A comparison of removal performance of volatile organic and sulfurous compounds between odour abatement systems

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ABSTRACT

Three types of odour abatement systems in sewer networks in Australia were studied for 18 months to determine the removals of different compounds. Six volatile sulfurous compounds and seven volatile organic compounds (VOCs) were further investigated. All types of odour abatement systems exhibited good removal of hydrogen sulfide with the biotrickling filters (BTFs) showing the highest consistent removal. Biofilters outperformed BTFs and activated carbon (AC) filters in the removal of dimethyl mono-, di- and tri-sulfide species at the low inlet concentrations typically found. AC filters exhibited little VOC removal with no compound consistently identified as having a removal greater than 0%. Biofilters outperformed BTFs in VOC removal, yet both had high removal variability.

Key words | abstract, odour, odour abatement, sewer networks

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INTRODUCTION

Community tolerance for odours from sewer infrastructure is lessening, providing pressure to water utilities to target and treat odour emissions from sewer networks (Mudliar *et al.* 2010). Gas phase odour abatement systems within sewer networks typically target hydrogen sulfide (H_2S) as an odorant and overall odour indicator. However, other compounds can occur naturally or through trade waste in sewer headspaces, which are either odorous themselves or may impact on the performance of odorant removal in odour abatement systems (Sivret *et al.* 2013; Wang *et al.* 2014; Sivret *et al.* 2017).

Odour abatement systems in sewer networks are predominantly biological or physical adsorption based (Sivret & Stuetz 2010; Shammay *et al.* 2016a), although a range of other approaches are also provided (Koe & Tan 1990; Davidson *et al.* 2004; Apgar *et al.* 2007). Performance studies of odour abatement systems removing odorous compounds at different operating conditions are typically fairly limited in duration and in scope, in that non-H_2S compounds are measured either once only or infrequently (Shammay *et al.* 2016a). This is a result of non-H_2S compounds being difficult and costly to measure (Muñoz *et al.* 2010; Wang *et al.* 2014). What studies there are show that H_2S is generally removed well under most conditions; however, the removal of other odorous compounds is variable (Gostelow *et al.* 2001;

Iranpour *et al.* 2005; Wang *et al.* 2014; Shammay *et al.* 2016a; Shammay *et al.* 2016b). A summary of removal efficiencies of different compounds relevant to this study found in the literature, adapted from Shammay *et al.* (2016a), is provided in Table 1.

Gaseous treatment methods generally remove H_2S well with removals consistently above 80% for biological systems and consistently above 79% for activated carbon (AC) systems. AC systems exhibit consistent methyl mercaptan removals above 72%. All other volatile sulfur compound (VSC) and volatile organic compound (VOC) removals, particularly with halogenated VOC removal, are inconsistent and generally low depending on the technology type. With H_2S being identified as less of a universal marker for odour (Sivret *et al.* 2016), the removal of other odorants is becoming more important.

AC systems tend to be more cost effective than other technologies in treating foul air with low H_2S concentrations. They also have a shorter start up time than biological alternatives and can treat sporadic flows where biological systems tend to only partially treat peak concentrations. However, AC systems release contaminants more often than biological systems and suffer from high operating costs due to the need for carbon changeout. Biofilters are appropriate for relatively low stable loads and are cost

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Table 1 | Summary of performance of gas phase odour abatement systems

		Biofilter		Biotrickling filter		Activated carbon	
	Compound	Removal (%)	Consistency	Removal (%)	Consistency	Removal (%)	Consistency
Volatile sulfurous compounds	Hydrogen sulfide	83 to >99	Good	80 to >99	Good	79 to 100 (22 outlier)	Good
	Carbon disulfide	13 to 100	Poor	0 to 40	Poor	$-\infty$ to 41	Poor
	Methyl mercaptan	62 to 100	Medium	56 to 78 (−638 outlier)	Good	77 to 100 (52 outlier)	Good
	Dimethyl sulfide	0 to 100	Poor	0	Poor (3 samples from 1 study)	−75 to 93	Poor
	Dimethyl disulfide	97 to >99 (17 outlier)	Medium	nd	–	−2,254 to 100	Poor
	Dimethyl trisulfide	51.5 to 100	Poor (6 samples in 1 study)	nd	–	−545 to 100	Poor (19 samples in 1 study with big spread)
Volatile organic compounds	Benzene	25 to 100	Medium	0 to 59 (Generally 20 to 30)	Medium	86 to 99	Good
	Xylenes	−175 to 100	Poor	0 to 57 (92 is outlier)	Medium	88 to 100 (outlier study to as low as −7,713)	Medium
	Toluene	43 to 100	Medium	0 to 85	Medium	90 to 100 (2 outliers as low as −852)	Medium
	1,3,5-Trimethylbenzene	nd	–	nd	–	$-\infty$ to 100	Poor
	Ethylbenzene	84 to 88	Poor	21	Poor	$-\infty$ to 100	Medium
	Dichlorobenzene	−18 to 100	Medium	0 to 48	Medium	−47 to 100	Medium

