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Evidence: Biofilter performance and operation as related to commercial composting

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Evidence

Biofilter performance and operation as related to commercial composting

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Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned and funded by the Environment Agency.

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This report was produced by the Scientific and Evidence Services team within Evidence. The team focuses on four main areas of activity:

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Miranda Kavanagh

Director of Evidence

Executive summary

The Environment Agency and the Department for Environment, Food and Rural Affairs (Defra) require a critical scientific review on the effectiveness of biofilters at odour and bioaerosol removal from composting facilities.

This report provides a critical review of available evidence as to how effectively the various categories and configurations of biofilter reduce bioaerosol and odour emissions from composting facilities. The review considers what operating parameters impact on biofilter performance, and hence what design, conditions and maintenance schedules need to be defined and adhered to in order to provide assurance that a given biofilter continues to perform adequately. The review draws on scientific and 'grey' literature derived from the UK waste management sector. Importantly, the report contains new findings from an Open University programme of laboratory experiments and fieldwork research based on two composting sites. Arising from the critical review and empirical studies, a list of topics is presented which represent areas of uncertainty where further research would be recommended.

The original project specification indicated that the scope of the critical review should include a number of topics relating to biofilter operation and the interrelated treatment of odour and bioaerosols. The authors of this report take the view that, in contrast to the large amount of information which is available on biological removal of odour, there is very little published information available relating to the generation and emission of bioaerosols during in-vessel composting, or the effect of biofiltration on bioaerosols. Equally, very little is known about the relationship between odour and bioaerosols during in-vessel composting and the simultaneous treatment of odour and bioaerosols in biofilters. For these reasons, this report will largely treat issues relating to odour and bioaerosols separately.

Odour

Evidence obtained for this project suggests that many UK in-vessel composting processes may be operating in an oxygen-limited mode in order to create suitable conditions for rapid waste sanitisation as required by Animal By-products Regulations. Monitoring of one typical in-vessel composting process provided direct evidence of very low aeration rates and very high methane concentrations being emitted in exhaust gases, indicating highly anaerobic pile conditions.

Aeration rate during in-vessel composting of source segregated household waste will largely determine the characteristics of exhaust gas emissions and the nature of the abatement technology that is required to treat them. For example, while aerobic conditions during composting are associated with exhaust gas emission of ammonia and fungi, anaerobic conditions will tend to favour the generation and emission of highly odorous reduced compounds and anaerobic bacteria.

This report contains strong evidence of very high odour concentrations being associated with in-vessel exhaust emissions. For example, fieldwork monitoring obtained a range of high odour concentrations in exhaust gases from one site (maximum value >2 million OUE m-3) and odour concentrations have been reported from other sources of > 6 and 8 million OUE m-3.

Even though biofilters are considered appropriate for the treatment of low odour/high volume gas flows, industry data is presented in this report showing that exceptionally high odour removal rates have been reported for very high strength composting

emissions (for example, input >8 million OUE m-3; output 1,630 OUE m-3; removal efficiency >99 per cent). Conversely, examples are reported of moderate or poor odour reduction, for example 66 per cent, 89 per cent and <10 per cent for relatively low input odours. The reasons cited for low odour reduction included residual odours being given off by the biofilter, air channelling and poor irrigation.

Literature findings suggest that, typically, ammonia derived from aerobic conditions would be easier to remove in biofilters (mainly by adsorption/absorption mechanisms) compared with volatile organic compounds (VOCs) such as methyl sulphides. However, low/moderate concentrations of ammonia (45ppmv and 100 ppmv) have been reported to inhibit microbial decomposition in biofilters and the use of acid scrubbers to remove ammonia prior to biofiltration should be considered. Laboratory findings confirm that for mixed exhaust emissions, biofilters appear to be better able to remove high concentrations of ammonia (>99 per cent) compared with methyl sulphides.

There is some evidence from fieldwork and laboratory experiments that, based on the selected range of odour compounds measured, methyl sulphides tended to be associated with higher odour biofilter emissions. In order to confirm this conclusion, further research needs to be undertaken.

Monitoring of an in-vessel composting biofilter demonstrated that for high exhaust gas odour levels (in this case > 700,000 OUE m-3), even very good odour removal rates (>98 per cent) may be insufficient to fully reduce emitted odour (>12,000 OUE m-3) to acceptable levels. Supporting material in this report suggests that industry has adopted an odour concentration of approximately 3,000 OUE m-3 as the threshold for acceptable odour from biofilters. Research confirmed that odour compounds can be stripped from biofilter materials, indicating that biofilters can emit residual odour. Meeting the industry odour threshold level on a consistent basis will be very challenging for many composting facilities, especially if exhaust gas odour concentrations are very high and dominated by compounds derived from anoxic conditions. Additionally, despite good removal rates for bioaerosols, emissions are still higher in many cases than guideline concentrations from open windrow sites.

Achieving and maintaining low odour exhaust emissions and effective biofilter odour reduction will require composting systems and biofilters to be operated optimally on a consistent basis. It is recommended that sites maintain good levels of aerobicity during the composting process and that routine monitoring of in-vessel exhaust gas characteristics (odour concentration and odour compound profile) and temperature is carried out. In addition, monitoring of biofilter moisture content, back pressure and the characteristics of the output emissions would also be recommended.

It should be noted that prevailing anaerobic conditions during the composting process will lead to poor rates of waste decomposition and will also tend to promote high levels of odour emission during outdoor compost maturation. This study has also shown it may lead to release of endotoxin from gram-negative anaerobic bacteria. To maximise effective in-vessel decomposition and minimise odour during maturation, it is recommended that a minimum level of stability for partially composted in-vessel material is introduced, or alternatively a specified level of biodegradability loss that must be achieved prior to maturation in open air.

A number of information gaps were identified during this project. It is recommended that further research is undertaken into a number of key topics including:

To better understand the in-vessel composting (IVC) sector and to confirm findings from this report, conduct an initial survey of UK in-vessel composting sites and a 12-month programme of field monitoring involving four selected sites.

A number of technical issues require further research to improve odour removal in biofilters and to perfect protocols for measuring odour. This work should include undertaking a number of experimental studies such as determining the effect of aeration rates on in-vessel exhaust emissions, quantifying ammonia inhibition effects, exploring the benefits of inoculating selected biofilter media with appropriate microorganisms, determining the effect of exhaust gas temperature on biofilter performance, and exploring how best to remove low residual odour from biofilters with particular emphasis on exploring the benefits of increasing Empty Bed Residence Time. It is recommended that current odour sampling techniques are evaluated and a set of standard monitoring protocols developed.

Bioaerosols

The literature review identified that bioaerosols within in-vessel facilities are likely to be primarily bacteria, potentially with a substantial proportion being anaerobic. It also identified that there are two aspects to consider when discussing biofilters and bioaerosols – emission from the material to the biofilter, and subsequently emission from the biofilter. Although many research papers identified good 'removal efficiencies' for bioaerosols via biofilters, there is some disagreement over whether the emissions entering the biofilter are the same as the species emitted from the biofilter. What they do agree on, however, is that biofilters remove bioaerosols via inertial impaction, for example a physical mechanism, and could potentially be liberated by shear forces on the material within the biofilter. The air flow at which this might occur was not reported. Interestingly, materials with larger surface areas are thought to remove bioaerosols more efficiently. Additionally, it is not unusual, in the studies identified, to see higher concentrations at the outlet than the inlet of a biofilter, and various explanation of this were put forward, such as biofilter materials being net emitters, anomalous results, air flow, growth within biofilters, and so on.

In the field studies both biofilters were seen to remove large concentrations of particulates, bioaerosols and their constituents seen at the inlet concentrations. However, despite very good removal efficiencies in some instances of 80-90 per cent, concentrations released to the atmosphere are still elevated above background levels, and are often in excess of both guideline (viable bioaerosols) and suggested standard concentrations (endotoxin). In particular, total mesophilic bacteria and gram-negative bacteria are exiting the biofilters in relatively high concentrations compared to background levels. It was also noted that at one site, endotoxin concentrations were much higher than viable bacteria and gram-negative bacteria would indicate, and it is possible that uncultured anaerobic species contributed. This aspect of the emission profile requires further study.

From the laboratory work, tentative conclusions are that peat and wood chip were seen to be net emitters for total mesophilic bacteria and gram-negative bacteria in these tests. Endotoxin and glucan concentrations are also of note. Despite the elevated inputs, there are some noticeable rises in output, particularly for peat and wood chip. Also of note, fungi were not detected in either the inputs or outputs of any of the samples in the laboratory. A separate sample of mature compost known to contain fungi also demonstrated that fungi were not found in the pipework.

This study has not achieved enough data collection to determine whether biofilter operating parameters would affect bioaerosol removal rates, and more data would be

needed to determine this. No particular biofilter was much better than other material across the entire study. The literature is also mixed on this point and tends to focus on material types rather than actual optimal operational conditions.

Finally, there is the question of whether odour and bioaerosol removal can be efficient and concurrent. Given that healthy populations of certain microorganisms are related to effective odour removal there is the possibility that an inverse relationship could occur. More data would be needed to investigate this further.

A number of information gaps were identified during this project. It is recommended that further research is undertaken into a number of key topics as listed in this report.

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1 Introduction

The Environment Agency is responsible for regulating all commercial biowaste treatment facilities, including open windrow (with or without negative aeration) and in-vessel composting (IVC), anaerobic digestion (AD) and mechanical biological treatment (MBT). The Environment Agency has a responsibility to ensure that levels of bioaerosol (including bacteria, fungi and fragments of organic material) and odours from biowaste treatment facilities do not adversely impact on the surrounding population. In recent years, the Environment Agency has been receiving a growing number of applications for permits to operate, which include proposals to use biofilters as a means of reducing both odour and bioaerosol output. To assess the effectiveness and make risk-based decisions on submitted proposals, the Environment Agency and the Department for Environment, Food and Rural Affairs (Defra) require a critical scientific review on the effectiveness of biofilters at odour and bioaerosol removal from composting facilities. In response to this, this report will provide a critical review of available evidence as to how effectively the various categories and configurations of biofilter reduce bioaerosol and odour emissions from composting facilities. The review will consider what operating parameters impact on biofilter performance, and hence what design, conditions and maintenance schedule need to be defined and adhered to in order to provide assurance that a given biofilter continues to perform adequately. The review will draw from scientific and 'grey' literature, and will generate new information through laboratory experiments and industry examples.

2 Odour scientific literature review

2.1 What is odour?

Odour can be defined as a stimulus of olfactory cells in the presence of specific compounds (organic and inorganic). It is a mixture of light and small molecules that upon coming into contact with the human sensory system, and is able to stimulate an anatomical response; the experienced perception being classified as odour. It is suggested that the human olfactory system serves three major purposes, relating to ingestive behaviour (such as detecting and identifying food), environmental hazard avoidance (such as identifying biological decay and poisons) and social communication (such as detecting pheromones) (Stevenson, 2010). Hedonic (the characterisation of pleasantness) odour judgement is not uniform across humans as it is strongly influenced by past experience, learning, familiarity and culture. Hedonic odour judgement may be partly determined by molecular size (with exceptions), as larger molecules that contain oxygen (except carboxylic acids) and at least six additional non-hydrogen atoms are more likely to be perceived as pleasant, with the opposite applying to smaller molecules, such as sulphurous compounds (Zarzo, 2011).

2.2 How to detect and measure odour compounds

Odour concentration is determined by an olfactometer test in accordance with EN13725. This test employs a panel of human noses of known perception to odour to act as sensors. A diluted odorous mixture (typically <30 hours since collection) and an odour-free gas (as a reference) are presented separately from sniffing ports to a group of panellists who are housed in an odour-neutral room. The responses of the panellists over a range of sample dilutions are used to calculate the concentration of the odour in terms of European Odour Units (OU_E m^{-3}). The main panel calibration gas used is Butan-1-ol, which at a certain dilution gives 1 OU_E m^{-3}. This analysis technique provides directly comparable data for different odour types and is used for input into dispersion models to determine odour impact in terms of annoyance and abatement efficiency assessments.

Analytical instrumentation allows the identification and quantification of the chemical compounds present in gases responsible for odour. The advantages of using scientific instrumentation are that they are objective, repeatable and accurate. Their limitation from an

odour perspective is that they do not indicate potential odour nuisance. A large range of instrumental techniques exist to identify and quantify the chemicals present in gases, this includes: gas chromatography, infrared and electrochemical sensors, differential optical absorption and fluorescence spectrometry, and reaction-based assays (Bruno *et al.*, 2007; Muñoz *et al.*, 2010; Brattoli *et al.*, 2011; Font *et al.*, 2011). Instrumentation allows the detection of the lowest concentration of a compound in the air that can be detected by smell (Table 1).

Table 1. Typical odour description and threshold concentrations of a variety of chemical compounds (Muñoz *et al.*, 2010).

Compound type	Odorant	Odour description	Odour threshold (ppmv)
Sulphur containing	Hydrogen sulphide	Rotten Eggs	0.0005
	Ethyl mercaptan	Rotten vegetables	0.00001
	Carbon disulphide	Disagreeable, sweet	0.007
	Dimethyl sulphide	Decayed cabbage	0.001
	Dimethyl disulphide	Rotten cabbage	0.000026
Nitrogen containing	Ammonia	Pungent	0.038
	Trimethylamine	Fishy, pungent	0.0004
Volatile fatty acids	Acetic acid	Vinegar	1.1
	Butanoic acid	Sour, perspiration	0.0003
	Isovaleric acid	Unpleasant	0.0006
	Propionic acid	Rancid, pungent	0.028
Ketones	Butanone	Sweet, minty	0.25
	Acetone	Fruity, pungent	20
Aldehydes	Acetaldehyde	Green sweet	0.0001
	Valderaldehyde	Pungent	0.028
Hydrocarbons	Toluene	Rubbery, mothballs	2.1
	Benzene	Sweet, solvent-like	1.4
	Phenol	Medicinal, sweet	46
	Styrene	Solventy, rubbery	0.047

Determining the relationship between specific chemical compounds and human olfactory response can be challenging, as odour perception varies on an individual basis. Despite this, Tsai *et al.*, (2008) found a linear correlation between high concentrations (0.25 to 100 ppm) of ethylbenzene, dimethyl sulphide, trimethylamine and *p*-cymene with odour concentration. At lower concentrations (0.002 to 1ppm) the pattern was more complex, with only trimethylamine presenting a linear correlation, whereas ethylbenzene and dimethylsulphide

showed logarithmic correlations and *p*-cymene was without correlation. Acetic acid showed a linear correlation with odour concentration from 0.1 to 50ppm, whereas ammonia had no correlation with concentrations ranging from 0.5 to 100ppm. The authors suggest the reason for no correlation with ammonia could be caused by the preferential occupancy of ammonia on sensory receptor sites that could affect olfactory acuity, combined with ammonia's ability to inflame and cause temporary pathological damage to olfactory tissues on exposure. Correlations between compost gas chemical constituents and olfactometry is further explored in the following section (2.3).

2.3 The origin and location of odour compounds during composting

Odour has been associated with at least three stages during the composting of source segregated household waste: reception/shredding/mixing of waste, initial composting, and thermophilic composting. In general, the nature of the odour from each stage is derived from different chemical groups. According to Eitzer (1995), most volatile organic compounds (VOCs) in aerobic composting plants are emitted during the early stages of processing such as at the tipping floors, at the shredder and during the initial active composting stage. Odorous emissions in the reception hall during shredding and mixing are often associated with volatilisation of terpene compounds (α-pinene, 3-carene, and D-limonene) from botanical material and so-called xenobiotic compounds (such as l,l,l-trichloroethane, toluene, and ethylbenzene). Alcohols, carbonyl compounds, esters and ethers are mainly released from the initial composting stage while the reduced sulphur compounds are emitted during the thermophilic composting stage.

Homans & Fischer (1992) showed that during thermophilic composting, anaerobic conditions due to incomplete or insufficient aeration will produce reduced sulphur compounds of intensive smell, while incomplete aerobic degradation processes result in the emission of alcohols, ketones, esters and organic acids. Also, during the thermophilic composting stage, Pagans *et al.*(2006a) cited ammonia as one of the main compounds responsible for generation of offensive odours and atmospheric pollution when composting organic wastes with high nitrogen content. Although the detection and recognition thresholds for ammonia are relatively high, ammonia gas has been found to be the main compound found in exhaust gases from composting, except for carbon dioxide (Beck-Friis *et al.*, 2001).

2.4 The main odorous chemical compounds formed during composting

The nature and the concentration of the odour compounds emitted from composting will be related to various factors such as waste composition, the stage of composting being studied (initial, mid or final stages), and the temperature and aerobicity of the composting pile.

In a laboratory scale experiment, Smet *et al*. (1999a) studied the composting of source segregated household waste that consisted of 70 per cent green waste, 20 per cent kitchen waste and 10 per cent paper. Emissions from this material were categorised into the following compound groups:

- Alcohols 285g t^{-1}

- Carbonyl compounds 158g t^{-1}

- Terpenes 82g t^{-1}

- Esters 53g t^{-1}

- Sulphur compounds 9g t^{-1}

- Ethers 3g t^{-1}

- Ammonia 152g/tonne (maximum concentration 227mg m^{-3})

- H_2S was not detected

Total emission of volatile compounds was 742g t^{-1} (including ammonia), while emission of VOCs was reported as 590g t^{-1}. Smet *et al*. (1999a) suggested that alcohols and carbonyl compounds made up 75 per cent of the total VOC emissions and were mainly emitted during week one, a period where oxygen was reduced in the waste gas. Limonene, ethyl acetate, 2-propanol, ethanol and acetone made up about 82 per cent of the total VOC emission from composting. The maximum ammonia concentration was found to be relatively high at 227mg m^{-3}, a level of emission that has been associated with biofilter toxicity and failure, however published data on this topic is often contradictory. Emission of reduced sulphur compounds was reported to be relatively low compared with other compounds, but due to their very low odour threshold values (Table 1) these compounds are often cited as the main contributors to odour (Epstein, 1997). The main sulphur compound detected was dimethyl sulphide (emission 8.2g t^{-1}; maximum concentration 8.2mg m^{-3}) with dimethyl disulphide and carbon disulphide also being present; emission was mainly during the thermophilic stage of

composting. The concentration of dimethyl sulphide emitted was approximately 10^3 greater than typical quoted odour threshold values for dimethyl sulphide (2.5µg m^{-3}; (Goldstein, 2002)).

2.4.1   Ammonia

The degree to which ammonia is formed and emitted from composting processes depends on a number of factors such as the initial microbial formation of ammonium, the chemical equilibrium/N ratio, aeration rate and pile temperature. In general, the generation and emission of high concentrations of ammonia in exhaust gas is associated with the composting of low carbon:nitrogen (C:N) ratio wastes, and high aeration rates. In contrast, Wilber and Murray (1990) contend that anaerobic conditions favour the formation of highly odorous volatile organic sulphur compounds, while the emission of these is strongly decreased with aeration.

Due to the difficulty in monitoring ammonia and other emissions on a continuous basis, there are few published studies derived from monitoring full size composting plants and therefore most ammonia emissions data has been obtained from laboratory-scale trials. The reported levels of ammonia produced during biodegradable waste composting (before treatment by scrubbing and/or biofilters) varies considerably. This may be due in part to the type and scale of the individual studies, differences in the C:N ratio and biodegradability of the starting materials composted, as well as the difficulties associated with defining the composting process itself (for example, air flow rates and duration).

The mechanism for ammonia emission from in-vessel composting processes using low C:N ratio feedstocks follows this sequence. During initial stages of composting when carbon and oxygen are often limited, ammonium ions from microbial decomposition of proteins predominate due to the lower temperatures and acidic conditions that prevail. As both the temperature and the pH of the composting system increase, it is normal for increased concentrations of ammonia gas to be produced and stripped from the composting pile by high rates of air flowing through in-vessel systems and subsequently emitted to air. At thermophilic temperatures, the solubility of ammonia gas is only half that at mesophilic temperatures, meaning that as pile temperatures increase, ammonia can be emitted to air very readily. Ammonia emission from composting under well-aerated conditions is normal, especially with highly biodegradable feedstocks such as municipal solid waste. Furthermore, it is also typical for ammonia to be emitted to air during the early stages of composting. For example, Eklind *et al.* (2007) reported that for a well-aerated laboratory composting system (16 per cent oxygen) utilising source separated household waste, up to 23 per cent of the

original nitrogen in the waste was lost as ammonia emissions after only 11 days of composting.

For a full-scale, open air, green waste composting operation, the rate of ammonia emission to air was reported to be approximately 600g t^{-1} (South Coast Air Quality Management District (SCAQMD), 2001) in total for all the processing stages, including composting and compost curing. For a pilot scale trial, composting green waste, kitchen and paper, Smet *et al.* (1999a) quoted emissions of 152g t^{-1} (maximum concentration 227mg NH_3 m^{-3}). Pilot scale composting trials have shown that ammonia losses during composting can be potentially very high, such as approximately 2250g NH_3-N t^{-1} for green waste, equating to a total nitrogen loss of approximately 23 per cent (Komilis & Ham, 2000). Other studies on composting source segregated household waste (SSHW) and the organic fraction of municipal solid waste (MSW) during mechanical and biological treatment (MBT) have found equally high ammonia losses. For example, Cadena *et al.* (2009) measured 3.9kg t^{-1} from the curing phase of composted SSHW, this equating to a nitrogen loss of 46 per cent. Clemens & Cuhls (2003) reported variable ammonia losses (0.018 to 1.15kg t^{-1}) for residual waste composting (MBT) plants in Germany (untreated by scrubbers/biofilter). Beck-Friis (2001) found losses of 2.12kg t^{-1} for biowaste composting, in a small scale trial. The European Commission (2006) cites ammonia levels in exhaust gases from MBT plants in the range 5-3700g t^{-1} waste composted and also quotes ammonia emissions of 545-1090g t^{-1} being recorded (cited as equating to concentrations 20-40mg NH_3 m^{-3}) prior to treatment by scrubbing/biofilter.

Authors of these studies frequently comment that ammonia emissions are strongly linked to waste and process characteristics. In particular, many authors have identified C:N as being an important parameter determining ammonia emissions. For example, Michel *et al.* (2004) showed that the initial C:N ratio of waste being composted (range 25:1 to 51:1) correlated significantly and linearly (R^2=0.78) with the loss of total nitrogen. For example, waste with a starting C:N ratio of 25:1 lost 32 per cent of its initial nitrogen, while material in two windrows with starting C:N ratios of 50:1 lost only 8 per cent and 7 per cent, respectively. They concluded that there may be a potential to increase windrow C:N ratios to substantially reduce nitrogen (ammonia) volatilisation during composting.

Ammonia in composting exhaust gas has been associated with biofilter toxicity, causing a reduction in biofilter capacity to adsorb and decompose ammonia and some VOCs. However, there is much debate about the minimum level of ammonia concentrations and loads that cause particular toxic effects. It is likely that even moderate ammonia concentrations in the order of 45-100mg NH_3 m^{-3} may contribute to microbial inhibition and

decreased biofilter performance. This uncertainty means that it is important to be aware of the range of ammonia concentrations that might be likely for particular waste types and types of composting systems to ensure that biofilter toxicity is minimised.

2.4.2 Volatile organic compounds (VOCs)

Smet *et al*. (1999a) showed that composting SSHW creates a complex mix of odorous VOCs. They reported a cumulative VOC emission of $590gt^{-1}$ during a pilot scale (224L) composting experiment, with VOCs of ethanol ($194mg\ m^{-3}$), acetone ($114mg\ m^{-3}$), limonene ($56mg\ m^{-3}$), ethyl acetate ($66mg\ m^{-3}$), dimethyl sulphide ($8.2mg\ m^{-3}$) and 2-ethyl furan ($4.0mg\ m^{-3}$) predominating. However, Wheeler *et al*. (2001), in a limited study of three UK composting sites, found that VOC concentrations were low and well below UK safety guidelines and thus were believed not to pose a threat to public health.

Pagans *et al*. (2006b) studied the emission of VOCs produced during composting of different organic wastes: source-selected organic fraction of municipal solid wastes (OFMSW), raw sludge (RS), anaerobically digested wastewater sludge (ADS) and animal by-products (AP). Composting was performed in a laboratory scale composting plant (30L) where maximum VOC emissions typically occurred during the first 48 hours of composting. Concentrations of VOCs in the composting exhaust gases for each waste type ranged from 50 to $695mgCm^{-3}$ for OFMSW (bulking agent:waste was 5:1), from 13 to $190mgCm^{-3}$ for OFMSW (bulking agent:waste was 1:1), from 200 to $965mgCm^{-3}$ for RS, from 43 to $2900mgCm^{-3}$ for ADS and from 50 to $465mgCm^{-3}$ for AP. They concluded that emission of VOCs was related to waste type and that the addition of bulking agents could increase VOC emissions due to release of terpenes.

Komilis *et al*. (2004) studied the volatile and semi-volatile organic compounds produced during composting of various SSHWs in a laboratory experiment. Mixed paper primarily produced alkylated benzenes, alcohols and alkanes. Yard wastes primarily produced terpenes, alkylated benzenes, ketones and alkanes, while food wastes primarily produced sulphides, acids and alcohols. The authors identified 13 key aromatic VOCs found in MSW composting facilities, of which toluene, ethylbenzene, 1,4-dichlorobenzene, p-isopropyl toluene, and naphthalene were present in the largest amounts. The laboratory experiment showed that unseeded mixed paper, seeded mixed paper, seeded yard wastes, unseeded yard wastes, seeded food wastes and unseeded food wastes produced total VOCs values that equalled *c.*6.5, 6.1, 2.1, 0.83, 2.5 and $0.33mg\ dry\ kg^{-1}$ respectively. All VOCs were emitted early during the composting process and their production rates decreased with time at thermophilic temperatures.

Soyez and Plickert (2002) studied the composting of residual waste during mechanical and biological treatment, and reported that non-methane VOC emissions amounted to approximately 600g t^{-1} of the original MSW, with treatment in a scrubber/biofilter estimated to reduce this to 300g t^{-1}. The highest rate of pollutant emission was found to occur during the self-heating phase in the very first days of the bioprocess and was largely completed within two weeks.

It may be concluded that untreated odours from composting SSHW are closely associated with VOC emissions arising from anaerobic conditions within composting piles. Highly aerobic piles may produce very high levels of ammonia as well as some odorous VOCs from anaerobic microsites. VOCs are mainly related to the initial procedures of preparing the waste and the early stages of the composting process. Reception hall activities are associated with odour derived from volatilisation of terpenes and xenobiotic compounds. Initial and early thermophilic composting will produce ammonia and terpenes, and under oxygen-limited conditions carbonyl compounds, alcohols and reduced sulphur compounds (such as dimethyl sulphide). With the predominance of odour emission from the initial stages of composting (often associated with oxygen-limited conditions), it might be expected that the shorter duration in-vessel composting processes required by the Animal By-Products Regulations (two weeks or less) are often characterised by high odour gaseous emissions, and odour generation may be greatly exacerbated by the use of low aeration rates. In these systems it should be noted that most commercial composting operations will operate a number of in-vessel composting units in parallel, and since starting times will be different for each unit it is likely that the profile of the combined exhaust gases going to the air treatment facility will be relatively consistent over time. Odours from composting SSHW will be typically derived from a complex mix of ammonia and many VOC compounds such as terpenes, alcohols and carbonyl compounds rather than being dominated by any one compound or group of compounds, although reduced sulphur compounds are often cited as the main contributors to odour. In general, the nature and the concentration of the odour compounds emitted from composting will be related to various factors such as the composition of the waste being composted, the stage of composting being studied (initial, mid, or final stages), and the aerobicity of the composting pile.

2.5 Typical aeration rates for in-vessel composting

Homans & Fischer (1992) reported that anaerobic conditions during thermophilic composting, due to incomplete or insufficient aeration, are known to produce odorous reduced sulphur compounds, while incomplete aerobic degradation processes will result in

the emission of alcohols, ketones, esters and organic acids. It is important that sufficient oxygen is present during thermophilic composting in order to maintain aerobic conditions within the composting pile to ensure good rates of decomposition and to reduce VOC emissions. Smet *et al.* (1999a) aerated SSHW at the rate of 5.6m^3 air/tonne waste/h during the first two weeks of composting and 3.1m^3 air/tonne waste/h thereafter, and reported that 90 per cent of the total respiration (that is, decomposition) occurred during the first four weeks. However, they observed low oxygen levels in the exhaust gas (levels not reported) and found that the range of compounds emitted during composting was similar to the range emitted during anaerobic digestion of similar waste. They concluded that the VOC compounds emitted during composting were produced in anaerobic microsites within the composting piles. Beck-Friis *et al.* (2003) composted SSHW at three levels of oxygen in process air – 16 per cent, 2.5 per cent and 1 per cent – and detected odorous volatile fatty acid emissions during the mesophilic stage from all oxygen treatments, indicating the development of anaerobic conditions even during the early stages of composting. Methane (indicative of anaerobic conditions) was detected during the thermophilic stage for the 2.5 per cent and 1 per cent oxygen levels (methane was not measured for the 16 per cent treatment). Sommer and Moller (2000) found methane emissions from composting even when the oxygen levels where greater than 10 per cent. Miller (1993) suggests that the minimum interstitial oxygen concentration should be 12 per cent to 14 per cent for composting, in order to prevent a decrease in microbial activity. In terms of odour emissions, Fraser & Lau (2000) found that maintenance of aerobic conditions did not stop the generation of strong odours from methyl mercaptan and dimethyl sulphide. Higher aeration rates and the associated higher oxygen levels led to lower concentrations of odour compounds but was also associated with higher mass emissions rates, presumably due to increased air stripping. They concluded that larger odour treatments facilities would be required for higher aeration rates.

Published aeration rates for forced air composting systems vary. Shen *et al.* (2011) refer to 'Chinese technical specification for static aerobic composting' (CJJ/T52-93) which recommends the optimum aeration rate to be 0.05-0.2m^3/m^3/min, which approximately equates to 6-24m^3/tonne/h (assuming typical waste bulk density of 0.5 tonne/m^3). He *et al.* (2000) used a continuous aeration rate in the range of 3.1 to 3.8m^3/tonne/h (assuming moisture content of 50 per cent) for composting food waste in laboratory scale reactors. De Guardia *et al.* (2008) studied nitrogen dynamics during composting and reported the following aeration regimes: low aeration (0.5m^3/tonne/h) and a range of aeration rates from 5.6m^3/tonne/h. Arslan *et al.* (2011) composted vegetable and fruit wastes at various aeration

rates and reported that the optimum rate for maximum reduction in C:N ratio was 0.62litres/min kg volatile solids, which equates to >30m^3/tonne/h.

2.6   Bioreactors and scrubbing technologies for odour control

2.6.1   Introduction

VOCs and odorous compounds can be removed from waste gas streams with technologies that use physical, chemical or biological processes. Non-biological processes include methods such as: condensation, activated carbon adsorption, absorption/scrubbing and incineration. These processes are generally only economical for gas streams that have high concentrations of odorous compounds due to the high energy requirements (for example in incineration) and operating costs (for chemical scrubbing, for example). Biological methods are effective and economical for biodegradable odorous compounds found at low concentration within waste gas streams, thus making them appropriate for treating composting gases. Air-phase bioreactors (such as biofilters) can treat highly soluble and low molecular weight VOCs and inorganic compounds, however low molecular weight aliphatic hydrocarbons such as methane, pentane and some chlorinated compounds are difficult to biodegrade (Devinny *et al.*, 1999). The by-products of microbial oxidation are primarily water, carbon dioxide, mineral salts, some VOCs and microbial biomass.

2.6.2   Mechanics of biofiltration

The removal of odorous compounds within a biofilter starts with the transfer of contaminants from the air to the water phase, followed by adsorption to the medium or absorption into a water film, and finally biodegradation of contaminants within the biofilm. The overall effectiveness of a biofilter is largely determined by the properties and characteristics of the support medium, which includes porosity, degree of compaction, water retention capacity, and the ability to host microbial populations.

At equilibrium, the transfer of odorous contaminants within the air to the water phase is described by Henry's law/constant (Equation 1):

$$P = K_H C$$

<div align="center">**Equation 1.**</div>

where P is the concentration of contaminant (partial pressure) in the gas phase (atm or g L^{-1} air), K_H is Henry's law constant/coefficient (L mol^{-1} or g L^{-1}$_{air}$ per g L^{-1}$_{water}$) that relates fugacity

of a dissolved nonelectrolyte to its concentration in a solution, and C is the equilibrium concentration of solute in the water phase (mol L^{-1}_{water} or g L^{-1}_{water}). K_H depends on the solute (contaminant), the solvent and the temperature. Using a non-dimensional Henry's coefficient, substances with values over 0.01 are considered volatile, with higher values indicating decreasing solubility in water. Table 2 compares Henry's coefficients for some common odorous substances in water.

