

**ODOR AND VOC REMOVAL FROM WASTEWATER TREATMENT PLANT
HEADWORKS VENTILATION AIR USING A BIOFILTER**

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ABSTRACT

Laboratory scale experiments and field studies were performed to evaluate the feasibility of biofilters for sequential removal of H₂S and VOCs from wastewater treatment plant waste air. The biofilter was designed for spatially separated removal of pollutants in order to mitigate effects of acid production resulting from H₂S oxidation. The inlet section of the upflow units was designated for H₂S removal and the second section was designated for VOC removal. Complete removal of H₂S and methyl *tert*-butylether (MTBE) was accomplished at loading rates of 8.3 g H₂S/m³·h (15 second EBRT) and 33 g MTBE/m³·h (60 second EBRT) respectively. In field studies performed at the City of Los Angeles' Hyperion Treatment Plant, excellent removal of H₂S, moderate removal of non-chlorinated VOCs such as toluene and benzene, and poor removal of chlorinated VOCs were observed in treating the headworks waste air. During spiking experiments on the headworks waste air, the percentage removals were similar to the unspiked removals when non-chlorinated VOCs were spiked, but feeding high concentrations of chlorinated VOCs reduced the removal percentages for all VOCs. Thus, biofilters offer a distinctive advantage over chemical scrubbers currently employed at publicly owned treatment works in that they not only remove odor and H₂S efficiently at low cost, but also reduce overall toxicity by partially removing VOCs and avoid the use of hazardous chemicals.

KEYWORDS

Waste air treatment, POTWs, headworks, biofilter, odor, H₂S, VOCs, MTBE

INTRODUCTION

Publicly owned treatment works (POTWs) are required by federal and local air quality regulations to quantify and control volatile organic compounds (VOCs) and toxic air pollutants emitted from wastewater and solids handling processes. In Southern California, the 1990 New Source Review regulations for air toxics requires establishment of Maximum Achievable Control Technology (MACT) standards for POTWs as outlined in the Federal Clean Air Amendments of 1990. Furthermore, POTWs in Southern California are required to meet facility-based standards for existing sources as imposed by proposed regulations from the South Coast Air Quality Management District (SC-AQMD).

Contaminated air at POTWs contains two major groups of pollutants: reduced sulfur species and a variety of volatile organic compound (VOC) species. Hydrogen sulfide (H₂S), the predominant reduced sulfur compound, is the principal cause of odor nuisance, and is usually present at concentrations up to 300 ppm_v (Iranpour *et al.*, 2001). VOCs commonly encountered include both non-halogenated (e.g., benzene, toluene) and halogenated (e.g., dichlorobenzene, methylene chloride) compounds (Iranpour *et al.*, 2001). Total VOC concentrations in POTW exhaust air is usually below 10 ppm_v. Odor control at POTWs

generally involves the use of chemical scrubbers. However, they are relatively expensive to operate because of their high rates of chemical consumption. Additionally, chemical scrubbers are ineffective for the removal of VOCs.

In Europe, biological treatment in biofilters has rapidly been gaining ground as a relatively simple, economical and efficient technology for emission reductions at POTWs (Devinsky *et al.*, 1998; Kennes and Veiga, 2001). A similar trend is now observed in the USA. Biological treatment involves the use of microorganisms that convert air pollutants into harmless end-products. Treatment costs are relatively low compared to those of alternatives such as incineration, chemical scrubbing and absorption, since the process is performed at ambient temperature and pressure with minimum or no chemical consumption. Traditionally, biological waste air treatment at POTWs has been focussed on odor abatement. Many studies discuss H₂S removal by biofiltration as effective and efficient (Iranpour *et al.*, 2001). However, less information is available regarding the simultaneous removal of odorous sulfur species and VOCs (Converse *et al.*, 2001; Cox *et al.*, 2001; Ergas *et al.*, 1992; Webster *et al.*, 1996; Wolstenholme and Finger, 1994; Schroeder *et al.*, 2000).

The objective of the present research was to determine the feasibility of biofilters in treating POTW waste air containing a mixture of odorous sulfur species and toxic VOCs. Because sulfuric acid production from H₂S oxidation potentially interferes with VOC biodegradation, the biofilter in the present study was designed for spatially separated sections for the removal of H₂S and VOCs. This principle was first demonstrated and investigated in a laboratory scale biofilter receiving an air stream with H₂S and methyl *tert*-butyl ether (MTBE) as model pollutants. In a second phase, pilot scale experiments were conducted at the Hyperion Treatment Plant (HTP) in Los Angeles, California, and biofilter performance in treating waste air from the headworks was evaluated.

MATERIALS AND METHODS

Lab-Scale Experiments

Simultaneous removal of H₂S and MTBE was investigated in a laboratory scale biofilter, as shown in Figure 1. The biofilter was designed with a first section for H₂S removal, followed by four sections for MTBE removal. Based on previous experiments (Ergas *et al.*, 1994), H₂S removal rates were expected to be sufficiently high for complete removal in the first section without penetration of H₂S into sections 2 to 5, which would then be dedicated to MTBE removal. The unit was constructed of plexiglass in five, 15-cm I.D. sections. Each section was 30 cm in length and packed with 25 cm of a compost, perlite and oyster shell mixture in a 2:2:1 volume ratio, respectively. A 5-cm plenum separated the sections. Nutrients were supplied as an aerosol into the air stream entering the biofilter. The nutrient composition and concentrations are listed in Table 1. The aerosol also provided water to the biofilter preventing the unit from drying. MTBE was injected into a portion of the main air stream using a syringe pump. H₂S was added to the air stream by passing the air through an H₂S generation bottle containing an HCl solution into which a Na₂S solution (variable concentration) was continuously fed at predetermined rates to obtain the desired H₂S gas phase concentrations. This system was used rather than H₂S supply from a cylinder with the saturated gas in order to prevent hazardous concentrations in case of leaks.

The H₂S removal section of the biofilter was seeded with recycle liquid obtained from a working H₂S removing biotrickling filter, operated at the Joint Water Pollution Control Plant of the Los Angeles County Sanitation Districts. The MTBE removal sections were seeded with a MTBE degrading culture maintained by the University of California.

The H₂S and MTBE removal sections were initially operated as separate, independent units receiving either H₂S or MTBE as single pollutants for periods of 124 and 236 days, respectively. Separate start-up was done to study the removal of H₂S and MTBE as single pollutants without potential cross inhibition by the presence of the other pollutant. Day 0 of the experiment run was the day the MTBE removal sections were seeded and started. Using the same time scale, the H₂S section was seeded and started on day 112, and all sections were combined on day 236 to investigate simultaneous treatment of a mixture of MTBE and H₂S. The gas flow rate was measured in the combined air stream prior to entering the biofilter unit. MTBE removal performance was determined at empty bed gas retention times (EBRTs) of 15-60 seconds and inlet concentrations ranging between 20-180 ppm_v (73-660 mg/m³). The H₂S section was operated at an EBRT of 15 seconds and H₂S inlet concentrations of up to 70 ppm_v (99 mg/m³).

Simultaneous treatment of H₂S and MTBE by the combined biofilter sections, as indicated in Figure 1, was investigated over days 236-260.

Pilot-Scale Experiments

HTP is the main wastewater treatment facility in Los Angeles, covering a service area of 600 square miles, inhabited by approximately 3.8 million people. The flow to HTP averages around 360 mgd, all of which receives primary and secondary treatment, the secondary being a high-purity oxygen activated sludge system. Experiments with the pilot biofilter were performed at the headworks building of HTP, where currently 170,000 m³/h of ventilation air is being treated in chemical scrubbers that use sodium hydroxide and hypochlorite.

The pilot biofilter (diameter 0.61 m; height 1.8 m) was constructed based on the results obtained from laboratory scale experiments (Figure 2). The first section (bottom) was 0.25 m deep and designated for removal of H₂S. The second section (top), for VOC removal, was 0.75 m deep. Both sections contained a mixture of compost, perlite and crushed oyster shells as the packing material similar to the packing in the laboratory scale biofilter previously described. Seeding of the packing was with the recycle liquid of a H₂S degrading biotrickling filter. The two sections were separated by a plenum and each section had an independent, timer-controlled system for supply of secondary effluent water through permeable soaker hoses on top of each section. Secondary effluent was supplied once a day for a period of about 10 min to provide moisture and nutrients at an approximate rate of 2 L/min to each of the H₂S and VOC removal sections. Excess water was drained from the biofilter through an outlet port located at the bottom of the first section.

