Literature Review of Air Pollution Control Biofilters and Biotrickling Filters for Odor and Volatile Organic Compound Removal

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A literature study was conducted to compare the feasibility of biofilters and biotrickling filters for the treatment of complex odorous waste air containing hydrogen sulfide (H_2S), organic reduced sulfur compounds, and chlorinated and nonchlorinated volatile organic compounds (VOCs). About 40 pilot-plant studies and full-scale applications at wastewater treatment plants and other facilities were reviewed. Reactor design and pollutant removal efficiencies were summarized in tables for easy reference and for a perspective on the current state of the art, 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 VOC-containing odorous waste air from wastewater treatment plants and other facilities. VOC removal efficiencies were in general lower than those of H_2S and odor, although concentrations of individual VOC species were relatively low. This indicates that for effective treatment of VOC-containing odorous waste air, the design and operation should emphasize VOC removal as the rate-limiting parameter. © 2005 American Institute of Chemical Engineers Environ Prog, 24: 254–267, 2005

Keywords: odor control; VOCs; H_2S; biofilter; biotrickling filter; POTW

INTRODUCTION

Waste air treatment at publicly owned wastewater treatment facilities (POTWs) usually focuses on reducing odor nuisance complaints from neighboring communities. For this purpose, chemical scrubbers are often used, which are effective in removing hydrogen sulfide (H_2S), the major odor-causing agent at POTWs. Apart from H_2S, the waste air contains a variety of volatile organic compounds (VOCs), usually at low concentrations. The VOCs include aromatics and chlorinated species. Development of technologies that combine effective removal of odorous sulfur species with the removal of VOCs is warranted because of growing concern about the potential toxicity and carcinogenicity of these VOCs. This is reflected by regulations on VOC emissions becoming stricter, such as federal regulations (the U.S. EPA National Emission Standards for Hazardous Air Pollutants and Title V permitting) as well as local and state regulations that may have additional requirements. For instance, the South Coast Air Quality Management District for the California South Coast Air Basin has several programs (Regulations XIII New Source Review; Regulations XIV Toxic Air Contaminants) that aim at reducing toxic VOC emissions from industrial sources.

In 1999 the University of California, Davis (UCD), the University of California, Riverside (UCR), and the

Hyperion Wastewater Treatment Plant (HTP) in Los Angeles started a collaboration to determine the efficacy of biological waste air 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 [1–3]. As part of this project, a literature survey was conducted to evaluate the simultaneous removal of odor and VOCs by biological technologies at POTWs and other facilities with similar composition of waste air. The findings are reported herein. Subsequently, HTP and other POTWs in Southern California have started wider implementation of biological techniques for the control of their odorous exhausts.

The principles of biological waste air treatment and the advantages over chemical and physical techniques have been extensively reviewed [4–12]. Biological waste air treatment is an established technology, although still in development with research on, for instance, the use of new media and designs [13–15], microbial structure analysis [16], and modeling of H_2S and VOC removal [17–19]. The literature also provides many laboratory studies on pollutant removal in biofilters and biotrickling filters (Tables 1 and 2). Nearly all of these studies address the removal of single pollutants under constant operating conditions. Such conditions are highly unusual at POTWs and other facilities. For instance, the headworks ventilation air at HTP and most other POTWs is a complex mixture of H_2S and other reduced sulfur compounds (such as carbon disulfide, dimethyl sulfide, and methyl mercaptan), aromatic hydrocarbons (such as toluene, benzene, and xylenes), chlorinated hydrocarbons [such as methylene chloride, chloroform, trichloroethylene (TCE) and perchloroethylene (PCE)], and possibly nitrogen compounds. The actual composition and individual concentrations often varies subtsantially over time. At HTP, H_2S is the major component with concentrations in general between 5 and 50 parts per million (ppm), depending on the time of day. Other pollutants are present at lower concentrations, typically between 0 and 150 parts per billion (ppb). Apart from fluctuations in the waste air composition, the performance of full-scale biofilters and biotrickling filters in the field may be affected by unsteady conditions (such as temperature and relative humidity) and discontinuous pollutant supply, system maintenance, or breakdowns [20].

