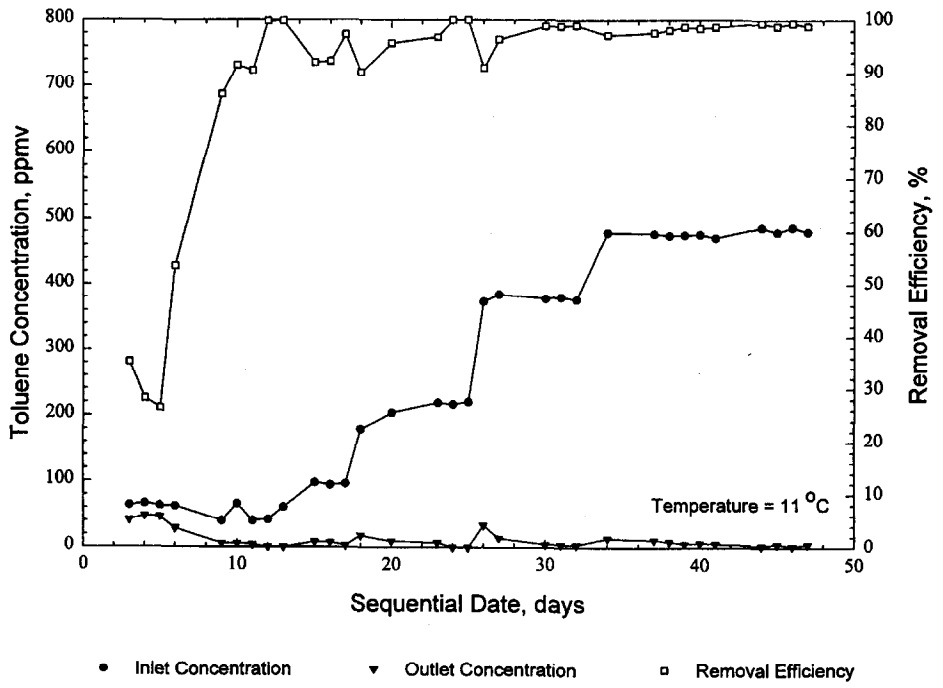

Fig. 2. Biofilter performance with respect to toluene removal at an EBRT of 12 min.

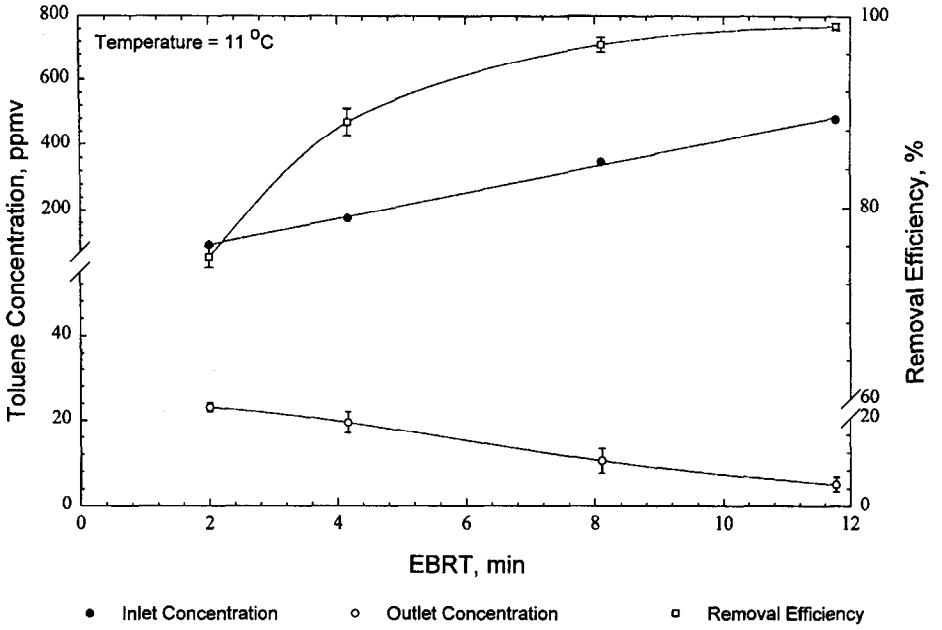

Fig. 3. Biofilter performance during residence time test at constant toluene loading of 0.71 kg COD m^{-3} per day (kg COD m^{-3} per day × 13.33 = g toluene m^{-3} h^{-1}).