nd – Not detected.

Good – Multiple studies, greater than 5, with 75% or more of studies showing the same outcome.

Medium – Multiple studies, greater than 3, showing different outcomes or few studies, less than 3, showing the same outcome.

Poor – Few studies, generally less than 3, showing different outcomes.

Negative values given where outlet concentration was greater than inlet concentration.

$-\infty$ – Outlet concentration was detected with none detected on the inlet.

Refer to Supplementary Material for references and inlet concentrations (available with the online version of this paper).

effective where space is available. There are many long-term studies showing the effectiveness of biofilters; however, removal of VOCs is generally low and inconsistent. Biotrickling filters (BTFs) provide a better level of control over removal rates than biofilters, particularly with intermittent peak concentrations, and are more cost effective for higher H_2S concentrations than AC systems (Shammay *et al.* 2016a).

METHODOLOGY

Site descriptions

Duplicate samples were taken from the inlet and outlet of 18 odour abatement systems in sewer networks (approximately 19 samples per site) or at the headworks of treatment plants in Sydney, Melbourne and Perth, Australia. In general, sites were selected so that they were not downstream of each other, in different catchments (where possible), contained mixed sewage (from both domestic and trade waste), and had a range of upstream chemical dosing.

Sites selected employed AC, BTFs or biofilters (BFs) as the most common forms of odour abatement in sewer networks (Sivret & Stuetz 2010). Details of sites investigated, including their empty bed residence times (EBRTs), are provided in Table 2.

Sample analysis

VOC analysis

VOC analysis was performed in duplicate using gas chromatography coupled to mass spectrometry (GC-MS) (Agilent 6890NGC, 5973NMSD, Agilent Technologies). Helium was used as the carrier gas at a flow rate of 1.8 mL/min. The temperature program for the GC was initially held at 50 °C for 2 min and then raised to 220 °C at a rate of 15 °C /min. The mass spectrometer acquired data in scan mode with mass-to-charge (m/z) intervals ranging from 35 to 335. The identity of compounds was verified using reference standards, by initially matching the mass spectra with a mass spectrum library (NIST02 library) available in the GC-MS system.

VSCs analysis

VSC bag samples were connected to an Air Server (CIA 8, Markes International, UK) and collected onto a specialised sulfur cold trap (U-T6SUL, Markes International, UK) prior to injection. Sample analysis was performed using a gas chromatograph equipped with a sulfur chemiluminescence detector (SCD) (7890N GC and 355 SCD, Agilent Technologies, USA) with helium as the carrier gas (flow rate of 1 mL/min). The gas chromatograph column temperature was initially held at 37 °C for 3 min, then raised at a rate of 15 WC/min to 225 °C, and then held for 2 min. DB-VRX (30 m × 0.25 mm × 1.4 μm) (Cheng *et al.* 2007) was used as the analytical column for both VOC and VSC separation.

The sample and chemical analysis methodologies are described in more detail in Sivret *et al.* (2016) and Wang *et al.* (2015).

RESULTS

Data analysis

Data were filtered to remove spikes and to separate rain events and non-warm periods. The remaining data were evaluated for completeness. Sites where there were insufficient data to make a meaningful analysis (generally <5 data points) were removed. Thirteen sites (six AC filters, five biofilters and two BTFs) were deemed to have sufficient information to analyse six VSCs further. Eleven sites (six AC filters, three BFs and two BTFs) were deemed to have sufficient information to analyse seven VOCs further. VSCs and VOCs investigated are listed in Table 3. The removal of these VSCs and VOCs during warm and dry weather were also compared to non-warm periods and to wet periods as discussed further in Shammay *et al.* (2016b), with the resulting graphs found in Figures S-1 to S-6 in the Supplementary Material (available with the online version of this paper).