Table 2. Henry's coefficient for some common compounds (Shareefdeen & Singh, 2005)

Compound	Henry's coefficient (non-dimensional)
Hexane	30.9
Oxygen	29.1
Hydrogen sulphide	0.92
Toluene	0.25
Benzene	0.22
MIBK (methyl iso-buty ketone)	0.016
Ethanol	0.0012
Ammonia	0.0005

A key concept of biofiltration is that more contaminant is likely to be in the water than air, thus allowing biodegradation to occur over longer a timescale than the empty bed residence time (EBRT). This partition and retardation effect is further increased through the adsorption of contaminant by biomass and support medium. The mass adsorbed will be much greater than the mass dissolved in water, therefore producing high retardation. Concentrations of pollutants are always higher near the surface of the water layer, where transfer from the atmosphere is occurring. The movement of contaminants through the water phase is best described by Fick's first law, where under steady state, the flux goes from regions of high concentration to regions of low concentration, with a magnitude that is proportional to the concentration gradient. Biodegradation in the water or biofilm, and adsorption at the surface of the support medium act as sinks within a biofilter.

The adsorption of contaminants is an important process within a biofilter. Contaminant molecules may be simply dissolved in the water, but they will also be adsorbed on the surface of the medium, taken up by living cells, adsorbed on the surface of biofilm organic matter, absorbed within organic matter in the biofilm or medium, or collected at the surface of the water (Devinny *et al.*, 1999; Shareefdeen & Singh, 2005). For highly soluble compounds (such as ethanol - Table 2), the dissolved form of removal is important, whereas

in more hydrophobic contaminants, the major removal mechanism may be adsorption on the surface of the medium and absorption within the organic matter. Contaminants vary in their affinities for water, medium and organic matter. For example, in a lab-scale biofilter study, Prenafeta-Boldú *et al*. (2012) reported that hydrophobic volatile compounds were more efficiently removed than the hydrophilic ones, and removal efficiency was poorly correlated with estimates of the VOCs' fast aerobic biodegradation rate. They concluded that substrate mass transfer (adsorption on the hydrophobic packing/biomass), rather than biodegradation rates, appears to be the main process governing the efficiency in conventional air biofilters applied for the treatment of odorous emissions.

The breakdown of contaminants within a biofilter happens in the biofilm. This is a mass of organisms growing on the surface of the solid medium that carry out metabolic activities that transform the contaminants to harmless products. A biofilm is generally <5 mm, however it can continue to grow to > 2 cm thick where it will then clog and overload biofilters. Microorganisms present in the biofilm are using the chemical energy contained in the molecular bonds of contaminants. The kinetics of contaminant degradation is often modelled using the Michaelis-Menten equation, developed for enzyme mediated reactions (Equation 2):

$$V = \frac{V_{max}[S]}{K_m+[S]}$$

Equation 2.

Where V is the specific substrate conversion rate, V_{max} represents the maximum rate achieved by the system at maximum (saturating) substrate concentrations; [S] represents the concentration of the substrate. The Michaelis constant is the substrate concentration at which the reaction rate is half V_{max}.

Biofilms contain a mixture of fungi, bacteria, yeasts, ciliated protozoa, amoebae, nematodes and algae. Bacteria and fungi are the two dominant microorganisms groups in biofilters, however as bacteria populations grow they can sustain protozoa and viruses. Chung *et al*. (2010) showed that a granular activated carbon and peat (1:2) biofilter that was inoculated with waste water sludge during dimethyl sulphide removal experiments, were dominated by microorganisms belonging to the phylums of *Proteobacteria*, *Firmicutes* and *Actinobacteria* . This included: *Acinetobacter calcoaceticus*, *Pseudomonas putida* (γ-*Proteobacteria*); *Desulfobacca acetoxidans, Desulfatirhabdium butyrativorans* (δ-*Proteobacteria*); *Hyphomicrobium facile* (α-*Proteobacteria*); *Pseudomonas acidovorans* (β-*Proteobacteria*); *Staphylococcus aureus, Clostridium thiosulfatireducens, Bacillus cereus* (*Firmicutes*); *Cellulosimicrobium cellulans*, and *Terrabacter terrae* (*Actinobacteria*). This diversity of

microorganisms may be attributed to the range of compounds that is created by dimethyl sulphide metabolism and the subsequent sulphur oxidation, anaerobic sulphate reduction, carbon oxidation and fermentation processes occurring simultaneously (creating compounds such as dimethyl sulphoxide, methyl mercaptan, hydrogen sulphide and/or sulphate, plus by-products of formic acid, formaldehyde and methanol). Chung *et al.* (2010) also demonstrated that the relative abundance of microorganism populations can vary in response to changing concentration of pollutant gases, with increasing concentrations of dimethyl sulphide reducing the diversity of microorganisms in their experiment.

Certain biofilter media (such as compost) will have inherent well-developed communities of microorganisms, whereas other materials (such as synthetic polymers) will be lacking the bacteria population required to degrade contaminants. Inoculation of support medium with either specific microbial strains dedicated to the removal of certain compounds, or more general inocula (such as activated sludge from water treatment plants), may enhance the removal efficiency of biofilters. Microorganisms in biofilters primarily use contaminants as energy sources creating water and carbon dioxide; however, a fraction is converted to biomass that can accumulate and clog the reactor over time. According to Groenestijn & Hesselink (1993), in a biofilter, compounds with a Henry's dimensionless air-water partition coefficient H up to 10 ($(mol.m^{-3})air/(mol.m^{-3})water$) can be removed because the gas residence time (30-60s) and the specific gas/liquid surface area (300 -1000$m^2 \cdot m^{-3}$) are high. However, Smet & Langenhove (1998) reported that, in contrast to the effective removal of hydrogen sulphide and numerous VOCs in biofilters, the reported removal efficiencies for volatile organic sulphur (VOS) compounds such as dimethyl sulphide (Me_2S) were rather low and variable.

Smet *et al.* (1999b) observed that while microbial inoculation of biofilters is rarely needed or advantageous because the ambient microbiota rapidly colonises and adapts to the pollutants, the biofiltration of volatile organic sulphur (VOS) compounds is an apparent and interesting exception since inoculation with *Hyphomicrobium* MS3 was necessary to obtain a high elimination capacity (for example, 680 g Me2S m^{-3} d^{-1} in an inoculated compost biofilter). The authors underlined the importance of inoculation with specific microorganisms to degrade VOS compounds. Since microbial decomposition of reduced sulphur compounds produces sulphuric acid, they also reported that microbial effectiveness is significantly reduced in acidic conditions and that it was essential to maintain pH adjustment, for example by initial incorporation of dolomite into the biofilter organic medium. The authors also highlighted the need for correct adjustment of moisture content and ensuring that adequate nutritional supplementation was maintained.
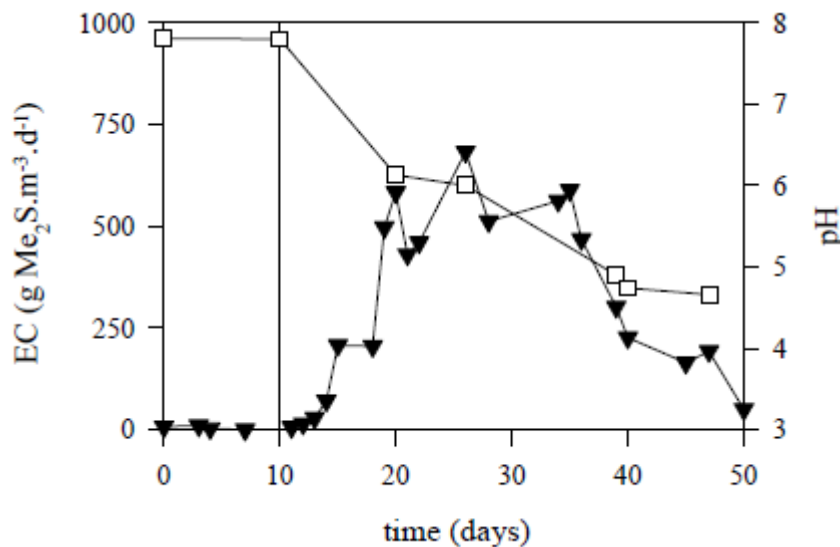
Figure 1. Elimination capacity (EC-triangles) of a compost biofilter for dimethyl sulphide (Me₂S) (gm^{-3}d^{-1}) and pH (squares) of the compost material before (days 0-10) and after (days 10-50) inoculation with *Hyphomicrobium* MS3(Smet & Langenhove, 1998).

2.6.3   Types of bioreactor

Biofilters, biotrickling biofilters, bioscrubbers and membrane biofilters are the four main types of bioreactor that are used to treat VOCs and odorous compounds (Shareefdeen & Singh, 2005; Mudliar *et al.*, 2010). The pollutant removal mechanisms are similar in all types, however differences exist in the use of microorganisms, packing media and treatable pollutant concentration range. A summary of VOC/odour treatment efficiency for the four main bioreactor types is shown in Table 3.

Biofilters

Biofilters are reactors in which a humid polluted air stream is passed through a porous packed bed that supports a mixed culture of pollutant-degrading organisms within a biofilm. Biofilters reduce odours by transferring pollutants to the water phase, which is then followed by adsorption to a medium or absorption to a biofilm. Adsorption to a filter medium provides good treatment during the initiation of a new biofilter, however once the adsorption capacity is occupied (often in a matter of days), biodegradation in the biofilm becomes the principle odour removal mechanism. Both odour removal processes are contingent on the movement of contaminated air to the water phase (gas-liquid mass transfer).

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Table 3. Comparative performance evaluation of bioreactors for VOC and odour control (Mudliar _et al._, 2010)

Bioreactor Type	Target VOCs/Odour conc. g/m³	Treatment efficiency for:				
		Low conc. of VOCs/odours	High conc. of VOCs/odours	High water soluble VOCs	Low water insoluble VOCs	Fluctuating feed conditions
Biofilter	< 1	High	Low	High	Low	Low
Biotrickling filter	< 0.5	High	Low	High	Low	Low
Bioscrubber	< 5	High	High	High	Low	High
Membrane bioreactors	High	High	High	High	High	Unknown

A healthy microbial biofilm is crucial in a biofilter as this is where odorous compounds are degraded. Biofilms are highly sensitive to a number of abiotic variables that need managing. The support medium (biofilter bed) for a biofilm can be either natural or inactive, however to support and promote a healthy biofilm and gas-biofilm mass transfer, the medium should have a high specific surface area, high porosity, good water retention capacity and intrinsic nutrients (see section 2.7). Biofilters are often periodically irrigated with nutrient solution to maintain their performance. The main advantage of biofiltration is that it can treat large volumes of low concentration VOCs and odorous compounds for little capital investment. They are however, highly sensitive to changes in operational parameters.

Biotrickling biofilters (BTFs)

This type of bioreactor passes polluted air through a packed bed similar to a traditional biofilter, but instead of periodic irrigation, they continuously recirculate aqueous solution containing essential nutrients. Pollutants are first dissolved into the falling liquid film and then transferred to the biofilm. This design feature makes BTFs more adept at eliminating water soluble VOCs. BTFs use inert or synthetic materials (such as resins, ceramics and polyurethane) that are inoculated with a suitable microbial culture. BTFs are subject to the same management considerations as traditional biofilters, however biomass accumulation in the filter bed and subsequent clogging of the medium and performance loss is more prevalent. BTFs share many of the same advantages of traditional biofiltration, however (at present) they cannot treat the same pollution concentration range.

Bioscrubbers

Bioscrubbing of polluted air brings together two distinct processes that create a system that is operationally stable and more easily controlled than biofilters and BTFs. A bioscrubber unit consists of two sections, an absorption column/scrubbing tower and a bioreactor. The scrubbing tower transfers the gaseous pollutants into a liquid phase, which is then circulated to an agitated, aerated bioreactor. Within the bioreactor the pollutant-laden liquid has a residence time of 20-30 days where it is microbially degraded before being recirculated back to the scrubber. Most reactor types use an activated sludge mixed with a nutrient solution. The advantages of this type of bioreactor are that they can treat high pollutant concentrations (high loading rates), there is a low risk of clogging, they have high bioprocess control and small space requirements.

Membrane bioreactors

In this type of reactor the pollutants in the gas phase are transferred to the biofilm through a membrane. The gas-liquid phase boundary is therefore larger than in traditional biofilters, making it better for removing high concentrations of polluting compounds and those with low solubility. Hollow fibres and flat sheets are the two types of basic configuration of membrane bioreactor. Each can be constructed from a very diverse range of materials that have different chemical (for example solubility and selectivity) and physical properties (such as porosity and thickness). This diversity allows membrane bioreactors to be designed with selective permeation for specific polluting compounds. The advantages of a system like this are flows can be varied without any problems and it is easy to scale up. A significant disadvantage to membrane biofilter is the high capital cost required.

2.7   Biofilter effectiveness, sensitivity and operating parameters for odour control

2.7.1   Typical biofilter media

Biofilters support biological biofilms on their media (filter bed) that are responsible for the degradation of organic polluting compounds. The choice of filter medium is therefore one of the most significant decisions facing an operator, as filter types can significantly vary in cost, performance and longevity. A summary of common biofilter materials and properties is shown in Table 4, however many other organic and inorganic packing materials are also used. For example, Barona *et al.* (2004) measured the highest hydrogen sulphide

elimination capacities from a mixture of pig manure and sawdust, when compared to soil and algae, sludge, and horse manure packing material.

Chen & Hoff (2009) reviewed the odour reduction performance of approximately 30 biofilter materials relating to a wide range of agricultural facilities and operating conditions. No obvious correlation between performance and media-type was apparent. The authors reported that a great variety of media materials have been verified suitable for biofilters. However, considering the practical application in agricultural facilities, factors such as cost and local availability must also be considered. The mixture of compost and wood chips (ratio of 30 to 70 by weight) has been recommended as one of the better choices.

Table 4. Summary of important properties of common biofilter materials (Devinny _et al._, 1999).

	Compost	Peat	Soil	Activated carbon + inert	Synthetic
Inherent Microorganisms	High	Medium-low	High	None	None
Surface area	Medium	High	Low-medium	High	High
Air permeability	Medium	High	Low	Medium-high	Very high
Assimilable nutrient content	High	Medium-high	High	None	None
Pollution sorption capacity	Medium	Medium	Medium	Low-high[a]	None to high[b], very high[a]
Lifetime	2-4 years	2-4 years	>30 years	>5 years	>15 years
Cost	Low	Low	Very low	Medium-high[a]	Very high
General applicability	Easy, cost effective	Medium, water control problems	Easy, low-activity biofilters	Needs nutrients, may be expensive[a]	Prototype only or Biotrickling filters

[a] Activated carbon

[b] Synthetics coated with activated carbon

Peat

Peat is the partially decomposed remnants of plant material that is synonymous with wetland habitats that contain high water tables. Peatlands are often sites of special scientific interest as they maintain unique flora and fauna. Wetlands and peatlands are an important component of the global carbon cycle because they account for 16-33 per cent of the world's soil carbon store (Gorham, 1991; Bridgham et al., 2006; Maltby and Immirzi, 1991). Peat has long been used as an energy source in many parts of the world and used within commercial composts. However, in the developed world (particularly in the UK), this practice has been in decline as peat extraction is a significant source of carbon emissions and habitat destruction. Peat is however, viewed as a good filter medium as it possesses a large specific surface

area and a high water retaining capacity, therefore providing good living conditions for microorganisms. The disadvantages are numerous however, as peat has low intrinsic nutrient concentrations, no nitrifying bacteria and prevailing acidic conditions. This means that each of these outlined issues needs addressing and managing to promote and sustain a healthy microbial population suitable for treating odorous gases.

Soil

Soil was one of the first types of media to be used in biological odour treatment as it is inexpensive and plentiful with a large indigenous microbial population. Soils are naturally hydrophilic, making them easier to rehydrate than compost or peat in the event of drying. The disadvantages of soils are that they have a tendency to aggregate, which creates preferential paths of air flow. When using a soil medium a large bioreactor design is required because of low specific activities, however because of its high bearing strength, soil can be layered with much less compaction than compost or peat. Soil biofilters have large gas residence times (minutes) due to their low permeability.

Compost

Compost has a large diversity and density of microorganisms. It has good water retention properties, neutral pH and a suitable organic content. Compost on its own can suffer from bed compaction over time and lead to pressure drop, therefore it is usually mixed with various proportions (20 to 80 per cent) of bulking agents (such as wood chip and perlite). Several compost types can be used (such as sewage sludge, green and household), however there appears to be no distinct advantage between types.

Wood chip or bark

Wood chip is often used as a bulking agent with compost, however it can also be used by itself with a regular supply of nutrients. Wood chip is good at preventing compaction and allowing homogeneous air flow. Common particle sizes are 1-5 cm. Commercially available pine-based wood chips may be relatively acid in character (pH 4.5 – 6) and this should be taken into consideration since biofilters are recommended to be operated under neutral conditions.

Activated carbon

Granular activated carbon can be used either alone or with bulking agent to attenuate pollution fluctuations. It has excellent structural properties, with uniform particle size and good resistance to crushing. While it has substantial water-holding capacity and provides a good surface for microbial attachment, activated carbon must be microbially inoculated and nutrients added before use.

2.7.2 Operational factors

Although biofiltration can be quite a simple technology, its effectiveness relies on optimising several parameters that promote and maintain a healthy microbial community capable of degrading odorous compounds within the biofilm. Table 5 shows a summary of the typical biofilter operating conditions for waste air treatment. The following sub-sections deal with the six most important parameters for optimising the microbial breakdown of pollutants.

Table 5. Typical biofilter operating conditions for waste air treatment (original by Devinny *et al.*, 1999)

Parameter	Typical value
Biofilter layer height	1-1.5m
Biofilter area	1-3000m^2
Waste air flow	50-300,000m^3 h^{-1}
Biofilter surface loading	5-500m^3 m^{-3} h^{-1}
Biofilter volumetric loading	5-500m^3 m^{-2} h^{-1}
Bed void volume	50 per cent
Empty bed residence time	15-60s
Pressure drop per meter of bed height	0.2-10cm water gauge (max. 10cm)
Inlet pollutant and/or odour concentration	0.01-5g m^{-3}, 500-50000 OU m^{-3}
Operating temperature	15-40°C
Inlet air relative humidity	>98 per cent
Water content of the support material	60 per cent by mass
pH of the support material	pH 6-8
Oxygen content of inlet air	5-15 per cent
Typical removal efficiencies	60-100 per cent

Oxygen content

Oxygen is vital to the operation of biofilters because most odour reducing microorganisms are aerobic. Aerobic heterotrophic bacteria present in biofilters require at least 5-15 per cent oxygen to be present within inlet gas streams (Shareefdeen & Singh, 2005). Oxygen

deprivation is undesirable because it can lead to partially oxidised by-products forming within the biofilm, such as carboxylic acids and aldehydes, which can cause odour. Oxygen content within a biofilter will be largely determined by the inlet gas and therefore dependent on the compost aeration rates used by operators. Oxygen limitation can also be caused by improper air distribution within a biofilter caused by poor design or filter bed compaction, leading to anaerobic pockets forming. Where this is the case, biofilter media should be unloaded and carefully repacked. Oxygen limitation is more likely to occur where air streams contain high concentrations of easily degradable hydrophilic compounds and in systems where thick biofilms exist (Devinny *et al.*, 1999). To increase the oxygen content of inlet gas to a biofilter, operators could investigate mixing ambient air to their gas stream.

Temperature

Microorganisms responsible for degrading odorous compounds within biofilms are strongly influenced by temperature. Biofilters contain hundreds or thousands of microbial species that each has a specific optimum rate of metabolic activity, thus making setting a biofilter operational temperature a biological compromise. It is suggested that to achieve optimum microorganism performance within a biofilter it should be operating between 30 and 40°C. For example, Yoon *et al.* (2002) showed that a compost-packed biofilter had a higher VOC removal efficiency at 32°C compared to when operated at 45°C and 25°C, with EBRT set to 1.5 minutes and VOC inlet concentration to 92g m^{-3}. In a similar study, Yoon & Park (2002) showed that a peat-packed biofilter had the highest removal efficiency (inlet VOC concentration = 92g m^{-3}) when biofilter temperature was set to 32°C (94 per cent) and EBRT to 1.5 minutes. Interestingly, decreasing the EBRT at 32°C caused a reduction in VOC removal efficiency to 81 per cent. Yoon & Park (2002) also showed that when running their peat-packed biofilter at 25°C, EBRT had to be increased to three minutes to get close to the removal efficiency (93 per cent) achieved at 32°C with an EBRT of 1.5 minute. Therefore, Yoon & Park (2002) clearly show that achieving optimal (VOC) removal efficiency in their experiments was a balance between temperature and residence time.
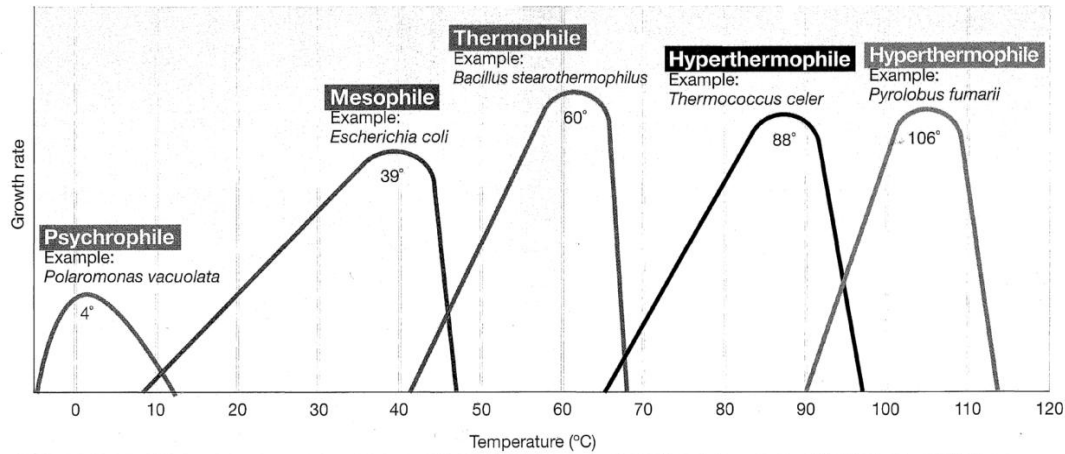
Figure 2. Relation of temperature to growth rates of a typical psychrophile, mesophile, thermophile and two different hyperthermophiles (Madigan & Martinko, 2006).

Operating a biofilter at a temperature of *c.* 40°C would appear to be advantageous as this represents the generic optimum for growth and activity of microbes in the mesophile category (Figure 2). However, if ammonia is present in the waste gas stream, then taking into account the optimum temperature of nitrifying bacteria (25 – 30°C, Figure 3) would be recommended. Aiming for a biofilter operating temperature therefore of 35°C may represent the best microbial compromise for the degradation of odorous compounds in a compost waste gas stream. Operating biofilters at low temperature will still provide limited treatment, however small increases above 40°C could potentially cause a dramatic decrease in removal efficiency due cell membrane collapse and protein denaturing of microorganisms in the biofilm. Equally, rapid operating temperature changes should be avoided as this will result in microbial species becoming inactive, therefore resulting in a decline in treatment.

Biofilter performance and operation as related to commercial composting)
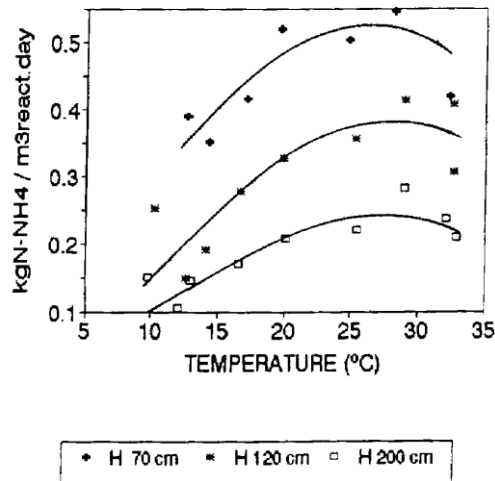
Figure 3. Ammonium oxidation rate (kg N/m³d) versus temperature. The symbols represent three different heights in a biofilter (Fdz-Polanco *et al.*, 1994).

Setting the biofilter temperature to 35°C may also limit unfavourable reductions in physicochemical interactions that higher temperatures may promote. For the majority of gases, solubility decreases with increasing temperature in accordance with Henry's law, as most heat or enthalpy change in dissolution reactions are negative (exothermic), therefore increasing temperature leads to gas evolution rather than absorption. This is an example of the Le Chatelier principle, where a system is responding to relieve a stress to reach equilibrium. The solubility of odorous gases would also be affected by pressure in a biofilter, as Henry's law states that the solubility of a gas in a liquid is directly proportional to the pressure of that gas above the surface of the solution. Therefore, if pressure is increased, gas molecules are 'forced' into the solution (biofilm) to relieve the pressure. In general, the biological effect is perceived to be more important than the chemo-physical at removing odour, which is why warm biofiltration is advantageous (Devinny *et al.*, 1999).

The control of temperature in a biofilter can be difficult and is often determined by the incoming gas stream. Direct heating or refrigerating of gas streams may be viewed as too expensive, however cheaper options may exist. For example, where waste air is too hot it could be mixed with ambient air; alternatively, if the incoming waste air and biofilter is too cold, insulating the ducting and biofilter may be a cost effective strategy.

Medium pH and alkalinity

pH has an important influence on biofiltration efficiency. To promote a healthy microbial population within a biofilm and subsequent effective odour treatment, the pH of packing material should be neutral, around pH6-8. For example, Lu *et al.* (2002) measured the

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optimal BTEX degradation between a pH of 7.5 and 8.0. Theoretical and laboratory studies of biofilter performance suggest that deviations in pH strongly influence the ability to remove certain odorous compounds, such as ammonia (Hartikainen *et al.*, 1996; Baquerizo *et al.*, 2005). It is common for some types of support medium to be naturally acid (such as peat) with low buffering capacities. Therefore, to fix and maintain support media to neutral pH levels, buffering materials (such as calcium carbonate and dolomite) can be added.

Moisture

Sufficient water content is one of the most important parameters for an effective biofilter, because microorganisms responsible for the degradation of odorous compounds require water to perform their normal metabolic reactions. In addition, the appropriate moisture content is required for gas-water phase transition and movement of odorous molecules into the biofilm. Sub-optimal moisture levels can also lead to bed drying and the development of fissures that can cause channelling and a reduction in biofilter efficiency. In contrast, excess water promotes the development of anaerobic zones within the biofilter leading to channelling of gas, increased back-pressure and the creation of odorous compounds. The suggested optimum moisture content is 30-60 per cent water (by weight) (Mudliar *et al.*, 2010), which is dependent on the support medium used. This may be achieved by pre-humidification of the inlet gas stream or the direct application of water to the biofilter support medium via sprinklers.

Nutrients

Microorganisms in the biofilm require mineral nutrients (such as nitrogen phosphorous, potassium, sulphur, calcium, magnesium, sodium and iron) for healthy growth and function. Organic support mediums have varying amounts of intrinsic nutrients, but progressive nutrient deficiency can reduce nutrient resources and limit biofilter performance (Morgenroth *et al.*, 1996; Delhomenie *et al.*, 2001). Inorganic support media generally have no or very limited supplies of inherent nutrients. Nutrients can be added during the construction/filling stage as slow release fertilisers that can replenish nutrients lost to leaching or biotransformation. An alternative approach would be to add commercial fertilisers to irrigation waters. Examples of the most common nutrients added include: KH_2PO_4, $Na_xH_{(2-x)}PO_4$, KNO_3, $(NH_4)_2SO_4$, NH_4CL, NH_4HCO_3, $CaCL_2$, $MgSO_4$, $MnSO_4$, $FESO_4$, Na_2MoO_4, and vitamins (such as B1) (Wu *et al.*, 1999).

Empty bed residence time (EBRT)

A commonly used concept in the design of biofilters is EBRT and is defined as the empty bed filter volume divided by the air flow rate. Theoretically, pollutants in the gas phase first need to be transferred to liquid phase, where they can be degraded by the microorganisms living in the biofilter. Therefore, a sufficient EBRT is necessary to allow the transfer and degradation of pollutants to occur, which makes EBRT a critical design and operating parameter. EBRT is a relative measure of gas residence time within the biofilter media. The actual gas residence time in the biofilter reactor is the result of the EBRT divided by the air-filled porosity available for gas flow, but such porosity data is rarely known. Different pollutants have different characteristics which affect the absorbing and adsorbing times and degradation processes, and thus need different EBRTs to be completely degraded. A reasonable EBRT is closely related to media moisture content and pollutant loading. Higher moisture content and lower pollutant loadings result in shorter EBRTs. In theory, EBRTs need not be long for most odour compounds but biofilters are typically designed to have EBRTs in the range of 15 to 60 seconds. For example, Chen & Hoff (2009) suggest that EBRTs between 4 and 10 seconds should be sufficient for a biofilter designed to control odours and VOCs from agricultural sites provided the moisture content is controlled adequately.

2.7.3 Common biofilter problems

Variation in operational conditions

One of the most common problems that can lead to odorous emissions from biofilters is a sudden change in operational conditions. This could be due to an equipment failure or a change in contaminant loading rates due to variations in feedstock. Barona *et al.* (2004) showed that after starvation (shut down) periods (days) removal efficiencies can recover quickly, suggesting brief starvation periods are not critical for the efficiency performance of biofilters. They also found that sudden inlet increases reduce removal efficiency and decreases in residence time reduce the elimination capacity in their experiments.

Blockages and biofilm clogging

Biomass accumulates in a biofilter when growth from the introduced organic carbon exceeds endogenous respiration. Excess accumulation may clog the filter bed and packaging

material and produce large pressure drops and create air flow channels (Iliuta & Larachi, 2004; Yang *et al.*, 2010). Back pressures in a biofiltration system can cause excessive wear and tear on blowing equipment; air channelling will reduce the contact time between odorous air and filter medium therefore negatively affecting removal efficiencies. Control strategies to rectify or prevent blockages and biofilm clogging can be categorised into physical, chemical and biological methods. For physical methods, mechanical or hydraulic forces are used to remove biomass from medium beds and break up compacted materials. This may include periodically mixing the support media or backwashing with water at a high flow rate. The two chemical options include: controlling or limiting the carbon and nutrients in the incoming gas flow or liquid solution (starving the microorganisms), or washing with chemical solutions (e.g. NaOH and NaCLO). A biofilter that has received a chemical wash may require a period of several days to readjust before maximum elimination capacities are restored. A biological option could be to introduce higher trophic level organisms such as protozoa, metazoa, and nematodes that can graze on microorganisms and consume dead cells. For example, van Groenestijn *et al.* (2001) demonstrated that the introduction of mites helped control excessive fungal growth and reduce pressure drop in their biofilter.

2.8   Biofilter treated compost emissions

2.8.1   Elimination capacity for different odour compounds from biofilters

The ability of biofilters to eliminate typical odorous compounds from waste gas streams are summarised in Table 6 to

Table 8.

Table 6. Biofilter efficiency in treating mechanical biological treatment waste gas streams (European Commision, 2006).

Substance (group)	Biofilter efficiency (%)
Aldehydes, alkanes	75
Alcohols	90
Adsorbable organic halogens, aromatic hydrocarbons (benzene)	40
Aromatic hydrocarbons (toluene, xylene)	80
Non-methane volatile organic compounds	83
Polychlorinated dibenzo-p-dioxins and dibenzofurans	40
Odour	95 - 99

Table 7. Effectiveness of well-maintained biofilters with upstream air humidifiers used at mechanical biological treatment plants (European Commision, 2006).