5 days for each EBRT. The vertical error bar in Fig. 2 represents the standard deviation from the average value. The residence time cycle test required 20 days to complete and ended on day 68.

The biofilter was then maintained at an EBRT of 12 min to investigate whether the previously high performance, i.e. 99% removal efficiency, could be re-established. However, by day 80, the removal efficiency was fluctuating only between 90% and 94%. It was speculated that some short circuiting was occurring within the biofilter. On day 81, samples of peat at different depths were taken from side ports along the biofilter for moisture content analysis. It was found that the bed was very dry at the top, with moisture level below 45%, while the moisture level at the bottom of the bed was 50%. The biofilter contents were then removed and mixed and the moisture level of the peat adjusted to 55%. The biofilter was then repacked. It should be noted that the peat medium biofilter received no liquid nutrient supply; hence, its moisture level (as weight per cent of water in the peat) was dependent only on the incoming humid air.

Correction to the weight per cent of water was made by measuring the water deficit and adding the necessary amount through a spray nozzle. The moisture content of the peat medium was measured by the difference in weight between samples before and after drying at 103–105 °C. The correction of the moisture content was carried out twice per week at an equivalent rate of about 12 ml water per day. The biofilter performance improved to the removal efficiency level of 99% within 3 days. However, continuous operation led to erratic performance, with removal efficiencies dropping to as low as 50%. On day 110, it was noticed that the biofilter started to drip substantial amounts of

water in the effluent. This was an indication that some of the added water was being repelled by the bed. Inconsistency in the peat moisture content with depth within the biofilter was observed, which eventually led to channelling of the air and erratic performance. The biofilter performance for this period is shown in Fig. 4.

For the above work, humidification of the air was accomplished by passing the air cocurrently with deionized water through a temperature-controlled packed column (Intalox saddles). However, this procedure was found to be inadequate for providing a relative humidity of 100% at high air flow rates. The maximum relative humidity of the air achieved for an EBRT of 2 min in the biofilter was only 65%. Therefore, it was found necessary to modify the humidification system for the second batch of peat. The humidification system was changed by using a frit in a temperature-controlled water bath, as indicated in Fig. 1. This procedure ensured consistent 100% humidification of the inlet air at low EBRTs. A fresh batch of the Bioton peat mixture was then loaded into this reactor for the commencement of the next run.

3.2. Run no. 2

The biofilter was started with an EBRT of 2 min and with 50 ppmv toluene (0.45 kg COD m^{-3} per day). The biofilter was not insulated until day 3. It was the summer season during this time and the biofilter operated at about 32.2 °C. The removal