A large number of biofilters have been installed throughout the world. In the United States alone, the number of biofilters installed at POTWs by seven major vendors is estimated to exceed 300. However, performance data are often published in sources difficult to access or not published at all, which makes an overall assessment of the technology difficult. In addition, biotrickling filtration is a relatively new technique, and experiences with biotrickling filters have mainly been at the pilot-scale.

In this paper we present an overview of field experiences with biofilters and biotrickling filters. The main focus is on biological treatment of VOC-containing odorous waste air at POTWs in the United States, but other facilities with similar composition waste air have been included as well. Reactor design and pollutant removal efficiencies 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.

APPROACH AND DEFINITIONS

The following sources were used for this survey: scientific journals, conference proceedings, progress reports, and review articles discussing case studies. The latter included documents provided by vendors supplying biofilters and biotrickling filters. This survey covers the developments from about 1990 up to 2004. The results are grouped in tables as follows:

- Tables 1 and 2: Examples of laboratory research with biofilters and biotrickling filters, respectively, treating odorous compounds and VOCs that are often found in waste air from wastewater treatment.
- Tables 3 and 4: Projects with on-site foul air treatment in biofilters with a general description of biofilter design (Table 3) and a summary of pollutant removal efficiencies (Table 4).
- Tables 5 and 6: Projects with on-site foul air treatment in biotrickling filters with a general description of biotrickling filter design (Table 5) and a summary of pollutant removal efficiencies (Table 6).

Although Tables 3 to 6 primarily 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 treating waste air from existing operations at wastewater treatment or other facilities.

Table entries include reactor design and operation and performance parameters. Design and operation of biofilters are described by the composition of the waste air 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 air. 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 follows:

$$EBRT = \frac{V}{F} \qquad \text{(s)} \tag{1}$$

$$RE = \frac{C_i - C_o}{C_i} \times 100 \qquad (\%) \tag{2}$$

$$EC = \frac{F(C_i - C_o)}{V} \qquad (\text{gm}^{-3}\,\text{h}^{-1}) \tag{3}$$

where V is the volume (m^3) of the packed bed section; F is the gas flow rate (m^3/h); and C_i and C_o are the inlet and outlet concentration (g/m^3) of the pollutant, re-

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

Reference	Packing	Waste air composition: Pollutant	Waste air composition: Concentration (mg/m^3)	EBRT (s)	Performance: RE (%)	Performance: EC ($gm^{-3}h^{-1}$)	Remarks
Nonchlorinated VOCs							
[21]	Peat with burned clay and lime	Styrene	250	81	70	12	Addition of nutrients and pH buffering lime required
[22]	Peat	Ethanol	3700	150	30	30	Water content of 50–70%; EC = 4 g m^{-3} h^{-1} at 35% water
[23]	Conditioned peat	Xylene-isomers	2300	102	52	43	EC *m*-xylene > *p*-xylene > *o*-xylene
[24]	50% compost, 50% perlite	Hexane	175–700	30–120	>95	21	Hexane mass loading rate was held constant
[25]	40% peat, 60% perlite	Toluene	620–2810	162–516	66–100	5–25	
[26]	66% peat, 33% glass beads	Phenol	1000–1500	54	>93	124	
Chlorinated VOCs							
[27]	50% compost, 50% perlite, oyster shells	DCM	10–175	42–60	>98	15	Rapid acidification and declining RE at 50 ppm
[28]	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%
[29]	Composted leafs, 10% GAC	TCE	25–250	336	>95	2.4	Cometabolism of TCE with methane/propane
Odorous N and S compounds							
[30]	33% peat, 33% perlite, 33% fern chips	Methylamine	136	220	100	2.6	Nitrification, N-assimilation
[31]	36% compost, 36% activated sludge, 27% GAC	NH_3	14–350	68	92–100	17	
[32]	Compost, 10% limestone	DMS	400	27	97	48	Strong inhibition by isobutyraldehyde
[33]	50% compost, 50% chaff	Triethylamine	320–3450	11–60	100	140	
[34]	Compost, various sources	H_2S	7–3750	23–200	>99.9	12–130	Performance depended greatly on type of compost

spectively. 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 by nature of field operation). Consequently, large fluctuations in the RE and/or EC were sometimes reported. 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 Air Treatment in Biofilters and Biotrickling Filters

Laboratory studies have demonstrated the biodegradation of a wide range of pollutants in biofilters and biotrickling filters. Selected examples are presented in Tables 1 and 2. These tables illustrate that most pollutants present in POTW waste air can be removed in biofilters and biotrickling filters. Efficient removal—as