VSC removal

Figure 1 summarises the removal of all VSCs within the study for each odour abatement system type. Data summarised in Figure 1 are only for the warm, dry periods under investigation as this is the period that most odour abatement systems are designed to treat. A comparison of performance between warm and dry, cold and dry, and wet periods for each of the sites is provided in the Supplementary Material. It was found that, in general, warm and dry periods were the times when the units performed the most poorly.

Activated carbon filters

Four of the six AC filters analysed for VSC removal performed well in terms of H_2S and MM removal under

Table 2 | Sites investigated for AC, BTFs and biofilters (BFs) performance

Site	Year installed Note 1	City	Media type	Upstream chemical dosing	Type	Approx. EBRT	Volume	Species investigated after data filtering
AC-1	2003	Sydney	AC – Sodium hydroxide (NaOH) Impregnated	Ferrous chloride	Closed-topped	18.0 s	72 m^3	VOCs only
AC-2	2008	Sydney	AC – 50% Caustic impregnated/50% Virgin	None	Closed-topped	9.5 s	9.5 m^3	VOCs only
AC-3	2003	Sydney	AC – Sodium iodide (NaI) impregnated	Ferrous chloride	Closed-topped	3.0 s	12 m^3	
AC-4	2004	Sydney	AC – Caustic impregnated	None	Closed-topped	2.7 s	5.3 m^3	VOCs only
AC-5	2010	Sydney	AC – Caustic impregnated	Ferrous chloride	Closed-topped	3.0 s	12 m^3	VSCs and VOCs
AC-6	2003	Sydney	AC – Sodium iodide (NaI) impregnated	Ferrous chloride	Closed-topped	3.5 s	11 m^3	VSCs and VOCs
AC-7	2003	Sydney	AC – Sodium iodide (NaI) impregnated	Ferrous chloride	Closed-topped	4.4 s	13 m^3	VSCs only
AC-8	2009	Melbourne	AC – 75% activated alumina/25% proprietary 'high H$_2$S' activated carbon	None	Closed-topped	5.4 s	0.8 m^3	VSCs only
AC-9	2006	Melbourne	AC – Caustic impregnated/virgin carbon blend (proportions unknown)	None	Closed-topped	Unknown Note 3	Unknown	VSCs only
BF-1	2006	Sydney	BF – 65% bark chip, 25% soil, 5% peat, 5% manure	Ferrous chloride/ Magnesium hydroxide	Open-topped	76 s	21 m^3	VSCs only
BF-2	2009	Sydney	BF – 45% shredded wood, 35% composted wood, 10% pine bark nuggets, 2% compost, 3% mushroom compost, 5% limestone	Magnesium hydroxide	Open-topped	25 s	56 m^3	VSCs and VOCs
BF-3	2009	Melbourne	BF – Proprietary blend	None	Closed-topped	52 s	8.6 m^3	VSCs and VOCs
BF-4	2010	Melbourne	BF – Proprietary blend	None	Closed-topped	61 s	6.3 m^3	VSCs only
BF-5 Note 2	2011	Perth	BF – Proprietary blend	None	Closed-topped	34 s	8.6 m^3	VSCs and VOCs
BTF-1	2010	Sydney	BTF – Polyurethane foam	None	Closed-topped	5.5 s	3.0 m^3	VSCs and VOCs
BTF-3	2007	Perth	BTF – HD-QPAC	Oxygen	Closed-topped	256 s	71 m^3	VSCs and VOCs

Note 1 – All AC sites had AC replaced close to the start of the monitoring period.
Note 2 – First stage only of two-stage process investigated.
Note 3 – 0.39 m^3/s flow rate.