Compounds of the exhaust air	Separation efficiency (%)		
	Facility A	Facility B	Facility C
Acetaldehyde	−18 to −99	99	99
n-Butylacetate	83 - 96	73 - 99	97 - 99
Camphor	60 - 88	60 - 90	88 - 91
Dichloromethane	−53 to −80	−300 to −33	43 - 62
Dimethyl sulphide	44 - 78	−55 to −89	10 - 31
2-Hexanone	75 - 80	-	80 - 82
Naphthalene	50 - 75	38 - 93	58 - 82
Phenol	−25 to −79	75 - 88	47 - 94
1,4-Dichlorbenzene	0 - 73	−1900 to −89	−130 to −13
Ethyl benzene	27 - 61	16 - 43	12 - 42
2-Ethyl toluene	14 - 89	25 - 55	33 - 41
3/4-Ethyl toluene	38 - 96	45 - 77	23 - 45
Limonene	94 - 98	30 - 63	29 - 40
Styrene	64 - 89	44 - 66	21 - 50
Toluene	29 - 50	7 - 36	16 - 39
m/p-Xylene	30 - 71	17 - 45	9 - 42
o-Xylene	7 - 63	20 - 45	23 - 41
Acetone	99 - 100	93 - 97	94 - 97
2-Butanone	94 - 99	95 - 100	99 - 100
Ethanol	94 - 99	100	100
Ethylacetate	74 - 93	82	97 - 99
α-Pinene	59 - 83	5 - 39	8 - 44
β-Pinene	53 - 81	38 - 49	12 - 44
Benzene	0 -17	-	0 - 20
Trichlorethene	−108 to −3	67 - 90	20 -46

Table 8. An example of critical load and elimination capacity of common odorous compounds. Full details see Devinny *et al*. (1999).

Contaminant(s)	Biofilter medium	Critical load (g m^{-3} h^{-1})	Maximum elimination capacity (g m^{-3} h^{-1}) (removal %)
Acetone	Compost-based	20-229	67-229 (90)
Benzene	Compost-based	1	8-12
BTEX (Benzene, toluene, ethylbenzene, xylenes)	Compost-based	N/A	23
	Carbon-coated foam	N/A	41-55
	Sand	N/A	14-30
	Carbon-coated foam	N/A	15-44
Butanol	Compost-based	30-40	70-80
Dimethyl sulphide	Compost/pine mulch	10	10-12
	Wood bark	8-10	70 (84)
	compost-based	N/A	11-13
Hydrogen sulphide	Compost	100	300
Methanol	Compost-based	10-42	18-70
	Compost/perlite	10-20	301
α-Pinene	Compost/perlite or compost/granular active carbon	N/A	35
Styrene	Perlite	62	62
	Peat	60-75	100
Toluene	Peat	N/A	4-10
	Compost	30-40	45-100
	Compost-based	<10	15-25
Xylene	Compost-based	10-15	25

2.8.2   Biofilter emissions

The odorous compounds found in composting off-gases, mainly comprising VOCs and ammonia, are often treated using biofilters. In general, while ammonia removal in biofilters is usually very high, for even highly effective biofilters it is likely that they will only decompose and remove a proportion of the total VOC content of emissions. There are many reasons for this such as the reduced effectiveness of microbial decomposition within the biofilter media. For example, some of the more odorous VOCs are very insoluble (dimethyl disulphide, for example) which precludes significant incorporation within the biofilm; many VOCs are

decomposed by a very limited range of microorganisms, which may be absent; pile conditions may become toxic to some microorganisms; and intermittent generation of specific odour compounds can lead to periodic reduced populations of the microorganisms that are required for their decomposition.

In the event of poor biofilter performance, the only way of diagnosing and correcting problems is to conduct a full analysis of the air treatment system. Hence, for example, failure to remove a significant proportion of VOCs may be caused by a number of transient or longer term problems which may be amenable to correction, such as microbial toxicity due to high ammonia concentrations, low biofilter pH or the absence of suitable microorganisms. Inappropriately designed biofilters, for example with empty bed residence times that are too low for effective treatment, may have to be extended or undergo structural alterations to improve performance. These systems and biofilter systems with unduly high levels of residual VOCs (such as methyl sulphides) in outlet gases may also benefit from the addition of final polishing technologies to reduce residual VOC levels, such as activated or impregnated carbon units or sea shell-based biofilters. It is important to know the range of VOC compounds, concentrations and loads that are typical for untreated emissions from SSHW composting to enable appropriate abatement systems to be designed.

Defoer *et al.* (2002) studied the biofilter emissions from four full-scale plants composting vegetable, fruit and green waste (VFG). They reported that the emissions mainly comprised terpenes (65 per cent of total VOCs), ketones (8 per cent), hydrocarbons (8 per cent), alcohols (7 per cent), esters (5 per cent), aldehydes (3 per cent) and sulphur compounds (3 per cent). This broadly reflected the composition of untreated emissions from composting similar waste types as reported by Smet *et al.* (1999a). Defoer *et al.* (2002) measured both odour and chemical concentrations of the biofilter emissions and reported that the total VOC concentration varied between 0.09 and 23.6mg m^{-3} while the odour concentrations (determined by olfactometry) varied from 390 to 13,050OU$_E$ m^{-3}. They concluded that the total VOC concentration was strongly correlated with odour concentration (R^2 = 0.97, *p*<0.001). Hence, the total VOC concentration of biofilter emissions from VFG composting can be used to give a good indication of the emission's odour concentration. This is not the case for all waste types being composted; for example Noble *et al.* (2001) found a close correlation (R^2=0.90) between the sum of the concentrations of hydrogen sulphide and dimethyl sulphide and odour concentrations of the emissions from mushroom composting.

Ammonia is a highly odorous gas produced by organic waste treatment facilities and emissions from composting can be high, especially for low C:N ratio feedstocks and well aerated composting systems. Elkind *et al.* (2007) studied ammonia emissions from SSHW in

the laboratory under good aerobic conditions (16 per cent oxygen in recycled process air). They reported higher levels of ammonia emissions at 67°C after 24 days (31.6 per cent of initial N) compared with 55°C (15.3 per cent) and 40°C (3.4 per cent). Smet *et al.* (1999a) reported concentrations up to 227mg m^{-3} (326ppm) ammonia in the exhaust gases from composting but warned that even low concentrations of ammonia (45mg m^{-3}) were known to inhibit biofilter performance. Smet *et al.* (2000) found that no ammonia toxicity effects relating to nitrifying ability in the biofilter media were detected at concentrations of ammonia up to 550mg m^{-3}, suggesting that even high initial levels of ammonia in exhaust gases may be removed effectively using biofiltration. However, Smet *et al.* (2000) also reported that due to osmotic effects a complete inhibition in nitrification and NH_3-removal was obtained at a measured NH_4NO_3 concentration in the compost material of 6–7g N kg^{-1}, corresponding to a cumulative NH_3-removal in the biofilter of 6000g m^{-3}. Also the removal of the odorant dimethyl sulphide (Me_2S) in a *Hyphomicrobium* MS3-inoculated compost biofilter was completely inhibited due to NH_3-toxicity at a waste gas concentration of 100mg NH_3 m^{-3}. Hence, biofilters may demonstrate very effective removal of ammonia until a maximum cumulative NH_3-removal load is exceeded and thereafter elimination capacities for both ammonia and VOCs may be significantly reduced. In addition, even moderate ammonia concentrations may inhibit removal of odorous VOCs.

Conversely, biotreatment of ammonia can be particularly difficult when input air has not been pre-treated, as high ammonia loading rates are associated with bacterial inhibition leading to a fall in treatment performance (Hartikainen *et al.*, 1996; Baquerizo *et al.*, 2005). A study on the modelling of ammonia biofiltration reported that high concentrations of free ammonia in the support material can strongly inhibit the biological activity of a biofilter (Baquerizo *et al.*, 2004). The effectiveness of biotreatment of ammonia depends on the capacity of the nitrifying microorganisms to oxidise ammonia to nitrate. This nitrification rate is affected by factors such as temperature, pH, nutrient availability and the presence of inhibitory compounds. Good nitrifying capacity has been measured at pH6 and none at pH4 (Hartikainen *et al.*, 1996).

High ammonia emissions are mainly associated with highly aerobic composting systems and very putrescible feedstocks. Equally, high ammonia emissions are a feature of effective composting but they also need to be well managed to prevent odour problems. Since the generation and emission of ammonia depends on a number of factors, it may be argued that ammonia is not a problem for all composting sites. However, it is important for operators to understand how and why ammonia emissions may occur for particular sites and to take

steps to minimise odour risks, for example by installing ammonia scrubbers prior to the biofilter stage of air treatment.

Pagans *et al.* (2006b) studied the emission of VOCs produced during composting of different organic wastes: source-selected organic fraction of municipal solid wastes (OFMSW), raw sludge (RS) and anaerobically digested wastewater sludge (ADS) and animal by-products (AP) and the subsequent biofiltration of these emissions. Composting was performed in a laboratory scale composting plant (30L) and the exhaust gases generated were treated by means of a compost biofilter. Mean VOC concentrations in the composting exhaust gases for each composting process are shown in

. These ranged from 50 to 695mgCm^{-3} for OFMSW (bulking agent:waste was 5:1), from 13 to 190mgCm^{-3} for OFMSW (bulking agent :waste was 1:1), from 200 to 965mgCm^{-3} for RS, from 43 to 2900mgCm^{-3} for ADS and from 50 to 465mgCm^{-3} for AP.

 also shows mean VOC concentrations in the exhaust gas from the biofilter. These ranged from 55 to 295mgCm^{-3} for OFMSW (5:1), from 12 to 145mgCm^{-3} for OFMSW (1:1), from 55 to 270mgCm^{-3} for RS, from 42 to 855mgCm^{-3} for ADS and from 55 to 315mgCm^{-3} for AP. Removal efficiencies up to 97 per cent were achieved although they were highly dependent of the type of waste that was composted and therefore the profile of VOCs emitted (0-57 per cent, 0-60 per cent, 71-91 per cent, 0-97 per cent and 0-82 per cent respectively). An important observation was that the compost biofilter itself emitted VOCs with an estimated concentration of 50mgCm^{-3}. The variable nature of the removal efficiencies is often a feature of laboratory studies and can be misleading. This effect can be explained by the fact that VOC emissions were continuously monitored for at least 100 days from individual batch composting systems. Hence, VOC emissions tended to peak early in each composting process and thereafter declined at different rates reflecting the different feedstocks being

studied. Removal efficiencies tended to peak when VOCs emissions were highest and to decline as VOC emissions declined. Removal efficiencies declined over time because, as noted above, the compost biofilter itself emitted VOCs and as compost VOC emissions declined over time, these compost levels often approached the residual biofilter levels giving low or even zero removal efficiencies.

Table 9. VOC emissions average (before and after biofilter), average and maximum and minimum values (in parenthesis) of loading rate and elimination capacity and removal efficiency range for the five composted wastes (Pagans *et al.*, 2006b).

	Average VOCs emissions (mg C m^{-3})		Loading rate (g C m^{-3} biofilter h^{-1})	Elimination capacity (g C m^{-3} biofilter h^{-1})	Removal efficiency (%)
	Before biofilter	After biofilter			
OFMSW (5:1)	237	155	9.83 (2.10–28.8)	3.52 (0–16.5)	0–57
OFMSW (1:1)	61.7	50.7	2.56 (0.55–7.95)	0.61 (0–2.90)	0–60
RS	550	110	22.9 (8.20–40.0)	18.3 (5.84–31.9)	71–91
ADS	716	192	29.7 (1.85–120)	21.7 (0–117)	0–97
AP	150	100	6.25 (2.20–12.0)	2.29 (0–15.7)	0–82

In a similar study, Pagans *et al.* (2005) reported pre and post-biofilter ammonia concentrations (Table 10). Very high removal efficiencies for ammonia for all waste types were obtained with one exception. Due to the high ammonia adsorption and absorption capacity of the compost media, no start-up period was observed by the authors for the removal of ammonia and this was ascribed to the new biofilter material providing good treatment for the first few days of operation because it acts as an adsorber. Therefore, a global removal efficiency of 98.8 per cent was obtained at a global loading rate of 846mgNH$_3$ m^{-3} biofilter h^{-1} (days 0–5 for OFMSW (5:1)), a global removal efficiency of 95.9 per cent was obtained at a global loading rate of 7500mgNH$_3$ m^{-3} biofilter h^{-1} (days 0–6 for OFMSW(1:1)) and a global removal efficiency of 99.4 per cent was obtained at a global loading rate of 6670mgNH$_3$ m^{-3} biofilter h^{-1} (days 0–6 for DS). Even after increasing the

global loading rate to 67,100mgNH$_3$ m^{-3} biofilter h^{-1} (days 0–4 for AP), the removal efficiency only slightly decreased to a global value of 89.5 per cent. However, for AP from day four on, the removal efficiency in the biofilter strongly dropped to an average value of 46.7 per cent (ranging from 90 per cent at the beginning of this period to some values well below 30 per cent at the end of this period). Pagans *et al.* (2005) thought that this phenomenon may be explained by two possible causes: the compost biofilter might have reached its maximum ammonia adsorption and absorption capacity, that is, during this period, as adsorption and absorption capacities are probably saturated, ammonia removal may only be possible by biological degradation. Alternatively, it was more probable that microbial activity was inhibited by waste gases containing high ammonia concentrations (>2000mg m^{-3}).

Table 10. Cumulative ammonia emissions (before and after biofilter), global loading rate, global elimination capacity and the resulting global removal efficiency for the four composted wastes (Pagans *et al.*, 2005).

	Cumulative NH$_3$ emissions (mg NH$_3$ m^{-3})		Loading rate (g NH$_3$ m^{-3} biofilter h^{-1})	Elimination capacity (g NH$_3$ m^{-3} biofilter h^{-1})	Removal efficiency (%)
	Before biofilter	After biofilter			
OFMSW (5:1)	773	11.3	846	829	98.8
OFMSW (1:1)	6310	289	7500	7171	95.9
DS	8510	89.2	6670	6580	99.4
AP (days 0-4)	53400	4580	67100	61300	89.5
Days (4-9)	36100	15300	37500	21700	46.7

Colon *et al.* (2009) studied an actual composting facility treating 14,500 ton year^{-1} of source segregated organic solid wastes. At this facility the composting process is carried out in six composting tunnels and the curing phase took place in non-aerated turned windrows placed in an enclosed building. The exhaust gases from the tunnels were treated in two biofilters (Biofilter 1 and Biofilter 2) whereas the gases produced in the curing building were treated in a separate third biofilter. The biofilters were originally filled with wood chips previously used as bulking agent in the composting process. Irrigation of biofilters was carried out by spraying tap water on the surface. No nutrient solution was added to the biofilters. After four years of continuous operation, the biofilter material was replaced in Biofilter 2 in December 2007 and Biofilter 1 in January 2008. Again, the new biofilter material was wood chips previously used as bulking agent in the composting process. The dimensions and retention time of the biofilters studied are shown in Table 11. Air flow and gas retention time varied for

each biofilter depending on the number of tunnels in simultaneous operation (one to four in Biofilter 1 and one to two in Biofilter 2). Table 12 and

Table 13 show that the removal efficiencies for Biofilter 1, for both VOCs and ammonia, appeared to increase considerably after the biofilter media was replaced, with the increase for ammonia being statistically significant. The improvement in removal efficiencies for VOCs and ammonia for Biofilter 2 was not as pronounced as for Biofilter 1.

Table 11. General characteristics of the studied biofilters (Colon *et al.*, 2009).

Parameter	Biofilter 1	Biofilter 2
Length (m)	21.3	10.7
Wide (m)	7.7	6.9
Height (m)	1	1
Surface area (m^2)	164	74
Volume (m^3)	164	74
Tunnels	4	2
Biofilter surface area per tunnel (m^2 per tunnel)	41	37
Biofilter volume per tunnel (m^3 per tunnel)	41	37
Air flow (m^3 h^{-1})	3950–15800	3950–7900
Gas retention time (s)	25–98	26–52

Table 12. Average VOC mass flow (before and after biofilter), global loading rate, global elimination capacity and resulting global removal efficiency. Different superscripts (a and b) in the removal efficiency column indicate statistically significant differences ($\alpha = 0.05$) among VOC removal efficiency values before and after material replacement for each biofilter. The values in parentheses show the minimum and maximum value of each parameter (Colon *et al.*, 2009).

	Average VOCs mass flow (g C h^{-1})		Loading rate (g C m^{-3} biofilter h^{-1})	Elimination capacity (g C m^{-3} biofilter h^{-1})	Removal efficiency (%)
	Before biofilter	After biofilter			
Biofilter 1 old	2959	1156	18.0 (5.5–35.6)	11.0 (0.9–29.9)	42 (14–83)[a]
Biofilter 1 new	3690	929	22.8 (7.8–40.2)	17.1 (1.9–29.7)	74 (53–92)[a]
Biofilter 2 old	839	198	11.3 (4.3–23.4)	8.6 (2.4–20.6)	65 (39–88)[a]
Bofilter 2 new	2548	547	34.4 (4.4–72.9)	27.0 (1.8–62.0)	71 (37–98)[a]

Table 13. Average ammonia mass flow (before and after biofilter), global loading rate, global elimination capacity and the resulting global removal efficiency. Different superscripts (a and b) in the removal efficiency column indicate statistically significant differences (α = 0.05) among ammonia removal efficiency values before and after material replacement for each biofilter. The values in parentheses show the minimum and the maximum value of each parameter (Colon *et al.*, 2009).

	Average ammonia mass flow (g C h^{-1})		Loading rate (g NH$_3$ m^{-3} biofilter h^{-1})	Elimination capacity (g NH$_3$ m^{-3} biofilter h^{-1})	Removal efficiency (%)
	Before biofilter	After biofilter			
Biofilter 1 old	439	256	2.68 (1.22–4.26)	1.12 (0.16–1.70)	41 (13–71)[a]
Biofilter 1 new	418	83	2.56 (0.52–8.06)	2.04 (0.52–3.51)	89 (50–100)[b]
Biofilter 2 old	94	25	1.25 (0.80–1.58)	0.9 (0.30–1.58)	74 (22–100)[a]
Biofilter 2 new	212	25	2.86 (0.49–7.54)	2.52 (0.43–7.43)	92 (64–100)[a]

3 Bioaerosol scientific literature review

3.1 What are bioaerosols?

Bioaerosols are defined as aerosols, aeroallergens, or particulate matter of microbiological, plant or animal origin (Defra, 2009). Bioaerosols can interact with living systems through infective, allergenic and/or toxic mechanisms. The biological agents that have been examined in relation to bioaerosol exposures associated with waste handling and treatment processes include pathogenic or non-pathogenic spores, live (viable) or dead (non-viable) bacteria, fungi, viruses, bacterial endotoxins, mycotoxins, and peptidoglycans. Although other types of biological component may also be present as airborne particles such as algal fragments, protozoa and nematodes, these have not been considered in studies of bioaerosols emitted by the waste industry (Defra, 2009).

Bioaerosols are aerosolised as clumps, aggregates and attached to larger mineral particles in the TSP size range (also noted by Wheeler *et al.,*2001). Hence they can settle fairly rapidly, within a minute or two and within 250m of the point of generation. Weather conditions can also affect generation and aerosolisation. Viability can deteriorate according to temperature, humidity and sunlight. Die off is generally exponential, although non-viable (dead) microorganisms may still be able to cause health effects (allergenic/toxic effects in sufficient concentrations).

As composting is the biological decomposition of organic material, this leads to multiplication of microorganisms within the composting substrate. This process begins at the kerbside, when organic material is stored awaiting collection. It is the potential for these microorganisms to become airborne as the material is being processed (which are then known as bioaerosols) that leads to concern that exposure could be detrimental to respiratory health.

3.2   Bioaerosol characterisation

3.2.1   How to detect and measure bioaerosols

There are many different components of bioaerosols that could be measured. These include:

- Viable bacteria: single celled organisms.
- Viable gram-negative bacteria: bacteria with a differential wall structure meaning they do not retain crystal violet dye in a gram-staining protocol. This structure, containing a lipopolysaccharide (LPS) layer is associated with health issues.
- Viable fungal spores: as a reproductive structure designed to aid dispersal.
- Endotoxin: toxin associated with the cell walls of certain gram-negative bacteria (lipopolysaccharide (LPS) of the cell membrane).
- Glucans: components of the cell walls of certain fungi and some bacteria.
- Mycotoxins from fungi.
- Particles containing other biologically active components such as enzymes, peptidoglycans, ergosterol and so on.

The current UK protocol for measuring bioaerosols downwind of open windrow composting sites relies on viable sampling for mesophilic bacteria and fungi (particularly *Aspergillus fumigatus*, which is a pathogen) (Association for Organics Recycling (AfOR), 2009) as colony forming units (cfu m^{-3}). However it should be recognised that the viable part of the 'bioaerosol mix' may only represent a small proportion of that which may be aerosolised. Viability relies on the ability to culture microorganisms once sampled in the laboratory. Components such as endotoxin and glucan are present in both viable and non-viable bioaerosols and require separate measurement and enumeration. Components such as mycotoxins, enzymes, peptidoglycans and ergosterol are still in the research phase and are not as commonly analysed, and although there is some evidence to suggest they may be linked to health outcomes they will not be further explored for the purposes of this research.

outlines the components that could be measured and the sampling and analysis methods.

Determinant	Sampling method	Analysis method	Rationale/comments
Total inhalable/ respirable dust	Filter + IOM / light scattering	Gravimetric	Standard measure against which other metrics can be assessed. Light scattering equipment can detect particle size and concentration.
Viable microorganisms such as bacteria, fungi, gram negatives	Filter + IOM / Andersen, Liquid impinger, 'CEN method'	Culture	Standard measure for AfOR (2009) is Andersen or IOM + filter and culture. However, this is for general environmental sampling. Andersens can overload. Liquid impingers can have more flexibility in highly contaminated environments that may also be very humid. The CEN method is a new European standard for environmental measurement of viable spores.
Endotoxin	Filter + IOM	LAL assay	Usually extracted from filters, but potential for extraction from liquid if the sample liquid is characterised.
Glucan	Filter + IOM	LAL assay modification	As for endotoxin but currently less data available and it is considered a non-standard measure

Table 14. Bioaerosols components and sampling/enumeration

The research undertaken in this project used a combination of light scattering dust sampling (with size analysis, Osiris, Turnkey Instruments) and liquid impingers (SKC Biosamplers). The Osiris offers a heated inlet to differentiate between humidity and particles. Liquid impingers are not part of the AfOR protocol, but for the purposes of this study they offer greater flexibility regarding the conditions of sampling in and around biofilters, where gases are very warm (20-30°C) and have a humidity of up to 100 per cent. Simultaneous culturing for viable bacteria, gram-negative bacteria and fungi (favouring *A. fumigatus*), and endotoxin and glucan analysis can also be carried out on the same samples collected.

3.3 Bioaerosol formation during composting

The potential for particulates to be liberated from organic waste treatment sites does exist. Airborne dusts and so bioaerosols are likely to be aerosolised by the handling of the waste materials accepted on site, their storage and movement, and by meteorological conditions (presence or absence of precipitation, wind, and so on). Current guidance indicates that turning is likely to generate the highest concentrations of bioaerosols (Environment Agency, 2009). Although little data is available regarding specific material types, waste that is being composted has the potential to be biologically active at this point, hence it is liable to be the point source likely to generate the most bioaerosols on an open windrow site.

At open windrow sites, Gilbert *et al.* (1999) investigated downwind measurements of bioaerosols at two composting facilities in the UK and found concentrations returned to background values within around 200m. In an Environment Agency report Wheeler *et al.* (2001) recommend a conservative limit of 250m based on dispersal monitoring during 1999 and 2000 where again it was found background concentrations were reached within 200m. This distance was further agreed by Swan *et al.* (2003) in a report for the Health and Safety Executive (HSE). It should be noted Wheeler also measured concentrations up to 10^7cfu m^{-3} during active turning operations but dispersal was still at background levels within 250m. ADAS (2005) reported that between 88 and 96 per cent of bioaerosols generated from composting sites were below 1000cfu m^{-3} within 125m from windrow sources and all sites could be expected to be at background levels within 200m. HSE (2010) determined that bioaerosol concentrations of 10^5 to 10^6cfu m^{-3} were found at source during agitation on open windrow sites, but this decreased significantly at 50m to 100m and again that concentrations were at background values within 250m in the majority of cases.

Also at open windrow sites, endotoxin has been found at concentrations significantly above background levels at 100m from composting activities (Pankhurst *et al.*, 2011), but is still at the research phase. Dispersion of bioaerosols and endotoxin are also associated with general farming activities (Swan *et al.*, 2003).

In terms of reported concentrations at compost sites, many of the above reports specify that concentrations are elevated during agitation only. During periods of little to no activity concentrations are similar to background. Indeed, the Environment Agency (2009) states that bioaerosol release is episodic (related to turning, screening and shredding) with turning potentially generating the highest releases.

It is important to note other activities and environments can affect local concentrations of bioaerosols. In terms of published scientific literature, a range of authors report natural concentrations of bacteria and fungi routinely range from 1000 to 100,000 (10^3 to 10^5) cfu m^{-3} air (Cox & Wathes, 1995). Hryhorczuk *et al.* (2001), in an investigation of a windrow composting site, reported high measurements of fungi off-site in wet woodland comparable to on-site. Additionally, it was reported that mowing a nearby meadow also significantly affected results of viable fungi and bacteria (160 and 480 respectively prior to mowing, 15.0 x 10^3 cfu m^{-3} and 17.6 x 10^3 cfu m^{-3} after). Some agricultural activities surrounding a site may also impact, such as crop harvesting, and agricultural activities have previously been identified as significant sources of bioaerosols, specifically 10^5 cfu m^{-3} of bacteria and 10^3 cfu m^{-3} of fungi including *Aspergillus fumigatus* (Swan *et al.*, 2003).

3.4 Bioaerosols and enclosed facilities

In enclosed facilities where the reception takes place within a hall where material is accepted, processed and composted within the vessels, it is not unknown for concentrations to exceed 10^{7-8} cfu m^{-3} (Schlegelmilch *et al.*, 2005). Many of these halls vent their emissions via a biofilter. As biofilters are intended primarily for odour control, the question is whether they can be regarded as an effective screen for particulate, and so bioaerosol reduction.

To understand the conditions the biofilter may be subject to, it is necessary to first understand the nature of the substrate that leads to bioaerosol generation. Microorganisms will grow on any material where there is a sufficient supply of nutrients and water, their role being to aid the breakdown of organic materials; hence organic wastes, including kerbside collected green and food waste will contain large amounts. In particular, household collections of food waste may be from enclosed containers that contain very wet material, which may have been stored outside for seven days or more. WRAP (2009) identified from a variety of research papers that an initial colonisation by bacteria of stored organic materials was demonstrated (within a residual fraction or as a separated garden waste collection) in a container, changing to a larger population of fungi by the second week. This would likely depend on access to air, which may not occur with food material wrapped in an enclosed container.

Previous studies on containers have demonstrated that a wide range of food spoilage microorganisms and toxic metabolites will grow on vegetable material as it breaks down. In a study on organic material in a compost bin, Tournas (2005) and Ryckeboer *et al.* (2003) found that fungi and yeast are not present during thermophilic breakdown of wastes.

It is therefore very likely that the material delivered to such facilities for treatment has primarily bacterial growth, with anaerobic activity. On arrival this material is discharged directly into enclosed areas, wet and already potentially containing an anaerobic population. As a result, in the first instance, anaerobic breakdown and multiplication of all types of bacteria will occur. Even in facilities with forced aeration, pockets of very wet material are unlikely to receive enough oxygen once deposited, unless agitation is enacted which is not usually practiced. The material will also get very hot, as it is intended to do so. Hence it is hypothesised that the majority of emissions from the material to the biofilters from such facilities would be primarily bacterial in origin during the initial stages of breakdown, with fungal spores developing as the material ages and cools. This means in the short amount of time this material is normally 'in-vessel' (three to seven days) bacteria are likely to dominate, potentially including substantial anaerobic populations. This is a very different emission profile from open windrow composting where fungi such as *A. fumigatus* dominate.

Once the emission has occurred there are several variables to consider when evaluating whether biofilters are effective at retaining bioaerosols. As well as whether they are primarily bacterial or fungal, issues include the concentrations emitted, the load rate into the biofilter, what the biofilter material consists of, and how sampling and analysis for bioaerosols is carried out. Table 15 shows a summary of some of the main papers identified in this area that have attempted to identify removal efficiencies for bioaerosols by biofilters. This literature review shows that several different methods were utilised to measure bioaerosols, including impingers, filters (whilst mentioning humidity was a major issue) and Andersen samplers with a very short sampling time. Further, pipework and various other inlets and outlets were sampled, but no mention is made of isokinetic sampling in any of the papers. A wide range of biofilter types (and inorganic biotrickling type filters) are reported with different removal efficiencies. These issues are addressed separately in sections 3.4.1 to 3.4.7.

Table 15. Scientific literature evaluating biofilter performance and bioaerosols.

Reference	Sampling method for bioaerosols	How sampling initiated	Load rate into biofilter cfu m^{-3} or EU/ng m^{-3}	Media type	Bacteria removal efficiency (%)	Fungal removal efficiency (%)	Other points to
Ottengraf & Konings, 1991	Millipore impinger	Not specified.	Bacteria n.d. – 10^4 Mould n.d.- 302	Polystyrene, compost Peat-heather	Not specified	Not specified	Used 'generalised medi
Seedorf & Hartung, 1999	Sampled 'particles'	Not found	Not found	Not found	11-71	71	Bioscrubber 22% efficie
Martens et al., 2001	Polycarbonate filters (total counts), glass fibre (endotoxin)	Inlet and outlet pipework (moisture taken from filters)	Means 10^6 bacterial cells, 10^5 fungal. 792.5 EU endotoxin.	Biochips Coconut fibre/peat Bark and wood 'Filter pellets' Biocompost	>90 >90 90+ 90+ 88 endotoxin	49-90	Five different biofilter ma
Seedorf & Hartung, 2002	AGI-30 impinger	In animal house, 2 points out	10^6 bacteria, 10^3 fungi, 10-216 EU.	Wood shavings	90 ~92 endotoxin	73	Dust 83%. Note 2 scrub
Sanchez-Monedero et al., 2003	Six-stage Andersen sampler 1 min	In halls, some in pipework pre & post biofilter	2.7 x 10^2 to 2.2 x 10^{5}cfu m^{-3}	Coarse fraction compost, peat Pine bark & roots	40	90	Media as for Af 78% AF 2.1µ 35% bacteria

Reference	Sampling method	Location	Inlet concentration	Biofilter media	Removal efficiency (%)		Notes
Schlegelmilch et al., 2005	AGI-30 impinger & polycarbonate filters (cfu)	'Capture hood' on surface biofilter	$1.0-4.2 \times 10^7$ biofilter inlet 1.0×10^8 'raw gas'	Coke/compost and root wood Coconut fibre	58-80 99	90	Bioscrubbers (21% meso re thermos)
Haumacher et al., 2005	Filters VDI 4252 /4253 gelatine & polycarbonate	'In waste gas'	10^{5-6} bacteria and 10^{5-6} fungi inc. *A. fumigatus*	Not specified, only that it is 'wet' or 'dry' at stages	90-100	90-100	Best results found for wet thermplasma
Tymczyna et al., 2007	AS-50 and PVC filters. Various agars, API strips, endotoxin	2 samples in inlet duct, 3 in outlet duct (each chamber)	10^2 gram-negative (GN) bacteria, 11ng m^{-3} endotoxin, 0.9 mg m^{-3} dust (means)	50% compost/peat only mix 40% compost/peat & 20% bentonite 40% compost/peat & 20% halloysite	100 GN 17 endotoxin 100 GN 52 endotoxin 99.6GN11 endotoxin	Not tested	Dust removed at 82-87% three biofilter m
Ho, K-L et al., 2008	Exhaust gas passed via water	Inlet and outlet	10^{5-6} TMC m^{-3} (total cells)	Granule activated carbon	90-98	Not tested	Same species at inlet
(Zhao et al., 2011)	Andersen 10s & Sartorius MD8 gelatine filter	'Incoming and outgoing air'	10^4 bacteria, 341-711 ug m^{-3} PM$_{10}$, 32-85 ug m^{-3} PM$_{2.5}$	Shredded tree roots/ polypropylene, both with acid scrubbers	46-84 Andersen, 69-96 MD8	Not tested	Up to 93% particulates

| Tymczyna *et al.*, 2011 | PN-EN 13098:2007 using GilAir 5 and filters | 2 samples in inlet duct, 4 in outlet duct (2x each chamber) | 8.3×10^{6} bacteria , 9×10^{4} gram-negative bacteria and 1.9×10^{5} fungi | Compost 40%, peat 40%, straw 20% + mix of oak chips and crushed bark | 76.5 30.4 | 69 63 | Malt extract agar used fo biofilters 50-68%, te |

Biofilter performance and operation as related to commercial composting)

3.4.1 Load rates

Load rates into the biofilters in these studies ranged from 10^3-10^6cfu m^{-3} bacteria, 10^2-10^4 gram-negative bacteria (where specified) and fungi from undetectable to 10^5cfu m^{-3}. Endotoxin load rates were between 11ng m^{-3} and 7-800EU m^{-3} (note 1ng=10EU approximately). These are significant concentrations and in excess of those linked to health effects (Defra, 2009). Where both were measured, concentrations of bacteria were always higher than fungi.

