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PRACTICAL EXPERIENCES WITH BIOLOGICAL TREATMENT OF ODOR AND VOCS AT POTWS IN USA

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ABSTRACT

A literature study was conducted to compare the feasibility of biofilters and biotrickling filters for the treatment of complex odorous waste gases containing H_2S, organic reduced sulfur compounds, and chlorinated and non-chlorinated volatile organic compounds (VOCs). About 40 pilot-plant studies and full-scale applications at wastewater treatment plants and other facilities were reviewed. Operational and performance parameters were summarized in tables for easy reference and for a perspective on the current state of the literature, and to allow comparison between different projects. The survey indicated that both biofilters and biotrickling filters are capable of combining a high H_2S and odor removal efficiency with VOC removal. Apart from odor abatement, biological treatment therefore holds promise for reducing the overall toxicity and potential carcinogenicity of waste gases at wastewater treatment plants. VOC removal efficiencies were in general less than those of H_2S and odor, although concentrations of individual VOC species were relatively low. This indicates that for effective treatment of complex odorous gases the design and operation should emphasize VOC removal as the rate-limiting parameter.

KEYWORDS

Odor control, POTW, Biofilter, Biotrickling filter, H_2S

INTRODUCTION

Waste gas treatment at wastewater treatment facilities usually focuses on reducing odor nuisance complaints from neighboring communities. For this purpose, chemical scrubbers are often employed, which are effective in removing H_2S as the major odor-causing agent at wastewater treatment plants. Apart from H_2S, however, the waste gas contains a variety of volatile organic compounds (VOCs) including aromatics and chlorinated species. Growing concern about the potential toxicity and carcinogenicity of these VOCs, as well as more stringent regulations from local and federal government, require the development of treatment techniques that combine effective removal of H_2S and VOCs.

In 1999, the University of California at Davis (UCD), the University of California at Riverside (UCR) and the Hyperion Wastewater Treatment Plant (HTP) in Los Angeles started a collaboration to determine the efficacy of biological waste gas treatment techniques for H_2S and VOC removal. This project involved practical on-site research with pilot-scale biofilters and biotrickling filters at the headworks of HTP to directly compare and evaluate their performance. The second part of the project was an extensive literature survey and discussion of past experiences obtained with biological waste gas treatment at wastewater treatment plants and other facilities. In this paper, we present the results and discuss the conclusions from the literature survey.

The principles of biological waste gas treatment and the advantages over chemical and physical techniques have been extensively reviewed (e.g., Ottengraf, 1986; Leson and Winer, 1991; Van Groenestijn and Hesselink, 1993; Deshusses, 1997; Cox and Deshusses, 1998). The literature also provides many laboratory studies on pollutant removal in biofilters and biotrickling filters (Table 1 and 2). Nearly all of these adress the removal of single pollutants under strictly defined and constant conditions.

Such conditions are highly unusual at wastewater treatment plants. For instance, the headworks foul air or exhaust air at HTP is a complex mixture of H_2S and other reduced sulfur compounds (e.g., carbon disulfide, dimethyl sulfide, and methyl mercaptan), aromatic hydrocarbons (e.g., toluene, benzene and xylenes), chlorinated hydrocarbons (e.g., methylene chloride, chloroform, trichloroethylene (TCE) and perchloroethylene (PCE)), and possibly nitrogen compounds. The actual composition and individual concentrations may greatly vary over time. H_2S is the major component with concentrations in general between 5 and 50 ppm depending on the time of day. Other pollutants are present at lower concentrations, typically between 0-100 ppb. Apart from fluctuations in the waste gas composition, the performance of full-scale biofilters and biotrickling filters in the field may be affected by unstable conditions (e.g., temperature, relative humidity), system breakdowns and sub-optimal operation (Webster *et al.*, 1999). These factors are important in assessing the feasibility of biofilters and biotrickling filters at wastewater treatment plants, but they have received little attention in laboratory studies.