Table 3 | VSCs and VOCs investigated in AC filters, biofilters and BTFs

Compound	Median concentration ($\mu g/m^3$)	Appearance frequency (%)	95th percentile odour activity value	Odour threshold value ($\mu g/m^3$) (Nagata 2003)	Odorant ranking[a] (Sivret et al. 2016)
Volatile sulfurous compounds					
Hydrogen sulfide	1,880	100	68,400	0.576	K
Methyl mercaptan	293	93.7	16,600	0.14	K
Carbon disulfide	11.0	91.7	0.053	659	L
Dimethyl sulfide	65.4	93.3	3.22	77	H
Dimethyl disulfide	8.72	91.3	5.60	8.5	H
Dimethyl trisulfide	6.40	88.5	–	–	N/A
Volatile organic compounds					
Ethylbenzene	2.37	79.9	0.16	744	M
m,p-Xylene	7.35	75.7	1.45	254	H
o-Xylene	0.31	33.8	0.074	1,664	N
Toluene	31.7	91.3	0.42	1,254	M
Trimethylbenzene	31.8	74.5	0.77	595	L
Trichloromethane	55.4	82.9	0.021	18,707	L
1,4-Dichlorobenzene	1.05	40.3	–	–	N/A

[a]K – Key, H – High, L – Low, M – Medium: odorant rankings based on methodology defined in Sivret et al. (2016).
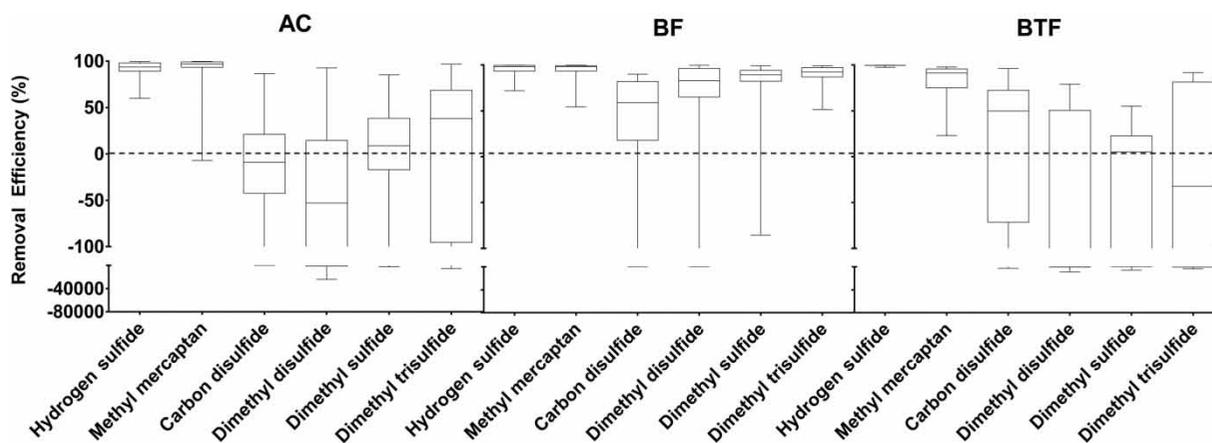
Figure 1 | Removal of volatile sulfurous compounds.

warm and dry conditions. The two remaining units still exhibited high removals compared to other VSCs. Overall, H_2S removal was greater than 90% in 74% of samples, where MM removal was greater than 90% in 90% of samples. This corroborates with what has been previously reported in the industry for H_2S and MM removal in AC systems (Wallis et al. 1996; Adams & Thomason 2004; Ball et al. 2004; Kyi 2014; Mohamed et al. 2014; Wang et al. 2014).

All AC filters exhibited poor removal for CS_2, DMS, DMDS and DMTS, which may be due to incompatible AC type used or too short EBRTs (Goyal et al. 2008; SWC 2011). In the case of DMDS, this may be due to the breakdown of MM generating DMDS (Bashkova et al. 2002). In most locations and for most non-H_2S and non-MM compounds, removal efficiency during non-warm periods was greater than during warm periods. This may be due to the removal mechanisms for DMS, DMDS,

DMTS and CS_2 being based on physisorption, which can be enhanced at lower temperatures, as opposed to the removal mechanisms for H_2S and MM being based on chemisorption, which is less temperature dependent (Shammay et al. 2016a).