The available pressure in the headworks ventilation air discharge line was sufficient to provide a slip-stream of initially on average 42.5 m³/h to the bottom of the biofilter (up-flow configuration), out of a total of 170,000 m³/h generated by the headworks facility. A gas flow rate of 42.5 m³/h corresponds to an overall EBRT in the biofilter of 25 sec. Actual gas flow rates to the biofilter over the course of the experiments were measured with an anemometer positioned in the inlet air stream of the biofilter. Over ten months of operation of the biofilter, increasing pressure drops over the biofilter caused a reduction of the gas flow rate and a gradual increase of the average EBRT to 52 sec (20.4 m³/h). The waste air to the biofilter contained between 10 to 50 ppm_v H₂S as the principal odor-causing agent, as well as a broad variety of chlorinated and non-chlorinated VOCs in concentrations ranging from 0 to 150 ppb_v. Performance of the biofilter was determined over ten months of operation with frequent analysis of the inlet and outlet air for VOCs and H₂S. On selected days, the frequency of sampling for H₂S and VOCs was increased to once every few hours to determine the short-term performance. In addition to routine operations with unmodified gas from the headworks, several brief test were made regarding biofilter performance on gas spiked with higher concentrations of various pollutants. One test used toluene, one used gasoline, which provided a mixture of benzene, toluene, and xylenes, and one used a combination of gasoline, dichloro methane and trichloro ethylene.

Analytical methods

Gas phase MTBE concentrations in laboratory scale experiments were determined by analysis in a Shimadzu 14A gas chromatograph, equipped with a 0.5 ml gas sampling loop, a 30 m long (0.53 mm ID) J & W Scientific DB-624 megabore column, and a flame ionization detector. H₂S concentrations in laboratory and pilot scale experiments were directly determined in inlet and outlet air streams by using a Jerome 631-X hydrogen sulfide analyzer (Arizona Instruments, Tempe, AZ). VOC removal in the pilot biofilter was determined on a semi-weekly basis by sampling the inlet and outlet air in 10 L Tedlar bags for about 4 minutes. Samples were analyzed usually within 24 h according to EPA method TO-14 using a GC equipped with photoionization and electrolyte conductivity detectors. Concentrations of organic reduced sulfur compounds were determined by Performance Analytical Inc. (Simi Valley, CA) after 253 days of operation of the pilot biofilter. Analyses were done in triplicate using a GC with a chemiluminescence detector. Grab samples were taken the same day and analyzed by an eight-member panel (Odor Science & Engineering, Bloomfield, CT) for odor dilution-to-threshold ratio (D/T) and odor intensity. Gas flow rates to the biofilter were regularly determined with an Omega anemometer model HHH300A (Stamford, CT).

RESULTS

Lab-Scale Experiments

Removal of MTBE as sole pollutant: MTBE removal was poor during the first two months of operation, presumably due to a nutrient limitation. Additional nitrogen supply and reseeded of the biofilter after two months increased the performance, until an elimination capacity of $8.2 \text{ g/m}^3 \cdot \text{h}$ was observed after 108 days of operation. Subsequent experiments focused on variation of the gas flow rate and MTBE inlet concentration to determine the maximum performance.

Biofilter performance from day 160 to day 260 is shown in Figure 3. During this period the EBRT was maintained at 60 seconds and the MTBE inlet concentration was varied between 20 and 180 ppm_v in order to determine the elimination capacity. MTBE removal was complete under most conditions and breakthrough of MTBE was only observed between days 206 and 210 when the MTBE inlet concentration was increased to 180 ppm_v. Figure 4 shows the mass of MTBE removed in the various 0.25 meter sections of the biofilter during steady state operation as a function of the sectional MTBE mass loading. The EBRT in each section was 15 s. MTBE removal was complete up to a loading rate of $12.5 \text{ g/m}^3 \cdot \text{h}$. Higher loading rates resulted in higher elimination capacities, but only at reduced removal efficiency. A maximum elimination capacity of $62.5 \text{ g/m}^3 \cdot \text{h}$ was observed at a loading rate of $167 \text{ g/m}^3 \cdot \text{h}$, corresponding to 37.5% removal.

Removal of H₂S as sole pollutant: The H₂S removal section was operated for about 4 months as a separate unit before this section was plumbed to precede the MTBE removal sections. The H₂S removal performance at an EBRT of 15 s is shown in Figure 5 (day 112-236). The inlet H₂S concentration was initially 9 ppm_v and was increased to 25 ppm_v, which is in most cases the approximate concentration expected in POTW waste. Nine days after start-up, removal of H₂S was complete with no detectable H₂S in the outlet air (< 1 ppb_v). H₂S removal was consistently greater than 99% over 4 months of operation. In addition, complete removal of H₂S spikes up to a concentration of 70 ppm_v (not shown) indicates that higher H₂S loads can be effectively treated at a residence time of 15 s.

Removal of a mixture of H₂S and MTBE: On day 236, the MTBE and H₂S sections were plumbed together. Examination of Figure 5 (days 236-260) reveals that the presence of 70 ppm_v MTBE had no effect on H₂S removal in the first section. Similarly, there was little or no impact to MTBE removal when the H₂S removal unit was placed in line with MTBE removal sections (days 236-260 in Figure 3). MTBE concentration profiles through the four sections for VOC removal remained essentially the same (Figure 6). This would be expected as H₂S was completely removed in the first section (Figure 5) and no significant breakthrough of H₂S to the MTBE degrading sections was observed.

Pilot-Scale Experiments

Gas flow rate and EBRT: Large fluctuations of the gas flow rate through the biofilter were observed with rates varying between 15 and 73 m³/h, and an overall average of 31 m³/h. These variations resulted from increasing pressure drops across the packing (long term effect), as well as by accumulation of water and loose packing material in the inlet air-duct (short-term effect). On a few occasions (days 177-184, day ~211, day ~235), the inlet air-duct became clogged causing large reductions of the gas flow rate through the biofilter. As a consequence of variable gas flow rates, similar fluctuations were seen for the EBRT. The EBRT in the lower H₂S removal section was on average 10 s (range 3.6-17 s). The average EBRT based on the total packed bed volume (1st and 2nd section) was 42 s (range 14-69 s).

H₂S removal: Long-term performance of H₂S removal in the pilot biofilter is shown in Figure 7A. As in the laboratory study, a rapid start-up was observed with greater than 99% removal within two weeks of operation. Over the entire experiment, the average H₂S removal efficiency was 99.3% at H₂S inlet concentrations fluctuating between 10 and 50 ppm_v. The H₂S outlet concentration averaged 0.14 ppm_v. The removal efficiency temporarily dropped to 95% over days 60-66. It is believed that an interruption of water supply to the biofilter during this period may have caused a relatively poor performance. Measurements of H₂S in the plenum between the H₂S and VOC removal sections indicated that H₂S removal occurred in the first section, hence, penetration of H₂S to the section designated for VOC removal was negligible. The H₂S concentration after the first section was often less than 0.1 ppm_v. The short-term performance data, presented in Figure 7B, show a general pattern of increasing H₂S inlet concentrations as the day progressed. Despite these large fluctuations, the dynamic response of the biofilter proved adequate by consistently removing H₂S to an average and relatively constant outlet concentration of 0.37 ppm_v during these short-term experiments. The short and long term performance of H₂S removal is summarized in Table 2.