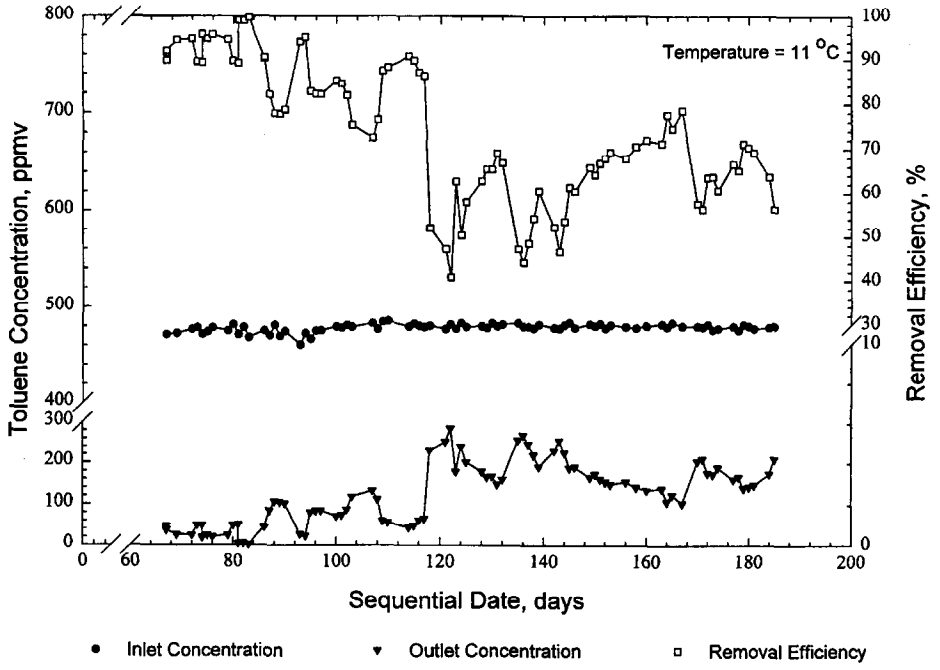

Fig. 4. Biofilter performance with respect to toluene removal at an EBRT of 12 min after the residence time test.

efficiency during this short period was about 97%. On day 3, the insulation was installed and the temperature was maintained at about 15.6 °C, with the efficiency staying roughly in the range 63%–67% until day 6. On day 6, the inlet cooling coil, which permitted the biofilter to achieve the desired start-up temperature of 11.1 °C, was installed. By day 17, the efficiency had stabilized at about 58%.

As a result of the unexpectedly high initial toluene removal rate at 32.2 °C, it was decided to investigate the effect of the temperature on the removal efficiency. The temperature was increased to 15.6 °C and maintained at this level until day 41. Initially, the efficiency increased to about 77%, then decreased after day 24 to about 66%–69%, and stabilized at 63% after day 32. On day 41, the temperature was increased to 21.1 °C, resulting in a gradual increase in efficiency to about 75% by day 47. On day 53, the temperature was increased to about 26.7 °C and the efficiency increased to about 83%–87%. On day 61, the temperature was increased to 32.2 °C and the efficiency increased to about 96%.

The impact of the temperature on the biofilter performance is shown in a semi-logarithmic plot in Fig. 5. Each data point represents the average of at least 10 samples collected during the stable period of the biofilter at the relevant temperature. The vertical error bar represents the standard deviation from the average value. The experimental removal efficiency data obtained at different temperatures were then correlated with a van't Hoff–Arrhenius-type equation, using non-linear regression analysis. We have

$$E = A_0 \exp(-A_1/T) \quad (1)$$

where E is the percentage removal efficiency, T is the temperature (in kelvin), and A_0

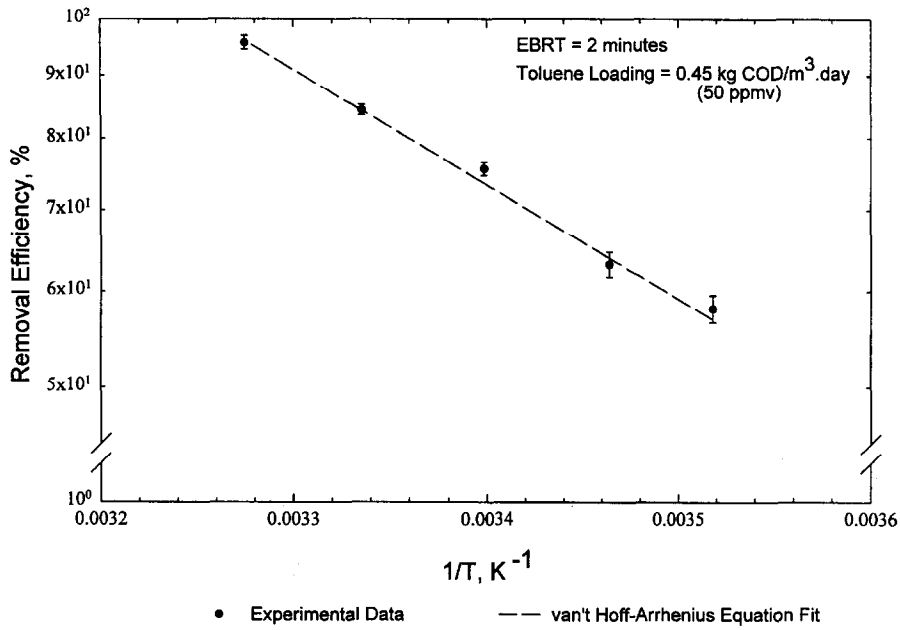

Fig. 5. Effect of temperature on biofilter performance.

and A_1 are the correlation parameters. The values of the correlating parameters A_0 and A_1 together with standard asymptotic errors are $1.221 \times 10^5 \pm 50.6$ and 2157.0 ± 7.7 respectively. The correlating model equation is represented by a broken line in Fig. 5. It can be seen that the equation correlates the experimental data reasonably well.