Biofilters

H_2S was removed well in BFs with removals over 90% exhibited over 98% of measurements. MM exhibited similar removals to H_2S, with removals over 90% exhibited over 97% of measurements. This is consistent with the literature, where MM removal was reported as either similar or less than H_2S removal (Wolstenholme & Finger 1994; Deshusses et al. 2001; Converse et al. 2003; Alix & Williams 2006; Wang et al. 2014).

Of all the VSCs, carbon disulfide exhibited the most consistently poor removal efficiency across all BFs, particularly at the open-topped units. No measurements recorded over 99% removal efficiency and only 4.7% of measurements had removals above 90%. Relatively few literature sources discuss CS_2 removal, perhaps as it is not commonly identified as an odorant of concern (Sivret et al. 2016). The few found reported mixed removals, with some reporting low removals in the range of 13–36% (Deshusses et al. 2001; Converse et al. 2003; Sorensen & Baadsgard 2004) whilst others reported removals up to 100% (Giggey et al. 1994; Wang et al. 2014). Rojo et al. (2012) found the accumulation of biodegradation byproducts impacts the removal of CS_2 in laboratory-scale biofilters. The open-topped units in this study exhibited better performance during non-warm weather compared to warm weather, and the closed-topped units showed little difference between warm and non-warm weather. This implies, as expected, that the temperature within the closed-topped units is more stable than in the open-topped units. It also implies that CS_2 removal is inversely related to ambient temperature, which may mean that CS_2 is removed more from sorption than bioactivity (McNevin & Barford 2000).

Compared to H_2S and MM, the dimethyl mono-, di- and tri-methyl sulfides were removed poorly, with median removals between 82–92% and greater than 90% removal occurring only 41–57% of the time. This low and inconsistent removal agrees with some previous studies (Deshusses et al. 2001; Converse et al. 2003; Wang et al. 2014), but not with others (Giggey et al. 1994; Sorensen & Baadsgard 2004; Alix & Williams 2006). DMS was generally removed well, with DMDS and DMTS exhibiting poorer removals compared to DMS at most BF sites.

Biotrickling filters

BTFs performed well in terms of H_2S removal under all conditions, with 100% of measurements showing greater than 90% removal and 65% of measurements showing greater than 99% removal. This is consistent with literature, where typically greater than 99% removal is recorded for BTFs even at low EBRTs (Webster et al. 2000; Cox & Deshusses 2001; Deshusses et al. 2001; Gabriel et al. 2002; Gilani et al. 2004; Morton et al. 2004; Rousseille et al. 2011).

Similar to BFs, MM exhibited fair removals; however, not as high as H_2S, with median removal of 82.7% recorded and removals over 90% exhibited over 78% of measurements. This is greater than that recorded in the literature of 56–78% (Deshusses et al. 2001; Converse et al. 2003) with one study as low as 21% (Rousseille et al. 2011).

Greater variability was exhibited for MM removal in BTFs when compared with MM removal in BFs and H_2S removal in BTFs. Similar to BFs, this higher variability was not impacted by EBRT with BTF-1 (5.5 s EBRT) exhibiting similar or lower variability than BTF-3 (256 s EBRT), which agrees with other studies (Patria et al. 2001; Lebrero et al. 2012a).

Poor and variable removals were recorded for CS_2, with median removals of 51% identified. No measurements recorded over 99% removal efficiency and only 4.7% of measurements had removals above 90%. Relatively few literature sources discuss CS_2 removal. The few found reported either no removal (Deshusses et al. 2001; Converse et al. 2003) or low removals of 30–40% (Gabriel et al. 2002).

The dimethyl mono-, di- and tri-methyl sulfides were removed poorly with high variability. DMS exhibited the lowest removals with only 19.6% of all samples showing removals over 50%, compared with 29.8% and 41.5% of samples for DMDS and DMTS respectively. Significant negative removals were identified for all three compounds, the worst being for DMDS where 59% of measurements showed a negative removal compared with 41% and 45% for DMS and DMTS respectively. Only one full-scale, field-based study could be identified which reported DMS removal in BTFs and it showed a 0% removal (Converse et al. 2003). DMDS and DMTS removals in full-scale, field based BTFs could not be found in the literature.

Comparison

H_2S removal was good throughout all types of odour abatement systems as can be expected as most odour abatement systems are designed to remove hydrogen sulfide. H_2S

removal was most consistent in BTFs compared to other technologies, with no negative removals identified.