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

Reference	Packing	Waste air composition: Pollutant	Waste air composition: Concentration (mg/m^3)	EBRT (s)	Performance: RE (%)	Performance: EC ($g\ m^{-3}\ h^{-1}$)	Remarks
Nonchlorinated VOCs							
[35]	PP Pall rings	Toluene	400–3500	56	35–100	80	
[36]	Lava rock or PP Pall rings	MTBE	600–1000	90	95	50	Long startup (>6 months)
[37]	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
[38]	Coal	BTEX	2200–2850	240	80	115	Temp. optimum 25–35°C
[39]	Lava rock	Styrene	104	23	98	32	
Chlorinated VOCs							
[40]	Ceramic saddles	Dichlorobenzenes	250–4400	180–530	79–96	60	Removal rate *o*-chlorobenzene about half the rate of *m*-chlorobenzene
[41]	Ceramic saddles	DCM	1000–10000	60	20–100	157	Operation at neutral pH
Odorous N and S compounds							
[42]	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
[43]	Ca-alginate beads	H_2S NH_3	80 116	72	>95	3.8 5.6	Cotreatment of H_2S and NH_3
[44]	Perlite	Nitrobenzene	100–300	24	80–90	13.1	Ammonia stripping

single pollutants in synthetic waste air streams—has been demonstrated for odorous sulfur and amino-nitrogen compounds, (oxygenated) aliphatics, aromatics, and chlorinated compounds. The removal of poorly biodegradable compounds (such as chlorobenzenes, MTBE), compounds that require cometabolism (TCE), or anaerobic conditions (PCE) has also been observed.

The elimination capacity of the VOC undergoing treatment depends on many factors related to the design and operation of the bioreactor, as well as the properties of the pollutant. In particular, the water solubility and pollutant Henry coefficient are important [45]. For easily biodegradable and hydrophilic VOCs, ECs of up to nearly 150 $gm^{-3}\ h^{-1}$ can be obtained. Hydrophobic VOCs such as alkanes are usually removed slower because of mass transfer limitations [46]. In addition, the EC can also be limited by the biological reaction rate, that is, in the case of poorly biodegradable and/or toxic pollutants. Interestingly, some poorly biodegradable VOCs such as MTBE require a long start-up phase (months rather than days) before significant removal is observed, but once the reactor reaches steady state, the EC is comparable to that of more easily biodegradable pollutants [36].

Depending on the inlet concentration and EBRT, removal efficiencies of individual compounds in biofilters and biotrickling filters can be near 100%. By comparing Tables 1 and 2, one can observe that biotrickling filters are in general operated at a shorter EBRT and at relatively high inlet concentrations. The maximum EC reported from laboratory studies was the highest in biotrickling filters, possibly as a result of better control of reaction conditions and higher biomass content, although it should be noted that the maximum EC is in general observed at relatively high pollutant concentrations when the removal efficiency is <100%. Near-complete pollutant removal is usually observed only at lower inlet concentrations and longer EBRTs. Finally, comparison of the studies in Tables 1 and 2 is very difficult because many of the systems were not tested to failure. 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 pollutant/substrate dependent.

Field Experiences with Biofilters

Table 3 presents an overview of projects and full-scale applications of biofilters. Most of those listed in Table 3 have been installed at POTWs, with waste air 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, such as peat, compost (from various sources), bark, and wood chips. Packing materials 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 mineral 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, perlite, or woodchips considerably extends the life of natural packings. To keep the pressure drop across the biofilter to a certain maximum (~10 cm water column), the vast majority of biofilters contain a packed bed with a height typically less than 1.2 m. Because of this restriction, biofilters in general require a larger footprint than that of biotrickling filters. Still, it has been reported that some biofilters operated at EBRTs longer than 1 min were constructed with bed height as high as 2.4 m, without significant bed compaction or pressure drop problems.