VOC removal: Air streams were routinely analyzed for 15 VOCs, of which only toluene, benzene, xylenes, dichlorobenzenes, methylene chloride, chloroform, trichloro ethylene, tetrachloro ethylene were present in concentrations consistently higher than the detection limit (0.5, 1 or 2 ppb_v). Vinylchloride,

vinylidenechloride, carbontetrachloride, 1,1-dichloroethane, 1,2-dichloroethane, chlorobenzene and methylchloroform were always below the detection limit. VOC removal was evaluated on a semiweekly basis, and on selected days more frequently at intervals of 3 hours. Representative examples of VOC removal over a period of one month are presented in Figure 8, whereas average VOC removal efficiencies are summarized in Table 2. Aromatic VOCs such as benzene, toluene, and xylenes were removed at average efficiencies of 74, 79 and 56%, respectively. Similar performance was observed throughout the 10 month experiment.

Removal was lower to nil for chlorinated VOCs depending on the particular compound. No removal was observed for chloroform, trichloro ethylene and tetrachloro ethylene. Moderate removal of dichlorobenzenes was observed intermittently, so that the average removal of 18% does not appear statistically significant. Highly fluctuating removal of dichloromethane (25-75%) was observed, but only after 200 days of operation, so the table shows that the mean removal percentage for this compound for the whole period is also very low.

Spiking experiments: In addition to the observations of filter performance in treating unmodified headworks waste air, during several periods of a few days apiece the air was spiked with much higher concentrations of several VOCs to test filter response to a wider range of gas compositions, as shown in Tables 3a to 3c.

The first test consisted of four days of spiking with a very high concentration of toluene on Days 133-136. As shown in Table 3a, the removal percentages of benzene and toluene decreased, but greatly increased removal percentages of dichlorobenzenes and dichloromethane were observed. It must be noted that the reduced removal percentage for toluene represents a much higher absolute removal than in the unspiked measurements.

Table 3b shows that when gasoline was spiked on days 196-204, a lower concentration was used than in the toluene spiking test, and the removal percentages for the compounds in gasoline (benzene, toluene and xylenes) were little different from the percentages in Table 2. However, the removal of dichloromethane was even better than in Table 3a. Table 3c shows that combining dichloromethane and trichloro ethylene with the gasoline during the third spiking test on days 217-226 resulted in poor performance on all the VOCs. When the concentration of a VOC was higher in the outflow than in the inflow, causing negative removal efficiencies, the biofilter was either producing the VOC or was releasing some that was absorbed earlier. In the case of chlorinated VOCs, desorption is more plausible on general grounds than synthesis, but this study did not attempt to determine the details of the processes performed by the culture on any of the detected compounds.

Overall performance: Table 4 presents an overview of the overall performance of the pilot biofilter with simultaneous measurement of the removal of H₂S, organic sulfur compounds, VOCs, and odor. This experiment was performed 253 days after start-up, at which time the overall EBRT was 33 s. Removal of H₂S was greater than 99%. As H₂S was present in concentrations up to three orders of magnitude higher than most other pollutants, it was the principal odorous compound. Hence, odor removal correlated with H₂S removal, and an odor reduction of greater than 99% was observed. For organic sulfur compounds, good removal was also observed for methyl mercaptan and possibly tert-butyl mercaptan, but removal of dimethyl sulfide and carbon disulfide was less than 40%. Removal of non-chlorinated VOCs was about 40-86%, whereas removal of chlorinated VOCs was in general poor in agreement with the results presented in Figure 8.

DISCUSSION

The results demonstrate that a mixture of MTBE and H₂S can be effectively removed by passing the waste air through a biofilter. MTBE is a compound that for long has been considered poorly biodegradable, but its biodegradation and removal from contaminated air has recently been demonstrated (Fortin and Deshusses, 1999). In addition, the University of California at Davis recently succeeded in isolating a pure species that can use MTBE as the only source of carbon and energy. This species was used to seed our laboratory biofilter. Although a relatively long adaptation period was required for start-up of the biofilter, the final maximum MTBE elimination capacity of 62 g/m³.h is comparable to the observed elimination capacities for other, more biodegradable VOCs (Deviny *et al.*, 1998). This demonstrates the feasibility of biofilters for MTBE treatment when the packing is seeded with pure cultures capable of MTBE biodegradation.

Effective treatment of a mixture of H₂S and VOCs may require a biofilter with separate sections for removal of each class of pollutants. The reason for this is potential inhibition of VOC removal by low pH resulting from H₂SO₄ production from H₂S oxidation. Although VOC biodegradation in low-pH biofilters has been observed (Webster *et al.*, 1997) significant removal was only observed after a long adaptation period and the removal efficiencies obtained were not always optimum. A possible solution is a two-stage system consisting of an acid biotrickling filter for H₂S removal followed by VOC treatment in a biofilter (Chitwood *et al.*, 1999). The biofilter design presented here is based on a similar principle with spatially separated removal of H₂S and VOCs. However, by housing the sections for H₂S and VOC in one bioreactor, significant reductions in capital costs and process complexity can be achieved. For both the laboratory and pilot biofilter, no cross interference between H₂S and MTBE/VOC removal was observed. As H₂S removal in biofilters is fast, it is removed first in the biofilter. MTBE biodegradation in the first section is unlikely to occur, because low pH inhibits MTBE biodegradation. Complete MTBE removal is achieved in the sections following the H₂S oxidation section, without interference by the preceding H₂S removal section as demonstrated by the MTBE concentration profiles presented in Figure 6. A crucial aspect in the design is that the H₂S removal section should be large enough for complete removal of H₂S in order to prevent penetration of H₂S into VOC removal sections. Separation of the H₂S and MTBE removal also allows for independent water control of each section. Using upflow and positioning the H₂S removal section below the VOC removal section in addition prevents acidic leachate from trickling into the VOC removal section.

H₂S removal performance data from the pilot test at the Hyperion plant were consistent with that of the laboratory biofilter. The pilot biofilter removed 10-50 ppm_v H₂S at greater than 99% efficiency and at a sectional EBRT of 3.7 to 17 s, depending on the actual gas velocity. Outlet concentrations were always less than 1 ppm, both during short-term and long-term experiments, which is the limit set by the SC-AQMD at that site. Biofilters are therefore an attractive alternative to chemical scrubbers, because comparable H₂S and odor removal can be achieved but at a lower cost and with less chemical consumption. As summarized by Iranpour *et al.* (2001), the number of biofilters deployed at POTWs is rapidly increasing. However, there is concern about the stability of biofilters when treating high loads of H₂S over several months or years. We observed increasing pressure drops over the biofilter, which is an indication of packing deterioration and air channeling. This may be due to sulfuric acid production, hence, biotrickling filters with inert packings may be preferred for treating high H₂S loads (Cox *et al.*, 2002), although the maximum H₂S load for cost effective biofilter use remains to be defined.

In addition to the near complete reduction of odor and H₂S, significant removal of non-chlorinated VOCs was observed. Removal of dichloromethane and dichlorobenzenes was observed when the concentrations of nonchlorinated VOCs were raised by spiking. This difference may be tentatively attributed to a change in culture resulting from the additional nonchlorinated VOCs. Other chlorinated VOCs were not significantly removed. VOC removal at first depends on the biodegradability of the species. Laboratory studies with biofilters and biotrickling filters have shown amongst others high removal rates of toluene, benzene, xylenes, dichlorobenzenes and dichloro methane, consistent with the results of the present study. Treatment of chloroform, trichloro ethylene and tetrachloro ethylene remains a challenge. Removal of these compounds in biofilters has been demonstrated (Devinny *et al.*, 1996; Webster *et al.*, 1996; Wolstenholme and Finger, 1994), but it either requires co-metabolism or anaerobic conditions, which are conditions difficult to control in biofilters.

CONCLUSIONS

The design of the biofilter with separate sections for H₂S and VOC removal allowed for effective treatment of waste gases containing mixtures of H₂S and VOCs in a single bioreactor. This was observed both in laboratory tests in which the VOC was MTBE and in pilot tests at the Hyperion Treatment Plant, where the headworks air contains several chlorinated and non-chlorinated VOCs. Thus, the biofilter not only reduces odor nuisance by near complete removal of H₂S, but also reduces the emission of air toxics and VOCs. The removal of non-chlorinated VOCs and some of the chlorinated VOCs could be significant to POTWs as they could get credit towards overall removal of cumulative VOCs by regulatory agencies. This is particularly true since similar removal efficiencies for non-chlorinated VOCs are observed over several orders of magnitude in the concentrations of these compounds, as long as incoming chlorinated VOC concentrations are modest. The removal of VOCs is a clear advantage of biofilters over chemical

scrubbers that only remove H₂S; hence the use of biofilters may help in further reducing air emissions from POTWs.