AC filters exhibited the highest median methyl mercaptan removal; however, there were occasions where removal efficiency reduced and became negative. ACs exhibited poor removal of CS_2 and DMDS with median removals below 0%. This supports other studies investigating the removal of carbon disulfide and dimethyl disulfide from ACs, which identified low or negative removals (Adams & Thomason 2004; Ball et al. 2004; Kyi 2014).

BTFs exhibited the poorest methyl mercaptan removal of the three odour abatement systems investigated (Deshusses et al. 2001; Gabriel et al. 2002; Rousseille et al. 2011). DMS and DMTS also exhibited particularly poor removal with median removals below 0%, however no other studies could be identified which investigated the removal of these compounds.

BFs exhibited the highest and most consistent removal of CS_2, DMS, DMDS and DMTS; however, removal was still fairly poor with frequent removal efficiencies less than 0%. Other studies have shown a wide range of removals for these substances (Giggey et al. 1994; Deshusses et al. 2001; Sorensen & Baadsgard 2004; Alix & Williams 2006).

Overall, whilst the number of compounds sampled and the length of sampling of this study is greater than most others, the results are somewhat consistent with previous studies identifying removal efficiencies of VSCs from each type of odour abatement systems in sewer networks (Shammay et al. 2016a).

VOC removal

Figure 2 summarises the removal of all VOCs within the study for each odour abatement system type. BFs exhibited the highest removal and least variability for most VOC species, however there was still a large variability identified. m,p-Xylene, the only VOC that has been identified as a 'High' risk odorant (Sivret et al. 2016), was removed the highest and most consistently by BFs.

Activated carbon filters

All compounds at all locations exhibited a wide range of removal efficiencies. No compound was identified where removal rates were consistently above 0%. This may be due to compounds being adsorbed between periods when spot samples were taken and occasionally desorbing. This would imply that these VOCs are only weakly adsorbed and can either be desorbed by atmospheric fluctuations or the presence of other compounds, or can be produced as part of the degradation of other compounds (Shammay et al. 2016a).

Units with higher EBRTs generally exhibited a greater removal, however there were specific locations, such as AC-2, which did not show this trend despite having an EBRT of 9.5 s.

Biofilters

In general, VOC removal was poorer than VSC removal, with negative removals being more often reported. Negative removals could be due to a number of factors, such as the generation of VOCs as biological byproducts (Mrowiec et al. 2005) or the desorption of previously adsorbed VOCs.

1,4-Dichlorobenzene had relatively good removal at BF-5, with poorer removals at BF-2. Median removal of 90.2% was measured across all sites and conditions, with removals
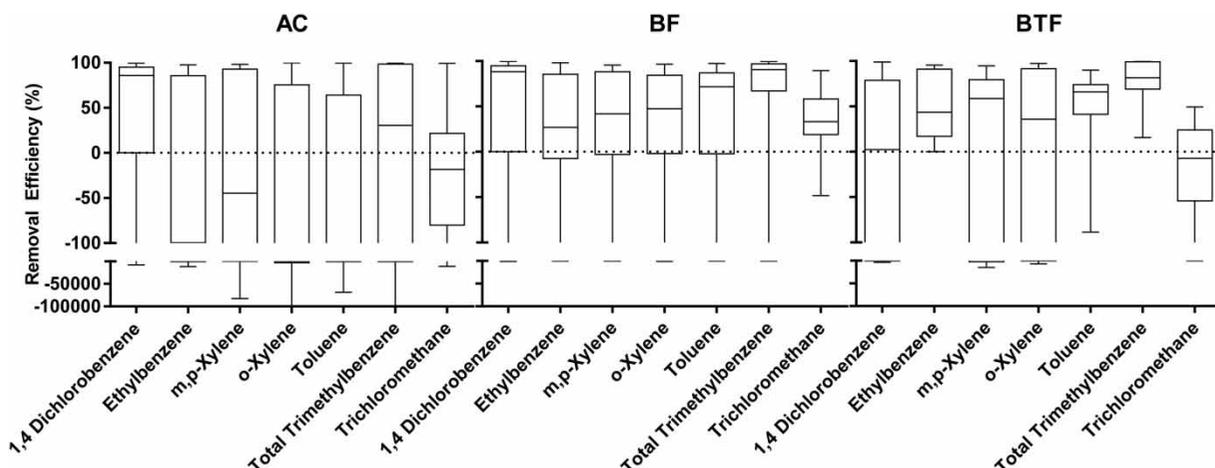