3.4.2 Removal efficiency

Removal efficiencies varied between studies. However, as a general trend bacteria had lower removal efficiencies in some of the studies than fungi (as low as 11 to 30 per cent in some studies, but 90 per cent or better in others). Fungi, where measured, appeared to have higher removal rates (from 49 per cent through to 100 per cent). Endotoxin had removal rates of 88-92 per cent in two studies, but very low rates of 11-52 per cent in another. General dust appears to have removal rates of 83 per cent or better in almost all of the studies, with scrubbers and biofilters together demonstrating some of the most efficient removal rates.

Other references to removal efficiency of biofilters can be found in the literature. For instance Kummera & Thielb (2008) reported on data that demonstrated *A. fumigatus* was reduced by up to 'two powers of ten' lower on the outlet than the inlet. Scharf *et al.* (2004) reported 'emission reduction factors' (no actual concentrations were given) for dust at 3, endotoxin at 12.5, and bacteria at 6.1. Gram-negative bacteria and fungi were not reduced but actually increased by 14.8 and 3.8 respectively. Acid scrubbers were recommended for use in conjunction with biofilters by some authors to achieve the best reductions (Aarnink *et al.*, 2005; Zhao *et al.*, 2011). It should be noted that Martens *et al.* (2001) found that there was a slight relationship showing that the best biofilters for removing odour had the poorest removal efficiencies for bacteria.

3.4.3 Capture and emission

Ottengraf & Konings (1991) theorised that there are two separate aspects to biofilters and bioaerosols – capture of microorganisms emitted by the material to the biofilter, and subsequently emissions from the biofilters themselves. Indeed other papers have mentioned that emissions from biofilters might be different from inputs, with different species as well as concentrations. Martens *et al.* (2001) highlighted that biofilters could be source emitters with

their own populations of microorganisms, and Scharf *et al.* (2004) reported that species of bacteria in an animal (duck) house and at the outlet of a biofilter were different, the majority being *Enterobacteriaceae* in the house and *Pseudomonadaceae* at the outlet. Schlegelmilch *et al.* (2005) in particular stated that 'secondary emissions' were non-pathogenic, compared to biofilter inputs. However, Ho *et al.* (2008) reported the species between a biofilter inlet and outlet were considered 95 per cent similar and the biofilter was thought to have no species selectivity. Conversely Tymczyna *et al.* (2011) discovered that some species were stopped better by one type of media than another, and bacterial removal efficiency could be very different between two biofilter materials. It is clear that the issue of whether secondary emissions are different from those captured has not been resolved.

In almost all of the studies shown in Table 15, emissions from the biofilters were of the order of 10^{3-4} cfu m^{-3} for bacteria. The profile for fungi is more complex; in some cases they were not detected and in others concentrations of 10^{2-4} cfu m^{-3} are reported. However, several studies have variable concentrations on input and output, with occasional higher outputs, for example Martens *et al.* (2001), Seedorf & Hartung (2002) and Tymczyna *et al.* (2011). Aarnink *et al.* (2005) reported in a conference paper that higher concentrations of bacteria were seen at the outlet of a biofilter compared to the inlet (increase from 6.1 x 10^{4} to 24.4 x 10^{4} cfu m^{-3}). Tymczyna *et al.* (2007) found higher endotoxin concentrations in output air than input air on some occasions and theorised that gram-negative bacteria were dying in the media and releasing endotoxin.

In other studies concerning emissions rather than capture, Wang *et al.* (2009) reported that a biofilter in combination with UV treatment reduced bioaerosol emissions from a biofilter from 1.38 x 10^{3} cfu m^{-3} to 60 cfu m^{-3} specified as 'background levels'. This study appears to be attempting to mitigate the emissions of bioaerosols from the biofilter itself, not a biological process (the biofilter was designed to filter chlorobenzene).

3.4.4   Particle size of bioaerosols

Sanchez-Monedero *et al.* (2003) reported that *A. fumigatus*, whose spores had a maximum diameter size distribution between 2.1 and 3.3μm, were more effectively captured in the biofilter than the bacteria, which had diameters mainly between 1.1 and 2.1μm (as demonstrated by where they were captured in a six-stage Andersen sampler). Zhao *et al.* (2011) on the other hand, noted that most of the bacteria were on the first three stages of the Andersen, indicating they were associated with larger particles. This same paper quoted -42 per cent to 20 per cent removal effectiveness of the bacteria in the size range of 0.65 to 3.3μm.

Also regarding particle size, Lim *et al.* (2012) report that 'dust clogging' can severely affect biofilter performance. Two elevated bed wood chip (pine) biofilters were evaluated at 127mm and 254mm depth. PM_{10} and TSP reductions were significant at 62.0 per cent and 89.7 per cent for the 127mm biofilters, and were 62.9 per cent and 96.3 per cent for the 254mm biofilters, respectively. Very low PM2.5 concentrations were observed for both treated and untreated air streams. There is little other information on particle size in the published studies.

3.4.5 Biofilter material

Schlegelmilch *et al.* (2005) stated that material types do not have much effect on a biofilter, but materials with larger and more structured surfaces can be more efficient. For this reason coconut fibre was found to be an efficient biofilter material, and this material was also cited by Martens *et al.* (2001) as being the most efficient. Compost oversize, wood chip and wood bark type filters probably benefit from this type of effect.

Zilli *et al.* (2005) examined removal of benzene by biofilters, but also emissions of airborne bacteria from peat and sugarcane bagasse and suggested the emission rate of a biofilter is related to the growth of bacteria in the biofilter and emission rate increases with increased biomass of material, independent of the actual packing material or load. Chung (2007) found that in a compost-based biofilter, variation in bioaerosol emission in the outlet was proportional to the microbial numbers in the biofilter regardless of the treated gases being emitted from the process. These studies indicate that biofilters such as peat and compost are laden with their own populations of microorganisms and could be net emitters. Indeed Chmielowiec-Korzeniowska *et al.* (2007) found significant reductions of bacteria, fungi and endotoxin at the outlet of a novel biofilter (concentrations not specified) but *Streptomyces* species growing in the biofilter's media contaminated the outcoming air.

On a slightly different note, water used to irrigate biofilters has been reported to be laden with endotoxin, and also large amounts of microorganisms, health-related microbes such as *Escherichia coli* (10^5, smear infection, endotoxin release), *Acinetobacter* ssp. (10^6, facultative respiratory infection, endotoxin release, high tenacity) or *Aspergillus* ssp. (10^2, allergenicity) could be found in the filters (Seedorf & Hartung, 2002; Seedorf *et al.*, 2005).

3.4.6 Air flow and residence time

Ottengraf &Konings (1991) stated that as flow rates into a biofilter increase, 'emission rate' of microorganisms within the biofilter increase – and that 'capture rate' is highly affected by

the gas velocity. Inertial impaction of particles was thought the major method of action in a biofilter with shear forces causing bioaerosols to be emitted from biofilters. Using scanning electron microscopy of the biofilm, Chung *et al.*(2004), concluded that retention of microorganisms on biofilter material was good, although increased air flow was thought a possible way of increasing emissions. Schlegelmilch *et al.* (2005) report that air flow rate has a minor effect on the efficiency of removal of bioaerosols in a biofilter. Zilli *et al.*(2005) states that shear stress is the main reason bacteria are liberated from biofilters, and goes on to imply that species of bacteria within a biofilter can affect how bioaerosols are detached. However, the conclusion of this paper was that velocity has no effect on emissions, because of the low shear stress exerted by the gas flow over the whole biofilter. None of the papers above considered whether residence time could impact on these conclusions. Bioaerosol removal was considered to be a simple physical capture mechanism only.

3.4.7 Other issues

Morey and Hoffman (2004) reported no increase of fungi over natural concentrations in the vicinity of a composting operation that used a biofilter. Taking a slightly different approach, Barth *et al.*(2002) investigated occupational exposure concentrations during biofilter media changes but found endotoxin at 'background levels'.

3.5 Summary

In summary, there are many different components of bioaerosols that could be measured. The most common approach is to elucidate viable bacteria, fungi (especially *A. fumigatus*), gram-negative bacteria and potentially endotoxin. Glucan had not previously been measured from biofilters. However, there are many methods by which these variables in biofilters can be measured. Many of the authors above recognised filters became too wet, and Andersen samplers required very short sampling periods. Several used impingers; it is likely an impinger-type methodology is more appropriate for measuring bioaerosols in these circumstances. It should be recognised that measuring viable microorganisms in isolation may represent a limited picture, but impingers can also be used to simultaneously measure endotoxin, or perhaps even total cells by fluorescence.

In the research studies identified, significant loads of bacteria, fungi and endotoxin were seen emitted to biofilters from a combination of animal and compost facilities. Bacteria were obviously the contaminant of most interest, and more latterly endotoxin. Removal efficiencies were generally relatively high, with the exception of endotoxin in one which was between 11 and 17 per cent. The research does seem to show that larger particulates and cells may be

effectively screened by biofilters, but generally data on smaller cells and endotoxin are patchier and in some cases potentially contradictory. Removal efficiencies were also linked to the size of material in the biofilter in some cases, with bigger material sizes theorised as having larger surface areas to 'cling' to bioaerosols. Velocity of air flow in the biofilter presented a more mixed picture. Although authors seem to agree the mechanism for filtering bioaerosols is physical impaction, and they are liberated by shear stress, there is disagreement over whether the velocity of air in a biofilter would be enough to force liberation of particles. As the mechanism for capture is largely physical, residence times do not appear as important as they might be for odour.

Finally, it is clear there are two distinct areas to consider with biofilters and bioaerosols – capture of microorganisms within the biofilters and, separately, emissions from the biofilter. Capture obviously relates to removal efficiency as already discussed. Emissions from biofilters are interesting in that they may not be the population that entered the biofilter, and may be emitted by the microorganisms within the biofilter itself. Indeed, some material types may be net emitters of their own microbial populations. Not all papers agree however, and further research is needed in this area.

In conclusion, the research information available for bioaerosols and biofilters is variable and sometimes contradictory. Bioaerosols are clearly removed to some degree by all biofilters, despite their design primarily for odour. The presentation of many different variables in the studies made the direct comparisons of efficiencies difficult. There is no doubt further research is needed in this area.

4 Literature review –Knowledge gaps

4.1 Odour & bioaerosols

4.1.1 UK composting missions

There is a lack of knowledge relating to the operational characteristics of actual UK in-vessel composting operations processing source segregated household waste (SSHW) and using in-vessel composting as a means of achieving compliance with the Animal By-products Regulations. This type of in-vessel composting is likely to be the dominant form of forced air composting undertaken in the UK. UK industry information and reports compiled for this project suggests that the UK operation of in-vessel composting processes could be fundamentally different to the operation and environmental impact of in-vessel composting processes as described in published papers and reports. In particular, UK in-vessel processes may be typically operated in an oxygen limited mode to achieve high sanitisation temperatures and this may contribute to very high levels of odour being reported. It may also lead to growth of anaerobic bacteria within the in-vessel, and will favour the growth of all bacteria over fungi. Information is required relating to typical operational parameters for UK plants such as process aeration rates, degree of aerobicity of composting piles, profile of untreated exhaust gases being generated including odour concentration/odour compounds and particulates and bioaerosols.

4.1.2 Biofilter effectiveness

There is a lack of knowledge relating to the effectiveness and performance of emissions treatment systems for typical UK in-vessel composting operations, especially related to treating anaerobic-type compounds and very high odour and bacteria/gram-negative bacteria (possibly also anaerobic species) loading rates. Information required would include: the types of biofilters employed, performance of biofilters, characteristics of odour and bioaerosols being emitted.

4.1.3　　Technical issues

There are numerous technical issues or gaps that have been identified relating to the operation, monitoring and performance of biofilter units operated under UK conditions. Some of the more relevant ones include:

- There appear to be a number of different types of biofilter material being used in the UK (such as wood chips, compost oversize, peat). It is not currently known how effective each of the material types is for the treatment of odour or bioaerosols or what maximum odour removal/particulate removal rates are possible.

- Collecting samples of input emissions and biofilter outputs for odour and bioaerosol monitoring appears to be undertaken in a variety of ways, therefore the development of a set of effective and consistent sampling protocols should be explored.

- In-vessel aeration rates in the UK may be very low, this needs to be confirmed and, if necessary, the benefits of increasing air flow in in-vessel plants for improved treatment of emissions should be investigated.

- Many UK biofilters are designed and built in-house and these (and others) may not have the appropriate suite of microorganisms present to fully decompose problematic odour compounds such as reduced sulphur compounds. This needs to be investigated as does the beneficial odour removal effects of inoculating biofilters with more effective microorganisms.

    There is a lack of basic information about how bioaerosols might be captured by biofilters. It is suspected the mechanism is physical, with air velocities perhaps being more important than residence time. There may also be a net emission of microorganism populations from within the biofilters themselves.

- Many biofilters may be working very effectively but may not be able to reduce odour sufficiently to prevent odour complaints. Addressing how best to reduce residual odour from biofilters should be explored, such as increasing empty bed residence time (EBRT), adding additional and targeted biofilter capacity (for example based on sea shell processes) or by using non-biological technology (such as impregnated activated carbon filters).

    Similarly, for bioaerosols, there may be some good removal rates demonstrated by various biofilter materials, as seen in the literature review. However, there may still be emissions post-biofilter above background concentrations.

- High concentrations of ammonia can inhibit biofilter performance. It is important to determine threshold ammonia concentrations and loads at which inhibition occurs for different biofilter materials, and to develop strategies to minimise these problems.

- Exhaust gas temperatures for UK in-vessel systems are known to be high and this could potentially reduce biofilter performance. The extent to which high exhaust gas temperatures reduce the effectiveness of UK biofilters should be investigated and measures to reduce this problem explored.

4.2   Aims for fieldwork and laboratory studies:

This scoping empirical programme, based on fieldwork and laboratory experiments, is undertaken to provide information relevant to some of the knowledge gaps outlined above. In particular, emphasis should be placed on increasing knowledge about the operation and environmental impact of UK in-vessel facilities and the odour and bioaerosol removal performance of typical biofilter materials, under controlled laboratory conditions.

4.2.1   Field research aims relating to typical commercial in-vessel composting operations

To generate original data relating to:

- typical operational characteristics;

- the characteristics of untreated emissions of odour and bioaerosols;

- the degree to which compost emissions may be reduced by biofiltration;

- the characteristics of untreated bioaerosols from such systems.

4.2.2   Laboratory study aims

On three selected biofilter materials:

- determine odour and bioaerosol removal rates when subjected to a typical composting exhaust gas stream under controlled conditions;

- determine the chemical characteristics of the biofilter inputs and outputs from each material to enhance understanding of the biofiltration process;

- determine the microbiological characteristics of the biofilter inputs and outputs from each material to enhance understanding of the biofiltration process;

- determine the nature and the characteristics of the residual odour and bioaerosols emitted from biofilter materials .

5 Field work

5.1   Introduction to field measurements

The broad aims of the field research were to generate original data on operational characteristics, emissions of odour and bioaerosols, and the degree of biofiltration of odour and bioaerosols by existing composting plants with biofilter emissions treatment systems. This was a scoping study only, and focused on sites considered likely to be representative of common existing practice. The objectives were to generate original data on two in-vessel composting sites on:

- operational parameters such as composting aeration rate and aerobicity;

- emissions from the composting process, especially odour, indicators of aerobic/anaerobic conditions, and bioaerosols from the in-vessel composting process;

- changes of concentration of odour, odour compounds and bioaerosols across each biofilter to evaluate the performance of biofilters in practice.

In addition, measurements were taken on one site before and after replacement of the biofilter material to evaluate the odour removal effectiveness of old compared to new biofilter material.

5.2   Site selection

Two in-vessel composting operations were identified as typical of UK in-vessel composting (IVC) sites processing source segregated household waste (SSHW). Both had experienced problems with odour emissions.

Site C was selected as the main site for the fieldwork and focused on characterising biofilter performance before and after a change of biofilter material. Monitoring of in-vessel exhaust gas and biofilter outputs was undertaken on three occasions: the first was a scoping exercise, followed by monitoring the performance of the existing biofilter material, and then the replacement biofilter material.

Site P was selected as part of this odour monitoring fieldwork because it was experiencing significant odour problems. This plant had made various changes to the biofilter system for which there was pre-existing data.

5.3   Site C

5.3.1   Study site description

Site C processes approximately 30,000 tonnes a year of mixed waste (source segregated green and food waste) and is compliant with ABPR (animal by-products regulations). In-vessel composting occurs in five tunnels of $1,000m^3$ capacity each, which accept approximately 400 tonnes of compost (compost volume approximately $800m^3$). Composting time in tunnels is typically between two and six weeks, until the ABPR temperature of 70°C is achieved, followed by a period of maturation in open windrows.

The tunnels are aerated by suction through pipes embedded in the concrete floor, combining through a manifold to a single extract pipe per tunnel (ID 250mm, cross section $0.05m^2$). Some fresh air may leak in under suction at the manifold. Each tunnel is equipped with a fan that operates on a 30-minute cycle. Fan cycles are offset giving changing flows over time. Mean flows over full half hour cycles are used in the flow calculations. The five aeration pipes combine into a single inlet pipe to the biofilter (ID 475mm, cross section $0.177m^2$) with sampling ports for gas and flow measurements. The inlet pipe drops to the biofilter base where compost gas is distributed through pipes/plastic crates along the biofilter base. There is a watering system to spray the surface of the biofilter material. The biofilter walls are made of freestanding concrete sections (3m high). The total surface area of the biofilter is $231m^2$.

The original biofilter material comprised a layer of coarse compost oversize overlain by a layer of wood chip material. This relatively fine wood chip was expected to be the most active biofilter layer. This material was replaced in February 2012 with fresh wood chips, mixed with some of the previous material to inoculate the new material with the necessary microorganisms.

5.3.2   Methods

Measurement of in-vessel exhaust gas and biofilter outputs was undertaken on three occasions; the first was a pilot study followed by snapshot measurements of the performance of the existing biofilter material, and then the replacement biofilter material. It

should be noted that bioaerosol measurements were only taken on replacement biofilter material.

Input gas sampling

The input gas to the biofilter was sampled directly from the inlet pipe through a 10mm port using integrated instrument pumps for on-line gas composition measurements and bioaerosol sampling. Samples were also collected for odour and additional gas measurement in Nalophan® bags with polytetrafluroroethylene (PTFE) and stainless steel fittings directly from the sampling port, which is under positive pressure. A similar 10mm sampling port was used for gas temperature and flow measurement. Measurements were performed over complete 30-minute cycles and data reported as means.

Output gas sampling

For the pilot test (9 December 2011), output samples were taken using two m2 plastic sheets replicated three times on the biofilter surface, weighted down or dug into the biofilter surface at the edges (Figure 4) following common practice for measurement of odour emissions from biofilter surfaces as advised by Silsoe Odours ltd. Gas samples were pumped from under the sheet using a low flow gas sampling pump at a rate of 100 ml min-1. The sheet creates a space that is flushed with output gas as it is forced out at the sheet edges, provided this is not disrupted by windy conditions. In low-flow conditions it may also accumulate diffusive gases, acting as a form of static chamber. There is a degree of uncertainty and lack of standardisation about this sampling technique and other available techniques such as flux hoods including various designs of Lindvall hood (BS-13725:2003).

Figure 4. Pilot test using two m^2 plastic sheets

For the main test on original biofilter material (30 January 2012), the whole biofilter surface was covered with a plastic sheet (11m × 30m). A single outlet point was equipped with a chimney constructed using impermeable plastic sheet on a wire mesh frame in four 1.2m-long cylindrical sections, diameter 360mm (Figure 5). The outlet flow followed the same 30-minute cycle as the inlet. The sheet formed a large headspace above the biofilter surface, which was allowed to flush through with the flow of biofilter-treated gas. The flow through the chimney was a sub-sample of the total biofilter output gas since the sides of the biofilter and edges of the plastic sheet were not completely sealed. This allowed some escape of biofilter-treated air and so pressure equalisation with atmosphere. There were no visible signs of pressure build-up in the headspace, and it was assumed that there was no significant effect on residence time or back-pressure within the biofilter. Concentration of gases and bioaerosols in the chimney were assumed to be representative of biofilter output while total output flow from the biofilter surface was assumed to equal input flow (that is, all compost gases were assumed to pass through the biofilter). Two 10mm ports at approximately 50cm from the top of the output chimney were used for gas sampling and simultaneous flow measurement. On-line gas composition measurements and bioaerosol sampling were taken as for the inlet pipe, whilst bags for odour measurement were collected using low flow gas sampling pumps.

Figure 5. Main tests covering entire biofilter surface with single outlet chimney

On this occasion (30 January 2012), one of the aeration fans was running throughout the tests due to a malfunction in the control software. It is therefore likely that one compost tunnel had more aerobic conditions than the other four. This resulted in a total aeration flow rate that was slightly higher than normal operation.

For the main test on new biofilter material (13 March 2012), the same plastic sheet and chimney were used. All gas samples were taken in Nalophan® bags. Pairs of samples were taken simultaneously, with one of each pair transported to Silsoe Odours Ltd for odour measurement and the other to the Open University lab for gas analysis. Analyses were all completed the same day.

On this occasion (13 March 2012) a malfunction in the site control software made all the fan programming unreliable and this was overcome by setting all aeration fans to run constantly. This resulted in a total aeration flow rate that was unusually high for this site and it is therefore likely that composting conditions were more aerobic than normal operation. It is also likely that compost and biofilter conditions were changing and it is possible that odour, gas concentrations and bioaerosols measured represented transient emissions. Data should be treated with caution.

Odour and gas composition analysis

The samples collected in Nalophan® bags were analysed for odour by olfactometry at Silsoe Odours Ltd. (Silsoe, Bedfordshire) according to the method specified in BSEN13725. An olfactometer (PRA Odournet B.V.) with a pre-dilution gas meter (Kimmon Model SK25) was used, and the reference odorant (n-butanol) concentration was 60ppm.

The composition of the compost gas before and after the biofilter was analysed by Fourier Transform Infrared (FTIR) spectroscopy. A multicomponent FTIR Gas Analyser (GASMET Dx-4000, Gasmet Technologies) was connected to a portable sampling system (PSS, Gasmet Technologies) and the portable gas sample probe (PSP4000, Gasmet Technologies) was inserted directly into the 10mm sampling port for both the inlet and outlet pipes, or gas sample bags as for odour analysis. The operating temperature of both the analyser and the heating line was 180°C and the sampling rate was 3L min^{-1}. A span check calibration gas (STG calibration gases: 250ppm CO, 140ppm NO, 20ppm SO_2 and 70ppm Propane in N_2) and an ammonia reference gas (STG calibration gases: 100ppm NH_3 in N_2) were used to verify the instrument calibration. Data analysis used a reference library developed to include indicative species of known odorous compound types (reference data provided by Quantitech ltd). While each is representative by quantification of a specific

compound, measurement relies primarily on recognition of molecular functional groups and will be affected by the presence of similar compounds. For example, quantification of ethanol may well include a contribution from methanol, propanol and so on, and may be taken as indicative of aliphatic alcohols. Aromatic hydrocarbons are quantified as benzene, but will include highly odourous compounds such as styrene as well as less odorous compounds such as toluene. FTIR analysis results presented in sections 0, 0 and 6.3.1 of this report should therefore be viewed with caution, as further more quantitative analysis would be required to verify them. Limited additional cross checking was carried out on some samples by selective ion flow tube mass spectrometry (SIFT-MS).

Gas composition was also characterised using a toxic vapour analyser (Thermo TVA-1000B) equipped with a flame ionisation detector (FID) and a photo-ionisation detector (PID). The FID was calibrated with 100ppm CH_4 in air and responds primarily to carbon compounds including methane. The PID was calibrated with 100ppm isobutylene in air and responds to non-methane organic molecules and ammonia. These measurements are often referred to as total volatile organic carbon. Hydrogen sulphide (H_2S) was measured with an H_2S analyser (Jerome 631X).

The gas stream temperature was measured with a K-type thermocouple probe inserted directly in the inlet and outlet pipes. The gas stream flow was measured by pitot tube anemometer (Airflow Instruments TA460-P) over whole multiples of the 30-minute flow cycle and data reported as means.

Particulate monitoring

Particulates as Total Suspended Particles (TSP) and particles 10μm diameter or less (PM_{10}) were measured using the Osiris particulate monitor (Turnkey Instruments Ltd, Cheshire). Tubing from the particulate monitor was fed directly into the area being sampled as described in section 0, including the input pipe through a 10mm sampling port and the output via the constructed vent. Sampling times were 10 minutes in length.

Viable counts of Aspergillus fumigatus and bacteria

Viable microbial counts were obtained using SKC BioSamplers connected to BioLite Air Sampling pumps (SKC Ltd). The BioSampler is a bioaerosol and biologically inert airborne particle collection device that traps airborne microorganisms into swirling liquid for subsequent analysis; that is, a liquid impinger. It is made of glass and consists of three parts:

inlet, nozzle section (with three tangential sonic nozzles), and collection vessel. The BioLite Air pump is a high-volume sonic flow pump, with a flow rate of 12.5L min^{-1}.

The BioSamplers were sterilised by autoclaving and loaded with 15ml of pyrogen free water (to enable later simultaneous endotoxin analysis), aseptically. One end of sterile tubing was connected to the BioSampler's inlet, and the other end into the area being sampled (through a sampling port). Unless otherwise stated, sampling was done in duplicate for 10 minutes. After sampling, the liquid was poured into sterile, pyrogen-free containers for transport to the lab. If the BioSamplers were to be used again for the sampling, they were sterilised in ethanol.

For viable counts, 0.1ml of the liquid was spread plated in triplicate onto nutrient agar (total bacteria), malt extract agar (fungi), and MacConkey agar (Gram negative bacteria), media as described by the AfOR protocol (2009). Temperature and incubation times were also as in the protocol. The colony forming units (cfu) were counted at the end of the incubation times, averages calculated and then converted to cfum^{-3}.

Endotoxin and (1→3)-β-D-glucan

The same sample from the viable count sampling was also used for endotoxin and (1→3)-β-D-glucan testing. For endotoxin and glucan there was some delay between sampling and analysis. However, previous studies have shown this storage length is not an issue (Liebers *et al.*, 2007) with all samples stored at -20°C until analysis.

For analysis, a kinetic chromogenic LAL assay (ACC, Associates of Cape Cod, Inc.) was used for quantification of endotoxin at 37°C, with kinetic readings recorded automatically every 30 seconds for a period of 90 minutes (British Standards Institute, 2003a). Five concentrations of Control Standard Endotoxin (CSE) were prepared and utilised, 50EUml^{-1} at serial dilution to 0.005EUml^{-1}. CSE was reconstituted with pyrogen free reagent water (ACC), and the LAL (Pyrotell-T) with Glucashield buffer (to prevent interference from Glucans).

For analysis of (1→3)-β-D-glucan, a kinetic chromogenic Glucatell kit (ACC) was used for quantification of glucans at 37°C, with kinetic readings recorded automatically each 30 seconds for a period of 90 minutes (British Standards Institute, 2003b). Six concentrations of Glucan standard were prepared and utilised, 100pgml^{-1} at serial dilution to 3.125pgml^{-1}. The standard was reconstituted with pyrogen free water (ACC), and the glucatell lysate with pyrosol buffer and pyrogen free water.

Samples were tested in triplicate. The data was converted to EUm^{-3} and ngm^{-3} for endotoxin and glucan data, respectively.

5.3.3 Results

Plant operational data

The operational data for site C can be seen in Table 16.

Odour and gas characterisation

The odour data for site C can be seen in

Table 17, odorous gas composition data in Table 18, and greenhouse gases including methane in Table 19 and Table 20.

Table 16. Operational data for site C biofilter on three sampling visits

Operational details	Pilot test 9/12/11	Test on original biofilter material 30/1/12	Test on new biofilter material 12/3/12
Flow ($m^3 h^{-1}$ (STP))	1154	2491	3788
Estimated compost aeration rate ($m^3 tonne^{-1} h^{-1}$)***	0.67	1.5	2.3
Total biofilter volume (m^3) *	507	507	623
Biofilter EBRT (s)	1370	628	504
Estimated active layer			
Layer volume m^3	92**	92**	311
EBRT (s)	249	114	252
Porosity (%)	53.8	53.8	57.4
True residence time (s)	134	61	145
Volumetric loading rate (m^3(STP) m^{-3}(biofilter) h^{-1})	12.5	27.0	12.2

* = Using height as defined by surface of biofilter material.
** = Defined by approximate depth of moist, active layer.
*** = Estimated aeration rate based on nominal 400 tonnes per active tunnel.

Table 17. Odour data for site C biofilter on three sampling visits

Parameter	Pilot test 9/12/11	Test on original biofilter material 30/1/12	Test on new biofilter material 12/3/12
Biofilter input ($OU_E\,m^{-3}$)	2,225,000	720,000	573,000
Biofilter output ($OU_E\,m^{-3}$)	353,000	12,000	1,700
Removal efficiency (%)	84.1	98.3	99.7
Volumetric loading rate (m^3(STP) m^{-3}(biofilter) h^{-1})	12.5	27.0	12.2
Mass loading (volumetric, active) ($OU_E\,m^{-3}$ (biofilter) h^{-1})	27,800,000	19,500,000	6,970,000
Elimination capacity (rate) ($OU_E\,m^{-3}$ (biofilter) h^{-1})	23,400,000	19,100,000	6,950,000

Assume all air flow into biofilter (STP) comes out, and is equally scrubbed (that is, output concentrations are representative).
9 December 2011, output sampling under 2 m^2 plastic sheeting on biofilter surface.

Table 18. Measurements of odorous gas composition at site C on three sampling visits.

Compounds	Pilot test 09/12/2011			Test on original biofilter material 30/01/2012			Test on new biofilter material 13/03/2012		
	Biofilter input (ppmv)	Biofilter output (ppmv)	Removal efficiency (%)	Biofilter input (ppmv)	Biofilter output (ppmv)	Removal efficiency (%)	Biofilter input (ppmv)	Biofilter output (ppmv)	Removal efficiency (%)
Hydrogen sulphide H_2S	1.13	0.04	96.6	0.05	0.02	65.9	0.27	0.51	+
Methyl sulphides (inc. DMS, DMDS)	26.5	20.0	24.4	9.3	6.3	31.7	7.2‡	1.2‡	
Carbon disulphide CS_2	26.2	0.0	100.0	7.9	0.0	100.0	0.0	0.0	
VFAs (quantified as acetic acid)	58.9	0.2	99.7	23.9	0.8	96.6	2.9	0.0	100.0
Ammonia NH_3	0.0	0.0		0.1	0.1	30.5	0.0	0.0	
Nitrogen dioxide NO_2	128.0	32.3	74.7	22.8	0.2	99.2	0.3	0.7	+
Alcohols (quantified as ethanol)	556.4	59.9	89.2	493.2	8.3	98.3	220.6	8.8	96.0
Ketones (quantified as butanone)	34.2	16.3	52.1	27.5	0.0	100.0	0.0	0.0	
Aldehydes (as formaldehyde)	0.0	0.0		0.0	0.0		0.0	1.0	+
Terpenes (quantified as pinene)	0.0	3.1	+	0.0	0.7	+	0.0	0.0	
Xylenes (quantified as m-xylene)	0.0	0.7	+	0.0	1.3	+	0.0	5.0	+
Aromatics (quantified as benzene)	50.3	12.4	75.5	22.1	2.2	90.2	14.8	3.4	76.8
Acetates (quantified as ethyl acetate)	49.3	19.3	60.9	46.1	0.0	100.0	9.5	0.0	100.0
Photo-ionisable gas (quantified as isobutylene)	n.a.	n.a.		19200	1480	92.3	70	13	81.0
Flame-ionisable gas (quantified as methane)	n.a.	n.a.		2814	659	76.6	1810	1600	11.2
Notes	Mean of 2 bags	Mean of 2 bags		Time average	Time average		Mean of 2 bags	Mean of 2 bags	

n.a. = not analysed.

+ Concentration increased post biofilter; - not applicable.