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REFERENCES

Chitwood, D.E., Devinny, J.S., and Reynolds, R.E. (1999). Evaluation of a two-stage biofilter for treatment of POTW waste air. *Environ. Progr.* **18**:214-221.

Converse, B.M., Schroeder, E.D., Cox, H.H.J., Deshusses, M.A., Zermeno, M., Moghaddam, O., and Iranpour, R. (2001). Odor and VOC removal from wastewater treatment plant headworks ventilation air using a biofilter. In *Proceedings Water Environment Federation 74th Annual Conference & Exposition*, October 13-17, 2001, Atlanta, GA.

Cox, H.H.J., Deshusses, M.A., Converse, B.M., Schroeder, E.D., Vosooghi, D., Samar, P., and Iranpour, R. (2001). Odor and VOC treatment by biotrickling filters: pilot scale studies at the Hyperion Treatment Plant. In *Proceedings Water Environment Federation 74th Annual Conference & Exposition*, October 13-17, 2001, Atlanta, GA.

Cox, H.H.J., Deshusses, M.A., Converse, B.M., Schroeder, E.D., Vosooghi, D., Samar, P., and Iranpour, R. (2002). Odor and VOC treatment by biotrickling filters: pilot scale studies at Hyperion Treatment Plant. *Wat. Environ. Res.*, in press.

Devinny, J.S., Webster, T.S., Torres, E.M., and Basrai, S.S. (1996). Biofiltration of odors, toxics, and volatile organic compounds from publicly owned treatment works. *Environ. Progr.* **15**:141-147.

Devinny, J.S., Deshusses, M.A., and Webster, T.S. (1998). *Biofiltration for air pollution control*, Lewis Publishers, Boca Rotan, FL.

Ergas, S.J., Schroeder, E.D., Chang, D.P.Y., and Morton, R. (1992). Control of VOC emissions from a POTW using a compost biofilter. In *Proc. of the 65th Annual Conference of the Water Environment Federation*, September 20-24, 1992, New Orleans, LO, pp. 23-34.

Ergas, S.J., Schroeder, E.D., Chang, D.P.Y., and Morton, R. (1994). Control of VOC emissions from a POTW using a compost biofilter. *Wat. Environ. Res.* **67**:816-821.

Fortin, N.Y., and Deshusses, M.A. (1999). Treatment of methyl tert-butyl ethyl vapors in biotrickling filters. 1. Reactor startup, steady-state performance and culture characteristics. *Environ. Sci. Technol.* **33**:2980-2986.

Iranpour, R., Samar, P., Stenstrom, M.K., Clarke, J.A., Converse, B.M., Schroeder, E.D., Cox, H.H.J., and Deshusses, M.A. (2001). Biological treatment of odor and VOCs in biofilters and biotrickling filters:

survey of field experiments. In *Proc. 94th Annual Conference & Exhibition of the Air and Waste Management Association*, June 24-28, 2001. AWMA, Pittsburgh, PA, paper 726.

Kennes, K., and Veiga, M.C. (2001). Conventional biofilters. In *Bioreactors for waste gas treatment*. Kennes, K., Veiga, M.C. (Eds), Kluwer Academic Publishers, Dordrecht, the Netherlands.

Schroeder, E. D., Eweis, J.B., Chang, D.P.Y., and Veir, J.K. (2000). Biodegradation of recalcitrant compounds. *Wat. Air Soil Pol.* **123**:133-146.

Webster, T.S., Deviny, T.S., Torres, E.M., and Basrai, S.S. (1996). Biofiltration of odors, toxics and volatile organic compounds from publicly owned treatment works. *Environ. Progr.* **15**:141-147.

Webster, T.S., Deviny, J.S., Torres, E.M., and Basrai, S.S. (1997). Microbial ecosystems in compost and granular activated carbon biofilters. *Biotechnol. Bioeng.* **53**:296-303.

Wolstenholme, P., and Finger, R. (1994). Long-term odor and VOC performance tests on biofilters. In *Proc. of the 67th Annual Conference & Exposition of the Water Environment Federation*, October 15-19, 1994, Chicago, IL, pp. 541-552.

Table 1. Nutrient solution for laboratory tests.

Nutrient	Concentration (mg/L)
KH_2PO_4	3470
K_2HPO_4	4267
NaNO_3	2335
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	460
$\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	18
$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$	1
H_3BO_3	0.3
$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$	0.2
$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$	0.1
$\text{MnCl}_2 \cdot 4\text{H}_2\text{O}$	0.03
$\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$	0.03
$\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$	0.02
$\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$	0.01

Table 2. Summary of performance during pilot tests at HTP (Figures 7 and 8).

Pollutant	Mean \pm standard deviation		
	Inlet conc.	Outlet conc.	Removal efficiency (%)
(a) Hydrogen sulfide (H ₂ S), ppm _v			
Long-term	23 \pm 9	0.14 \pm 0.31	99 \pm 2
Short-term	26 \pm 8	0.37 \pm 0.34	98 \pm 1
(b) Volatile organic compounds (VOCs), ppb _v			
Short-term			
Benzene	8 \pm 3	2 \pm 2	74 \pm 23
Toluene	68 \pm 18	12 \pm 10	79 \pm 20
Xylenes	79 \pm 35	31 \pm 21	56 \pm 28
Dichlorobenzenes	14 \pm 4	11 \pm 4	18 \pm 17
Dichloromethane	42 \pm 27	38 \pm 24	5 \pm 21
Chloroform	74 \pm 19	74 \pm 20	0 \pm 4
Tetrachloro ethylene	79 \pm 24	80 \pm 24	-1 \pm 2
Trichloro ethylene	9 \pm 2	9 \pm 2	0 \pm 6

Table 3. VOC removal with spiking during pilot tests at HTP.**(a) Toluene, days 133-136.**

VOC	N	Inlet concentration (ppb _v)		Removal efficiency (%)	
		Mean \pm standard deviation	Range	Mean \pm standard deviation	Range
Benzene	7	6 \pm 3	3 to 12	27 \pm 22	3 to 59
Toluene	6	24921 \pm 15466	4817 to 41617	59 \pm 37	14 to 99
Xylenes	7	77 \pm 31	40 to 118	55 \pm 28	19 to 93
Dichlorobenzenes	7	6 \pm 5	2 to 14	58 \pm 36	18 to 100
Dichloromethane	7	31 \pm 14	17 to 49	59 \pm 44	-12 to 95
Chloroform	7	70 \pm 18	53 to 100	6 \pm 15	-9 to 36
Tetrachloro ethylene	7	49 \pm 17	24 to 72	20 \pm 36	-11 to 90
Trichloro ethylene	7	4 \pm 2	2 to 7	13 \pm 24	-9 to 62

(b) Gasoline, days 196-204.

VOC	N	Inlet concentration (ppb _v)		Removal efficiency (%)	
		Mean \pm standard deviation	Range	Mean \pm standard deviation	Range
Benzene	7	330 \pm 144	16 to 483	73 \pm 11	54 to 88
Toluene	7	1778 \pm 721	163 to 2472	75 \pm 14	49 to 97
Xylenes	7	2339 \pm 875	378 to 3298	50 \pm 16	26 to 68
Dichlorobenzenes	7	16 \pm 4	10 to 21	30 \pm 17	8 to 50
Dichloromethane	7	46 \pm 19	24 to 70	81 \pm 7	68 to 92
Chloroform	7	76 \pm 12	54 to 86	4 \pm 5	-4 to 12
Tetrachloro ethylene	7	122 \pm 60	43 to 226	1 \pm 5	-7 to 10
Trichloro ethylene	0				

(c) Gasoline, dichloromethane and trichloro ethylene, days 217-226.