Moisture content of the packing has been identified as the most critical parameter to control in biofilters [68]. 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 often >80% at POTWs, the waste air is frequently humidified in packed towers before entering the biofilter. Most applications also have a sprinkling system for direct additional water supply onto the packed bed. Prehumidification in spray towers also removes particulate matter from the waste air, thus preventing clogging of the packed bed. An alternative would be the use of cyclones, electrostatic precipitation separators, or venture scrubbers, although these are expensive. Waste air from composting facilities frequently has temperatures greater than the optimum of most microorganisms (15–35° C). In those cases, cooling may be achieved by evaporative cooling after addition of dilution air or by using heat exchangers. Both options substantially increase the overall treatment costs.

Performance data of biofilters at industrial applications are summarized in Table 4. Concentrations of individual pollutants are in general much lower than those of substances 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 EBRTs from 20 to 200 s, which is comparable to that of laboratory studies. Removal of H_2S, the major component in most odorous, industrial waste air, is in general between 90 and 100%, indicating that significant odor reduction can be obtained by treatment in biofilters. The few studies that include odor panel analysis confirm this: the observed odor reduction is often >80%. Removal of odorous compounds other than H_2S (such as DMS, DMDS, and MM) is often lower, with reported removal efficiencies ranging from about 20 to 100%. A few studies have also focused on the removal of VOCs (see, for example, Deshusses *et al.* [1], Ergas *et al.* [49], Webster *et al.* [55], and Wolstenholme & Finger [57]). These seem to indicate that biofilters for H_2S and odor treatment are also capable of removing a broad range of VOCs. However, VOC removal efficiencies are generally <90% (sometimes as low as 20%, although usually with a 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: random dump plastic packing, lava rock, structured packing, and open-pore polyurethane foam. The high porosity of these packings causes less headloss compared to that of 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 air containing reduced sulfur compounds, production of sulfuric acid with declining pH and/or accumulation of sodium sulfate (after neutralization with caustic soda) is an important design parameter. However, most references cited in Table 5 provided limited information on parameters related to liquid recirculation, 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 relatively low EBRTs. Thus, biotrickling filters appear to be a good option when the gas to be treated contains high concentrations of H_2S and possibly other reduced sulfur compounds. Relatively few 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 included VOCs indicate that, although H_2S removal may be faster in biotrickling filters, the VOC removal is in general lower than that in biofilters.

DISCUSSION

H_2S/odor removal in biofilters and biotrickling filters has been well documented and many applications can

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

Reference	Location	Target pollutants	Reactor dimension area × height (m^2 × m)	Packing	Pretreatment
Publicly owned treatment works					
[1]	Headworks; Los Angeles, CA	VOC, Cl-VOC, S, odor	0.29 × 1	Compost, perlite, oyster shell	NS
[47, 48]	Headworks; Ojai Valley, CA	VOC, Cl-VOC, S	2.36 × 0.77	Lava rock	NS
[49]	Screening; Carson, CA	VOC, Cl-VOC, S, odor	3 × 0.9	Compost, wood chips, oyster shell, perlite	NS
[50]	Septage treatment; Yarmouth, MA	VOC, S, odor	2800 × 0.9	Compost, bark mulch, wood chips	Humidification, chemical misting
[51]	Lift station; Tampa, FL	S	10.5 × 1.4	Top soil, peat, mulch	Humidification
[52]	Sludge handling; Albany, NY	S, odor	Modular tray design	NS	NS
[53]	Sludge handling; Glen Falls, NY	S	Modular tray design	NS	Humidification, temperature
[54]	Pump station; Hillsborough, FL	S	18 × 1.2	Pine bark	Humidification
[54]	Lift station; Boca Grande, FL	S	10 × 1.2	Peat, wood chips, top soil	Humidification
[54]	Headworks; Charlotte, NC	S	1115 × 1.2	Wood chips, compost, perlite, granular fill	NS
[55]	Headworks; Fountain Valley, CA	VOC, Cl-VOC, S	1 × 1	Two units with GAC and yard waste compost	Air filter
[56]	DAF thickening; Martinez, CA	S, odor	33 × 1.2	Wood chips, yard waste compost, lime	Humidification
[57]	DAF thickening; Renton, WA	VOC, Cl-VOC, S, N, odor	1.5 × 0.9	Bark, topsoil, compost, peat moss, oyster shells	Humidification
Biosolids composting					
[50]	Lewiston-Auburn, MN	Odor	2800 × 0.9	Compost, bark mulch, wood chips	Humidification
[58]	Darmouth, MA	S, N, odor	548 × 0.9	Bark mulch, wood chips, leaf compost	NS
[59]	Somerset, MA	VOC, S, N, odor	1.2 × 1.2	Pine/spruce/fur or leaf/bark/ woodchip	Ammonia scrubbing
[60]	Fraser Valley, Canada	N	504 × 1	Compost, wood waste, loam soil	
[61]	Moerewa, New Zealand	S	42 × 1	Compost	
Rendering plants					
[62]	Israel	VOC, S, N	25 × 1	Peat, polyurethane	Humidification, cooling
[63]		Odor	0.31 × 0.77	Bark	Dust removal in cyclone separator, cooling
Livestock					
[64]	Cow manure handling	S, N, odor	14.4 × 0.9	Compost, wood chips	
[64]	Swine manure handling	S, N, odor	82 × 0.23	Compost, brush chips	
VOC remediation					
[65]	Refinery; location NS	VOC	1.2 × NS	GAC	Humidification, temp. control
[65]	Soil vapor extraction; Camarillo, CA	BTEX	12 × NS	GAC	Humidification, temp. control
[66]	Soil vapor extraction; Richmond, CA	BTEX	1.3 × 1	Compost, perlite	Humidification control
[67]	Soil vapor extraction; Hayward, CA	BTEX	1.5 × 1	Compost, perlite	Humidification control