The next task of the study was to investigate the impact of the toluene loading on the biofilter performance at an EBRT of 2 min. On day 77, the toluene inlet concentration was increased to 70 ppmv (0.63 kg COD m^{-3} per day) and, by day 79, the efficiency stabilized at 95%. On day 80, the inlet toluene concentration was increased to 95 ppmv (0.83 kg COD m^{-3} per day) and the removal efficiency began to decrease, stabilizing at 88% by day 108. On day 109, the concentration was increased to 110 ppmv (0.96 kg COD m^{-3} per day) and, by day 115, the removal efficiency stabilized at 83%. Further increases in the toluene concentration continued to produce lower removal efficiencies. For a toluene concentration of 125 ppmv (1.1 kg COD m^{-3} per day), the removal efficiency stabilized at 76% after 10 days; for a concentration of 150 ppmv (1.32 kg COD m^{-3} per day), it stabilized at 72% after 10 days; and, for a concentration of 175 ppmv (1.57 kg COD m^{-3} per day), it was initially stable at about 60% but later dropped to 57%. The operation of the biofilter at a toluene loading of 1.57 kg COD m^{-3} per day was carried out for a period of 18 days. A summary of the effect of the toluene loading on the biofilter performance is shown in Fig. 6.

The toluene concentration was then lowered to determine if the previous removal efficiencies could be attained. On day 153, the concentration was decreased to 150 ppmv and the performance continued to show low removal efficiencies. From this study, it was deduced that a nutrient deficiency had developed in the medium. A concentrated nutrient solution that contained the essential macro- and micro-nutrients [23] was sprayed

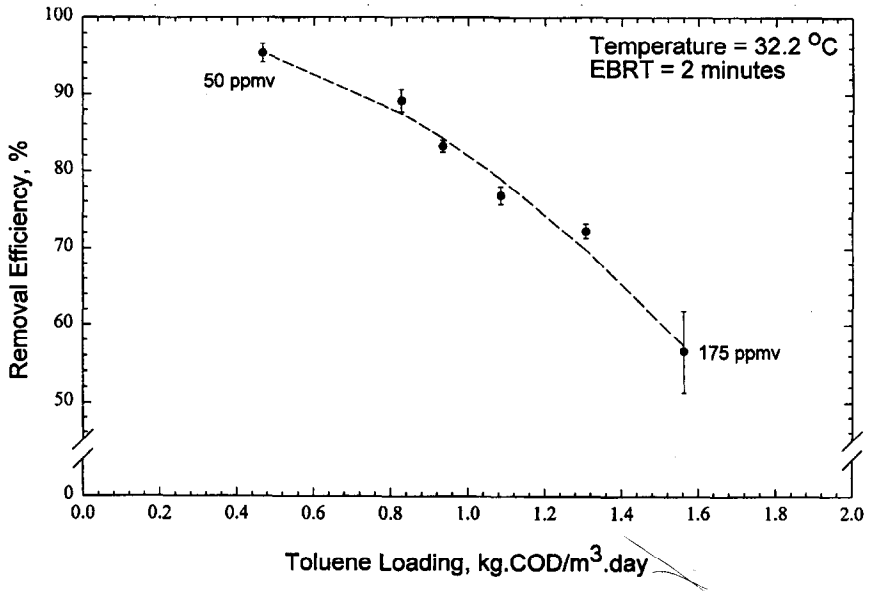

Fig. 6. Effect of toluene loading on biofilter performance.