VOC	N	Inlet concentration (ppb _v)		Removal efficiency (%)	
		Mean \pm standard deviation	Range	Mean \pm standard deviation	Range
Benzene	5	216 \pm 29	183 to 246	17 \pm 11	5 to 33
Toluene	6	1093 \pm 202	900 to 1311	26 \pm 11	9 to 39
Xylenes	6	1425 \pm 265	1116 to 1710	41 \pm 9	28 to 53
Dichlorobenzenes	2	9 \pm 0.2	8 to 9	4 \pm 0.1	3 to 4
Dichloromethane	6	7097 \pm 2527	4064 to 9881	-31 \pm 12	-50 to -17
Chloroform	2	62 \pm 16	51 to 73	-2 \pm 4	-5 to 1
Tetrachloro ethylene	3	97 \pm 26	75 to 125	-13 \pm 19	-34 to 4
Trichloro ethylene	5	3191 \pm 1047	1905 to 4199	-49 \pm 11	-65 to -33

Table 4. Performance during pilot tests on day 253, range values are data from morning, afternoon and evening determinations.

Pollutant	Inlet	Removal efficiency (%)
<i>Sulfur compounds</i>		
H ₂ S	15 – 24 ppm _v	99 – 99.8
Carbonyl sulfide	19 – 52 ppb _v	30 – 33
Methyl mercaptan	149 – 165 ppb _v	91 – 94
Dimethyl sulfide	8 – 12 ppb _v	0 – 21
Carbon disulfide	6 – 8 ppb _v	32 – 36
Tert-butyl mercaptan	<2 – 3 ppb _v	>31 ^a
<i>VOCs</i>		
Benzene	0.5 – 1 ppb _v	0 – 50
Toluene	20 – 60 ppb _v	42 – 86
Xylenes	40 – 150 ppb _v	40 – 75
Dichlorobenzene	4 – 8 ppb _v	43 – 60
Dichloromethane	NA	NA
Chloroform	50 – 75 ppb _v	0 – 17
Tetrachloro ethylene	50 – 140 ppb _v	0 – 9
Trichloro ethylene	NA	NA
<i>Odor</i>		
Odor reduction	35,000 – 46,000 D/T	99 – 99.4

^a This compound was present in a concentration close to the detection limit. An accurate estimation of the removal efficiency is not possible.

FIGURE LEGENDS

Figure 1. Schematic of laboratory biofilter for simultaneous removal of H₂S and MTBE.

Figure 2. Schematic of pilot biofilter at Hyperion Treatment Plant, S1, S2, and S3 are sample locations.

Figure 3. MTBE removal in laboratory at EBRTs of 15-60 s (day 160-236, operation as single unit for removal of MTBE only; day 236-260, operation as a combined unit for removal of H₂S and MTBE).

Figure 4. Steady state MTBE elimination capacity of 25 cm sections (EBRT of 15 s per section) of biofilter as determined over day 177-236 (solid line for complete removal).

Figure 5. H₂S removal in first section of laboratory biofilter at an EBRT of 15 s (seeding on day 112, after which operation as separate unit for removal of H₂S only; in-line placement of this unit with MTBE removal sections on day 236).

Figure 6. MTBE concentration profiles before and after introduction of H₂S oxidation system.

Figure 7. Long-term and short-term H₂S removal performance in pilot tests.

Figure 8. Short-term performance of VOC removals in pilot tests.