A large number of pilot- and full-scale biofilters and biotrickling filters have been installed throughout the world. We present below an overview of field experiences with these types of reactors. The main focus was on, but not limited to, biological waste gas treatment at wastewater treatment plants, in particular on the treatment of complex waste gas streams containing odorous compounds as well as VOCs. Operational and performance parameters are summarized in tables for easy reference, for a perspective on the current state of the literature, and to allow a direct comparison between different projects. Readers are encouraged to consult the original references for additional details.

MATERIAL AND METHODS

The following sources were used for the survey: scientific journals, conference proceedings, progress reports, and review articles discussing case studies, the latter including documents provided by vendors supplying biofilters and biotrickling filters. All references are alphabetically listed at the end of this paper. In some cases, we were unable to retrieve the origin of a particular paper; copies of those can be requested from the corresponding author (R. Iranpour).

The results of the literature study are grouped in tables as follows:

- Tables 1 and 2: examples of laboratory research with biofilters and biotrickling filters.
- Tables 3 and 4: projects with on-site foul air treatment in biofilters with general information and operational and performance parameters.
- Tables 5 and 6: projects with on-site foul air treatment in biotrickling filters with general information and operational and performance parameters.

Although Tables 3 to 6 mainly contain examples with pilot/full-scale reactors, bench-scale experiments were also included. The only criterion for selection into Tables 3 to 6 was that the reference should deal with field experiments or full-scale applications at existing industrial facilities or remediation sites.

Table entries include operational and performance parameters. Operation of biofilters is described by the composition of the waste gas and the observed range of concentrations of individual pollutants, the reactor dimensions, the type of packing, the empty bed gas residence time (EBRT), and pretreatment of the waste gas. For biotrickling filters, data concerning liquid trickling and/or recirculation and pH control are also provided.

The performance is described by the removal efficiency (RE) and/or the elimination capacity (EC) at the specified EBRT. These three parameters are defined as:

$$EBRT = \frac{V}{F} \tag{1}$$

1) EBRT (s) = V/F

$$RE = \frac{C_i - C_o}{C_i} x100 \tag{2}$$

2) RE (%) = $(C_{in} - C_{out})/C_{in}x100\%$

$$EC = \frac{F(C_i - C_o)}{V} \tag{3}$$

3) EC ($g/m^3.h$) = $(C_{in} - C_{out})xF/V$

where V = volume,m^3, of the packed bed section, F = gas flow rate m^3/hr, C_{in} and C_{out} = inlet and outlet concentration, g/m^3,of the pollutant. Operational parameters such as the pollutant inlet concentration and the EBRT are in general not constant, but fluctuate within certain ranges (either intentionally in laboratory studies, or unavoidably in field studies). Consequently, large fluctuations in the RE and/or EC are sometimes observed. Whenever possible, the tables presented herein show the boundaries of parameter ranges, rather than average values.

Abbreviations used in Tables 1 to 6 and unit conversion are defined in Appendix A.

RESULTS

Laboratory Research on Waste Gas Treatment in Biofilters and Biotrickling Filters

Tables 1 and 2 illustrate that most pollutants present in wastewater treatment plants' waste air can be removed in biofilters and biotrickling filters. Efficient removal - as single pollutants in artificial waste gases - has been demonstrated for odorous sulfur and amino-nitrogen compounds, (oxygentaed) aliphatics, aromatics, and chlorinated compounds. Also the removal of poorly biodegradable compounds (e.g., chlorobenzenes, MTBE), compounds that require cometabolism (TCE) or anaerobic conditions (PCE) has been observed.

Depending on the inlet concentration and EBRT, removal efficiencies of individual compounds in biofilters and biotrickling filters can be near 100%. Comparing Tables 1 and 2, it can be observed that biotrickling filters are in general been operated at a shorter EBRT and at relatively higher inlet concentrations. The maximal pollutant removal rate (EC) reported from laboratory studies was the highest in biotrickling filters, possibly due to a better control of reaction conditions and a higher biomass content. It should however be noted that the maximal EC is in general observed at relatively high pollutant concentrations when the removal efficiency is less than 100%. Near complete pollutant removal is usually observed only at lower inlet concentrations and a relatively long EBRT. Finally, comparison of the studies in Tables 1 and 2 is very difficult because many of the systems were not tested to failure and thus maximum loading rates were not determined, because removal may have been impacted by reactor configuration or operation, and because the rates of removal are highly substrate dependent.