Figure 2 | Removal of volatile organic compounds.

greater than 50% being recorded for 68% of measurements. This level of removal is consistent with the findings of some (Sorensen & Baadsgard 2004) but greater than that reported by others (Deshusses *et al.* 2001; Converse *et al.* 2003). Removal of halogenated VOCs in general in biological systems has been reported as poor, or requiring long EBRTs to treat, predominantly due to their hydrophobicity (Cox *et al.* 2002; Delhoménie & Heitz 2005; Iranpour *et al.* 2005; Kennes *et al.* 2009; Muñoz *et al.* 2015).

Ethylbenzene also had relatively good removal at one site (BF-5) with poorer removals at others (BF-2 and BF-3 in particular). Median removal of 62.3% was measured across all sites, with removals greater than 50% being recorded for 52.4% of measurements. Only one previous study was identified that reported on the removal of ethylbenzene (Wang *et al.* 2014), which reported higher levels of removal than measured in this study.

Removal of all isomers of xylene was relatively poor across all sites, with median removals of 66.4% and 62.9% for *m,p-* and *o-*isomers, respectively. This is consistent with the findings from some (Deshusses *et al.* 2001; Converse *et al.* 2003; Wang *et al.* 2014), however higher removals have been reported when granular AC was used as biofilter media (Webster *et al.* 1996). These removals are greater than those reported by others (Wolstenholme & Finger 1994; Chitwood *et al.* 1999).

Toluene was removed relatively well from two sites (BF-2 and BF-5) but exhibited poor removal from a third (BF-3). Median removal of 76.9% was recorded with removals above 50% occurring in 62.1% of measurements. This is consistent with some studies (Webster *et al.* 1996; Chitwood *et al.* 1999; Deshusses *et al.* 2001; Converse *et al.* 2003; Wang *et al.* 2014) yet others (Ergas *et al.* 1995; Sorensen & Baadsgard 2004) reported higher removals. Toluene has been known to be formed during biogenic processes, particularly during anaerobic digestion (Mrowiec *et al.* 2005) however only one site (BF-3) exhibited consistent negative removals of toluene. This may indicate that BF-3 was operating under anaerobic conditions, or had pockets of anaerobic areas if short-circuiting and overwetting occurred.

Total trimethylbenzene was well removed at two sites (BF-2 and BF-5) and poorly removed at a third site (BF-3). A median removal of 95.0% was recorded across all sites and conditions with removals above 50% occurred in 87.1% of measurements. No literature could be found reporting the removal of total trimethylbenzene in field-based biofilters; however, a maximum removal of 70% was identified in a single-contaminant loaded biofilter under laboratory conditions (Delhoménie *et al.* 2003).

Trichloromethane exhibited relatively poor removals compared to other VOCs in this study with a median removal of 33.0% being recorded, despite having a similarly low Henry's law constant. Removals above 50% occurred in 33.4% of measurements. No literature could be found relating to the removal of trichloromethane in field-based biofilters; however, removal of dichloromethane has had mixed removal efficiencies reported in biofilters ranging from negative values to as high as 98% (Webster *et al.* 1996; Chitwood *et al.* 1999; Deshusses *et al.* 2001; Converse *et al.* 2003; Sorensen & Baadsgard 2004).

Biotrickling filters

Similar to BFs, VOC removal was generally poorer than VSC removals.

1,4-Dichlorobenzene was removed poorly at both sites with the second lowest median removal (after trichloromethane) of 14.9% measured across all sites, with removals greater than 50% being recorded for 40.6% of measurements. At BTF-3, removal increased with lower temperatures. No literature could be found for comparison on 1,4-dichlorobenzene removal in BTFs in field-based full-scale systems.