‡ Values quoted are from further testing data by SIFT-MS and comprise DMS, DMDS and ethanthiol. However data are not directly comparable to other data in this table and should be treated with caution. FTIR data produced high residual error terms making this FTIR data questionable.

Photo-ionisable gas (PID) includes ammonia, VOCs. Flame-ionisable gas (FID) includes methane, VOCs. VOCs giving higher response on PID than FID include: alcohols, ethyl acetate, ethylene.

Table 19. Measurements of greenhouse gases at site C on three sampling visits.

Test date	Category	Compound		
		CH_4 (ppmv)	N_2O (ppmv)	CO_2 (%)
Pilot test, 09/12/2011	Biofilter input	500	0.1	2.4
	Biofilter output	696	0.5	2.9
Test on original biofilter material, 30/01/2012	Biofilter input	992	0.0	2.8
	Biofilter output	764	0.0	1.9
Test on new biofilter material, 13/03/2012	Biofilter input	1144	0.5	1.4
	Biofilter output	1041	3.9	1.5

Table 20. Estimated fluxes of greenhouse gases at site C as CO_2 equivalents on three sampling visits.

Test date	Category	Compound			
		CH_4 (kg day^{-1} CO_2 eq.)	N_2O (kg day^{-1} CO_2 eq.)	CO_2 (kg day^{-1} CO_2 eq.)	Total (kg day^{-1} CO_2 eq.)
Pilot test, 09/12/2011	Biofilter input	247	2	1286	1535
	Biofilter output	344	9	1577	1930
Test on original biofilter material, 30/01/2012	Biofilter input	1059	0	3245	4304
	Biofilter output	815	1	2241	3057
Test on new biofilter material, 13/03/2012	Biofilter input	1857	26	2488	4371
	Biofilter output	1690	206	2688	4584

Carbon dioxide equivalent values are calculated using published values for Global Warming Potential (GWP), calculated relative to carbon dioxide over a 100-year time horizon (Forster et al., 2007).

Bioaerosol characterisation

Bioaerosol data for field-testing on site C on 13 March 2012 can be seen in Table 21.

5.3.4 Observations on site C

Compost aeration and odour emissions

The tunnel composting operation composts highly biodegradable waste for a typical period of two to six weeks to comply with animal by-products regulations (ABPR), using a relatively low process air flow rate. This type of operation may be typical of many of the smaller ABPR compliant plants in the UK. This type of composting system is likely to produce a highly odorous composite process air stream going to the biofilters for treatment since the most odorous compounds at the highest concentrations are emitted during the early stages of composting (section 2.4.2). In addition the high ABPR temperature needed and the low air

flow through the tunnels is likely to produce anaerobic conditions and formation of odorous reduced sulphur compounds (such as methyl sulphides, hydrogen sulphide). The low air flow would also have the effect of concentrating the levels of pollutants in the air stream. Composting/sanitising waste for around two weeks only in tunnels does not give the option of diluting the odorous process air with less odorous air from the latter stages of composting.

Table 21. Bioaerosol field-testing at site C with fresh wood chip biofilter material, 13 March 2012. Data reported as means (with ranges in parenthesis).

Parameter	Biofilter input **	Biofilter output **	Removal efficiency (%)
TSP ($\mu g\ m^{-3}$)#	221	1.3	99.4
PM_{10} ($\mu g\ m^{-3}$)#	207	1.2	99.4
Viable bacteria (x 10^3cfu m^{-3})	331 (282-373)	33.4 (25.2-42.0)	89.9
Viable gram negative (x 10^3cfu m^{-3})	110 (67.2-181)	3.6 (0-6.0)	96.7
Viable fungi *(A. fumigatus)* (x 10^3cfu m^{-3})	23.4 (9.6-42.0)	u.d.	100
Endotoxin (EU m^{-3})	58200 (56400-60000)	579 (369-862)	99.0
Glucan (ng m^{-3})	871 (691-1082)	5.15 (4.2-5.8)	99.4

** Two samples of 10 continuous minutes $ calculated from averages of all replicates.

One 20-minute sample; u.d. = undetectable.

The operational data in Table 16 confirm the low aeration rates. The highest estimated average aeration rate was recorded for the test on new material (13 March 2012) at 2.3m^3 tonne^{-1} h^{-1} and was below recommended levels for aerobic composting (see section 2.1.5). This was however an unusually high aeration rate for this site, with all fans working constantly. A high concentration of methane was recorded (Table 19) indicating the presence of anaerobic conditions. The lack of ammonia is also typical of anaerobic conditions. On the earlier visits the aeration rates were lower still, estimated at 0.67 and 1.5m^3 tonne^{-1} h^{-1} on 9 December 2011 and 30 January 2012 respectively. The compost process gas on all occasions contained reduced sulphur compounds, indicating strongly anaerobic conditions. Methane concentrations, however, were lower at the lower aeration rates. It is possible that at lower aeration methanogenesis was inhibited by increasing acid conditions. The extremely high PID result on 30 January 2012 supports this and could have been caused by high levels of complex acetates and fatty acids formed in such conditions.

The odour concentration results in

Table 17 confirm the high odour nature of the biofilter input air. Odour values in the process gas were particularly high at the lower aeration rates. Even the highest aeration rate produced an odour of 573,000 OU_E m^{-3}. This is above the range targeted by many commercial biofilter systems (section 9.3).

The dominant odorous gas components are likely to be reduced sulphur gases for most process gas and biofilter outputs due to the low odour thresholds of these compounds.

Both the reception hall and sanitised waste from the tunnels matured outdoors on the pad are also likely to have a relatively high potential to emit odour and this should be evaluated as part of an overall odour assessment for the site.

Comparison of original and new biofilter material

Measurements taken before and after a change of biofilter material indicated very high odour removal efficiencies: 98.3 per cent and 99.7 per cent. The odour concentrations of the biofilter emissions were 12,400 OU_E m^{-3} (existing biofilter material) and 1,720 OU_E m^{-3} (replacement biofilter material). The higher odour from the existing biofilter material was associated with a relative high concentration of methyl sulphides, however repeated measurements would be needed to confirm this. These measurements are essentially snapshots taken under different conditions for aeration rate and input gas and are not sufficient to determine whether the replacement biofilter material improved removal efficiency overall. Odour measurements in particular have high level of uncertainty. For only a measured reduction of 90 per cent across a biofilter using only two replicate odour measurements (as in this study), BS 13725 calculates a 95 per cent confidence interval of 77.9 per cent to 95.5 per cent due to the odour measurement alone (BS 13725). In addition to this uncertainty, input gases differed on the two sampling days. Many more measurements would be required to confirm a significant change in odour removal efficiency.

It may be easier to identify changes in the reduction of specific compounds between the different biofilter materials. However on this occasion the different input gas composition prevents any reliable interpretation.

Greenhouse gases

In addition to odour and bioaerosol emissions, compost sites produce greenhouse gases, especially carbon dioxide, methane and nitrous oxide. Estimates of global warming potential (GWP) were made using published carbon dioxide equivalent values calculated relative to carbon dioxide over a 100-year time horizon. The biofilter appears to have little effect on methane concentration and may be a source of nitrous oxide, most notably with the new biofilter material. While the major greenhouse gas is carbon dioxide, there is a substantial contribution to GWP from methane (18 to 37 per cent of total for outputs on the three sampling dates).

Bioaerosols

In Table 21 high concentrations of particulates, bacteria, gram-negative bacteria, fungi (*A. fumigatus*) and endotoxin and glucan can be seen at the input of the biofilter. Particulates, including TSP but particularly PM_{10} were high on the input. Bacteria were two orders of magnitude higher than fungi at the input. Endotoxins (associated with gram-negative bacteria) were also much higher than glucan (associated with fungi).

On the day of sampling, the recently replaced fresh wood chip biofilter at site C achieved very high reduction rates of 96 per cent or better for the majority of variables tested, and has been particularly effective at screening out fungi which were undetectable in the output stream. Screening of particulates of both sizes was also very efficient at over 99 per cent. For bacteria the removal efficiency is lower at almost 90 per cent, which could still be considered a very good removal efficiency.

5.4   Fieldwork (site P)

Site P was selected as part of this odour monitoring fieldwork because it was experiencing significant odour problems. Site P continued to experience odour complaints even after it had replaced its previous biofilter material in an attempt to improve the effectiveness of the biofilter.

5.4.1   Site description

Site P is a five-vessel IVC site with the capacity to process up to 35,000 tonnes of green and food waste per year. The reconstructed site was opened in 2010. Process air is re-circulated through the five vessels and periodically extracted to air via a biofilter. The air stream

processed by the biofilter is a mixture of process air and air from other parts of the site including the waste reception hall. The biofilter comprises two parallel chambers (systems 1 and 2) from which the two outputs are combined and emitted to atmosphere through a stack.

5.4.2 Background/historical data

An odour modelling exercise had been conducted in August 2011 with the following conclusions:

'On the basis of the modelled operating profile of the site, in terms of biofilter fan operation, an odour emission concentration from the biofilter of <3,800 OU_E m^{-3} is predicted to achieve compliance with the Environment Agency's H4 indicative odour criteria for aerobic green waste composting of 3 OU_E m^{-3}. This is considered well within the performance capabilities of the type in place at [site P] considering the process and dimensions of the biofilter.

Overall it is therefore evident that whilst increased stack height will lead to decreases in ground level impacts at the receptors, the magnitude of these reductions is not considered to be significant. Therefore an increase to the stack height is not supported by the results of the dispersion modelling as the predicted impact associated with the existing height is likely to be below the applicable benchmark from the Environment Agency's H4 guidance.'

Relatively new wood chip biofilter material was present in the biofilter facility dating back to 2010, but odour samples taken from the output stack in 2011 gave a mean odour concentration of 219,000 OU_E m^{-3}. The biofilter material was subsequently replaced with new chipped pine material and new odour measurements were taken in December 2011 (mean odour concentration 32,200 OU_E m^{-3}) and on 24 January 2012 (mean odour concentration 43,100 OU_E m^{-3}, mean hydrogen sulphide concentration 0.016ppm).

Thus odour concentration results from the two odour monitoring programmes showed actual stack odour levels to an order of magnitude or more greater than the required modelled value.

5.4.3 Measurements

A further programme of odour testing was carried out on 20 February 2012, with the Open University assisting with the monitoring of selected odour compounds using FTIR gas analysis, hydrogen sulphide, total VOCs and bioaerosols. Field measurement methods were the same as at site C (section 5.3.2). Samples of mixed input gases were taken from the

plenum below the biofilter material in the two biofilter units. Output samples were taken from output pipes close to the biofilter. Valid air flow measurements were not possible.

5.4.4 Results and discussion

Odour and odorous compounds

Odour monitoring on 20 February 2012 gave the results in Table 22. The input odour concentrations were relatively low. Odour was not greatly reduced in passing through the biofilters.

Table 22. Odour data for site P biofilter systems (sampling date 20 February 2012). Data are presented as geometric means of three replicates.

Parameter	Biofilter system 1	Biofilter system 2
Biofilter input (OU_E m^{-3})	7,850	11,000
Biofilter output (OU_E m^{-3})	5,340	8,910
Removal efficiency (%)	32.0	19.0

Measurements of odorous compounds are presented as means of the two biofilter systems in Table 23. Results suggest that while the concentrations of odorous compounds in the input gas were relatively low, the removal efficiencies for these compounds as a result of biofiltration were also low.

In addition, samples of the biofilter material were collected and subjected to odour and bioaerosol testing in the laboratory. These data are presented in Section 6 of this report. These results suggested that the biofilter material itself was associated with an odour.

Table 23. Measurements of odorous component gases at site P (sampling date 20 February 2012).

Compounds	Biofilter input (ppmv)	Biofilter output (ppmv)	Removal efficiency (%)
**Hydrogen sulphide H_2S	0.4	0.7	+
Methyl sulphides (inc. DMS, DMDS)	4.3	3.3	22.5
Carbon disulphide CS_2	0.0	0.7	+
VFAs (quantified as acetic acid)	0.4	0.6	+
Ammonia NH_3	0.2	0.1	44.8
Nitrogen dioxide NO_2	3.3	2.3	31.3
Alcohols (quantified as ethanol)	8.4	3.6	57.5
Ketones (quantified as butanone)	0.0	0.0	*
Aldehydes (as formaldehyde)	0.1	0.1	*
Terpenes (quantified as pinene)	0.3	0.3	3.3
Xylenes (quantified as m-xylene)	0.2	0.3	*
Aromatics (quantified as benzene)	2.5	2.1	14.8
Acetates (quantified as ethyl acetate)	0.1	0.0	97.8
Photo-ionisable gas (quantified as isobutylene)	7.4	7.7	+
Flame-ionisable gas (quantified as methane)	31	27	11.2

Photo-ionisable gas (PID) includes ammonia, VOCs. Flame-ionisable gas (FID) includes methane, VOCs. VOCs giving higher response on PID than FID include: alcohols, ethyl acetate, ethylene.
* Low concentrations close to detection limits give unreliable values for removal efficiency.
** H_2S analysed with SIFT-MS, mean of two bags.
+ Concentration increased post biofilter; - not applicable.

Biofilter odour removal was again assessed on 13 April 2012 (see Table 24) and the odour removal rate was found to be poor (38 per cent) this time with higher odour input gas. Further developments by the site operator involved engaging an odour consultant, which led to an improved biofilter irrigation system being installed, the virgin wood chip biofilter material being sequentially inoculated with selected strains of microorganisms as shown in

Table 25, and fertiliser was also applied to provide the necessary nutrients. It should be noted that it is likely that virgin pine chip biofilter material would tend to be naturally acidic as cited in the Melcourt Industries biofilter data sheet for wood and bark materials (pH4.5 - 6.0). This low pH is in contrast to the recommended neutral pH range (6.0-8.0) for biofilters (the acid-neutralising environment that is favoured for removal of reduced sulphur compounds).

Table 24. Odour data for site P biofilter systems (sampling date 13 April 2012).

Parameter	Mean for two biofilter systems
Biofilter input ($OU_E\,m^{-3}$)	80,600
Biofilter output ($OU_E\,m^{-3}$)	49,800
Removal efficiency (%)	38.3

The effectiveness of these measures will be evaluated later in 2012 but the operator has reported that since inoculation of the wood chips, a biofilm has begun to develop and biofilter odour has reduced. One observation from this fieldwork case study is that some biofilter materials, devoid of the appropriate microorganisms to decompose recalcitrant odour compounds, will require some form of inoculation and nutrient addition to achieve acceptable levels of odour reduction.

Table 25. Microorganism species inoculated into biofilter.

Treatment 1	Treatment 2
Bio treat GF which contains:	Bio-treat GF
Acinetobacter sp	*Thiobacillus* sp (*starkeya novella*)
Pseudomonas strains x 4 *pseudomonas*	Thiobacillus thioparus
Fluorescens Pseudomonas putida Pseudomonas sp	*Paracoccus versutus*
Pseudomonas stutzeri	
Volume 150 litres applied over a period of five days	Volume 50 litres applied two weeks following on from GF application

Bioaerosols

Table 26 shows bioaerosol field-testing at site P (Sampling date 13 April 2012).

Elevated concentrations of bacteria, gram-negative bacteria, fungi (*A. fumigatus*) and endotoxin can be seen at the input of the biofilter. Bacteria were one order of magnitude higher than fungi at the input. It should be noted that fungi was not found at all in some of the duplicates on the input or output and were generally much less evident. Endotoxins (associated with gram-negative bacteria) were also much higher than glucan (associated with fungi).

The lowest removal efficiencies were seen for bacteria and gram-negative bacteria at 70-73 per cent. However, endotoxin shows a very high reduction at 99 per cent. Fungi results are

more variable as some input samples could not detect *A. fumigatus* and only some output samples were able to, hence the quoted 87.5 per cent should be treated with caution. These figures could still be considered good removal efficiency.

Table 26. Bioaerosol field-testing at site P (sampling date 13 April 2012). Data reported as means of sampling and analysis replicates with ranges in parenthesis.

	Biofilter input **	Biofilter output **	Removal efficiency (%)
Viable bacteria (x 10^3 cfu m^{-3})	64.4 (5.4-78.0)	19.6 (15.6-25.2)	69.6
Viable gram negative (x 10^3 cfu m^{-3})	14.2 (10.8-18.0)	3.8 (1.2-6.0)	73.2
Viable fungi *(A. fumigatus)* (x 10^3 cfu m^{-3})	1.6 (0-3.6)	0.2 (0-1.2)	87.5
Endotoxin (EU m^{-3})	3700 (3286-4115)	29 (10-44)	99.2
Glucan (ng m^{-3})	7.7 (6.0-8.4)	1.5 (0.8-2.3)	80.5

** two samples of 10 continuous minutes $^\$$ calculated from averages of all duplicates.

5.5 Field studies discussion

Operational composting characteristics were determined and biofilter input and output gases and particulates were measured for two in-vessel composting operations (site C and site P). Both sites composted source segregated household waste and both used the in-vessel systems as a means of sanitising the waste by achieving a pile temperature of 70°C in compliance with Animal By-products Regulations (ABPR). In particular, odour concentrations, concentrations of selected types of odour compound, and bioaerosol profiles were measured.

The main site for the fieldwork was site C. Monitoring of in-vessel exhaust gas and biofilter outputs was undertaken on three occasions: a pilot study, measurements of the performance of the existing biofilter material, and then the replacement biofilter material. The pilot test output sampling method was not suitable for bioaerosol measurements. Due to equipment failure, bioaerosols were measured only at the replacement material. These were carried out on single days and provide only snapshots of plant and biofilter operation.

5.5.1 Discussion of field measurements, odour

Sampling methods

Sampling methods for gas emissions from a wide surface area such as the site C biofilter are not well characterised. It was considered that combining the whole output and sub-sampling a stream output gas as for the main tests at site C was likely to be more reliable than small areas of sheeting, however a detailed comparison of methods was beyond the scope of this study.

Gas analysis methods

Compost plant emissions, and compost process gases especially, are extremely complex mixtures. Some important odorous compounds may be present at very low concentration within a high concentration of less odorous gases such as methane. This is a significant analytical challenge. FTIR analysis gives a useful initial profile of the types of compounds present though it is not possible to interpret this as specific compounds in many cases. For instance the measurement of methyl sulphides includes at least the highly odorous dimethyl disulphide (DMDS) as well as methyl sulphide (DMS) and more complex sulphide groups. This data should be treated with caution.

More detailed analysis can be found from various mass spectrometry techniques which target specific compounds such as GC-MS or SIFT–MS. However quantifying a limited range of known compounds may also be misleading as important component gases could be missed. A combined approach using complimentary methods is likely to be most successful.

Aeration rates and compost emissions

The aeration rates for the in-vessel composting system during the two main studies at site C were estimated at 1.5 and 2.3m^3 tonne^{-1} h^{-1}. These aeration rates would be considered to be low for in-vessel composting systems and piles operating under these conditions would be likely to be oxygen limited.

The higher of these aeration rates produced a methane concentration in the in-vessel exhaust gas of greater than 1,000ppmv, strongly indicating that piles were significantly anaerobic rather than aerobic. Significant levels of reduced sulphur compounds were also present. For the pilot test, the aeration rate was lower still, estimated at 0.67m^3 tonne^{-1} h^{-1}. On this occasion, reduced sulphur compounds were present, though methane concentration

was lower, possibly suppressed by acidification in the compost. Only trace amounts of ammonia were present in all cases.

It was not possible to draw strong conclusions about the compost emissions at site P since the measured biofilter input was a mixture of gases from different parts of the plant. However the presence of some reduced sulphur species suggests a degree of anaerobicity was present.

The odour concentrations of the in-vessel compost exhaust gas entering the biofilter during the main tests at site C were 720,000 OU_E m^{-3} (13 January 2012) and 573,000 OU_E m^{-3} (30 March 2012). These gas streams would be considered to be highly odorous, above the levels many commercial biofilters are designed to handle. On the day measurements taken at site P, the input odour concentration was low (mean 9,500 OU_E m^{-3}). The process air at this plant is diluted with air from other parts of the plant before reaching the sampling point at the biofilter input.

The analysis of odour compounds at both sites showed that the input gas contained almost zero ammonia and odour was dominated by anaerobic-related compounds such as methyl sulphides.

Biofilter removal efficiency for odour

Measurements were taken once before and once after a change of biofilter material at site C, using the same sampling methods for biofilter output emissions. The odour concentrations of the biofilter emissions were 12,400 OU_E m^{-3} (existing biofilter material) and 1,720 OU_E m^{-3} (replacement biofilter material). The respective odour removal efficiencies were very high – 98.3 per cent and 99.7 per cent – demonstrating that both biofilter materials performed exceptionally well. These two snapshot measurements under different conditions for aeration rate and input gas were not sufficient to determine whether the replacement biofilter material improved removal efficiency.

Odour from the site C existing biofilter material was still relatively high (12,400 OU_E m^{-3}) if a value of under 3,000 OU_E m^{-3} is considered to be the industry target value. The reason for the higher biofilter output odour value for the original material is not clear, but it may be relevant that input gas composition and the input odour concentrations differed between the two measurement days.

The biofilter at site P only achieved an approximately 26 per cent reduction in odour concentration. Very little reduction in the concentrations of all of the selected compound

types was observed (approximate 20 per cent reduction in methyl sulphides; 60 per cent reduction in alcohols). However input gas was unusually low in odour and odorous compounds on the day of sampling. Output air odour may have been dominated by compounds previously deposited on the biofilter substrate. It is also possible that the relatively new biofilter material lacked the necessary microbial community to successfully treat the odorous components of the input gas.

Further developments by the site operator, as advised by odour consultants, have involved improving the biofilter irrigation system and inoculating the virgin wood chip biofilter material with selected strains of microorganisms and nutrients. The effectiveness of these measures is still to be evaluated. One observation from this case study is that new biofilter materials, devoid of the appropriate microorganisms to decompose odour compounds, will probably require some form of inoculation and nutrient addition for optimum performance.

5.5.2 Discussion of bioaerosol field measurements

The biofilter at site C removed between 89.9 and 100 per cent of the particulates, bioaerosols and their constituents that were measured at the inflow. The biofilter at site P was slightly less efficient, but still removed between 69.6 and 99.2 per cent of the input. Overall both biofilters appear to be effective at removing bioaerosols, site C very well and site P relatively well. Bacteria and to some extent gram-negative bacteria are not removed quite as efficiently as some other bioaerosols and constituents.

If absolute values are considered however, there are still issues to highlight. Current Environment Agency guidance (Environment Agency, 2009) for bioaerosols at open windrow compost sites use the following values:

- bacteria 1000cfu m^{-3}

- fungi (*Aspergillus fumigatus*) 500cfu m^{-3}

- gram-negative bacteria 300cfu m^{-3}

These concentrations are usually to be met by the site boundary, and are to be elicited using an agreed standardised method for measuring their concentrations (AfOR, 2009). In these field sites the media, temperature and time for culturing of viable bioaerosols from the inlet and outlet was as required by the AfOR protocol. Obviously how these concentrations are dispersed around the site, and whether they are transported off-site, is a separate consideration. However, the output concentrations for bacteria and gram-negative bacteria from the biofilters tested above are in excess of these guidelines. At site P fungi is also

above guidelines. So although the biofilters are demonstrating good removal efficiencies, the emissions to air for these parameters remain in excess of recommended values.

Endotoxin also needs to be considered. The Dutch Expert Committee on Occupational Safety (DECOS) proposed a health-based occupational exposure limit of 50EUm[-3] ('EU' are Endotoxin Units which are used to measure the lipopolysaccharide action of endotoxin; as an approximation, 10EUs is equal 1ng). This was later revised to a temporary legally binding limit of 200EUm[-3] due to feasibility difficulties when meeting the lower limit (the economic effects of meeting this standard were prohibitive for industry) (Douwes *et al.*, 2003 ; Spaan, 2008). DECOS recently signed an agreement with other Nordic countries to push through new endotoxin standards (European Agency for Safety and Health at Work (EU-OSHA), 2011). The new current standard is to be 90EUm[-3] (NordicExpertGroup, 2011).This was based on the capability of endotoxin to impact on lung function at higher concentrations.

Despite the extremely good removal efficiency demonstrated by the biofilter, emissions of endotoxin are still well in excess of these concentrations at site C. At site P they are within guidelines. It should also be noted that at site C, one endotoxin measurement on input air was so high it could not be elucidated, so in fact the biofilter may be performing extremely well.

Fewer exposure standards have been proposed for glucan, and papers generally tend to quote 10ngm[-3] based on work in Sweden by Rylander (1997). Emissions from both biofilters are within those concentrations.

In conclusion, both biofilters are removing large concentrations of particulates, bioaerosols and their constituents seen at the inlet concentrations. However, despite very good removal efficiencies in some instances, concentrations released to the atmosphere are still elevated above background, and are often in excess of both guideline (viable bioaerosols) and suggested standard concentrations (endotoxin). In particular, bacteria and gram-negative bacteria are exiting the biofilters in relatively high concentrations compared to background.

6 Laboratory biofilter experiments

6.1 Introduction

Investigation of biofilter materials in laboratory conditions allows more controlled conditions and avoids much of the uncertainty and practical difficulty relating to site conditions and sampling methods in the field. A lab-scale biofilter test rig was constructed to test a range of biofilter materials taken from active biofilters on compost sites. The aims were to determine odour and bioaerosol removal rates for a range of typical and well-characterised biofilter materials when subjected to a typical composting exhaust gas stream under laboratory conditions. Specific objectives were:

- to construct, commission and operate a laboratory-scale biofilter test rig;

- to determine the nature and the characteristics of the background odour and bioaerosols emitted from three biofilter materials by testing each using fresh air or low-background air inputs;

- to generate a composting exhaust gas with an odour profile typical of well managed in-vessel composting systems treating SSHW;

- to generate a composting exhaust gas with a bioaerosol profile representative of in-vessel composting systems treating SSHW;

- to determine the odour removal rates for three biofilter materials and the removal rates of selected odour compounds;

- to determine the bioaerosol removal rates for three biofilter materials.

6.2 Methodology

6.2.1 Air supply to biofilters

Preliminary experiments used low-background air from outside the laboratory drawn in using a dedicated 'clean' diaphragm pump. This was expected to be low in odour and bioaerosols though with some possible contamination from lab operations. In addition, fresh air from roof

level supplied by an oil-free compressor through nylon tubing was used for additional odour tests. This was expected to be unaffected by lab operations or passing traffic.

To produce compost odours, three 270L insulated composter units (Figure 6) were filled with mixed shredded green waste and food waste material collected from the AmeyCespa Composting Facility (Waterbeach, Cambridge) and additional food waste. Output aeration pipes were combined through a manifold and aerated under suction using a diaphragm pump, controlled with an electrical timer. Aeration rates differed between the three composter units, producing a mixture of aerobic and anaerobic composting conditions. Temperatures were also monitored in all three composters.

Figure 6. Composting units used for odour production.

6.2.2   Lab-scale biofilter units

Lab-scale biofilter units were constructed using vertical PVC 300mm diameter pipe. Each end was sealed with using a neoprene gasket to a removable flat plate. The biofilter flow was downward with input air connected using 25mm diameter plastic pipework and fittings. The biofilter material was supported on a 10mm mesh about 800mm from the bottom, and similar fittings allowed output air to be piped away. Inlet sampling ports were supplied in the headspace above the level filled with biofilter material. Outlet sampling ports were made

below the supporting mesh. In-line rotameters were used to measure flow before and after the biofilter unit, bypassed during compost gas runs to avoid clogging.

Each of the three biofilter units was connected to the outlet from the in-line composter units' aeration pump or similar positive pressure fresh air source and allowed to reach steady-state flow before measurements were taken. The experimental rig is shown in Figure 7.
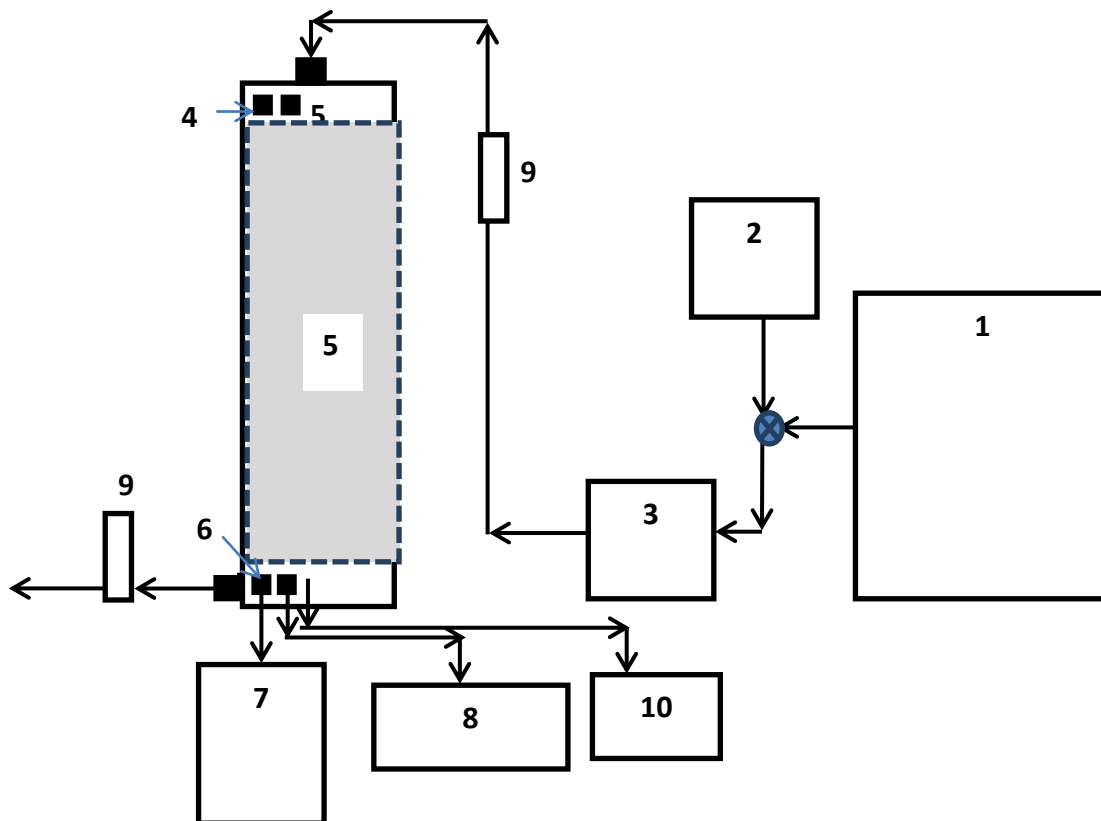
Key:
1 - Compost tank
2 - Fresh air delivered from outside lab or rooftop
3 - Pump
4 - Inlet sampling ports
5 - Biofilter
6 - Output sampling ports
7 - Particulate monitor
8 - Impinger/isokinetic pump
9 - Flow meters
10 - Gas collection for odour/on-line gas analysers

Figure 7. Schematic for laboratory measurements of odours and bioaerosols in lab-scale biofilters.

The biofilter material types used were (Table 27):

- wood chip from site C
- peat from site G
- pine chip from site P

Table 27. Biofilter materials used in lab tests.

Material	Source	Description
Wood chip	Site C	Chipped wood from mixed sources taken from active layer of biofilter
Peat	Site G	Peat material taken from working biofilter
Pine chip	Site P	Chipped virgin pine including bark taken from working biofilter

Operational details varied to some degree between biofilter columns depending particularly on the material used. Operating parameters used are shown in Table 28. Actual residence time was measured by timing a pulse of nitrous oxide injected into the headspace of the biofilter and measured at the outlet. This is in all cases longer than 'true residence time', which is calculated using only the empty bed residence time and porosity; other factors will include pressure differences, path length and tortuosity between particles of biofilter material, and drag effects.

6.2.3   Analytical

Gas samples were taken for odour measurements, gas composition and bioaerosols by the same methods as site C (section 5.3.2). Samples were collected in Nalophan® bags with PTFE and stainless steel fittings with the aid of a low flow pump. Samples were collected in duplicates from the inlet to each biofilter and the respective outlet, giving a total number of 12 gas samples.

As particulate and bioaerosol sampling were carried out simultaneously, it was important to ensure enough total flow through the biofilter column to provide sufficient output flow for both the bioaerosol sample impingers (12.5L min^{-1}) and Osiris particulate monitor (0.6L min^{-1}).

The compost reactor was not disturbed between each sampling occasion to mirror conditions in a working in-vessel facility.

Table 28. Laboratory scale biofilter operating parameters.