Field Experiences with Biofilters

Table 3 presents an overview of projects and full-scale applications of biofilters. Most have been installed at wastewater treatment facilities, with waste gases containing odorous sulfur compounds as major components. Some are at livestock and composting facilities which emit relatively high concentrations of odorous nitrogen compounds.

A great variety of packing materials have been used in biofilters, e.g., peat, compost (from various sources), bark and wood chips. Packing material are selected to provide high specific surface area, high porosity, and compressive strength. Many materials provide satisfactory support for bacterial growth and this consideration is generally not a problem. "Natural" packings such as compost, peat, and soil have been widely used. Compost provides a rich community of microorganisms as well as some nutrients. Both compost and peat decompose with time causing deterioration of the bed structure and increases in head loss. Adding a bulking agent such as vermiculite or perlite extends the life of natural packings considerably.. To keep the pressure drop across the biofilter to a certain minimum (~10 cm water column), the vast majority of biofilters contain a packed bed with a height typically less than 1.2 meter. Due to this restriction, biofilters in general require a larger footprint as compared to biotrickling filters.

Moisture content of the packing has been identified as the most critical parameter to control in biofilters (Van Lith *et al.*, 1997). Indeed, many references listed in Table 3 mention system upsets causing excessive drying of the packed bed and declining performance. Although the relative humidity of the air undergoing treatment is sometimes sufficiently high, the waste gases are often humidified in packed towers prior to entering the biofilter. Most applications also have a sprinkling system for additional water supply onto the packed bed. Pre-humidification in spray towers may also remove particulate matter from the waste gas, thus preventing clogging of the packed bed. An alternative would be the use of cyclone separators. Waste gases from composting facilities frequently have temperatures greater than the optimum of most microorganisms (15-35^{0}C). In those cases, cooling may be achieved by temperature control of the water in the spray-tower, or by using heat exchangers. The latter option is quite uncommon as it would substantially increase the overall cost of treatment.

Performance data of biofilters at industrial applications are summarized in Table 4.. Concentrations of individual pollutants are in general much lower than used in the laboratory studies (Table 1), especially those of the VOCs. For this reason and the fact that gas flow rate values are much more variable, only removal efficiencies are presented. Calculated elimination capacities for individual pollutants would be small fractions of what is attainable in the laboratory. Biofilters at industrial applications are operated at an EBRTs from 20 up to 200 s, which is comparable to laboratory studies. Removal of H_2S, the major component in most odorous, industrial waste gases, is in general between 90-100%, indicating that significant odor reduction can be obtained by treatment in biofilters. The few studies that include odor analysis confirm this: the observed odor reduction is often greater than 80%. Removal of odorous compounds other than H_2S, e.g., DMS, DMDS and MM, is often less complete with reported removal efficiencies ranging from about 20 to 100%. A few studies have also focused on the removal of VOCs. These seem to indicate that biofilters for H_2S and odor treatment are also capable of removing a broad range of VOCs. VOC removal efficiencies are, however, generally below 90 (sometimes as low as 20 percent, although usually with wide range of variation), even for easily biodegradable VOCs such as acetone and toluene.

Field Experiences with Biotrickling Filters

As a relatively new technique, field experience with biotrickling filters has been principally through feasibility studies with pilot-plant installations (Table 5). Various types of packing materials have been used: plastic random dump packing, lava rock, structured packing and polyurethane foam. The high porosity of these packings causes less headloss as compared to biofilters with organic packings, even though biotrickling filters are operated at a higher gas velocity. A distinctive feature of biotrickling filters is the continuous trickling of liquid over the packing which allows for improved control of nutrient addition, pH, acid product neutralization, end product removal, and potentially temperature. In the case of odorous waste gases containing reduced sulfur compounds, production of sulfuric acid with declining pH and/or accumulation of sodium sulfate (after neutralization with caustic soda) is the main concern. However, most references in

Table 5 reveal limited information on parameters related to liquid recirculation and velocity, pH control, nutrient supply and water demand.