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

Reference	EBRT (s)	Start-up (days)	Removal of VOCs: Pollutant	Concentration (mg/m^3)	RE (%)	Removal of odorous S and N compounds: Pollutant	Concentration (mg/m^3)	RE (%)	Remarks
Publicly owned treatment works									
[1]	14–69	14	Benzene	0.002–0.003	0–50	H_2S	10–50	>99	
			Xylenes	0.18–0.66	40–75	Carbon disulfide	0.02–0.03	32–36	
			Toluene	0.077–0.23	42–86	MM	0.30–0.33	91–94	
			Dichlorobenzene	0.024–0.049	43–60	DMS	0.02–0.03	0–21	
			Chloroform	0.25–0.40	0	Carbonyl sulfide	0.05–0.13	30–35	
			PCE	0.35–0.97	0	Odor (D/T)	35,000–46,360	>99	
[47, 48]	18–54	NS	MTBE	1.8	20	H_2S	0.01–42	>90	
			Acetone	1.6	80				
			Toluene	2.3	60				
			Xylenes	1.3	40				
			DCM	3.5	30				
			Chloroform	0.3	15				
[49]	45–180	NS	Benzene	3.0	83–95	H_2S	13.9	>99	Poor removal of Cl-VOC
			Toluene	4.0	88–97	Odor	1.2e6 OU	>99	
			m,p-Xylene	1.1	88–93				
			o-Xylene	0.4	88–91				
[50]	45	NS	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 (D/T)	214	94	
[51]	60	14				H_2S	7–120	100	
[52]	150	NS				H_2S	200	100	
						DMS	8.8	21	
						DMDS	0.78	0	
						MM	22	66	
						Odor (OU)	247,000	>99	
[53]	NS	NS				H_2S	28–170	91–96	
[54]; Hillsborough, FL	115	NS				H_2S	140	99.5	
						DMDS	936	97	
						Carbon disulfide	618	82	
						MM	330	100	
[54]; Boca Grande, FL	130	NS				H_2S	140	100	
[54]; Charlotte, NC	111	NS				DMS	625	100	
						Carbon disulfide	448	100	
[55]	17–70	NS	Benzene	0.01	36–93	H_2S	4.3	>99	VOC removal was much better in the GAC biofilter than in the compost biofilter
			Tolunene	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				
[56]	38	NS				H_2S	0.11	>95	
						DMS	0.03	>68	
						DMDS	0.01	>41	
						MM	0.054	>90	
						Odor (D/T)	382	98	
[57]	40–60	NS	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 (OU)	870–1500	85	
			PCE	0.02–0.5	40				
			Chloroform	0.10–0.21	43				
Biosolids composting									
[50]	72	NS				Odor (D/T)	115–338	90	Low temp, inhibition by NH_3
[58]	55–95	NS				DMS	0.08	55	
						DMDS	1.1	83	
						MM	0.034	>90	
						NH_3	34–106	98–99	
						Odor (D/T)	500–970	>80	