Figure 1

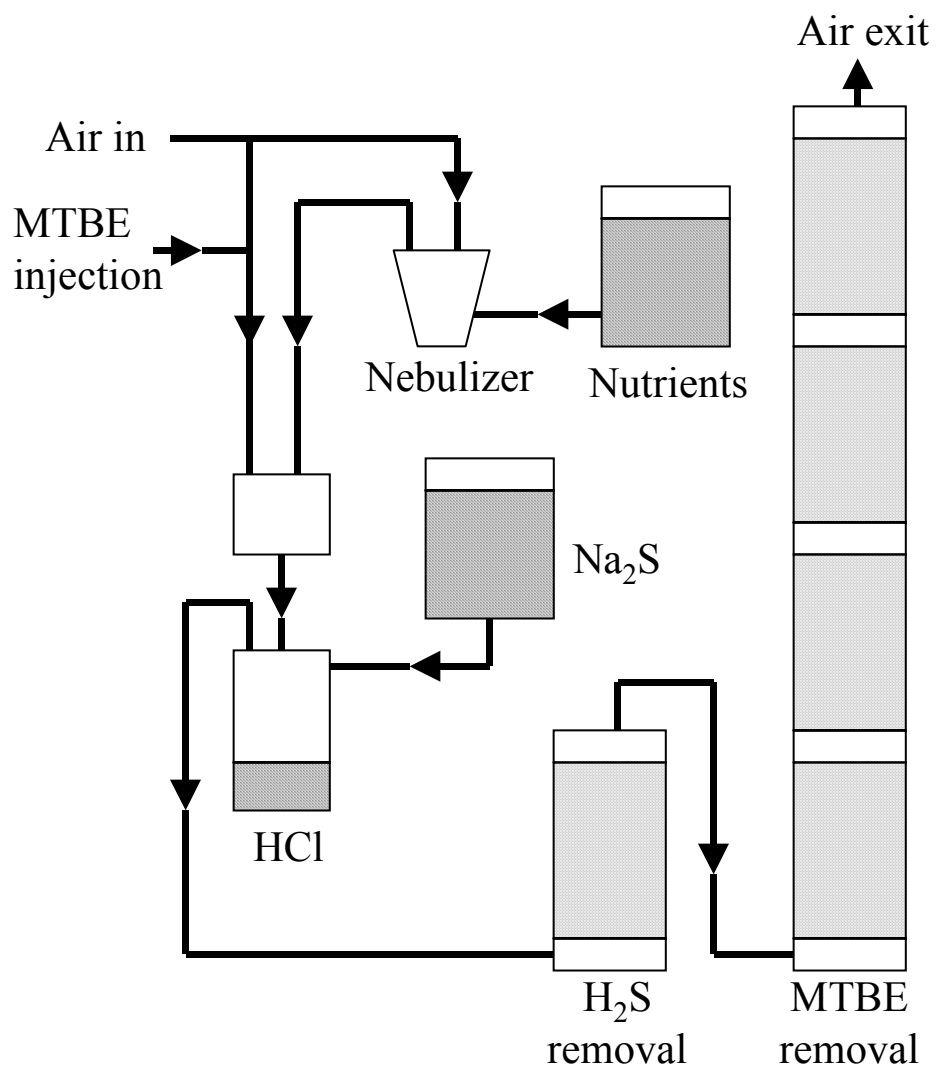


Figure 2

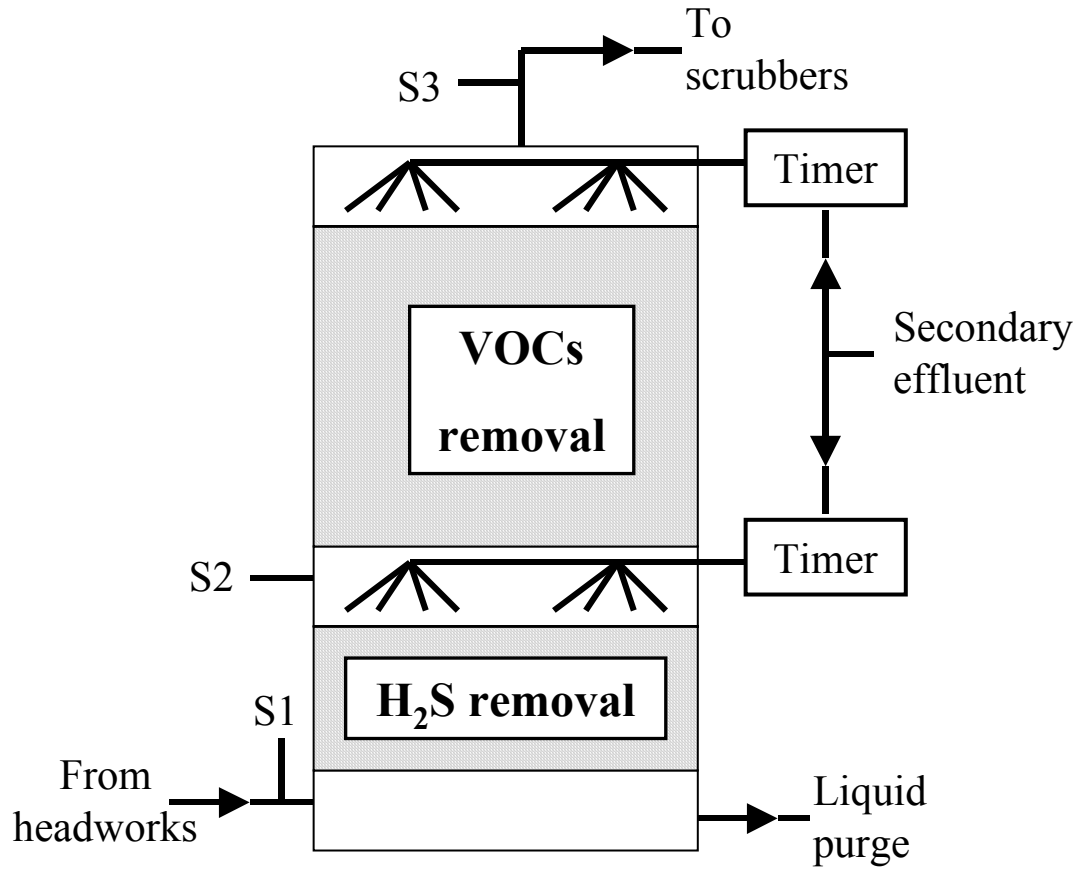


Figure 3

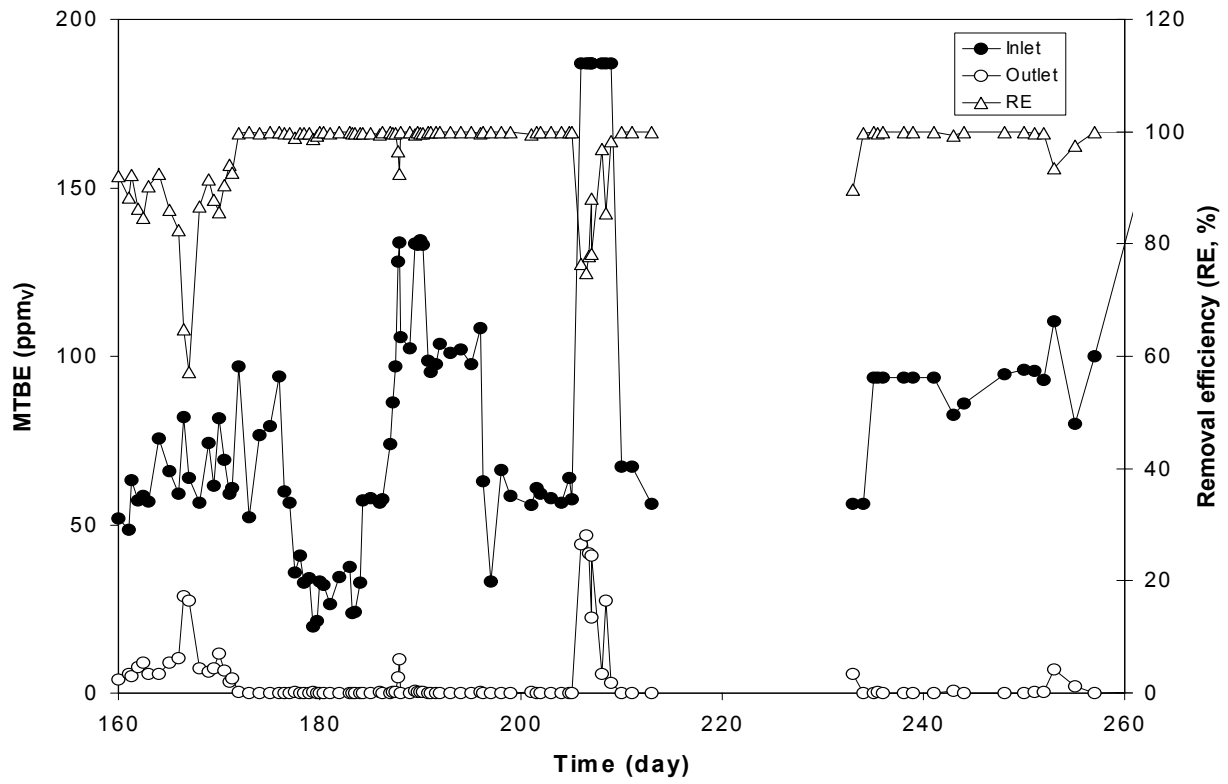


Figure 4