Performance data for biotrickling filters (Table 6) indicate that these reactors are capable of efficient removal of high concentrations of H_2S at a relatively low EBRT. Thus, biotrickling filters appear to be the a good option when the gas to be treated contains high concentrations of H_2S and possibly other reduced sulfur compounds. No data are available on the removal of DMS, DMDS and MM or the overall odor reduction by biotrickling filters, and only a few studies have addressed the removal of VOCs. The studies that include VOCs indicate that although H_2S removal may be faster in biotrickling filters, the VOC removal is in general less than in biofilters.

DISCUSSION AND CONCLUSIONS

H_2S/odor removal in biofilters and biotrickling filters has been well documented and many applications can be found at wastewater treatment plants and other facilities. Comparing the two systems, biotrickling filters appear to perform better when the waste gas contains high H_2S concentrations, when the objective is to remove H_2S at the highest volumetric elimination rate or when extremely short residence times are considered. Biofilters tend to be used for applications with lower H_2S loadings because of the concerns of inhibition by sulfuric acid production, although there are examples of successful biofilters operated at low pH and high H_2S concentrations in the tables below.

This survey must be considered preliminary because of the lack of data from comparable systems. However, the potential of biofilters and biotrickling filters for the combined removal of H_2S/odor and VOCs is clear. . Simultaneous removal of VOCs, including aliphatics, aromatics and chlorinated compounds, has been observed. Although only a few studies have investigated the co-treatment of VOCs and H_2S, those that have been made seem to indicate that biofilters can obtain higher VOC removal efficiencies than biotrickling filters. This can be plausibly explained by considering the low solubility of most VOCs in water. The water layer in a biotrickling filter would be expected to act as a barrier separating these gases from the degrading microorganisms. Hydrophilic VOCs, such as ethanol and acetone, may be more suited to treatment in biotrickling filters than in biofilters. Further work will be needed to determine mass transfer limitations of VOCs at low concentrations in biotrickling filters, and whether any other mechanism also contributes to the observed behavior. Caution is needed in interpreting the results in the tables, because the varying methodologies used in the respective studies raise difficulties for making comparisons and many questions suggested by the data cannot be answered from the references. For example, Lu *et al.* (1999) (Table 2) obtained good removal of BTEX at a high inlet concentration, using a biotrickling filter packed with coal, but no other study in any of the tables used this material, and some of the removal might have been absorption into the coal rather than biodegradation. Likewise, comparing the biofilter results in Table 3 and 4 with each other and with the biotrickling filter results in Tables 5 and 6 is hampered by the huge variety of biological materials used as packings in the majority of biofilter studies, and the use of non-biological packing materials in biotrickling filter studies.

Making all allowances for these uncertainties, the literature indicates strongly that for both biofilters and biotrickling filters, VOC removal is the limiting process when treating complex odorous waste gases containing VOCs. The design and operation of such bioreactors should therefore aim at maximizing VOC removal.

In both biofilters and biotrickling filters, VOC removal is not complete although the VOC load and elimination capacity in practical applications is much lower than the maximal elimination capacity observed in the laboratory. In order to improve VOC removal, the following issues should be addressed:

1. Removal of VOCs, present at concentrations less than a few mg/m^3: Most laboratory studies have investigated VOC removal at much higher concentrations and the performance at the concentrations prevailing at most wastewater treatment plants has largely been ignored.
2. Optimization of the pH and pH control: It is likely that VOC removal is inhibited by sulfuric acid production from H_2S oxidation. Determining the pH range for VOC removal and better pH control in biofilters and biotrickling filters may improve VOC removal.