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

			Removal of VOCs			Removal of odorous S and N compounds			
Reference	**EBRT (s)**	**Start-up (days)**	**Pollutant**	**Concentration (mg/m^3)**	**RE (%)**	**Pollutant**	**Concentration (mg/m^3)**	**RE (%)**	**Remarks**
[59]	90	NS	THC (methane)	31	15	DMS	0.38	25–36	
						DMDS	0.56	19–28	
						MM	0.10	20–49	
						NH_3		59–79	
						Odor (D/T)	394	64	
[60]	36–55					NH_3	28–50	95	
[61]	~170					H_2S	13–1150	>99	
Rendering plants									
[62]	17	NS	Aldehydes	1.4–2.1 ppm	20–40	H_2S	4.2	90	Temp. up to 40°C
						Amines	20–40 ppm	15–65	
[63]	207					Odor (OU/m^3)	0.49–1.1e6	75–91	
Livestock									
[64]; cow dairy	5	60				H_2S	0.01–0.27	75–100	
						NH_3	1.4–8.2	60–100	
						Odor (OU)	320–1450	57–95	
[64]; swine facility	5	NS				H_2S	0.17–1.1	74–98	
						NH_3	0.36–8.2	0–75	
						Odor (OU)	199–862	50–86	
VOC remediation									
[65]; refinery	120–180	NS	Total VOCs	80–5000 ppm	97–100				
[65]; Camarillo, CA	34	NS	BTEX	1.6–36 ppm	92–99				
			ROC	73–110 ppm	49–72				
[66]	282–366	20	BTEX	0–55 ppm	90–100				
[67]	60–120	21	BTEX	75–150 ppm	50–100				

be found at POTWs and other facilities. Comparing the two systems, biotrickling filters appear to perform better when the waste air 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. For example, a recent study has demonstrated that biotrickling filters can effectively remove H_2S at an EBRT as low as 1.6 s, which is the normal gas contact time in chemical scrubbers at POTWs [78]. Biofilters tend to be used for applications with lower H_2S loadings because of the concerns of inhibition of H_2S removal and packing deterioration by sulfuric acid production over the long term. However, there are examples of successful biofilters operated at low pH and high H_2S concentrations in Tables 1 and 4.

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 raised by careful examination of the data cannot be answered from just reading the cited references. Likewise, comparing the biofilter results in Tables 3 and 4 with each other and with the biotrickling filter results in Tables 5 and 6 is hampered by the large variety of materials used as packings in biofiltration and biotrickling filtration studies. This survey must thus 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 evident. Simultaneous removal of VOCs, including aliphatics, aromatics, and chlorinated compounds, has frequently been observed, and therefore one can reasonably affirm that biofilters and biotrickling filters are a positive development toward the control of air toxic releases from POTWs. Although only a few studies have investigated the cotreatment of VOCs and H_2S, they seem to indicate that biofilters can achieve VOC removal efficiencies higher than those of 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.

Making all allowances for these uncertainties, the literature strongly indicates that for both biofilters and biotrickling filters, VOC removal is the limiting process when treating complex odorous waste air containing both H_2S and VOCs. The design and operation of such bioreactors should therefore aim at maximizing VOC removal. One can reasonably speculate that, in most cases, this may result in improved odor removal, although further proof in the field is required. In both biofilters and biotrickling filters, VOC removal is not complete, although the VOC load and elimination capacity in field applications is orders of magnitude smaller than the maximum elimination capacity observed in the laboratory. Inhibition of VOC removal by the presence of H_2S is unlikely. Laboratory studies

Table 5. On-site treatment in biotrickling filters, grouped by type of facility: general description.