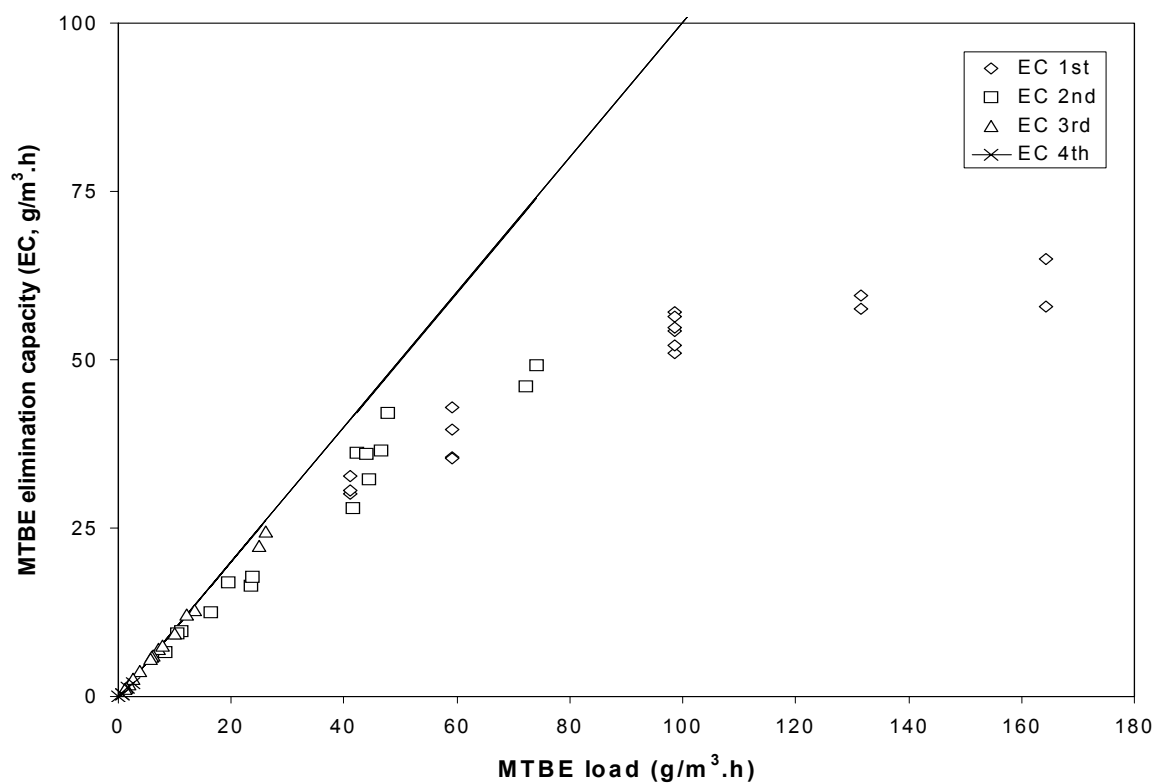


Figure 5

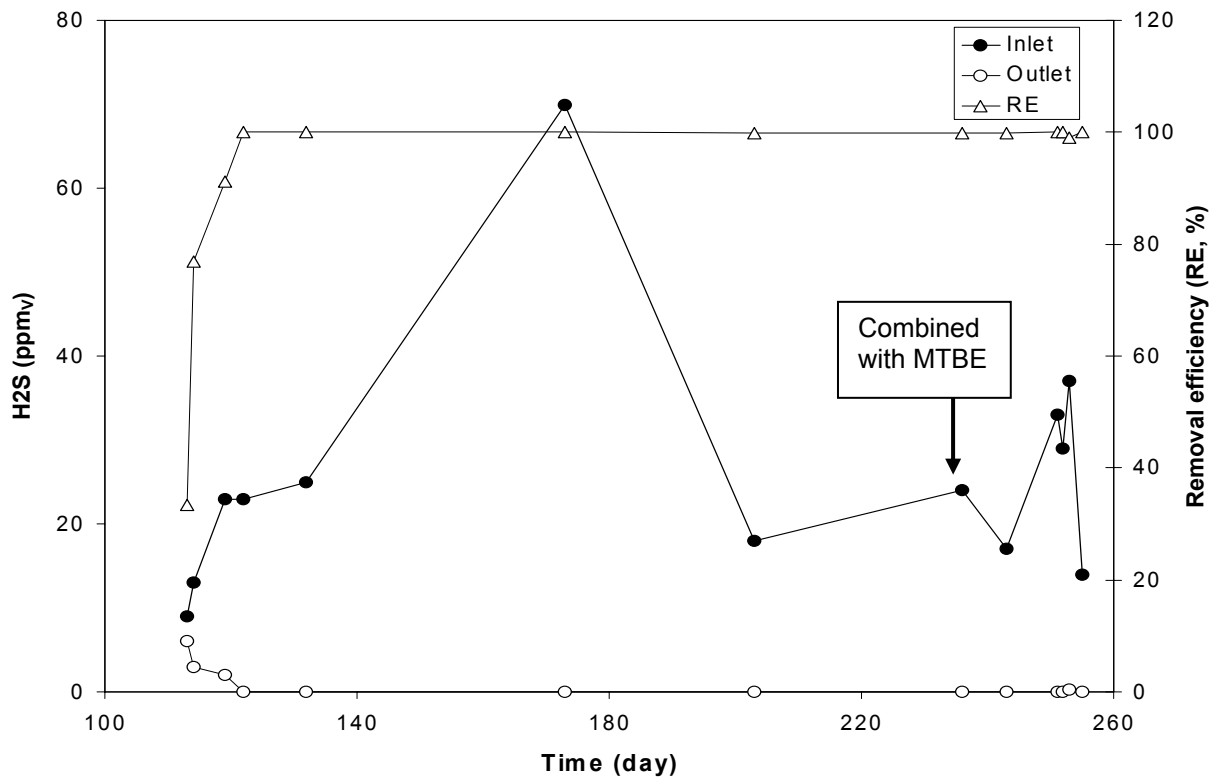


Figure 6

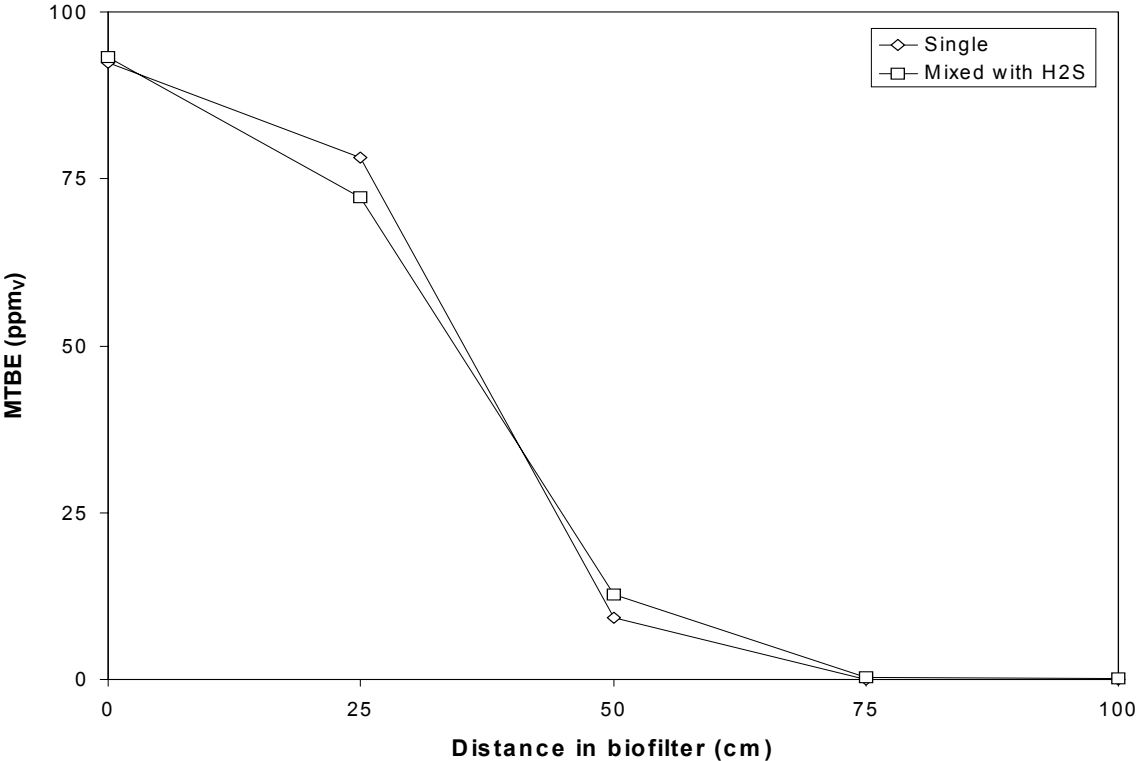


Figure 7.