Operational details	Lab tests(fresh air)			Lab tests (low background air)			Lab tests (compost air)		
	Wood chip from site C	Peat from site G	Pine chip from site P	Wood chip from site C	Peat from site G	Pine chip from site P	Wood chip from site C	Peat from site G	Pine chip from site P
Standard calculations									
Flow ($m^3 h^{-1}$ (STP))	1.8	1.8	1.8	0.82	0.82	0.82	0.68	0.79	0.81
Total biofilter volume (m^3)	0.081	0.082	0.081	0.081	0.082	0.081	0.081	0.082	0.081
Biofilter EBRT (s)	150	152	149	318	323	317	381	334	319
Calculations based on height filled with biofilter material									
Volume of biofilter (m^3)	0.06	0.06	0.07	0.06	0.06	0.07	0.062	0.056	0.068
EBRT (s)	114	104	126	242	220	268	290	227	270
Porosity (%)	53.8	38.4	64.6	53.8	38.4	64.6	53.8	38.4	64.6
True residence time (s)	61	40	82	130	85	173	156	87	175
Measured residence time (s)				256	99	207			
Volumetric loading rate ($m^3 m^{-3} h^{-1}$)	31.6	34.7	28.5	14.9	16.3	13.4	12.4	15.8	13.3

6.3   Results

6.3.1   Odour

Table 29 to Table 32 show the odour and gas characterisations of the laboratory experiments.

Table 29. Odour results from lab tests on three biofilter materials collected from active biofilters.

	Units	Wood chip from site C	Peat from site G	Pine chip from site P
Lab tests (fresh air)				
Biofilter input	$OU_E\,m^{-3}$	1,040	1,040	1,040
Biofilter output	$OU_E\,m^{-3}$	2,010	2,990	2,450
Removal efficiency	%	+	+	+
Volumetric loading rate	$m^3\,m^{-3}\,h^{-1}$	29.2	32.0	26.3
Mass loading (volumetric, active)	$OU\,m^{-3}$ biofilter h^{-1}	30,300	33,300	27,400
Elimination capacity (rate)	$g\,m^{-3}$ biofilter h^{-1}	+	+	+
Lab tests (low-background air)				
Biofilter input	$OU_E\,m^{-3}$	4,790	4,790	4,790
Biofilter output	$OU_E\,m^{-3}$	4,130	2,390	3,290
Removal efficiency	%	13.8	50.1	31.4
Volumetric loading rate	$m^3\,m^{-3}\,h^{-1}$	13.2	14.5	11.9
Mass loading (volumetric, active)	$OU\,m^{-3}$ biofilter h^{-1}	63,400	69,600	57,200
Elimination capacity (rate)	$g\,m^{-3}$ biofilter h^{-1}	8,750	34,800	18,000
Lab tests (compost air)				
Biofilter input	$OU_E\,m^{-3}$	98,300	131,000	116,000
Biofilter output	$OU_E\,m^{-3}$	5,630	3,480	6,720
Removal efficiency	%	94.3	97.3	94.2
Volumetric loading rate	$m^3\,m^{-3}\,h^{-1}$	11.0	14.1	11.8
Mass loading (volumetric, active)	$OU\,m^{-3}$ biofilter h^{-1}	1,086,000	1,840,000	1,370,000
Elimination capacity (rate)	$g\,m^{-3}$ biofilter h^{-1}	1,020,000	1,790,000	1,290,000

+ Concentration increased post biofilter; - not applicable

Table 30. Measurements of odorous component gases in lab test using fresh air

		Wood chip from site C		Peat from site G		Pine chip from site P	
	Inlet conc (ppmv).	Outlet conc (ppmv).	Reduction (%)	Outlet conc (ppmv).	Reduction (%)	Outlet conc (ppmv).	Reduction (%)
Hydrogen sulphide H_2S	0.06	0.05	*	0.05	*	0.04	*
Methyl sulphides (inc. DMS, DMDS)	0.11	0.48	+	0.58	+	0.59	+
Carbon disulphide CS_2	0.00	0.00	*	0.00	*	0.00	*
VFAs (quantified as acetic acid)	0.19	0.32	+	0.32	+	0.33	+
Ammonia NH_3	0.00	0.00	*	0.00	*	0.00	*
Nitrogen dioxide NO_2	0.48	0.53	+	0.34	27.9	0.46	3.2
Alcohols (quantified as ethanol)	2.09	1.86	10.9	10.33	+	5.10	+
Ketones (quantified as butanone)	0.12	0.01	92.5	0.03	78.0	0.00	100.0
Aldehydes (as formaldehyde)	0.05	0.04	*	0.02	*	0.02	*
Terpenes (quantified as pinene)	0.01	0.06	*	0.04	*	0.05	*
Xylenes (quantified as m-xylene)	0.09	0.13	*	0.13	*	0.08	*
Aromatics (quantified as benzene)	0.34	0.26	23.0	0.25	26.7	0.13	62.5
Acetates (quantified as ethyl acetate)	0.00	0.00	*	0.00	*	0.00	*
Photo-ionisable gas (quantified as isobutylene)	10	36	+	30	+	35	+
Flame-ionisable gas (quantified as methane)	1.8	1.3	*	2.0	*	1.5	*

* Low concentrations close to detection limits give unreliable values for removal efficiency.
+ Concentration increased post biofilter; - not applicable.

Table 31. Measurements of odorous component gases in lab test using low-background odour air.

	Inlet conc (ppmv).	Wood chip from site C		Peat from site G		Pine chip from site P	
		Outlet conc (ppmv).	Reduction (%)	Outlet conc (ppmv).	Reduction (%)	Outlet conc (ppmv).	Reduction (%)
Hydrogen sulphide H_2S	0.005	0.003	*	0.003	*	0.003	*
Methyl sulphides (inc. DMS, DMDS)	0.18	0.31	*	0.19	*	0.15	*
Carbon disulphide CS_2	0.00	0.00	*	0.00	*	0.00	*
VFAs (quantified as acetic acid)	0.02	0.00	*	0.74	*	0.00	*
Ammonia NH_3	0.26	0.25	5.4	2.89	+	0.62	+
Nitrogen dioxide NO_2	0.45	0.35	23.7	0.39	13.2	0.32	29.0
Alcohols (quantified as ethanol)	2.12	1.81	14.5	11.37	+	8.75	+
Ketones (quantified as butanone)	0.11	0.05	55.4	0.03	73.5	0.02	78.0
Aldehydes (as formaldehyde)	0.16	0.14	12.8	1.34	+	0.10	36.7
Terpenes (quantified as pinene)	0.00	0.01	*	0.01	*	0.00	*
Xylenes (quantified as m-xylene)	0.02	0.05	*	0.02	*	0.03	*
Aromatics (quantified as benzene)	0.53	0.33	37.0	0.51	4.7	0.30	43.4
Acetates (quantified as ethyl acetate)	0.00	0.00	*	0.00	*	0.00	*
Photo-ionisable gas (quantified as isobutylene)	6.9	6.3	9.3	16.0	+	12.4	+
Flame-ionisable gas (quantified as methane)	0	0	*	0	*	0	*

* Low concentrations close to detection limits give unreliable values for removal efficiency.
+ Concentration increased post biofilter; - not applicable

Biofilter performance and operation as related to commercial composting)

Table 32. Measurements of odorous component gases in lab test using compost gases.

Compounds	Wood chip from site C			Peat from site G			Pine chip from site P		
	Biofilter input (ppmv)	Biofilter output (ppmv)	Removal efficiency (%)	Biofilter input (ppmv)	Biofilter output (ppmv)	Removal efficiency (%)	Biofilter input (ppmv)	Biofilter output (ppmv)	Removal efficiency (%)
Hydrogen sulphide H_2S	0.73	0.18	75.7	0.61	0.07	88.4	0.37	0.01	96.8
Methyl sulphides (inc. DMS, DMDS)	6.0	2.5	58.7	4.8	2.0	57.2	3.7	0.9	74.4
Carbon disulphide CS_2	0.0	0.0	*	0.2	0.0	*	0.0	0.0	*
VFAs (quantified as acetic acid)	2.3	0.1	97.2	2.5	0.0	98.2	2.5	0.0	99.4
Ammonia NH_3	473	2.9	99.4	490	1.3	99.7	505	2.4	99.5
Nitrogen dioxide NO_2	1.2	0.7	43.3	1.2	0.7	36.6	0.9	0.4	54.9
Alcohols (quantified as ethanol)	19.5	19.8	+	16.8	15.9	4.9	16.8	16.3	2.9
Ketones (quantified as butanone)	0.2	0.0	*	0.0	0.0	*	0.0	0.0	*
Aldehydes (as formaldehyde)	0.1	0.0	*	0.3	0.1	*	0.3	0.1	*
Terpenes (quantified as pinene)	1.5	0.9	41.3	1.4	0.7	45.1	1.3	0.4	71.2
Xylenes (quantified as m-xylene)	0.0	0.0		0.0	0.1	*	0.0	0.1	*
Aromatics (quantified as benzene)	0.5	1.7	+	0.4	1.2	+	0.3	0.7	+
Acetates (quantified as ethyl acetate)	0.0	0.0	*	0.0	0.0	*	0.0	0.0	*
Photo-ionisable gas (quantified as isobutylene)	1080	97	91.0	953	63	93.4	1122	39	96.6
Flame-ionisable gas (quantified as methane)	40	33	17.5	34	29	14.1	35	33	6.8

* Low concentrations close to detection limits give unreliable values for removal efficiency.
+ Concentration increased post biofilter; - not applicable.
Photo-ionisable gas (PID) includes ammonia, VOCs.
Flame-ionisable gas (FID includes methane, VOCs.
VOCs giving higher response on PID than FID include: alcohols, ethyl acetate, ethylene.

6.3.2   Bioaerosols

Table 33 and Table 34 below show bioaerosol measurements from two laboratory studies, the first passing low-background air through used biofilter material, and the second using the laboratory scale composting reactors as described in section 6.2.2 as a source of air and passed through the same biofilter material.

The first test run was designed to pass low concentration outside air (low-background) via the biofilter material to ascertain whether the material could produce a net emission. In terms of particulates, wood chip shows a definite rise in TSP and PM_{10} post-biofilter. For bacteria, both peat and wood chip show higher concentrations at exit where there were none detected at input – this is also evident for gram-negative bacteria. Peat in particular has a strong post-biofilter signature of these variables at concentrations of the order of $10^3 cfum^{-3}$. Fungi were not found either at input or output.

For endotoxin and glucan, unexpectedly high values were seen at input in all test runs. It is unclear why this is the case, but the pump used to push air through the system is suspected (which was situated between the external intake and input to the biofilter). Endotoxin is seen in noticeable concentrations on output of peat in particular, but is also evident at the wood chip and pine chip outputs. Glucan is particularly elevated in association with wood chip.

For compost air tests, very good removal efficiencies were seen for particulates in wood chip, and although peat and pine chip show lower percentages, the concentrations in and out were relatively low so caution may need to be taken with this result.

Concentrations of bacteria and gram-negative bacteria increased post-biofilter for peat, as for low background air. The relatively small inputs for wood chip were matched at the output for the same two variables. Pine chip showed the best removal rates and proved to be very efficient at 97 per cent removal or better.

Of particular interest is the failure to measure any discernible fungi in the input or output on any of the experimental periods. The material in the laboratory scale composting reactors is expected to be very similar to conditions within an active in-vessel system.

Endotoxin and glucan increased post-biofilter in all of the experimental periods. In the case of peat, a large increase was seen post-biofilter. It is hypothesised that this used material had a reservoir of cells which were released during this run.

Table 33. Bioaerosol components in lab test using low-background air. Data reported as means (with ranges in parenthesis)

	Wood chip from site C			Peat from site G			Pine chip from site P		
	Biofilter input *	Biofilter output **	Removal efficiency (%)	Biofilter input *	Biofilter output **	Removal efficiency (%)	Biofilter input *	Biofilter output **	Removal efficiency (%)
TSP ($\mu g\ m^{-3}$)#	17	82	+	22	8	63.6	31	13	58.1
PM$_{10}$ ($\mu g\ m^{-3}$)#	3	54	+	6	3	50	20	5	75
Viable bacteria (x 10^3 cfu m^{-3})	u.d.	0.2 (0-1.2)	+	u.d.	5 (2.4-6)	+	u.d.	u.d.	+
Viable gram negative (x 10^3cfu m^{-3})	u.d.	0.4 (0-1.2)	+	u.d.	2.4 (1.2-7.2)	+	u.d.	spr	+
Viable fungi *(A. fumigatus)* (x 10^3cfu m^{-3})	u.d.	u.d.		u.d.	u.d.		u.d.	u.d.	
Endotoxin (EU m^{-3})	34 (26-49)	56 (31-99)	+	111 (105-112)	88 (25-259)	20.7	35 (32-37)	36 (11-58)	+
Glucan (ng m^{-3})	45.1 (42.3-50.3)	62.6 (54.9-69.1)	+	58.3 (57.4-60.1)	5.4 (4.4-6.5)	90.7	11.7 (11.5-11.8)	4.3 (2.7-5.8)	63.2

+ Concentration increased post biofilter; - not applicable.
u.d. undetectable.

* Sample of 10 continuous minutes;

** Two samples of 10 continuous minutes.

One 20-minute sample.

Table 34. Bioaerosol components in lab test using compost gases. Data reported as means (with ranges in parenthesis).

	Wood chip from site C			Peat from site G			Pine chip from site P		
	Biofilter input *	Biofilter output **	Removal efficiency (%)	Biofilter input *	Biofilter output **	Removal efficiency (%)	Biofilter input *	Biofilter output **	Removal efficiency (%)
TSP µg m^{-3}#	351	37	89	24	5	63.6	20	9	58.1
PM$_{10}$ (µg m^{-3})#	306	34	89	17	1.7	50	13	3.5	75.0
Viable bacteria (x 10^{3}cfu m^{-3})	0.4 (0-1200)	0.4 (0-1200)	0	0.4 (0-1200)	96 (39.6-132)	+	8 (7.2-13.2)	0.2 (0-1.2)	97.5
Viable gram negative (x 10^{3}cfu m^{-3})	u.d.	u.d.	u.d.	u.d.	42.8 (19.2-73.2)	+	10 (3.6-13.2)	0.2 (0-1.2)	98
Viable fungi *(A. fumigatus)* (x 10^{3}cfu m^{-3})	u.d.	u.d.	u.d.	u.d.	u.d.		u.d.	u.d.	
Endotoxin (EU m^{-3})	13 (11-14)	54 (20-112)	+	13 (13-14)	5880 (175-11276)	+	113 (112-116)	134 (115-170)	+
Glucan (ng m^{-3})	3.5 (3.5-3.6)	4.1 (3.3-4.7)	+	1.1 (1.0-1.2)	5.5 (4.8-5.8)	+	0.6 (0.5-0.7)	3.2 (2.8-3.8)	+

u.d. undetectable.
* Sample of 10 continuous minutes.
** Two samples of 10 continuous minutes.
 # One 20-minute sample.
+ Concentration increased post biofilter; - not applicable
NB: compost percolate bacteria 2270cfuml^{-1}, gram negative bacteria 1077cfuml^{-1}, all fungi undetectable. Compost drum samples similar to input.

Table 35. Bioaerosol components in lab test using imported compost from maturation pad. Data reported as means (with ranges in parenthesis)

	Direct from tank*	Wood chip from site C			Peat from site G			Pine chip from site P		
		Biofilter input *	Biofilter output **	Removal efficiency (%)	Biofilter input *	Biofilter output **	Removal efficiency (%)	Biofilter input *	Biofilter output **	Removal efficiency (%)
TSP µg m^{-3}#	-	6.4	16	+	15	1.4	90.7	11	1.2	89.1
PM$_{10}$ (µg m^{-3})#	-	2.1	11	+	4	0.8	80	7.2	0.5	93.1
Viable bacteria (x 10^{3}cfu m^{-3})	101.2 (87.6-109.2)	3.6 (2.4-4.8)	5.2 (3.6-6)	+	52.4 (42-61.2)	3.6 (1.2-4.8)	93.1	6 (2.4-9.6)	1.6 (0-2.4)	73.3
Viable gram negative (x 10^{3}cfu m^{-3})	42.4 (34.8-52.8)	2.8 (1.2-4.8)	0.8 (0-1.2)	71.4	43.2 (34.8-48)	u.d.	100	0.8 (0-1.2)	0.4 (0-1.2)	50
Viable fungi (*A. fumigatus*) (x 10^{3}cfu m^{-3})	7.6 (8.4-9.6)	u.d.	u.d.	+	u.d.	u.d.	+	u.d.	u.d.	+
Endotoxin (EU m^{-3})	113 (106-124)	3 (3)	71 (43-100)	+	96 (91-101)	8 (7-9)	91.7	71 (43-100)	6 (6-7)	91.5
Glucan (ng m^{-3})	67.3 (60.1-76.0)	1.28 (0.9-1.5)	2.24 (2.1-2.3)	+	9.65 (6.3-12)	8.1 (6.0-10.8)	16.1	7.15 (7-7.2)	3.26 (3.1-3.4)	54.4

u.d. undetectable.

* Sample of 10 continuous minutes.

** Two samples of 10 continuous minutes.

One 20-minute sample.

+ Concentration increased post biofilter; - not applicable.

In the laboratory a large amount of liquid was also present in the compost reactors. This was plated out as per the AfOR protocol to ascertain whether there were viable populations. It was found that the compost percolate contained viable bacteria of 2270cfuml^{-1}, viable gram negative bacteria of 1077cfuml^{-1}, and all fungi were undetectable. These results reflected the fact that no fungal bioaerosols were found.

To ascertain whether the lack of fungi was as a result of the treatment of the laboratory scale material, a third set of sampling was undertaken using compost taken from the maturation pads of site C. Sampling was as previously described, but in this instance a direct sample was also taken from the compost reactor after agitation. The drums were also agitated before compost gas was passed through the biofilter material between each sampling occasion.

The matured compost once agitated in the laboratory drum is clearly seen to be emitting viable bacteria at 10^5cfu m^{-3}, viable gram-negative bacteria at 10^4cfu m^{-3}, and viable *A. fumigatus* at 10^3cfu m^{-3}. Elevated concentrations of endotoxin and glucan are also evident.

Peat and pine chip show good removal of particulates in the TSP and PM$_{10}$ range – these were slightly increased post-biofilter for wood chip. A similar pattern was seen for viable bacteria, although removal efficiencies were lower. Peat in particular appeared to remove all gram-negative bacteria on this sampling occasion. Wood chip and pine chip had lower removal efficiencies. Again, no fungi were found in the input or output, despite testing that showed it existed at the compost drum. Removal of 90 per cent and above was seen for endotoxin in peat and pine chip, and lower removal efficiencies for glucan were evident (although the concentrations were also much lower and hence may be subject to more variability). Wood chip showed a slight increase in endotoxin and glucan at the output.

6.4   Discussion of laboratory studies

To determine the performance of three selected biofilter materials from commercial composting operations, laboratory measurements were taken of odour concentration, concentrations for selected odour compounds and bioaerosol profiles, pre- and post-laboratory biofilter. All of the biofilter material was sourced from active sites and all were used until collected.

Three biofilter materials sourced from site C (wood chips), site P (pine chips) and site (an MBT/SSHW composting site (peat)) were subjected to testing in a laboratory scale test facility as described in section 6.2. The odorous input gas stream used to test the biofilter materials was derived from composting a simulated SSHW mix in the laboratory. The input

gas stream was characteristic of the emissions from a well-managed, aerobic, in-vessel composting facility and contained a moderate concentration of ammonia gas (400-500ppmv) as well as lower concentrations of other odorous compounds such as DMDS, DMS, volatile fatty acids (VFAs), alcohols and terpenes. The odour range for the input air tested was 98,000 to 130,000 OU_E m^{-3}. The biofilter materials were also tested using fresh air (1,040 OU_E m^{-3}) and low background odour air (4,790 OU_E m^{-3}).

6.4.1 Odours

All three biofilter materials achieved similar rates of odour removal for the compost gas stream: site C 94.3 per cent, site G 97.3 per cent and site P 94.2 per cent. Without further testing it is not possible to determine whether these removal efficiencies were significantly different. This particular input gas included components characteristic of both aerobic and anaerobic composting. In terms of concentration, the gas mixture was dominated by the presence of ammonia, which contributed significantly to the input odour. However the odour appeared to be dominated by reduced sulphur compounds due to the low odour threshold of these compounds. Of the compound types measured, the contribution from methyl sulphides is estimated to be highest. All three biofilter materials were highly effective in removing ammonia from the gas stream: site C 99.4 per cent, site G 99.7 per cent and site P 99.5 per cent. High levels of ammonia removal found for this study reflect findings in the literature, which confirm that ammonia may be easily removed in biofilters through adsorption and absorption with a proportion of this being subsequently removed by nitrification. It is typical for new biofilters to have the capacity to remove very high concentrations of ammonia until the sorption limit of the material is reached, thereafter removal rates for ammonia decline rapidly. However, even moderate concentrations of ammonia are known to inhibit nitrification and the microbial decomposition of other odorous compounds.

These biofilters were run at relatively low temperature, in general lower than optimum but still conducive to nitrification. Temperature in full-scale biofilters may often be affected by the high temperature of input gases. Nitrification may be inhibited at the higher temperatures reached.

For the compost gas input, all three biofilter materials were much less effective at removing other odorous compounds compared with ammonia. For example, reductions of methyl sulphides were 58 per cent at site C, 57 per cent at site G, and 74 per cent at site P.

When all three biofilter materials were subjected to fresh air only, the resulting biofiltered air for each was found to have a higher odour concentration compared with the fresh air input.

The odour concentration increased from 1,040 OU_E m^{-3} to a mean value of 2,480 OU_E m^{-3} in these tests. Analysis of odour compounds in the fresh and filtered air confirmed that stripping of some odour compounds from the biofilter materials had taken place. This reflects literature findings and suggests that biofilter materials on their own will emit a residual odour and this may be significant in the context of an industry target odour of 3,000 OU_E m^{-3}.

For low odour air inputs (4,790 OU_E m^{-3}), the three materials achieved poor removal efficiencies: site C 13.8 per cent, site G 50.1 per cent and site P 31.4 per cent. The low removal rates were probably due to the residual odour of the biofilter materials derived either from odour molecules adsorbed from previous odorous input gases, or intrinsic odour of the matrix itself.

6.4.2   Bioaerosols

Tentative conclusions are that peat and wood chip were seen to be net emitters for bacteria and gram-negative bacteria in these tests. Endotoxin and glucan concentrations are also of note; despite the elevated inputs there are some noticeable rises in output, particularly for peat and wood chip. Peat in particular appeared to have much higher concentrations at the output than the input in the initial round of tests from material matured in the laboratory. An obvious anomalous result is seen in Table 34 for endotoxin at 5880EU m^{-3}. For imported compost air, however, good removal efficiencies were seen, and this peak did not reoccur. It is assumed that previously trapped material from the previous use of the peat was emitted in the laboratory.

With the exception of particulates in the laboratory-produced compost, wood chip showed higher concentrations at the output than the input in almost all cases. Pine chip showed higher endotoxin and glucan at the output in the laboratory-manufactured compost, but good removal efficiencies from the imported compost.

As for on-site sampling, many of the absolute values at output exceed stated guidelines:

- bacteria 1000cfu m^{-3}

- fungi (*Aspergillus fumigatus*) 500cfu m^{-3}

- gram-negative bacteria 300cfu m^{-3}

- endotoxin 90EU m^{-3}

- glucan 10ngm^{-3}

Indeed, peat exceeded this as a net emitter for bacteria and gram-negative bacteria, and wood chip for endotoxin and glucan. Peat clearly exceeded these also for bacteria and gram-negative bacteria and endotoxin from laboratory compost, and pine chip for laboratory compost where concentrations increased at the output. Bacteria and gram-negative bacteria were also exceeded for all material types for the imported compost.

Finally, there were no fungi in any of the inputs or outputs on any of the laboratory runs, despite sampling demonstrating that it was seen in the original compost drum when using imported maturing compost.

7 Summary and main conclusions

The authors of this report take the view that, in contrast to the large amount of information available on the biological removal of odour, there is very little published information available relating to the generation and emission of bioaerosols during in-vessel composting or the effect of biofiltration on bioaerosols. Equally, very little is known about the relationship between odour and bioaerosols during in-vessel composting and the simultaneous treatment of odour and bioaerosols in biofilters. For these reasons, the following summary and conclusions sections will largely treat issues relating to odour and bioaerosols separately, as was the case with the main report.

7.1 Odour summary

7.1.1 Principles behind odour removal

Odour generation

In-vessel composting of source segregated household waste (SSHW) is known to generate and emit a range of odorous compounds. The nature and the concentration of the odour compounds emitted from composting will be related to various factors such as the composition of the waste being composted, the stage of waste preparation and composting being studied, the composting temperature and the degree of aerobicity of the composting pile.

Odour has been associated with at least three stages during the composting of source segregated household waste: reception/shredding/mixing of waste, the initial composting phase and the thermophilic composting phase. Most volatile organic compounds (VOCs) in composting plants are considered to be emitted during the early stages of processing: at the tipping floors, at the shredder, and during the initial active composting stage. Odorous emissions in the reception hall during shredding and mixing are often associated with volatilisation of terpenes while alcohols, carbonyl compounds, esters and ethers are mainly released from the initial composting stage. During thermophilic composting, anaerobic conditions due to incomplete or insufficient aeration will produce reduced sulphur compounds of intense smell, while incomplete aerobic degradation processes result in the emission of alcohols, ketones, esters and organic acids. Also, ammonia has been cited as one of the main compounds responsible for generation of offensive odours.

Emitted compounds are detected at very different concentrations or thresholds and this, coupled with variation in characteristic odour, can make some compounds much more offensive than others. For example, dimethyl disulphide (DMDS) can be detected at a concentration of 0.000026ppmv (rotten cabbage odour) while ammonia is detected at a concentration of 0.038ppmv and has been characterised as having a pungent odour.

Effective composting requires aerobic conditions but even recommended aeration rates for in-vessel composting plants fall within a very wide range (6-24m^3 tonne^{-1}h^{-1}) and the rate of aeration will significantly affect the profile of odour compounds emitted. In summary, in-vessel composting of SSHW will typically emit a range of odorous compounds associated with both aerobic and anaerobic conditions that co-exist within composting piles, such as ammonia, carbonyls, alcohols ethers, hydrogen sulphide and numerous volatile organic compounds (VOCs) including the highly odorous methyl sulphides.

Biological treatment of odours

Biological methods are effective and economical for treating biodegradable odorous compounds found at low concentration within composting exhaust gas streams. Biofilters are reactors in which a humid polluted air stream is passed through a porous packed bed that supports a mixed culture of pollutant-degrading organisms within a biofilm. Biofilters reduce odours by transferring pollutants to the water phase, which is then followed by adsorption to a medium or absorption to a biofilm. Adsorption to filter medium provides good treatment during the initiation of a new biofilter, however once the adsorption capacity is occupied (often in a matter of days), biodegradation in the biofilm becomes the principle odour removal mechanism. A healthy microbial biofilm is crucial in a biofilter as this is where odorous compounds are degraded. Biofilms are highly sensitive to a number of abiotic variables that must be managed. The support medium (biofilter bed) for a biofilm can be either natural or inactive, however to support and promote a healthy biofilm and gas-biofilm mass transfer, the medium should have a high specific surface area, high porosity, good water retention capacity and intrinsic nutrients. Biofilters are often periodically irrigated with nutrient solution to maintain their performance. The main advantage of biofiltration is that it can treat large volumes of low concentration VOCs and odorous compounds for little capital investment. They are, however, highly sensitive to changes in operational parameters.

7.1.2   Types of biofilter and configurations

Biofilters support biological biofilms on their medium (filter bed) that are responsible for the degradation of organic polluting compounds. The choice of filter medium is therefore one of

the most significant decisions facing an operator, as filter types can significantly vary in cost, performance and longevity. Typical media include compost, peat, wood chips or bark, soil and synthetic types. Biofilms contain a mixture of fungi, bacteria, yeasts, ciliated protozoa, amoebae, nematodes and algae. Bacteria and fungi are the two dominant microorganisms groups in biofilters, however as bacteria populations grow they can sustain protozoa and viruses. Certain biofilter media (such as compost) will have inherent well-developed communities of microorganisms, whereas other materials (such as synthetic polymers) will be lacking the bacteria population required to degrade contaminants. Inoculation of support medium with either specific microbial strains dedicated to the removal of certain compounds, or a more general inocula (such as activated sludge from water treatment plants), may enhance the removal efficiency of biofilters. For example, the reported removal efficiencies for volatile organic sulphur (VOS) compounds such as dimethyl sulphide in typical biofilters has been cited as rather low and variable, and to improve removal efficiencies numerous aerobic microorganisms with degradative properties towards volatile organic sulphur compounds have been isolated.

A limited review of commercially available biofilter systems suggests that:

- Standard biofilter systems are best regarded as suitable for treating high volume and low odour emissions streams. Many suppliers offer a range of odour treatment technologies such as acid scrubbers and carbon filters in addition to biofilters, and are keen to design bespoke odour abatement systems for particular applications.
- Biofilters can be tailored to a wide variety of odour removal applications including wastewater treatment (targeting specific compounds such as hydrogen sulphide and reduced volatile organic sulphur compounds) and composting applications (for a broader spectrum of odour compounds).
- Biofilters performance claims tend to be based on tightly specified levels of input odour and specific odour compounds (such as ammonia, organic sulphides) in exhaust gases (odour up to 400,000 OU_E m^{-3} for a sea-shell based system; up to 100,000 OU_E m^{-3} for a peat system; odour compounds organic sulphides up to 15ppm for typical sea-shell based systems and peat).
- Many different types of biofilter material are available and these have very different claimed design lives, for example: wood-based up to 3-4 years, peat up to 10 years and pumice stone up to 25 years.

For a limited search of supplier's information, no claims of 100% odour or odour compound removal were found. Examples of high odour reduction for relative low odour emissions are often cited (for example, 90-98 per cent for input odour 5,000 – 100,000 OU_E m^{-3}). Biofilter

suppliers will often offer odour reduction guarantees subject to compliance with specified exhaust gas concentration ranges.

In the report by Silsoe Odours Ltd (with Recogen Ltd), based on a number of odour assessments commissioned for this report, the authors observed that in-vessel exhaust air temperatures of 60°C had been found and that high ammonia levels had also been recorded. The authors commented that once-through biofilters generate high odour loadings and high temperature air flows to the biofilters. This, combined with saturated air and ammonia, means that even high wood content biofilters have been seen to be composting in situ. In addition, irrigation systems on some biofilters, combined with the composting effect, have caused the structure to fail and the biofilters to collapse in parts, increasing localised waterlogging from the irrigation or rainfall.

Importantly, the data set provides some evidence that odour sampling techniques for open biofilters, involving taking spot samples from the biofilter surface, can produce variable results, presumably reflecting the lack of uniformity within the biofilter material and the presence of preferential air channelling. The authors also note that the data set does not contain odour values for multiple samples due to the high costs of doing this.

7.1.3   Biofilter optimum conditions and sensitivity

Although biofiltration can be quite a simple technology, its effectiveness relies on optimising several parameters that promote and maintain a healthy microbial community capable of degrading odorous compounds within the biofilm. A commonly used concept in the design of biofilters is EBRT and is defined as the empty bed filter volume divided by the air flow rate. Different pollutants have different characteristics that affect the absorbing and adsorbing times and degradation processes, and thus need different contact time with the biofilm to be completely degraded. EBRT is used as an indication of this contact time, though actual residence time in the biofilter will also depend on factors such as porosity and back-pressure. In theory, EBRTs need not be long for most odour compounds (less than 10 seconds) but biofilters are typically designed to have EBRTs in the range 15 to 60 seconds. Data from industry reports obtained for this report (for example, site N) suggests that some in-vessel sites may not have sufficiently long EBRTs to completely degrade odour compounds. In this example, additional biofilter capacity was advised in order to increase EBRT to 45 seconds. In the report by Silsoe Odours Ltd (with Recogen Ltd), based on a number of odour assessments commissioned for this report, the authors observed that there has been no common basis for designing and sizing the biofilters, although there was evidence that the Environment Agency's H4 guidance 45 second contact time is commonly

referred to. EBRT does not take into account the odour strength of gas flows and it is possible that higher EBRTs might be required for very high odour emissions, associated with some types of in-vessel systems.