Reference	Location	Target pollutants	Packed bed diam. × H (m)	Packing	Gas flow	pH-control	Liquid flow	Superficial liquid velocity (m/h)
Publicly owned treatment works								
[1]	Headworks; Los Angeles, CA	VOC, Cl-VOC, S, odor	1.5 × 2.1	Structured PVC	Up	Yes, pH 7–9, caustic soda	Continuous	0.8
[69]	Sewer trunkline and pump vent	S, odor	1.8 × 2.8	Polyurethane foam	Up	Yes, pH 1.8–2.2, using plant water	Continuous	1.7
[70]	Stripper; location NS	S, odor	NS	Presumably a polyurethane foam	Up	Yes, caustic soda	Continuous	NS
[70]	Settling tank; location NS	S	NS	Presumably a polyurethane foam	Up	Yes, caustic soda	Continuous	NS
[71]	Headworks; Los Angeles, CA	S	Volume 10 m^3	Lava rock	Down	NA	Continuous	NS
[72]	Primary clarifier; Fountain Valley, CA	VOC, Cl-VOC, S	0.74 × 4.5	Continuous synthetic type	NA	Yes, caustic soda	Continuous	NS
[73]	Industrial wastewater treatment; San Diego, CA	VOC, Cl-VOC, S	3.1 × 4.2	Random inorganic	Down	Yes, caustic soda	Continuous	NS
Biosolids composting								
[74]	Germany	VOC, odor	1.95 × 2.9	PVC	Up	NS	Continuous	1.1
VOC remediation								
[20]	Bath tub manufacturer; Anaheim, CA	VOC	0.8 × 6.8 (2 units)	Jaeger Tripack spheres	Down	Yes, pH 6–8, caustic soda	Continuous	8.5
[75]	Spray paint booth; San Diego, CA	VOC	0.6 × 1.6	Random inorganic	Down	Yes	Continuous	NS
Other								
M+W Zander Facility Engineering [case study in 11]	Cigarette production; Germany	Odor	6 units, total volume 500 m^3, height 2.5 m	Polyurethane foam	Down	NS	Intermittent trickling	NS
[76, 77]	Sponge manufacturing; Mexico	S	2 × 12.2 (2 units)	Structured packing	Up	Yes, caustic soda	Continuous	NS

Table 6. On-site treatment in biotrickling filters, grouped by type of facility; performance VOC and odorous compounds removal.

			Removal of VOCs			Removal of odorous S and N compounds			
Reference	**EBRT (s)**	**Start-up (days)**	**Pollutant**	**Concentration (mg/m^3)**	**RE (%)**	**Pollutant**	**Concentration (mg/m^3)**	**RE (%)**	**Remarks**
Publicly owned treatment works									
[1]	24	28	Benzene	0.002–0.003	0	H_2S	10–50	>99	
			Xylenes	0.18–0.66	0–23	Carbon disulfide	0.02–0.03	0	
			Toluene	0.077–0.23	0–17	MM	0.30–0.33	64–72	
			Dichlorobenzene	0.024–0.049	0–6	DMS	0.02–0.03	0	
			Chloroform	0.25–0.40	0	Carbonyl sulfide	0.05–0.13	0	
			DCM	0.14–0.32	0	Odor (D/T)	35,000–46,360	97–99	
			PCE	0.35–0.97	0				
[69]	1.6–2.3	10	Benzene	0.5	32	H_2S	7–35	>99	Max. EC of H_2S ~105 g m^{-3} h^{-1}
			p + *m*-Xylene	2.1	41	Carbon disulfide	0.22 ± 0.06	35 ± 5	
			o-Xylene	0.5	44	MM	0.39 ± 0.07	67 ± 11	Avg. ± SD. *N* = 23 for S, *N* = 9 for odor panel. Unit replaces an existing chemical scrubber
			Toluene	2.8	29	COS	0.20 ± 0.02	44 ± 11	
			Ethyl benzene	0.6	41	Odor (D/T)	1980 ± 480	65 ± 21	
			DCM	0.5	36				
			Chloroform	1.6	30				
			TCE	0.08	46				
			PCE	1.5	28				
[70]; stripper	NS	14				H_2S	50–200	>95	
						Odor	1.2E6 OU/m^3	>99	
[70]; settling tank	NS	14				H_2S	300–1000	>95	
						Odor	3.5E6 OU/m^3	>95	
[71]	14	3				H_2S	14–100	99	Unit replaces an existing chemical scrubber
[72]	11–20	NS	Benzene	0–0.11	19–29	H_2S	1.8–16	87–99	System upsets, short acclimation and short EBRT probably caused poor Cl-VOC removal
			Xylenes	0.08–0.42	6–57				
			Toluene	0.10–0.74	50–74				
			1,1,1,-Trichloro-ethane	0.08–0.64	0–38				
			Carbon tetrachloride	0.003–0.012	2–15				
			Chloroform	0.05–0.17	0–25				
			DCM	0.07–0.57	0–61				
			TCE	0.01–0.04	0–24				
			PCE	0.36–4.8	0–8				
			Vinylchloride	0.003–0.02	0–13				
[73]	36	30–60	Benzene	0.03	59	H_2S	0–2	>99	
			Xylenes	3.5	92				
			Toluene	0.7	85				
			MTBE	0.09	60				
			Chloroform	0.01	3				
			DCM	1.2	11				
			PCE	0.02	0				
Biosolids composting									
[74]	25–100	NS	TOC	NS	30–70	Odor (OU/m^3)	5000–60,000	90–99	
VOC remediation									
[20]	126	NS	Styrene	Up to 800	70–85				
[75]	11–39	NS	THC	~10–20	83–93				
Other									
M+W Zander Facility Engineering [case study in 11]	11	60				Odor (OU)	800–1200	>90	
[76, 77]	41	180				H_2S	NS	99	
						Carbon disulfide	Up to 8000	90	