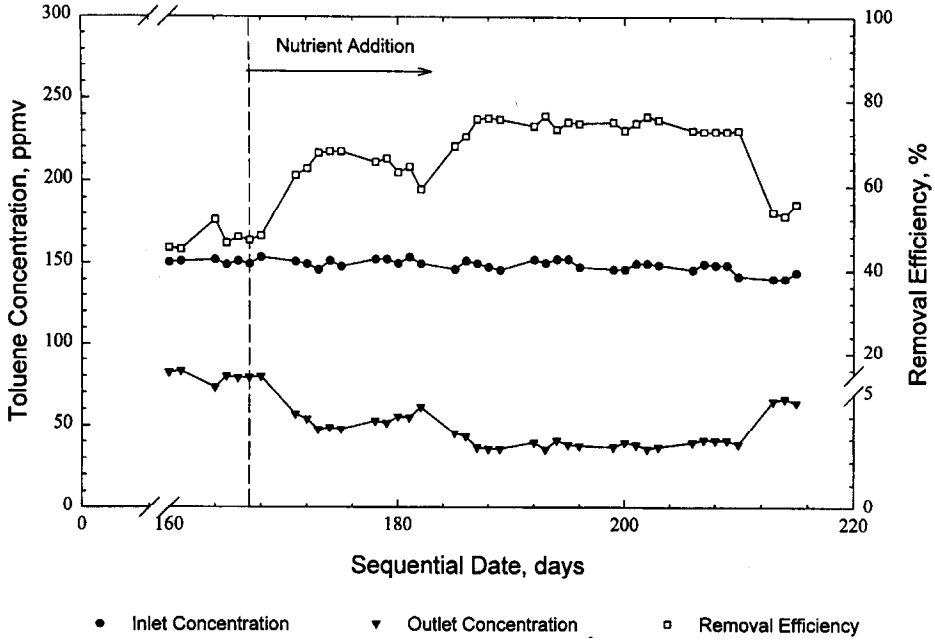

Fig. 7. Biofilter performance with respect to toluene removal at an EBRT of 2 min after nutrient addition.

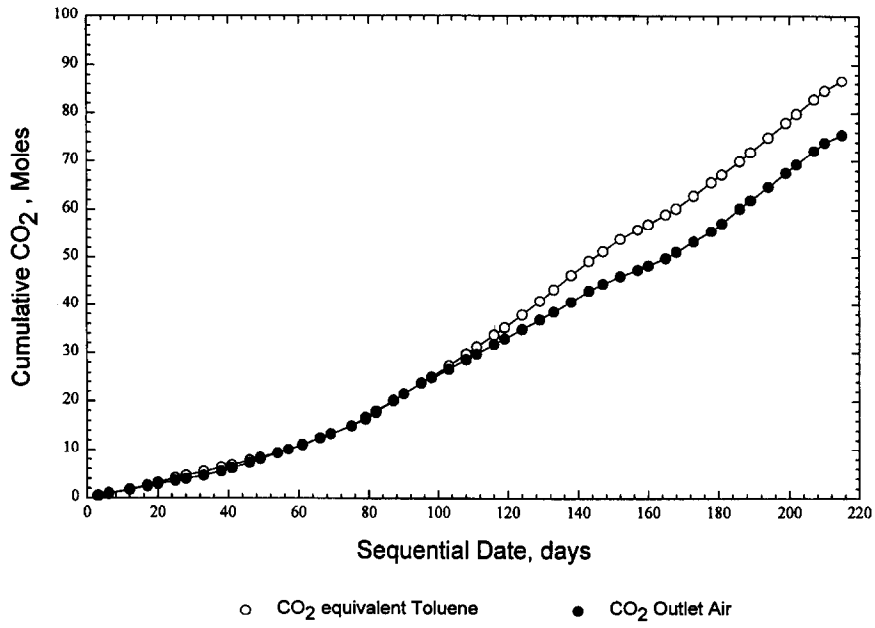

Fig. 8. Development of biofilter with time (CO_2 closure).

periodically over the medium at a rate of 25 ml h^{-1}. The nutrient addition was started on day 167.

Fig. 7 shows the response of the biofilter after the addition of nutrients (see Table 2). Initially, the performance improved, increasing from about 49% to 67% by day 177, but it then dropped to about 59% by day 182. At this point, it increased sharply, reaching about 75% by day 187. The performance was nearly stable until day 209, when it suddenly dropped to below 60%. On day 215, the operation of this biofilter was terminated and the medium was dumped. At this time, it was noted that the medium was very wet, with a moisture content of about 70%. This run demonstrated that the addition of nutrients to the peat medium could produce improvements in the performance for a short period of time. The deterioration in performance observed later resulted mainly from exceeding the allowable moisture content of the medium (55%–60%).