Four of the most important parameters for optimising the microbial breakdown of pollutants in biofilters are temperature, media pH and alkalinity, moisture content, and nutrient availability. Microorganisms responsible for degrading odorous compounds within biofilms are strongly influenced by temperature. Aiming for a biofilter operating temperature of 35°C is likely to represent the best microbial compromise for the degradation of odorous compounds in a compost waste gas stream.

Biofiltration efficiency is strongly influenced by pH. To promote a healthy microbial population within a biofilm and subsequent effective odour treatment, the pH of packing material is often recommended to be neutral, at pH 6-8. However, compost emissions can contain many hundreds of compounds and to decompose these, biofilm microbial populations need to be equally diverse. It is likely that biofilter conditions will vary significantly throughout the matrix as will the nature of effective microbial populations found within micro-sites. It is common for some types of support medium to be naturally acid (peat, for example) with low buffering capacities, and decomposition of sulphur compounds and ammonia can create acidic conditions over time. Therefore, where appropriate, to fix and maintain support medium to neutral pH levels buffering materials (such as calcium carbonate and dolomite) can be added.

Sufficient water content is one of the most important parameters for an effective biofilter, because microorganisms responsible for the degradation of odorous compounds require water to perform their normal metabolic reactions. In addition, the appropriate moisture content is required for gas-water phase transition and movement of odorous molecules into the biofilm. Sub-optimal moisture levels can also lead to bed drying and the development of fissures that can cause channelling and a reduction in biofilter efficiency. In contrast, excess water promotes the development of anaerobic zones within the biofilter, leading to channelling of gas, increased back-pressure and the creation of odorous compounds. The suggested optimum moisture content is 30-60 per cent water, the optimum level of which is dependent on the support medium used. Microorganisms in the biofilm require mineral nutrients (nitrogen phosphorous, potassium, sulphur, calcium, magnesium, sodium and iron) for healthy growth and function. Organic support mediums have varying amounts of intrinsic nutrients, however progressive nutrient deficiency can reduce nutrient resources and limit biofilter performance. Nutrients can be added during the construction/filling stage as slow

release fertilisers that can replenish nutrients lost to leaching or biotransformation. An alternative approach would be to add commercial fertilisers to irrigation waters.

7.1.4   Effectiveness of odour removal

There is no compelling evidence that individual biofilter materials differ significantly in their ability to remove odour, and effective odour removal is more likely to depend on maintaining the optimum conditions appropriate to specific biofilter materials. The removal of odorous compounds within a biofilter starts with the transfer of contaminants from the air to the water phase, followed by adsorption to the medium or absorption into a water film, and finally biodegradation of contaminants within the biofilm. The overall effectiveness of a biofilter is largely determined by the properties and characteristics of the support medium, which include porosity, degree of compaction, water retention capacity, and the ability to host microbial populations. While highly soluble and low molecular weight VOCs and inorganic compounds such as ammonia are often effectively treated, low weight aliphatic hydrocarbons such as methane, pentane and some chlorinated compounds are difficult to biodegrade.

In terms of a compound's capacity to be transferred from the air to the water phase and then into the biofilm, an important concept is Henry's non-dimensional coefficient, which provides a measure of a compound's volatility in water. Substances with values over 0.01 are considered volatile, with higher values indicating decreasing solubility in water. While ammonia is highly soluble in water (with a value of 0.0005), other more complex organic and often odorous compounds such as dimethyl disulphide (0.03) styrene (0.01) and methanethiol (0.12) are considered to be more insoluble to various degrees and this characteristic contributes to the difficulty in removing them from exhaust gases.

In general, the generation and emission of high concentrations of ammonia in exhaust gas is associated with the composting of low C/N ratio wastes and high levels of aeration (high in-vessel aeration rates). In contrast, anaerobic conditions tend to favour the formation of odorous compounds from incomplete decomposition and volatile organic sulphur (VOS) compounds.

While ammonia removal in biofilters is usually considered to be high, for even highly effective biofilters it is likely that they will only decompose and remove a proportion of the total VOC content of emissions. For example, the European Commission (2006) quotes typical non-methane VOC removal efficiencies as 83 per cent but also provides evidence

that elimination of specific VOCs in actual waste treatment plants can be highly variable, with DMDS removal varying between 10 per cent and 89 per cent for three facilities.

Removal rates for ammonia are often reported to be high (>95 per cent) with ammonia being easily adsorbed onto the carrier material and being absorbed into the water fraction coupled with approximately 50 per cent being further nitrified. However, even relatively low concentrations of ammonia (45mg m^{-3}) are known to inhibit nitrification, and the removal of the odorant dimethyl sulphide (DMS) was found to be completely inhibited due to NH_3-toxicity at a waste gas concentration of 100mg NH_3 m^{-3}. In addition, osmotic effects have been reported to produce complete inhibition in nitrification and NH_3-removal at a measured NH_4NO_3 concentration in the compost material of 6–7g N kg^{-1}. Hence, even relatively low concentrations of ammonia (45-100mg NH_3 m^{-3}) may inhibit removal of odour compounds. Furthermore, biofilters may demonstrate very effective removal of ammonia until a maximum cumulative NH_3-removal load is exceeded and thereafter elimination capacities for both ammonia and VOCs may be significantly reduced. The installation of acid scrubbers should be considered if composting plants are generating and emitting even relatively low concentrations of ammonia on a consistent basis.

Although much emphasis is often placed on achieving rates of odour reduction from biofilters, it should be noted that even exceptionally high rates of odour removal (such as 98 per cent) can result in high levels of odour being emitted from biofilters if the input emissions from in-vessel composting are high (> 1 million OU_E m^{-3}). This suggests that in addition to odour removal rates, it is necessary to take account of absolute concentrations of odour if odour complaints are to be minimised. Data from industry reports obtained for this report (for example, site N) suggests that odour concentration of no greater than 3,000 OU_E m^{-3} is considered by odour consultants to be the benchmark for odour emissions. Achieving this threshold would be particularly challenging for those in-vessel composting processes producing very high odour exhaust gas.

Examples of odour sampling data supplied by Silsoe Odours Ltd (with Recogen Ltd) show that some in-vessel processes place huge and inappropriate demands on the biofilters in terms of odour concentration. For example, odour concentrations of exhaust gas inputs included values from three sites exceeding 8 million OU_E m^{-3}, 6 million OU_E m^{-3} and 2 million OU_E m^{-3}.

Despite very high odour levels, there was evidence that biofilters often performed exceptionally well. For example, input odour >8 million OU_E m^{-3}; output 1,630 OU_E m^{-3} with a removal efficiency >99.9 per cent. Other examples were input >6 million OU_E m^{-3}; output 6,330 OU_E m^{-3} with a removal efficiency >99.9 per cent, and input 2 million OU_E m^{-3}; output

162,000 OU_E m^{-3} with a removal efficiency of 93 per cent. Conversely, there are examples of moderate or poor odour reduction, for example 66 per cent, 89 per cent and <10 per cent for relatively low input odours. The reasons cited for low odour reduction included residual odours being given off by the biofilter, air channelling and poor irrigation.

7.1.5 Risks and operation

Provided biofilters are operating correctly, research suggests that start-up times can be relatively rapid. Immediate and high removal of ammonia has been reported since ammonia is very easily adsorbed and absorbed by new biofilter media. Start-up times of three to five days and high removal efficiencies have been reported for VOCs. One of the most common problems that can lead to odorous emissions from biofilters is a sudden change in operational conditions. This could be due to an equipment failure or a change in contaminant loading rates due to variations in feedstock. However, after starvation (shut down) periods (days), removal efficiencies can recover quickly, suggesting brief starvation periods are not critical for the efficient performance of biofilters. Other effects such as sudden inlet increases have been reported to reduce removal efficiency, and decreased residence time reduces elimination capacity.

Biomass accumulates in a biofilter when growth from the introduced organic carbon exceeds endogenous respiration. Excess accumulation may clog the filter bed and packaging material and produce large pressure drops and create air flow channels. Back pressures in a biofiltration system can cause excessive wear and tear on blowing equipment, and air channelling will reduce the contact time between odorous air and filter medium, therefore negatively affecting removal efficiencies. Control strategies to rectify or prevent blockages and biofilm clogging can be categorised into physical, chemical and biological methods. For physical methods, mechanical or hydraulic forces are used to remove biomass from medium beds and break up compacted materials. This may include periodically mixing the support media or backwashing with water at a high flow rate. The two chemical options include: controlling or limiting the carbon and nutrients in the incoming gas flow or liquid solution (starving the microorganisms), or washing with chemical solutions (such as NaOH and NaClO).

For reasons outlined in this report, routine monitoring of in-vessel exhaust gas characteristics (odour concentration and odour compound profile) and temperature would be recommended. In addition, monitoring of biofilter moisture content and back pressure and the characteristics of the output emissions would also be recommended.

7.1.6 Fieldwork and laboratory studies

To enhance understanding of the nature of in-vessel composting in practice and to determine the performance of actual biofilters and biofilter materials, a programme of fieldwork and laboratory studies was undertaken.

Operational composting characteristics were determined and biofilter input and output gases were measured for two in-vessel composting operations (site C and site P). Both sites composted source segregated household waste and both used the in-vessel systems as a means of sanitising the waste by achieving a pile temperature of 70 °C in compliance with Animal By-Products Regulations. In particular, odour concentration and the concentrations of selected odour compounds as well as bioaerosol profiles were measured. In addition, to determine the performance of three selected biofilter materials from commercial composting operations, laboratory measurements were taken (pre- and post-laboratory biofilter) of odour concentration, concentrations for selected odour compounds and bioaerosol profiles.

Fieldwork

The main site for the fieldwork was site C. Monitoring of in-vessel exhaust gas and biofilter outputs was undertaken on three occasions: a pilot study, measurements of the performance of the existing biofilter material, and then the replacement biofilter material. The existing material was composed of compost oversize and overlain by wood chips while the replacement material comprised coarse shredded wood mixed with some of the previous material to inoculate the new material with the necessary microorganisms.

The key findings relating to odour at site C were as follows.

The aeration rates for the in-vessel composting system during the two main studies at site C were estimated at 1.5 and 2.3m^3 tonne^{-1} h^{-1}. These aeration rates would be considered to be low compared with recommended aeration rates (6-24m^3 tonne^{-1} h^{-1}) for in-vessel composting systems, and piles operating under these low aeration-rate conditions would be likely to be oxygen-limited. On both occasions methane concentration in the in-vessel exhaust gas was close to 1,000ppmv, strongly indicating that piles were significantly anaerobic rather than aerobic.

The odour concentrations of the in-vessel exhaust gas entering the biofilter were 720,000 OU_E m^{-3} (existing biofilter material) and 573,000 OU_E m^{-3} (replacement biofilter material). These gas streams would be considered to be highly odorous.

Gas composition measurements indicated the presence of highly odorous reduced sulphur compounds but only trace amounts of ammonia, characteristic of largely anaerobic composting conditions. Gas composition measurements on this kind of mixed gas stream are challenging, best addressed using a variety of complementary techniques.

The odour concentrations of the biofilter emissions were 12,400 OU_E m^{-3} (existing biofilter material) and 1,720 OU_E m^{-3} (replacement biofilter material). The respective odour removal efficiencies were very high – 98.3 per cent and 99.7 per cent – demonstrating that both biofilter materials performed exceptionally well. However, odour from the existing biofilter material was still relatively high (12,400 OU_E m^{-3}) if a value of under 3,000 OU_E m^{-3} is considered to be the industry target value.

The presence of high methane levels may be important in relation to greenhouse gas balance.

Site P was selected as part of this odour monitoring study because it continued to experience odour complaints even after its biofilter material was replaced to improve effectiveness and eliminate complaints. Around four months after replacement of the biofilter material with virgin wood chips (pine), odour assessment showed that odour from the biofilter exceeded 43,000 OU_E m^{-3}, whereas a modelling exercise suggested that a maximum value of 3,800 OU_E m^{-3} was needed to prevent complaints. As part of an on-going programme by the operator to determine the reasons for the poor performance of the biofilter, the composition of selected input and output odour compounds in gas samples analysed for odour concentration was determined. The results showed that the input odour concentration was low (mean 9,500 OU_E m^{-3}) and that the biofilter only achieved approximately 26 per cent reduction in odour concentration. The analysis of odour compounds showed that the input gas contained almost zero ammonia and odour was dominated by anaerobic-related compounds such as methyl sulphides. Very little reduction in the concentrations of all of the selected compounds was observed (approximately 20per cent reduction in methyl sulphides; 60 per cent reduction in ethanol). The site P biofilter material was selected as one of three biofilter materials for further evaluation in the laboratory trials.

Further developments by the site operator, as advised by odour consultants, have involved improving the biofilter irrigation system, inoculating the virgin wood chip biofilter material with selected strains of microorganisms, and applying fertiliser to provide the necessary nutrients. The effectiveness of these measures will be evaluated later in 2012 but the operator has reported that since inoculation of the wood chips, a biofilm has begun to develop and biofilter

odour has reduced significantly. One observation from this case study is that new biofilter materials, devoid of the appropriate microorganisms to decompose odour compounds, will probably require some form of inoculation and nutrient addition.

7.1.7   Laboratory studies

Three biofilter materials sourced from site C (wood chips), site P (pine chips) and site G, an MBT/SSHW composting site (peat) were subjected to testing in a laboratory-scale test facility. The compost input gas stream used to test the biofilter materials was derived from composting a simulated SSHW mix in the laboratory. The input gas stream was characteristic of the emissions from a well-managed, aerobic, in-vessel composting facility and contained a moderate concentration of ammonia gas (400-500ppmv) as well as lower concentrations of other odorous compounds such as methyl sulphides, volatile fatty acids (VFAs), alcohols and terpenes. The odour range for the input air tested was from 98,000 to 130,000 OU_E m^{-3}. The biofilter materials were also tested using fresh air (1,040 OU_E m^{-3}) and low-odour air (4,790 OU_E m^{-3}).

Key findings from the laboratory studies include:

- All three biofilter materials achieved similar rates of odour removal for the compost gas stream: site C 94.3 per cent, site G 97.3 per cent and site P 94.2 per cent. This particular input gas included components characteristic of both aerobic and anaerobic composting. In terms of concentration, the gas mixture was dominated by the presence of ammonia, which contributed significantly to the input odour. However the odour appeared to be dominated by reduced sulphur compounds due to the low odour threshold of these compounds. Of the compound types measured, the contribution from methyl sulphides is estimated to be highest. All three biofilter materials were highly effective in removing ammonia from the gas stream: site C 99.4 per cent, site G 99.7 per cent and site P 99.5 per cent. High levels of ammonia removal found for this study reflect findings in the literature, which confirm that ammonia may be easily removed in biofilters through adsorption and absorption with a proportion of this being subsequently removed by nitrification. It is typical for new biofilters to have the capacity to remove very high concentrations of ammonia until the sorption limit of the material is reached, thereafter removal rates for ammonia decline rapidly. However, even moderate concentrations of ammonia are known to inhibit nitrification and the microbial decomposition of other odorous compounds.

- For the compost gas input, all three biofilter materials were much less effective at removing other odorous compounds compared with ammonia; for example, reductions of methyl sulphides were: site C 58 per cent, site G 57 per cent and site P 74 per cent.

- When all three biofilter materials were subjected to fresh air only, the resulting biofiltered air for each was found to have a higher odour concentration compared with the fresh air input. The odour concentration increased from 1,040 OU_E m^{-3} to a mean value of 2,480 OU_E m^{-3} in these tests. Analysis of odour compounds in the fresh and filtered air confirmed that stripping of some odour compounds from the biofilter materials had taken place. This reflects literature findings and suggests that biofilter materials on their own will emit a residual odour and this may be significant in the context of an industry target odour of 3,000 OU_E m^{-3}.

- For low odour air inputs (4,793 OU_E m^{-3}), the three materials achieved poor removal efficiencies: site C 13.8 per cent, site G 50.1 per cent and site P 31.4 per cent and the residual odour from the biofilter material probably contributed to this effect.

7.2   Bioaerosols

In the literature review several issues were identified of interest to this project. It should be noted that the grey literature reviewed as part of this study did not have any mention of bioaerosols at all. It is very clear that biofilters are marketed solely on their odour reduction potential. This necessarily means there is less information on biofilters and bioaerosols then there is for odour, which also carries through into the scientific literature where only some 12 papers were identified that had directly carried out work on the topic.

7.2.1   Principles behind bioaerosol removal

Bioaerosol generation

Microorganisms will grow on any material where there is sufficient supply of nutrients and water, their role being to aid the breakdown of organic materials; hence organic wastes, including kerbside collected green and food waste, will contain large amounts of microorganisms. In particular, household collections of food waste may be from enclosed containers that contain very wet material, which may have been stored outside for seven days or more.

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The literature review identified that bacteria might be the primary coloniser in such conditions, particularly when the waste material enters a thermophilic phase. Due to the nature of the storage conditions, which are generally enclosed containers which may have further wrapping of the material inside, it is also likely that material is delivered to facilities in at least a partially anaerobic state. As the material is wet and delivered into an enclosed vessel, these conditions are likely to prevail. Hence the majority of bioaerosols generated from such conditions are likely to be bacteria, gram-negative bacteria and as a result endotoxin – some from anaerobic gram-negatives. Fungi may grow but it is likely to do so either on the surface of the material in the vessel, or as the material dries and begins to mature. As a result, the concentrations of fungal bioaerosols released may be lower than bacteria, although not all studies have shown this outcome. This is a very different emission profile from open windrow composting where fungi such as *A. fumigatus* dominate.

In enclosed facilities, concentrations of bioaerosols have been known to exceed 10^{7-8}cfu m^{-3} (Schlegelmilch *et al.*, 2005). In the identified published papers for this research, load rates into various biofilters ranged from 10^3-10^6cfu m^{-3} bacteria, 10^2-10^4 gram-negative bacteria (where specified) and fungi from undetectable to 10^5cfu m^{-3}. Endotoxin load rates were between 11ng m^{-3} and 7-800 EU m^{-3}. These are significant concentrations and in excess of those linked to health effects (Defra, 2009) (it should be noted however, that the papers encompassed both animal and waste facilities).

Bioaerosol capture

Ottengraf & Konings (1991) theorised that there are two separate aspects to biofilters and bioaerosols: capture of microorganisms emitted by the biofilter, and subsequently emissions from the biofilters themselves. Although authors seem to agree the mechanism for filtering bioaerosols is due to inertial impaction of particles, and they are liberated by shear stress, there is disagreement over whether the velocity of air in a biofilter would be enough to force liberation of particles. As the mechanism for capture is largely physical, residence times do not appear as important as they might be for odour (Ottengraf & Konings, 1991; Zilli *et al.*, 2005).

Another important aspect is that Scharf *et al.* (2004) and Schlegelmilch *et al.* (2005) have mentioned that emissions from biofilters might be different from inputs, for example different species as well as concentrations. However, not all of the literature agrees on this aspect. Ho *et al.* (2008) reported very similar species at the inlet and outlet of a biofilter for instance. Hence the question of whether emissions are similar to inputs is not resolved. However there is a good body of material that demonstrates biofilters are potentially net emitters in their

own right, Wang *et al.* (2009) in particular addressing emissions from biofilter material, not inputs.

Removal efficiencies between inputs and outputs also varied between studies. As a general trend, bacteria had lower removal efficiencies in some of the studies than fungi (as low as 11 to 30 per cent in some studies, but 90 per cent or better in others). Fungi, where measured, appeared to have higher removal rates (from 49 per cent through to 100 per cent). Endotoxin had removal rates of 88-92 per cent in two studies, but very low rates of 11 to 52 per cent in another. General dust appears to have removal rates of 83 per cent or better in almost all of the studies, with scrubbers and biofilters together demonstrating some of the most efficient removal rates. However, there was a clear demonstration that many of the authors obtained results where emissions were higher at the exit of the biofilter than the inputs (Martens *et al.*, 2001; Seedorf & Hartung, 2002; Tymczyna *et al.*, 2011). Mechanisms as to why this was the case were not always clear, and varied from being interpreted as anomalous results, to being as the result of specific conditions or the biofilter material itself.

7.2.2 Types of biofilter and media

The literature review highlighted that materials with larger surface areas were thought more effective at removing bioaerosols than finer media, hence wood chip, pine chip and similar were thought better at removing bioaerosols than perhaps peat or other finer materials.

Additionally, some materials were seen as net emitters, such as peat, as described in the previous section. Most of the papers identified were either testing different commonly available materials, or specialised media that had been developed. Hence the various claims for the different materials are difficult to interpret (particularly when combined with the different bioaerosol sampling methodologies). Those that compared commonly available materials did not tend to show vast differences in efficiency of removal (Martens *et al.,* 2001). However, more specialised mixes did demonstrate larger differences (Tymczyna *et al.*, 2007, Tymczyna *et al.*, 2011).

7.2.3 Biofilter optimum condition and sensitivity

The literature evaluating bioaerosols and biofilters remains fairly sparse, and to date no paper has been identified that evaluates the condition of a biofilter in relation to its ability to remove bioaerosols and particulates (other than those materials with larger surface areas may be more effective). However, at this time, other than to ensure free air flow and prevention of excessive overgrowth of microorganisms on the biofilter (which Chmielowiec-

Korzeniowska *et al.* (2007) in particular mention can affect emissions from biofilters), there does not appear to be any information on whether parameters such as moisture, temperature, pH or similar affect removal of bioaerosols. As the mechanism for removal is physical impaction, it may be that the most important feature is to ensure the biofilter is not too wet, but there is not enough data to support this at present.

7.2.4   Risk of operation

There is little information on the issues that may directly affect biofilter performance for bioaerosols. However, clogging of a biofilter is well-known in terms of odour performance, and one paper does mention 'dust clogging' as a potential issue which could affect removal of bioaerosols (Lim *et al.,* 2012). If a biofilter becomes too wet or if pathways offer no resistance, then removal efficiencies may potentially be reduced.

7.2.5   Laboratory and field studies

Fieldwork

Impingers were found to be a reliable method by which to sample bioaerosols as they do not suffer problems with overloading or with high humidity. The sample could also be used both for viable culturing and non-viable analysis (endotoxin and glucan). A disadvantage is that size separation of particulates cannot be elucidated.

Load rates into two field biofilters were of the order of 10^4-10^5cfu m^{-3} for bacteria and gram-negative bacteria, 10^3-10^4 for *Aspergillus fumigatus*, extremely high endotoxin concentrations at site C (60,000EU m^{-3} plus) and relatively high at site P (3700EU m^{-3}) with significant amounts of glucan at site C (871ng m^{-3}). It should be noted 60,000EU m^{-3} is one of the highest measurements ever recorded for endotoxin, and out of proportion with 10^5cfu m^{-3} of viable gram-negative bacteria, which hints that large amounts of anaerobic bacteria may be present at site C which are potentially dying on aerosolisation.

Emissions to atmosphere in the field were still of the order of 10^4cfu m^{-3} for bacteria, 10^3cfu m^{-3} for gram-negative bacteria, undetectable to 10^2cfu m^{-3} for *A. fumigatus* and endotoxin were still averaging at 579EU m^{-3} on output at site C.

Both biofilters demonstrated very good removal efficiencies for TSP and PM$_{10}$ sized particulates. Pine chip was slightly less efficient at removing bacteria (69.6 per cent) compared to wood chip (89.9 per cent), and viable bacteria and gram-negative bacteria overall were removed less efficiently than fungi, particulates or endotoxin and glucan.

However, despite very good removal efficiencies in some instances, concentrations released to the atmosphere are still elevated above background, and are often in excess of both guideline (viable bioaerosols) and suggested standard concentrations (endotoxin).

The field study was not able to solve how to sample isokinetically from pipework on site, as the equipment is designed with an inlet efficiency requiring 12.5L min^{-1}, and the flow of air in the site pipework could not be altered to match this. Hence results at the inlet should be treated with caution. However, it is probable that concentrations have been slightly under-represented rather than over-represented and as a result it is not thought problematic as regards the interpretation of the data in the study.

Laboratory studies

Laboratory studies also indicated some interesting findings:

Impingers were a very good method of measuring bioaerosols within the laboratory where pipework flows could be matched to the impinger flow rates. Viable bioaerosols and endotoxin and glucan could be accurately determined from a single sample, with no apparent difficulties related to temperature or relative humidity.

Load rates from laboratory-manufactured material were generally lower than in the field (with the exception of input of gram-negatives into pine chip) but more of the same order for imported maturation pad material. Fungi could not be detected at all in either input or output pipework for either material, despite being found within the air of the composting drum. Concurrently, glucan concentrations were relatively low throughout despite being found in elevated concentrations in the drum.

Emissions from the biofilter material as measured in the lab were variable. Endotoxin was always higher on output for all materials from the laboratory-manufactured material, but a good removal rate was seen for peat and pine chip with imported material. Bacteria were being emitted at concentrations of the order of 10^3cfu m^{-3}. As before, fungi were not found and glucan remained low. Removal efficiencies were as a result rather mixed.

Passing fresh air through the biofilter materials illustrated that peat and wood chip were able to be net emitters of bacteria and gram-negative bacteria (although inputs of endotoxin and glucan were higher than expected).

It should be noted that one very large measurement of endotoxin was seen in relation to peat material. It was thought this related to previous use of the peat on site and released during this round of sampling.

Summary of outcomes from field and laboratory work

The field and study work supported the use of impingers, as used by Ottengraf and Konings (1991), Seedorf and Hartung (2002) and Schlegelmilch *et al.* (2005), as the most appropriate method for sampling at biofilters. The studies that used filters suffered with moisture and those using Andersen samplers were taking samples of very short duration (10 seconds to 1 minute) to prevent overloading. Andersen samplers are very sensitive to low environmental concentrations, and are perhaps not best suited for these types of environment. They may also pick up fungi and other material living on top of biofilter material when used near a biofilter surface. A standardised approach to how and where the impingers are used, and the media for plating out viable colonies would be of benefit at open biofilters such as those in the study.

Input concentrations and the loading of biofilters with bacteria and gram-negative bacteria in the field were similar to those previously reported in the literature (as seen in Table 15). For endotoxin, the large measurement at the input of site C was unexpected. It is noted that none of the papers reviewed concerning biofilters considered potential populations of anaerobic gram-negative bacteria. However, as clearly seen in the literature review in section 3.4 regarding material sent to such facilities, it is likely that material can be anaerobic on arrival and during treatment. This indicates that endotoxin may be emitted in large concentrations from sites if they are anaerobic, and the concentration measured in this study could be illustrating cell death, which occurs rapidly on aerosolisation. Interestingly, simultaneous odour measurements at site C also report anaerobic gases.

Site data also illustrated that despite good removal rates that agreed largely with the literature seen in Table 15 (with bacteria showing slightly lower removal efficiencies), the resultant emissions to air may still be over recommended exposure limits. Schlegelmilch *et al.* (2005) commented that biofilters were incapable of reducing bioaerosols to background concentrations. Schlegelmilch *et al.* (2005) also commented that biofilters in the field were not as efficient as laboratory models, but this was not particularly seen in this study. Both Zilli *et al.* (2005) and Ho, KL *et al.* (2008) recorded emissions of bacteria from biofilters at concentrations of 10^3-10^4cfu m^{-3}, which agrees with the study data.

Of particular interest was the fact that fungi were lower than bacteria on site, and could not be detected in the pipework in the laboratory. This has been seen in other studies: Ottengraf and Konings (1991) reported concentrations of moulds from source material were negligible, and Martens *et al.* (2001) mention that fungi were low in comparison to bacteria.

Concentrations of glucan were also generally low, indicating this was not just a factor related to viability, but that the fungi are not growing in the same concentrations as the bacteria.

It has been proposed that capture and emission may well be two different processes, as discussed by Ottengraf and Konings (1991). The data collected in this study could not discern whether species were different at input and output as described by Schlegelmilch *et al.* (2005) or similar as put forward by Ho, KL *et al.* (2008). The laboratory study illustrated that biofilters could be net emitters, particularly of bacteria, gram-negative bacteria and endotoxin, a proposal also suggested by Martens *et al.* (2001). But it was clear from inputs of fresh air that bioaerosols could be generated from the material itself, particularly peat.

This study did not show vastly different removal efficiencies for different sized particulates (TSP and PM_{10}). However, the data is limited. The drawback of the impinger is that size differentiation cannot be discerned for the bioaerosols. Sanchez-Monedero *et al.* (2003) report better removal rates for larger particles, and Lim *et al.* (2012) observed better removal rates for TSP rather than PM_{10} (90 per cent compared to 62 per cent, approximately). This paper also observed very low $PM_{2.5}$ concentrations generated in these conditions, potentially due to the high moisture content of the outputs.

This study has not collected enough data to determine whether operating parameters of biofilters would affect bioaerosol removal rates, and more data would be needed to determine this. No particular biofilter was much better than other material across the entire study. The literature is also mixed on this point and tends to focus on material types rather than actual optimal operational conditions. The mechanism of capture of bioaerosols in biofilters is thought to be physical, and although there are varied discussions on air flows and shear forces and whether these could be causing their liberation (Ottengraf & Konings, 1991; Chung *et al.*, 2004; Zilli *et al.*, 2005), papers disagree as to whether this would in fact occur. Other suggestions are that large particle material was more efficient than smaller (Schlegelmilch *et al.*, 2005), and that some materials, particularly peat and compost based biofilters, could emit more than was inputted (Martens *et al.*, 2001). However, there are no overall conclusions that can be drawn at this stage.

Finally, there is the question of whether odour and bioaerosol removal can be efficient and concurrent. Martens *et al.* (2001) clearly state that there is no clear positive or negative relationship between simultaneous bioaerosol and odour removal, although a slight relationship was seen that the best filters for removing odour were the poorest at removing bacteria. Indeed, Chung (2007) put forward that biofilter bioaerosol emissions were related to the populations of bacteria within the biofilters rather than input gases, and given that

healthy populations of certain microorganisms are related to effective odour removal, there is the possibility that an inverse relationship could occur. The only other paper that commented on this was Zhao *et al.* (2011) who state that 'biological biofilters' have the best removal efficiencies for odour, but that acid scrubbers were better for bioaerosols. This study does not contain enough data to draw any definitive conclusions in this regard.

7.3   Main conclusions

7.3.1   Odour

Evidence obtained for this project suggests that many UK in-vessel composting processes may be operating in an oxygen-limited mode in order to create suitable conditions for rapid sanitisation of waste as required by Animal By-products Regulations. Monitoring of one typical in-vessel composting process provided direct evidence of very low aeration rates and very high methane concentrations being emitted in exhaust gases, indicating highly anaerobic pile conditions.

Aeration rate during in-vessel composting of source segregated household waste will largely determine the characteristics of exhaust gas emissions and the nature of the abatement technology that is required to treat them. For example, while aerobic conditions during composting are associated with exhaust gas emission of ammonia and fungi, anaerobic conditions will tend to favour the generation and emission of highly odorous reduced compounds and anaerobic bacteria.

This report contains strong evidence of very high odour concentrations being associated with in-vessel exhaust emissions. For example, fieldwork monitoring obtained a range of high odour concentrations in exhaust gases from one site (maximum value >2 million OU_E m^{-3}) and odour concentrations have been reported from other sources of > 6 and 8 million OU_E m^{-3}.

Even though biofilters are considered appropriate for the treatment of low odour/high volume gas flows, industry data is presented in this report showing that exceptionally high odour removal rates have been reported for very high strength composting emissions (for example, input >8 million OU_E m^{-3}; output 1,630 OU_E m^{-3}; removal efficiency >99 per cent). Conversely, examples are reported of moderate or poor odour reduction such as 66 per cent, 89 per cent and <10 per cent for relatively low input odours. The reasons cited for low odour reduction included residual odours being given off by the biofilter, air channelling and poor irrigation.

Literature findings suggest that, typically, ammonia derived from aerobic conditions, would be easier to remove in biofilters (mainly by adsorption/absorption mechanisms) compared with volatile organic compounds (VOCs) such as methyl sulphides. However, low/moderate concentrations of ammonia (45ppmv and 100ppmv) have been reported to inhibit microbial decomposition in biofilters and the use of acid scrubbers to remove ammonia prior to biofiltration should be considered. Laboratory findings confirm that for mixed exhaust emissions, biofilters appear to be better able to remove high concentrations of ammonia (>99 per cent) compared with methyl sulphides.

There is some evidence from fieldwork and laboratory experiments that, based on the selected range of odour compounds measured, methyl sulphides tended to be associated with higher odour biofilter emissions. In order to confirm this conclusion, further research should be undertaken.