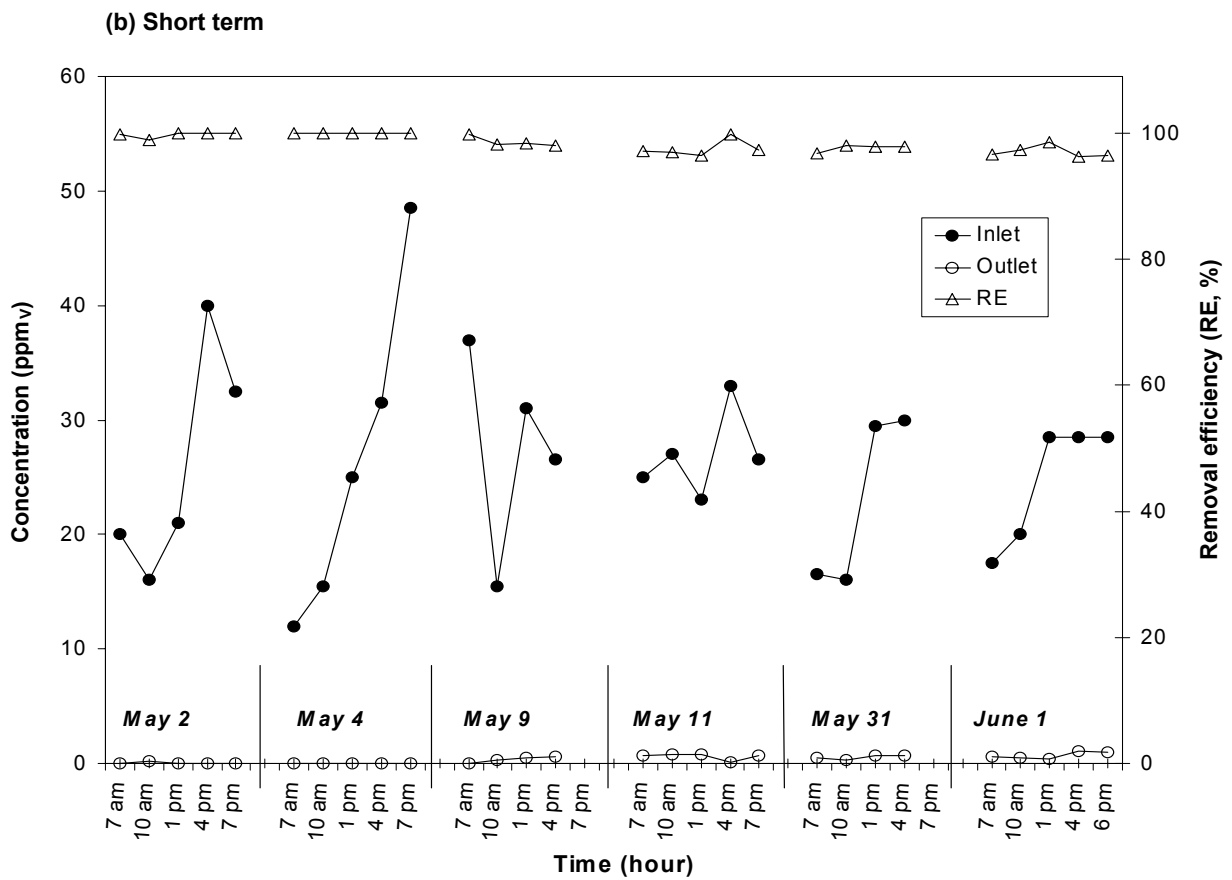
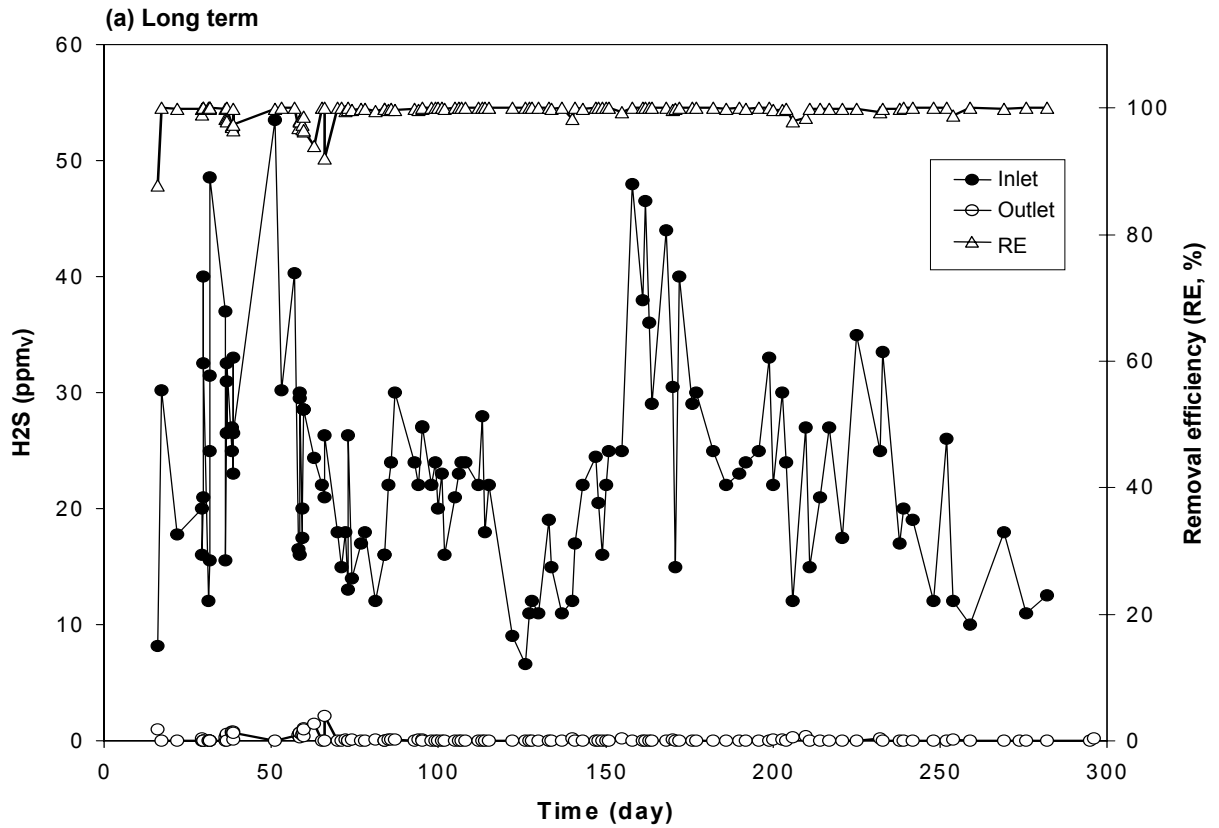


Figure 8.

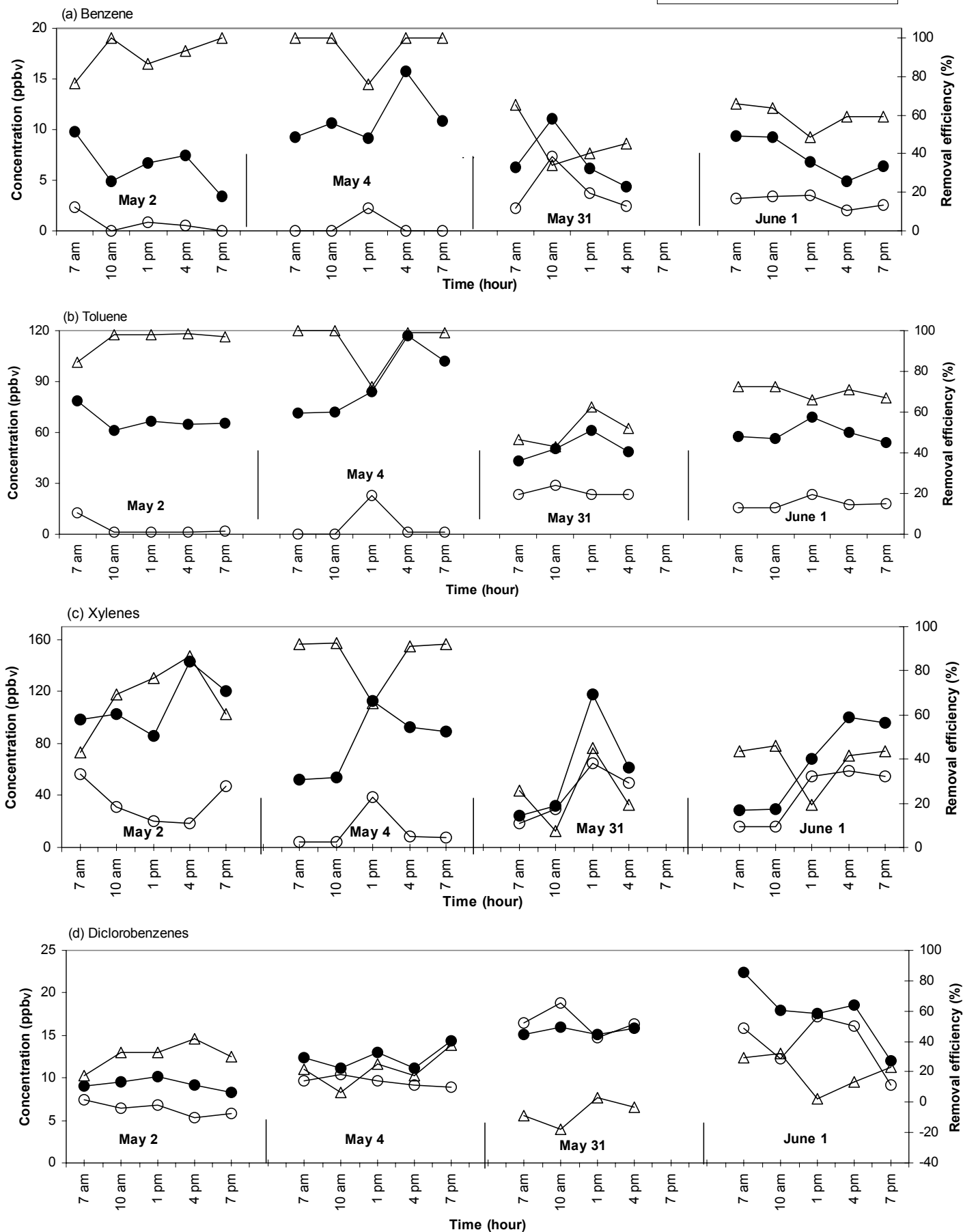
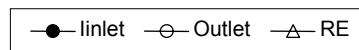


Figure 8 continued.