APPENDIX A

BTEX = benzene, toluene, ethylbenzene, xylenes;
Cl-VOC = chlorinated volatile organic compounds;
DCM = dichloromethane (methylene chloride);
DMDS = dimethyl disulfide;
DMS = dimethyl sulfide;
D/T = dilution to threshold;
EBRT = empty bed gas residence time;
EC = elimination capacity;
GAC = granular activated carbon;
MM = methyl mercaptan;
MTBE = methyl *tert*-butylether;
N = nitrogen compounds, organic and inorganic;
NA = not available;
OU = odor unit;
PCE = tetrachloroethylene;
PP = polypropylene;
PVC = polyvinyl chloride;
RE = removal efficiency;
ROC = non-methane reactive organics;
S = sulfur compounds, organic and inorganic;
TCE = trichloroethylene;
TGNMO = total gaseous non-methane organics;
THC = total hydrocarbons;
VOC(s) = volatile organic compound(s).

Pollutant concentrations are reported as mass per volume or ppm_v; conversion of volumetric to mass concentrations is done using the ideal gas law which reduces to the equation below at room temperature.

$$\text{Concentration}\ (\text{g m}^{-3}) = \frac{\text{Concentration}\ (\text{ppm}_v) \times \text{molecular weight of pollutant}\ (\text{g mol}^{-1})}{24{,}776}$$

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Table 1. Removal of commonly found odorous compounds and VOCs in laboratory biofilters.

Ref. #	Authors	Packing	Waste gas composition		EBRT (s)	Performance		Remarks
			Pollutant	Conc. (mg/m^3)		RE (%)	EC (g/ m^3.h)	
Non-chlorinated VOCs								
4	Arnold *et al.* (1997)	Peat with burned clay and lime	Styrene	250	81	70	12	Addition of nutrients and pH buffering lime required
5	Auria *et al.* (1998)	Peat	Ethanol	3700	150	30	30	Water content of 50-70%; EC=4 g/m^3.h at 35% water
28	Jorio *et al.* (1998)	Conditioned peat	Xylene-isomers	2300	102	52	43	EC m-xylene>p-xylene>o-xylene
38	Morgenroth et al. (1996)	50 % compost 50% perlite	Hexane	175-700	30-120	>95	21	Hexane mass loading rate was held constant.
44	Shareefdeen *et al.* (1994)	40% peat, 60% perlite	Toluene	620-2810	162-516	66-100	5-25	
62	Zilli *et al.* (1993)	66% peat, 33% glass beads	Phenol	1000-1500	54	>93	124	
Chlorinated VOCs								
18	Ergas *et al.* (1994)	50% compost, 50% perlite, oyster shells	DCM	10-175	42-60	>98	15	Rapid acidification and declining RE at 50 ppm.
49	Sukesan and Watwood (1997)	Composted leafs, 10% GAC	TCE	25-250	336	>95	2.4	Cometabolism of TCE with methane/propane
19	Ergas *et al.* (1995)	50% compost, 50% perlite, oyster shells	DCM, TCE, PCE	0.35-0.7 (each)	30-120	11-49		Toluene and benzene also present at 2 mg/m^3 with RE=10-80%
Odorous N and S-compounds								
61	Yang and Allen (1994)	Compost, various sources	H_2S	7-3750	23-200	>99.9	12-130	Performance depended greatly on type of compost
35	Liang *et al.* (2000)	36% compost, 36% activated sludge, 27% GAC	NH_3	14-350	68	92-100	17	
48	Smet *et al.* (1997)	Compost , 10% limestone	DMS	400	27	97	48	Strong inhibition by isobutyraldehyde
9	Chou and Shiu (1997)	33% peat, 33% per-te, 33% fern chips	Methylamine	136	220	100	2.6	Nitrification, N-assimilation
50	Tang *et al.* (1996)	50% compost, 50% chaff	Triethylamine	320-3450	11-60	100	140	

Table 2. Removal in laboratory biotrickling filters of commonly found odorous compounds and VOCs.