Removal of ethylbenzene was similar to that exhibited by 1,4-dichlorobenzene. Median removal of 32.1% was measured across all sites and conditions with removals greater than 50% being recorded for 38.7% of measurements. Only one study was identified which reported on the removal of ethylbenzene (Gabriel *et al.* 2002) which reported lower levels of removal, 21%, than measured in this study but at shorter EBRTs (1.6–2.3 s).

Removal of all isomers of xylene was mixed across all sites, with median removals of 56.3% and 46.5% for m, p- and o- isomers respectively. This is greater than the findings from most studies (Torres *et al.* 1996; Webster *et al.* 2000; Deshusses *et al.* 2001; Gabriel *et al.* 2002; Converse *et al.* 2003; Gilani *et al.* 2004).

Removal of toluene was mixed between the two BTFs. Overall median removal of 62.1% was recorded, which was lower than from the BFs; however, removals above 50% were found to occur in 63.7% of measurements, which is similar to the BFs. This is similar to those reported by Torres *et al.* (1996), greater than those reported by others (Deshusses *et al.* 2001; Gabriel *et al.* 2002; Converse *et al.* 2003; Gilani *et al.* 2004) and lower than those reported by Webster *et al.* (2000) and in laboratory-scale results (Lebrero *et al.* 2012b).

Total trimethylbenzene showed the greatest removal of all VOCs under investigation, similar to BFs; however, the

overall median removal was lower than BFs. A median removal of 81.5% was recorded across all sites and conditions, with removals above 50% occurring in 76.8% of measurements. No literature could be found reporting the removal of total trimethylbenzene in field-based BTFs.

Trichloromethane exhibited the lowest removals compared to other VOCs in this study, with a median removal of −11.2% being recorded. Removals above 50% occurred in only 11% of measurements, which is lower than those experienced in BFs. No literature could be found relating to the removal of trichloromethane in field-based BTFs; however, removal of dichloromethane has been widely reported as poor in biologically based systems (Webster *et al.* 1996; Chitwood *et al.* 1999; Deshusses *et al.* 2001; Converse *et al.* 2003; Sorensen & Baadsgard 2004).

Comparison

The biological based filters (both BFs and BTFs) showed a greater removal of total trimethylbenzene than in the AC systems. BFs had the highest toluene removal, yet BTFs had the least variable toluene removal. BFs exhibited the highest and most consistent xylene removal. BFs and AC filters exhibited similar removal of 1,4-dichloro benzene.

In general, AC filters exhibited little VOC removal, with only 1,4-dichloro benzene consistently identified as having a removal greater than 0%.

These findings generally support previous investigations; however, no data have been found in the literature for some of the compounds/odour abatement system combinations under investigation (Wang *et al.* 2014; Shammay *et al.* 2016a; Shammay *et al.* 2016b).

The results imply that, if there are more compounds than H_2S and MM, the ability to treat these other compounds should form part of the technology selection process. If DMS, DMDS, DMTS or many VOCs are present, a biological system may be more beneficial than an AC system at treating these compounds. Two-stage systems, whilst outside the scope of this study, would be expected to provide additional compound removal. In two-stage systems, careful consideration should be given as to whether the second stage is biological or physical, depending on the type of residual compounds expected after the first stage.

CONCLUSIONS

Most odour abatement systems are designed to treat H_2S due to the ease of measurement and the wealth of literature on how H_2S is degraded in odour abatement systems. However, other compounds are present in sewer atmospheres, which, when discharged, can be the cause of odour complaints or could potentially impact on the removal of odorants in odour abatement systems.

Three odour abatement systems commonly found in sewer networks: AC, BTFs and biofilters, were evaluated for long-term removal of common volatile sulfurous and organic compounds. Whilst all odour abatement systems were found to readily remove hydrogen sulfide, methyl mercaptan was best removed by AC and biofilters showed the greatest and most consistent removal of all other VSCs.

Biofilters exhibited the greatest and most consistent removal for most VOCs, with the exception of toluene and ethylbenzene, which was most readily removed by BTFs. AC systems exhibited the poorest removal of all VOCs.

Given the differences in removal efficiencies of different compounds by different odour abatement systems, a knowledge of what is in the foul air to be treated is essential prior to designing odour abatement systems. If an odour abatement system is designed purely to remove hydrogen sulfide, other compounds will not be treated as effectively leading to a greater risk of odour complaints.

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