showed that toluene [79] and MTBE [1] removal in single-stage biotrickling filters for cotreatment of H_2S and the VOC were not affected by H_2S in concentrations up to at least 150 ppm. Likewise, Sologar *et al.* [18] did not observe significant interaction effects between H_2S and methanol during cotreatment in a biotrickling filter. H_2SO_4 production from sulfide oxidation and decreasing pH potentially interfere with VOC biodegradation, given that most VOC degrading microorganisms prefer a neutral pH, although VOC removal at low pH in bioreactors treating VOC/H_2S mixtures has been observed [78–81]. Low pH might indeed have been the cause of poor VOC removal in some of the applications described in Tables 3 to 6, especially in biofilters where controlling the pH is more difficult to achieve than in biotrickling filters. On the other hand, VOC removal in

field biotrickling filters operated at a neutral pH was lower than expected (for example, see Deshusses *et al.* [1] and Torres *et al.* [72]). This indicates that factors other than the presence of H_2S or low pH could be involved. One factor of particular importance could be the relatively low concentration of the VOCs. Whereas a greater than 99% removal rate of 50–2000 ppm VOC can easily be achieved in the laboratory (Tables 1 and 2), as well as in full-scale systems in VOC remediation (Tables 4 and 6), resulting outlet concentrations are still 5–20 times higher than the concentrations present in the waste air of POTWs. Removal of such low concentrations (10–1000 ppb_v) has received scant attention in biological waste air treatment research, and it poses additional challenges to effective treatment. One point of concern is that VOC concentrations are too low to sustain an active, heterotrophic population degrading the VOCs [82]. This may be of particular importance in biotrickling filters, in that the packing, contrary to compost, does not initially contain a native population of microorganisms and alternative substrates that can be used to sustain heterotrophic organisms.

Waste air from liquid processes at POTWs typically contains relatively high concentrations of H_2S, whereas waste air from solids-handling processes can be highly odorous and have a more complex composition [83–85]. We believe that there are many opportunities for using biofilters and biotrickling filters as a replacement of the chemical scrubbers that are currently used for these waste air streams at many POTWs.

CONCLUSIONS

This survey confirms the feasibility of biofilters and biotrickling filters as effective H_2S and odor-treatment technologies for waste air from POTWs. Biological treatment also holds promise for removing VOCs, thereby potentially reducing the overall toxicity and carcinogenicity of the waste air. This may be significant to POTWs because they could receive credit toward overall removal of cumulative VOCs by regulatory agencies. However, VOC removal in field applications is lower than what has been achieved in the laboratory. This indicates that for effective treatment of complex odorous air streams the design and operation should emphasize VOC removal as the rate-limiting parameter.

APPENDIX

The following abbreviations are used:

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*-butyl ether
N = nitrogen compounds, organic and inorganic
NS = not specified
OU = odor unit
PCE = perchloroethylene
POTW(s) = publicly owned treatment work(s)
PP = polypropylene
PVC = poly(vinyl chloride)
RE = removal efficiency
ROC = nonmethane reactive organics
S = sulfur compounds, organic and inorganic
TCE = trichloroethylene
TGNMO = total gaseous nonmethane 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 at room temperature reduces to the following equation:

$$\text{Concentration } (g/m^3) = \frac{\text{Concentration } (ppm_v) \times \text{molecular weight of pollutant } (g/mol)}{24{,}776}$$

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