Ref. #	Authors	Packing	Waste gas composition		EBRT	Performance		Remarks
			Pollutant	Conc. (mg/m^3)	(s)	RE (%)	EC (g/m^3.h)	
Non-chlorinated VOCs								
22	Fortin and Deshusses (1999)	Lava rock or PP Pall rings	MTBE	600-1000	90	95	50	Long startup (>6 months)
29	Kirchner *et al.* (1989)	Activated carbon	Methyl ethyl ketone, propionaldehyde, or ethylacetate	10-90	1-6	50-90	Up to 160	Easily biodegradable compounds, similar removal as single pollutants
36	Lu *et al.* (1999)	Coal	BTEX	2200-2850	240	80	115	Temp. optimum 25-35^{0}C
42	Pol *et al.* (1998)	Lava rock	Styrene	104	23	98	32	
12	Cox and Deshusses (1999)	PP Pall rings	Toluene	400-3500	56	35-100	80	
Chlorinated VOCs								
16	Diks and Ottengraf (1991)	Ceramic saddles	DCM	1000-10000	60	20-100	157	Operation at neutral pH
6	Baltzis and Mpanias (1998)	Ceramic saddles	Dichlorobenzenes	250-4400	180-530	79-96	60	Removal rate o-chlorobenzene about half the rate of m-chlorobenzene
N and S-compounds								
40	Oh and Bartha (1997)	Perlite	Nitrobenzene	100-300	24	80-90	13.1	Ammonia stripping
10	Chung *et al.* (2000)	Ca-alginate beads	H_2S NH_3	80 116	72	>95	3.8 H_2S 5.6 NH_3	Cotreatment of H_2S and NH_3
1	Allen and Ellis (2000)	PP Pall rings	TRS methanol	64 (as S) 67	25	80-90 >95		Cotreatment of methanol and equal conc. of H_2S, MM, DMS, and DMDS
26	Hugler *et al.* (1999)		Carbon disulfide					

Table 3. On-site treatment by biofilters, grouped by type of facility: general description.

Ref. #	Authors	Location	Target pollutants	Reactor dimension Area x height (m^3)	Packing	Pretreatment
Wastewater treatment						
20	Finger *et al.*	Renton, WA	VOC, Cl-VOC, S, N, odor	1.5x0.9	Bark, soil peat, moss, compost	Humidification
33	LeBeau and Milligan	Tampa, FL	S	10.5x1.4	Top soil, peat, mulch	Humidification
55	Webster *et al.* (1996)	Fountain Valley, CA	VOC, Cl-VOC, S	1x1	Two units with GAC and yard waste compost	Air filter
47	Singleton *et al.* (1994)	Glen Falls, NY	S	Modular tray design		Humidification, temperature
23	Giggey *et al.*	Yarmouth, MA	VOC, S, odor	2800x0.9	Compost, bark mulch, wood chips	Humidification, chemical misting
60	Wolstenholme and Finger (1994)	Renton, WA	VOC, Cl-VOC, S, N, odor	1.5x0.9	Bark, topsoil, compost, peat moss, oyster shells	Humidification
59	Williams *et al.*	Martinez, CA	S, odor	33x1.2	Wood chips, yard waste compost, lime	Humidification
52	Vaith and Heydorn	Hillsborough, FL	S	18x1.2	Pine bark	Humidification
52	Vaith and Heydorn	Boca Grande, FL	S	10x1.2	Peat, wood chips, top soil	Humidification
52	Vaith and Heydorn	Charlotte, NC	S	1115x1.2	Wood chips, compost, perlite, granular fill	
7	Bonnin *et al.* (1997)	Carry Sausset, France	S, N, odor	60x0.8	Peat	
46	Singleton and Milligan	Albany, NY	S, odor	Modular tray design		
17	Ergas *et al.* (1992)	Carson, CA	VOC, Cl-VOC, S, odor	3x0.9	Compost, wood chips, oyster shell, perlite	
Composting (biosolids, rendering plants)						
2	Amirhor *et al.* (1994)	Darmouth, MA	S, N, odor	548x0.9	Bark mulch, wood chips, leaf compost	
30	Kolton-Shapira	Israel	VOC, S, N	25x1	Peat, polyurethane	Humidification, cooling
23	Giggey *et al.*	Lewiston-Auburn, MN	Odor	2800x0.9	Compost, bark mulch, wood chips	Humidification

Table 3, continued.