A comparison between a plot of the cumulative CO_2 equivalent toluene and a plot of the cumulative CO_2 produced within the biofilter is shown in Fig. 8. The CO_2 equivalent toluene is the amount of CO_2 evolved from complete oxidation of the toluene, and is estimated from the amount of toluene consumed by the biofilter. The cumulative CO_2 produced was based on the CO_2 measured in the outlet gas from the biofilter, because the inlet air was essentially free of CO_2 (the CO_2 in the inlet air was

Table 2
Nutrient feed concentrations of salts and vitamins

Component	Concentration (mg l^{-1})
Na^+	684
Ca^{2+}	8.94
K^+	57.7
Mg^{2+}	14.37
Mn^{2+}	0.64
Mo^{6+}	0.553
NH_4^+	1714
Zn^{2+}	0.77
B^{3+}	0.06
Co^{2+}	0.35
Cu^{2+}	0.37
Cl^-	3448
SO_4^{2-}	142
PO_4^{3-}	1016
CO_3^{2-}	1142
p-Aminobenzoic acid	0.037
Biotin	0.013
Cyanocobalamin (B_{12})	0.0007
Folic acid	0.013
Nicotinic acid	0.037
Panothenic acid	0.037
Pyriodoxine hydrochloride	0.0767
Riboflavin	0.0367
Thiamin hydrochloride	0.0367
Thioctic acid	0.0367

removed by the purification system). From Fig. 8, it can be seen that closure was obtained for the CO_2 analyses up to day 120. After day 120, deviations between the two plots started to appear, giving a maximum deviation of 12%. It is speculated that the later deviations encountered between the two CO_2 balances could be the result of accumulation of biomass that led to nutrient deficiency. This might have affected the microbial activity, which is reflected by the CO_2 balance in the outlet air.

4. Conclusions

A pilot-scale biofilter with a peat mixture as the microbial attachment medium was evaluated in this study for the treatment of air contaminated with toluene. The main focus was to determine the best operating conditions for high removal efficiencies. The parameters considered were the EBRT, temperature and toluene loading.

The residence time tests were performed at a constant toluene loading of 0.71 kg COD m^{-3} per day and a temperature of 11 °C. The EBRT was varied between 12 and 2 min. For an EBRT of down to 8 min, the removal efficiency was over 97%. With an EBRT of 2 min, the removal efficiency was as low as 75%. Maintaining the biofilter after the residence time test at an EBRT of 12 min led to erratic performance, as a result of inconsistency of the moisture content through the depth of the biofilter. This operational problem was overcome by using a temperature-controlled humidification system to achieve a relative humidity of the incoming air near 100%.

The biofilter performance was found to be highly dependent on the operational temperature. For a toluene loading of 0.45 kg COD m^{-3} per day at an EBRT of 2 min, the removal efficiency was 99% at 32.2 °C; in contrast, at a temperature of 11.1 °C, the removal efficiency was as low as 58%. The experimental data collected at different temperatures were correlated reasonably well by a van't Hoff–Arrhenius-type equation.

Investigations on the impact of the toluene loading on the performance of the biofilter showed that, up to a toluene loading of 0.63 kg COD m^{-3} per day at an EBRT of 2 min and a temperature of 32.2 °C, the removal efficiency was over 95%. Increases in the toluene loading led to lower removal efficiencies and later nutrient deficiencies within the biofilter. The addition of liquid nutrient to the biofilter improved its performance. However, deterioration in the biofilter performance was observed later, as a result of exceeding the allowable moisture content of the medium.

Implicit limitations of the experimental apparatus used in this study may have resulted in the observed reduced performance. Specifically, the peat suppliers had recommended using a width-to-depth ratio of 1:1 rather than 1:8. They also stated that, from their experience, the only effective means of determining the bed moisture content was to weigh the entire biofilter. This was impossible with the heavy stainless steel reactor used in this study. The several moisture measurement and control strategies attempted were not adequate to ensure that the bed moisture content could be consistently controlled to within the reported optimum range, i.e. between 50% and 60%. Therefore, it was concluded that the sometimes erratic performance was probably induced by variations in the bed moisture content.

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