Ref. #	Authors	Location	Target pollutants	Reactor dimension Area x height (m^3)	Packing	Pretreatment
3	Amirhor *et al.*	Somerset, MA	VOC, S, N, odor	1.2x1.2	Pine/spruce/fur or leaf/bark/woodchip	Ammonia scrubbing
43	Rands *et al.* (1981)	Moerewa, New Zealand	S	42x1	Compost	
37	Luo and Van Oostrom (1997)		Odor	0.31x0.77	Bark	Dust removal in cyclone separator, cooling
32	Lau *et al.* (1996)	Fraser Valley, Canada	N	504x1	Compost, wood waste, loam soil	
Livestock						
27	Janni and Nicolai (2000)	Cow dairy	S, N, odor	14.4x0.9	Compost, wood chips	
27	Janni and Nicolai (2000)	Swine facility	S, N, odor	82x0.23	Compost, brush chips	
VOC remediation						
24	Graham	A refinery, CA	VOC	1.2x?	GAC	Humidification, temp. control
24	Graham	Camarillo, CA	BTEX	12x?	GAC	Humidification, temp. control
44	Romstad et al. (1998)	Richmond, CA	BTEX	1.3x1	compost, perllite	Humidification control
61	Wright et al (1997)	Hayward, CA	BTEX	1.5x1	Compost, perlite	Humidification control

Table 4. On-site treatment in biofilters, grouped by type of facility; performance of VOC and odorous compounds removal.

Ref. #	Authors	EBRT (s)	Startup (days)	Removal of VOCs			Removal of odorous S and N compounds			Remarks
				Pollutant	Conc. (mg/m^3)	RE (%)	Pollutant	Conc. (mg/m^3)	RE (%)	
Wastewater treatment										
20	Finger *et al.*	40-80	NA	Acetone	0.03-0.09	55	H_2S	0.02-0.17	>98	
				Benzene	0.01-0.24	25	Amines	**2-6 ppm**	ND	
				Xylenes	0.15-0.71	0	Odor	21-143 ou	>96	
				Chloroform	0.10-0.21	43				
				TCE	0.02-0.05	44				
				PCE	0.02-0.51	40				
33	LeBeau and Milligan	60	14				H_2S	7-120	100	
55	Webster *et al.* (1996)	17-70	NA	Benzene	0.01	36-93	H_2S	4.3	>99	VOC removal was much better in the GAC biofilter than in the compost biofilter
				Toluene	0.1	24-99				
				Xylenes	0.08	0-96				
				DCM	0.07	0-35				
				Chloroform	0.06	0-11				
				TCE	0.01	0-82				
				PCE	0.37	0-98				
				TGNMO	26 ppm	0-99				
47	Singleton *et al.*, (1994)	NA	NA				H_2S	28-170	91-96	
23	Giggey *et al.* at Yarmouth, CA	45	NA	α-pinene	675 ppb	100	DMS	0.02	100	Low temperature
				β-pinene	345 ppb	100	DMDS	0.16	100	
				D-limonene	70 ppb	97	Carbon disulfide	0.01	100	
							MM	0.006	100	
							Odor	214 D/T	94	
60	Wolstenholme and Finger (1994)	40-60	NA	Acetone	0.03-0.09	55	H_2S	1.5-34	97	
				Benzene	0.01-0.25	25	Mercaptans	0.16-3.8 ppm	62	
				Xylenes	0.15-0.7	0	Amines	2.5-6 ppm	>60	
				TCE	0.02-0.05	44	Odor	870-1500 ou	85	
				PCE	0.02-0.5	40				
				Chloroform	0.10-0.21	43				
59	Williams *et al.*	38	NA				H_2S	0.11	>95	
							DMS	0.03	>68	
							DMDS	0.01	>41	
							MM	0.054	>90	