Monitoring of an in-vessel composting biofilter demonstrated that for high exhaust gas odour levels (in this case > 700,000 OU_E m^{-3}), even very good odour removal rates (>98 per cent) may be insufficient to fully reduce emitted odour (>12,000 OU_E m^{-3}) to acceptable levels. Supporting material in this report suggests that industry has adopted an odour concentration of approximately 3,000 OU_E m^{-3} as the threshold for acceptable odour from biofilters. Open University research confirmed that odour compounds can be stripped from biofilter materials, indicating that biofilters can emit residual odour. Meeting the industry odour threshold level on a consistent basis will be very challenging for many composting facilities, especially if exhaust gas odour concentrations are very high and dominated by compounds derived from anoxic conditions. Additionally, despite good removal rates for bioaerosols, emissions are still higher in many cases than guideline concentrations from open windrow sites.

Achieving and maintaining low odour exhaust emissions and effective biofilter odour reduction will require composting systems and biofilters to be operated optimally on a consistent basis. It is recommended that sites maintain good levels of aerobicity during the composting process and that in-vessel exhaust gas characteristics (odour concentration and odour compound profile) and temperature are regularly monitored. In addition, monitoring of biofilter moisture content, back pressure and the characteristics of the output emissions would also be recommended.

It should be noted that prevailing anaerobic conditions during the composting process will lead to poor rates of waste decomposition being achieved and will also tend to promote high levels of odour emission during outdoor compost maturation. This study has also shown it may lead to release of endotoxin from gram-negative anaerobic bacteria. To maximise

effective in-vessel decomposition and minimise odour during maturation, it is recommended that a minimum level of stability for partially composted in-vessel material is introduced, or alternatively a specified level of biodegradability loss that must be achieved prior to maturation in open air.

A number of information gaps were identified during this project. It is recommended that further research be undertaken into a number of key topics, detailed below.

To better understand the in-vessel composting sector and to confirm findings from this report, conduct an initial survey of UK IVC sites and a 12-month programme of field monitoring involving four selected sites.

A number of technical issues require further research to enhance the effectiveness of odour removal in biofilters and to improve protocols for measuring odour. This work should include undertaking a number of experimental studies such as determining the effect of aeration rates on in-vessel exhaust emissions, quantifying ammonia inhibition effects, exploring the benefits of inoculating selected biofilter media with appropriate microorganisms, determining the effect of exhaust gas temperature on biofilter performance, and exploring how best to remove low residual odour from biofilters with particular emphasis on exploring the benefits of increasing Empty Bed Residence Time. It is recommended that the evaluation of current odour sampling techniques is carried out and a set of standard monitoring protocols developed.

7.3.2   Bioaerosols

The literature review identified that bioaerosols within in-vessel facilities are likely to be primarily bacteria and gram-negative bacteria, potentially with a substantial proportion being anaerobic. It also identified that there are two aspects to consider when discussing biofilters and bioaerosols – emission from the material to the biofilter, and subsequently emission from the biofilter. Although many research papers identified good 'removal efficiencies' for bioaerosols via biofilters, there is some disagreement over whether the emissions are in fact the same as the species emitted to the biofilter. What they do agree on, however, is that biofilters remove bioaerosols via inertial impaction, a physical mechanism, and could potentially be liberated by shear forces on the material within the biofilter. The air flows this might occur at were not known, however. Interestingly, materials with larger surface areas are thought to remove bioaerosols more efficiently. Additionally, in the studies identified it is not unusual to see higher concentrations at the outlet than the inlet of a biofilter, and various

explanations were put forward, such as biofilters materials being net emitters, anomalous results, air flow, growth within biofilters, and so on.

In the field studies, both biofilters were seen to remove large concentrations of particulates, bioaerosols and their constituents seen at the inlet concentrations. However, despite very good removal efficiencies (in some instances of 80-90 per cent), concentrations released to atmosphere are still elevated above background, and are often in excess of both guideline (viable bioaerosols) and suggested standard concentrations (endotoxin). In particular, bacteria and gram-negative bacteria exit the biofilters in relatively high concentrations compared to background. It was also noted that, at one site, endotoxin concentrations were much higher than viable bacteria and gram-negative bacteria would indicate, and it is possible uncultured anaerobic species contributed. This aspect of the emission profile requires further study.

In laboratory work, tentative conclusions are that peat and wood chip were seen to be net emitters for bacteria and gram-negative bacteria in these tests. Endotoxin and glucan concentrations are also of note, despite the elevated inputs there are some noticeable rises in output, particularly for peat and wood chip. Also of note, fungi were not detected in either the inputs or outputs of any of the samples in the laboratory. A separate sample of mature compost known to contain fungi also demonstrated that fungi were not found in the pipework.

This study has not collected enough data to determine whether the operating parameters of biofilters would affect bioaerosol removal rates, and more data would be needed to determine this. No particular biofilter was much better than other material across the entire study. The literature is also mixed on this point and tends to focus on material types rather than actual optimal operational conditions.

Finally, there is the question of whether odour and bioaerosol removal can be efficient and concurrent. Given that healthy populations of certain microorganisms are related to effective odour removal there is the possibility that an inverse relationship could occur. More data would be needed to investigate this further.

8 Knowledge gaps and future research

8.1 Summary recommendations

The recommendations are to:

- build on the standardisation of methodology for monitoring both odour and bioaerosols;

- carry out further fieldwork on the effects of externalities such as inputs, temperature and biofilter conditions on emissions;

- carry out further laboratory work to determine the relationships between conditions within an IVC, emissions and biofilter performance;

- further elucidate the relationship between odour and bioaerosol emissions from biofilters to determine the extent to which biofilters may be used to effectively reduce both odour and bioaerosols, and to identify best practice techniques for optimising biofilters to maximise control of both odour and bioaerosols emissions.

8.2 Odour gaps and new research

8.2.1 Introduction and key findings from the scoping study

There appears to be very little detailed information available on the nature of the UK in-vessel composting sector and how extensive odour problems might be from IVC biofilters, or indeed what odour types and odour concentrations might be causing problems. There is therefore a pressing need for more background information to help the Environment Agency identify the specific nature and extent of the problems that are associated with odour from biofilters, from the UK IVC sector. Equally, it is not clear at present what level of absolute odour (in odour units OU_E m^{-3}) or odour reduction (percentage) that biofilters operating in the IVC sector might be expected to deliver on a consistent basis. A number of information and technical gaps have been identified in this report along with details of how these gaps may

be resolved. It is recommended that longer term monitoring of selected UK plants is undertaken to determine current operational characteristics and problems. It is also recommended that more detailed laboratory studies are carried out in parallel to help understand the nature of some key fundamental biofilter mechanisms and to assist with optimising biofilter operation.

Findings from the scoping study clearly showed that biofilters are very unlikely to eliminate 100 per cent of odours and suppliers of biofilters and biofilter media typically cite odour reduction values of up to 95 to 98 per cent. These levels of odour reduction may be considered to be acceptable when treating composting exhaust gases with relatively low levels of odour. However, when treating very high odour composting exhaust gases (for example 500,000 OU_E m^{-3}), biofilters achieving excellent odour reduction results such as 98 per cent can still emit gases to atmosphere with moderate levels of odour (approximately 10,000 OU_E m^{-3}) and this level of odour has the potential to give rise to complaints. Hence, odour problems and complaints may be associated with both serious biofilter failures and biofilters that are performing exceptionally well but not sufficiently well in the particular circumstances. Odour problems associated with biofilters can arise from a number of on-site factors and finding odour solutions requires an understanding of the complete waste composting system and an appreciation of the nature of the offending odours.

Findings from the scoping study suggest that exhaust gases from some IVC tunnels may have odour levels which are much greater than might be expected and this in turn may impact on the ability of the biofilter systems to treat these emissions. Very high odour exhaust gases may be derived from IVC facilities that run plants with very low air flow rates to achieve high pile temperatures and rapid ABPR waste sanitisation, at the expense of achieving good levels of decomposition/stabilisation. This can have the effect of promoting profound and prevailing anaerobic conditions within the composting piles, which can result in exhaust gas emissions containing a range of recalcitrant odour compounds (such as reduced sulphur compounds) at relatively high concentrations and being characterised by very high levels of odour (>>1 million OU_E m^{-3}). Reported untreated IVC exhaust gas odour concentrations found during the scoping study were very variable, but some concentrations were excessively high (6 million OU_E m^{-3}). In contrast, recommended odour limits for treatment in commercial biofilter units can be as low as 100,000 OU_E m^{-3}. Consequently, biofilter odour loading rates may often be much higher than previously known for IVC systems and these very high levels of odour may significantly impact on the effectiveness of biofilter operation.

The range of odour levels associated with untreated composting exhaust gas emissions being managed by the IVC composting sector is unknown. The extent of the problem of excessively high odour composting exhaust gas emissions being treated by biofilters within the composting industry is also unknown. Also unknown is the level of odour from biofilters that the IVC sector deems to be acceptable, and there is a lack of detailed information relating to the levels of odour currently emitted from biofilters which are likely to give rise to complaints. The composting industry appears to use the level of 3,000 OU_E m^{-3} as a target level for biofilter odour emissions. However, it is not clear from where this figure has been derived from, and given that the scoping study showed that biofilter materials themselves can produce odours of around 2,000 OU_E m^{-3}, it is not known whether biofilters can consistently produce very low odour emissions of around 3,000 OU_E m^{-3} in practice.

Findings from the scoping study fieldwork suggest that it is possible for biofilters to achieve very high odour removal rates (>99 per cent) and very low odour outputs (<2,000 OU_E m^{-3}) even for input emissions characterised by high odour concentrations (>500,000 OU_E m^{-3}). This result was associated with new, conditioned wood chip biofilter material and an empty bed residence time (EBRT) that would appear to be higher than typical used in the industry. In contrast, other scoping study evidence suggests that replacing existing biofilter material with high quality wood chip biofilter material, which was not pre-inoculated with microorganisms, did not appear to lead to reduced odour levels (site P) when compared with the replaced material.

Scoping study findings suggest that IVC composting processes may be characterised as either predominantly aerobic in nature or predominantly anaerobic in nature, largely dependent on the rate of air flow through the system. In very general terms, highly aerobic systems are associated with high emissions of ammonia while anaerobic systems have a tendency to emit lower volume but relatively high concentrations of highly odorous compounds such as reduced sulphur compounds (such as dimethyl disulphide). In practice most IVC systems will exhibit an initial anaerobic phase due to fresh waste having a very high oxygen demand at the start of composting, which is difficult to satisfy. A laboratory-based biofilter experiment, which formed a part of the scoping study, using a well aerated IVC system and high ammonia exhaust gas, reflected published findings in the sense that the laboratory biofilters achieved ammonia removal values exceeding 99 per cent, while removal of dimethyl disulphide was typically only moderate at best (maximum removal 77 per cent). This confirms that ammonia is more easily removed by well-maintained biofilters than many of the more odorous compounds that are derived from highly anaerobic conditions.

However, there are two main problems with treating/removing high ammonia emissions in composting exhaust gases. Firstly, it is accepted that new biofilter material will readily absorb and adsorb high concentrations of ammonia into the biofilter material and will nitrify a significant proportion of the nitrogen in the biofilm, but these effects will happen only up to a maximum threshold. After this time, the biofilter will tend to fail to remove ammonia effectively as adsorption sites get saturated and osmotic effects preclude further nitrification. Secondly, even moderate concentrations of free ammonia have been found to significantly inhibit microbial oxidation of dimethyl disulphide. The extent of the problem of excessive ammonia emissions from UK IVC sites is not known, but anecdotal evidence suggests that dealing with ammonia emissions is a major issue for some ABPR compliant sites during spring and summer months. Ammonia may be effectively scrubbed from exhaust gases prior to biofilter treatment, but this is expensive and more information is needed about actual concentrations of ammonia generated by sites and the maximum ammonia loads that different biofilter materials can tolerate without prejudicing performance.

The scoping study identified exhaust gas temperature as being a critical parameter relating to biofilter performance. Optimum biofilter operating temperature is widely accepted to be approximately 35°C whereas exhaust gas temperatures up to 60°C have been reported. High temperatures will reduce odour compound solubility and absorption onto the biofilm and will also inhibit mesophilic microbial activity. The prevalence of high exhaust gas temperatures in the UK IVC sector is unknown and the effect of high temperatures on biofilter performance – in practice – is also unknown. In addition to requiring actual data on biofilter operating temperatures and performance, practical information is also required on the effectiveness of different methods of cooling exhaust gases prior to biofilter treatment.

8.2.2 Knowledge gap and study suggestion one

There appears to be very little detailed information available on the nature of the in-vessel composting sector, the extent of odour problems from IVC biofilters, or what odour-types and odour-concentrations might be causing problems.

It is proposed that any laboratory-based biofilter research programme is preceded or complemented by an initial survey of UK IVC sites and a 12-month programme of field monitoring involving four selected sites. The AfOR draft 2010 survey estimates there to be approximately 90 IVC sites in the UK, with about half of these sites undertaking related outdoor composting activities (compost maturation).

The aims of the survey would be:

- to develop a profile of the IVC sector (the AfOR 2010 survey contains minimal details);

- to enhance understanding of IVC composting processes and the nature of current odour problems;

- to determine the extent to which findings from the scoping study are reflected in the UK IVC sector;

- to identify four suitable and representative IVC sites at which to undertake longer term monitoring for 12 months to address the types of questions posed below.

The initial survey and 12-month monitoring of selected sites should, as a minimum, address the following questions:

- What types of IVC systems are currently operating in England and what their key operating and site characteristics are (for example waste types and preparation, air flow rates, exhaust gas temperatures).

- What types of biofilter systems are in operation and their key characteristics.

- Whether sites assess odour, what range of odour levels plants typically produce, and what target odour emission levels is the industry aims to achieve.

- The AfOR 2010 unpublished survey indicates that around half of the IVC sites also undertake outdoor maturation and many others will be associated with green waste composting. For such sites, to what extent is it possible to attribute odour complaints to particular composting activities or technologies such as biofilters.

- Whether particular types of IVC facilities or process management regimes are more prone to odour complaints arising from biofilters.

- How key IVC process parameters vary from plant to plant (for example, air flow rate) and what effect these have on biofilter odour profiles and loading rates.

- What levels of odour typically give rise to complaints.

- Whether it is possible to identify particular groups of compounds or individual compounds that typically cause problems (for example specific compounds such as ammonia or reduced sulphur compounds).

- Whether the source of odours causing complaints can be identified (such as ammonia).

- Whether composting exhaust gas and biofilter odour profiles and concentrations vary significantly throughout the year.

- Are complaints more common at certain times of the year (e.g. spring/summer) and are these associated with particular compounds (e.g. ammonia).

- Whether complementary technologies are employed (such as acid and caustic scrubbers).

- What polishing techniques are employed (such as impregnated carbon filters) to eliminate low odour emissions.

- What 'best practice' odour reduction guidelines can be identified.

- What 'best practice' biofilter management techniques are carried out.

- How biofilter odour sampling techniques vary in terms of collecting representative odour samples and producing accurate odour results.

8.2.3   Knowledge gap and study suggestion two

The accuracy of different biofilter odour sampling techniques is unknown and the development of a standard odour sampling protocol for biofilters is recommended.

The typical way of measuring odour from biofilters is to first collect 'grab' samples of gases in gas-bags emitting from either the surface of the biofilter or from a stack if this is part of the air handling system. The collected gases are then subjected to dynamic olfactometry (BS.EN13725:2003) to determine the odour strength, and results are expressed as odour concentrations (OU_E m^{-3}). While the olfactometry measurement is undertaken strictly in accordance with British Standard BSEN13725:2003, there are no standard protocols for collecting representative samples of gas from diffuse sources such as biofilter surface.

There are a variety of sampling techniques in operation including:

- Flux hoods such as the Lindvall hood, which use a turbulent flow of odour-free air to mimic real-world air flow, though designs and operating conditions are highly variable. The flow rate and length of flow path of introduced air are likely to be key variables.

- Forms of static chamber including plastic sheets on the surface of the biofilter. In these systems specific gas concentrations will change over time due to diffusion across the biofilter surface. If the chamber is imperfectly sealed at the biofilter surface this may also behave like a through-flow system to some degree.

- Through-flow sampling hoods directing flow from a known surface area to a defined outflow point. British Standard BSEN13725:2003 recommends the entire surface should be covered if possible, though multiple small sampling points may be used. Ideally the normal flow through the biofilter should not be disturbed, though this is difficult to ensure.

It is not known how repeatable or reproducible each technique is or how results from individual techniques compare with each other in terms of collecting representative samples. However, it is clear that there is no set of agreed protocols for sampling emissions from biofilters, or from before and after biofilters have been used if biofilter odour reduction capability is being measured.

Moreover, it is not known what effect individual gas collection and sampling techniques have on the accuracy and precision of the final odour concentration results. It should be noted that even the results from olfactometry measurement, which is carried out strictly according to BSEN13725:2003, have a relatively large possible error term. For example, for a typical set of three sample replicates at a mean value of 1000 OU_E m^{-3}, the 95 per cent confidence interval is 633 to 1580 OU_E m^{-3}. This is a relatively large error range and reflects the use of human subjects as the monitoring sensors. However, in contrast to the high known error for BSEN13725:2003 odour measurements, the error related to the range of gas collection and sampling techniques is currently unknown. To enable odour concentration and odour loading results to be used with confidence for regulatory and other purposes, it is essential to develop a set of consistent sampling protocols for different applications similar to the Protocol for monitoring bioaerosols (AfOR, 2009).

At present, site odour problems are typically evaluated using the methods outlined above, and odour concentration results as determined by BSEN13725:2003 are treated with much respect and value, despite the large associated error term. However, there is no doubt that the overall error associated with the entire odour sampling and measurement process is much greater than for the odour measurement alone and this has important implications for the regulation of odour emissions. It is proposed that individual sampling techniques are evaluated and benchmarked as a priority. It is also proposed that a set of standardised protocols for sampling odour from various biofilter applications are developed. It is proposed

that odour sampling techniques are evaluated and a set of standard protocols are developed during the 12-month study of selected composting facilities as outlined in study suggestion one, above.

8.2.4   Knowledge gaps and study suggestion three

There are a number of specific technical information gaps and issues that should be addressed. It is proposed that the following laboratory-based studies are undertaken:

- A study of the relationship between the air flow rates used for composting and the creation of anaerobic versus aerobic conditions within composting piles, and the subsequent emission of recalcitrant exhaust gases with particular characteristics in the form of odour compound profiles and odour concentrations. The hypothesis being tested would be that operating the composting process more aerobically (compared with anaerobically) will produce exhaust gases containing fewer, less concentrated and less odorous compounds which would therefore reduce gas odour concentration and render the exhaust gases more amenable to biofilter treatment.

- An exploration of the importance of seeding/inoculating a range of new biofilter materials with appropriate microorganisms capable of degrading odour compounds from anaerobic and aerobic composting processes. The research would also focus on identifying the most effective and cost-effective means of obtaining and inoculating the microorganisms. Such means may range from inoculating with selected, targeted microorganisms to inoculation of microorganisms using a mixed culture derived from aerobic sludge treatment. The hypothesis being tested would be that seeding new biofilter materials with appropriate microorganisms would result in enhanced biological degradation of compounds particularly for those highly odorous compounds which are derived from anaerobic pile conditions such as reduced sulphur compounds (for example, dimethyl disulphide).

- A study of the relationship between empty bed residence time (EBRT) and odour reduction for a range of biofilter materials and odour concentrations with the aim of exploring the possibility of increasing EBRT (in other words, biofilter capacity) as a simple means of reducing output odour levels, especially for particularly odorous gases arising from anaerobic conditions. The hypothesis being tested would be that increasing the EBRT, for example by increasing the capacity/size of the biofilter, would reduce the odour concentration of gases emitted. This research could be extended to include exploring the effect of additional or enhanced specification

biofilters specifically to treat relatively low level emissions from well-performing biofilters (<10,000 OU_E m^{-3}) which are difficult to treat and which are known to give rise to complaints.

- An investigation of the effect of a range of ammonia concentrations and loads on the capability of selected biofilter media to remove ammonia and selected odorous compounds. There would be two main components to this study. Firstly, the research would subject a minimum of three types of biofilter material to a range of ammonia concentrations to determine for each material the threshold ammonia concentration at which removal of selected compounds such as dimethyl disulphide is inhibited, and the maximum degree to which removal rates are reduced. Secondly, the study would subject similar biofilter materials to a range of ammonia loads to determine the ammonia threshold loads at which biofilter failure (that is, significantly reduced ammonia removal) occurs. The research would involve a significant amount of physicochemical characterisation of biofilter material throughout the study.

- A study of the effect of exhaust gas temperature and biofilter operating temperature on the capability of a range of biofilter materials to remove selected odour compounds. Optimum biofilter operating temperature is widely accepted to be approximately 35°C and this research will evaluate the effect of temperature on removal performance within the range 30°C to 60°C. This research would be complemented by further work on practical gas cooling techniques carried out as part of the 12-month IVC site monitoring study.

8.3   Bioaerosol gaps and new research

8.3.1   Introduction and key finding from the scoping study

This study took a 'first look' at bioaerosols and biofilters, and found that there were very few papers on the subject produced within the UK or internationally. The papers that were identified concentrate on percentage reduction of bioaerosols that have passed through a biofilter with different specified filtration materials, but very often there are many parameters not specified in the papers, for example the characteristics of the generating medium (compost) are not well defined; residence times, velocities of gas passing through the biofilters, particulate sizes and so on are not detailed. There are also difficulties with comparing studies as there are many different measurement techniques for gathering the particulates, and for subsequent analysis of the bioaerosol components. Typically, analysis included viable bacteria, fungi (especially *A. fumigatus*), and gram-negative bacteria.

Another common measurement was endotoxin (however, glucan has not been previously measured). Sampling equipment is an important variable to consider, and varied from Andersen samplers on the surface of the biofilter to SAS type samplers. Hence in conjunction with what was being measured, the sampling methodologies themselves may actually represent varying efficiencies in collecting different particle sizes, and maintaining viability and hence interpretation of published results should be undertaken with caution. These types of issues are not unique to biofilters and are probably akin to the situation with bioaerosols from green waste sites two or three years ago, and where now there is a standardised protocol.

As regards the biofilter materials themselves, most studies appear to be designed to demonstrate effectiveness of various new media. A small number of studies considered biofilters as emitters of bioaerosols. There is no doubt that biofilter materials provide a good medium for microorganism growth in situ (they are warm, moist, dark and mostly aerated). However little evidence was seen regarding testing of biofilter beds as emitters. Hence the emission of microorganisms independent of initial load is another area identified as an evidence gap.

The literature review did also identify that biofilter manufacturers do not focus on bioaerosol reduction. Biofilters are designed and manufactured to reduce odour, but custom and practice indicate that it is inherently assumed that biofilters are also containing particulate emissions (although reduction efficiencies are not quoted in the same way as for odour). The theoretical basis of whether a biofilter is an effective way to reduce bioaerosols, either by a 'film' or as a physical trap for all particle sizes, has been initiated, but not fully explored.

The review also highlighted that the inter-relationship between ideal odour removal conditions and ideal bioaerosol removal conditions is not clear. Indeed, it is possible that the two may conflict.

Initial findings from the scoping study on sites found that elevated concentrations of bioaerosols were being inputted into the biofilters (some $10^4/10^5$ cfu m^{-3}) and large concentrations of endotoxin (60000 EU m^{-3}+ in one instance, which is an extremely high measurement, more than you might expect from the measured cfu m^{-3}). Limited reduction was seen in viable bacteria, but endotoxin was significantly reduced as were glucan (and fungi). Why is not clear, as bacteria could be expected perhaps to be in a similar size range to particles containing endotoxin. It should also be noted that emission concentrations from the biofilter for bacteria and gram-negative bacteria are in excess of current guidelines for composting sites. However, we do not know the dispersal characteristics of this emission

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and whether it would behave in a similar or different way to green waste composting emissions (perhaps the particles are all finer, for instance).

The laboratory studies demonstrated that passing background air through biofilter material did generate bacteria, gram-negative bacteria and to some extent endotoxin and glucan, illustrating that biofilters can be net emitters. Indeed, the peat substrate in particular showed high concentrations of bacteria and endotoxin on outputs that were higher than inputs of compost air. Also of note was that fungi could not be found airborne from the compost substrate, neither in nor out of the biofilter. When mature compost was imported to check this, *A. fumigatus* was measured airborne in the active compost drum. However, again it could not be found at input or output. It is notable that fungi were also either very low or not found in outputs from the field studies. This suggests that the conditions in the pipework (wet and moist) might be as important in retaining larger particles such as spores as the biofilter itself.

8.3.2 Knowledge gap and study suggestion: Biofilters and emissions

- As per odours, it would be useful to know the size and extent of biofilter use in the industry, and whether the sites have stated they expect their biofilters to also contain bioaerosol emissions. Individual sites may have smaller studies or grey literature that supports this assertion.

- There is still a lack of basic information about the behaviour of materials during the IVC process and whether they are anaerobic, aerobic or both. This could be an important factor when determining bioaerosol emissions. Laboratory studies developed from the scoping study approach to investigate this would further this knowledge.

- Building on the point above, there is also the possibility of a changing population within the biofilter depending on the time of year and material inputs (which are seasonal), and whether the process is aerobic or anaerobic. It is of note that in the scoping study fieldwork, very high endotoxin concentrations were seen entering the biofilter at one of the sites, but viable bacteria and gram-negative bacteria were of the order of 10^5cfu m^{-3}. Usually the relationship between these variables is more apparent. The hypothesis is that a substantial population of anaerobic bacteria are also being emitted and are dying rapidly once aerosolised. Hence work to test whether this is in fact the case may point to an emission that has yet to be measured

in any meaningful way and may have consequences for health associated with dispersal (endotoxins from anaerobic gram-negative bacteria have been reported upon in medical papers, particularly in relation to infection). This is new for IVCs as it might not be expected that the same predominant anaerobic conditions would prevail in open windrows.

- It would be particularly interesting to track bioaerosol concentrations alongside odour measurements to determine whether higher odour emissions are associated with higher bioaerosol releases. Hence alongside the proposed programme of odour monitoring, simultaneous bioaerosol monitoring could be undertaken, building from the experience of the pilot study.

- Any 'best practice' for bioaerosol emissions as per odour can also be investigated.

8.3.3 Knowledge gap and study suggestions: Methodology

- The laboratory study has generated a good outline methodology for testing biofilter materials using a liquid impinger that is not subject to overloading and is not affected by the damp atmosphere in surrounding pipework. It was also possible to utilise the resulting samples to simultaneously measure viable microoganisms (bacteria, fungi and gram-negative bacteria), endotoxin and glucan. However, the study is limited in that the air passing through the biofilter material has to match the fixed flow rate of the impinger, so the study is driven by this factor rather than what might be termed 'real world' flow rates. Some of the results were also surprising – for instance high input concentrations, or in the case of peat, much higher output concentrations than was originally measured inwards. This could have been due to retention of bioaerosols in the peat from previous use. To determine if this is repeatable, these measurements need further duplication, in particular 'fresh' and 'used' biofilter material should be compared. This will also help elucidate whether biofilter material is a net emitter in a virgin state.

- In the field there is no standardised approach for assessing bioaerosol release from biofilters. The method employed – covering the entire filter and sampling from a 'chimney' – needs further refinement. The atmosphere below the cover is warm and damp and may be trapping some particulates that would normally become airborne. Similarly, equipment for measuring bioaerosols in pipework on site that has the ability to match the flow of the material within the inputting pipework to the biofilter needs further development.

- This study also used the AfOR protocol media for viable counts, which may be useful to review.

8.3.4 Knowledge gap and study suggestion: External parameters

- A parallel set of measurements to the odour study are suggested to determine effects of temperature on bioaerosol concentrations, both inputted and outputted from the biofilter. Further work is also required on particle size (of emissions and of the biofilter material), residence times in biofilters and effects on emissions. Currently there simply is not enough research to comment in detail on operating parameters that may impact on the efficiency of a biofilter to remove bioaerosols, and there are likely to be several important variables. For instance, characterising the conditions of a biofilter and emissions thereof could be incorporated into a longer field study.

9 Appendices

9.1   Appendix A – Site N case study

Industry-supplied odour literature

Summary

This section presents the executive summary of an odour assessment report on an in-vessel composting site with on-going odour complaints. An odour consultant reported the exhaust odour threshold concentrations to be in the range of 49,490 to 65,246 OU_E m^{-3}. Given that the site had a 28m stack, the consultant estimated that the exhaust odour limit on the upgraded odour control system would need to be no greater than 2,000 to 3,000 OU_E m^{-3} in order to ensure no odour complaints.

To achieve this, a number of improvements were suggested, including:

- refurbishing and cleaning the acid scrubbers;
- installing back-pressure and temperature sensors;
- increasing biofilter moisture content from the 22-31 per cent basis recorded;
- upgrading the water irrigation system and incorporating the capacity to supply essential nutrients
- restricting input gas temperature to no more than $39^{o}C$.

Increasing the biofilter volume by 52 per cent by increasing the bed height using light expanded clay aggregates (LECA) biofilter material was recommended in the first instance, with two further biofilter cells to be installed at a later date to further increase volume and provide an EBRT of 45 seconds.

As a result of improvements, odour monitoring over four months recorded only two odour readings over 2,000 OU_E m^{-3}.

Site N report

Executive summary

An odour consultant was commissioned by site N to perform an odour control system investigation of the operating composting facility. Following a preparatory briefing and study of documentation, the odour investigation survey was performed on 17 and 18 May 2011. This is part of on-going investigative work performed by the facility management on odours

generated at the facility. Numerous odour threshold concentration assessments and a technical review of the functionality of the existing odour control system were performed.

This overall technical odour audit report provides information on the performance of the odour control and management systems in operation at site N. Standardised monitoring techniques for odour, total organic carbon (TOC) and flow distribution were utilised throughout the study.

This document presents the results of the survey performed including discussion and conclusions and provides general information on a two-stage approach (stage one – short term, within one to three months, and stage two – long term, within three to six months) to increase odour treatment performance at the operating facility.

A number of key observations and conclusions were made as a result of the study. In brief, they are outlined as follows:

Odour control plant and equipment

- The current stage 1 acid scrubbing towers on odour control system (OCS) 1 and 2 require cleaning. The packing from each stage 1 tower should be removed and all residual solids should be removed from the packing. It is evident that increased back pressure on the stage 1 scrubber could lead to plugged flow and ineffective scrubbing of inlet odorous air. The measured back pressure on the OCS 1 stage 1 acid scrubber was 1,814Pa. (Pascals). The liquid distribution weir on all scrubbing towers should be checked and verified as delivering equal liquid distribution to each packed tower. A full service analysis should be performed during the proposed stage one improvements of the odour management systems at the facility.

- Currently, each scrubber liquid containing sump is operated in batch mode, whereby the recirculation liquid is emptied approximately every two weeks to four weeks. Based on an assessment of the inlet odour loadings, performance and liquid analysis results, it is recommended that these sumps be emptied at least once per week depending on accepted feedstock, and as frequently as twice per week especially in the warmer summer months (for example when air temperatures greater than 287K). This will make wet scrubbing of odorous compounds in the air stream more effective and essentially buffer out any cyclic loads that may be experienced by the biofiltration system. Allowing contaminants to build up within the scrubbing system sumps will lead to ineffective odorous gas removal, which will result in higher loads being experienced by the biofilter. This improvement should be implemented immediately.

- Adequate facilities should be put in place to allow for closed loop emptying of each scrubber sump. The current procedure for emptying liquid for each sump is inadequate and leads to the release of odours to the atmosphere. This will be performed as part of the stage one improvements of the odour management systems at the facility.

- Investigation of the airflow rate distribution throughout biofilter cells 1 to 4 suggests that there is a significant variance in the airflow rate distribution throughout each biofilter cell. Airflow rate standard deviations of between 32.06 per cent and 53.84 per cent were recorded. This suggests that airflow surface and volumetric loading is highly variable, which will lead to inefficient treatment of odour through the biofilter packing media.

- The measured back pressure on the inlet to the biofiltration system was between 836 and 845Pa. This would appear to be high for such a media given its overall depth. Typical backpressures would be in the region of 300 to 400Pa. This suggests media blinding and blocking. This in itself could lead to variance in the airflow rate distribution and channelling. Static pressure sensors should be fitted on each stage of the odour control system. In the short term during stage one improvements, manual magnehelic manometers could be installed and the values on each one recorded manually each day when performing the operational checks on the odour control system. In addition, inlet temperature sensors should be fitted on the inlet to the biofiltration system. Biofilters are sensitive to cyclic temperature shock and temperature levels of no greater than 312K should be allowed into the biofilter. This should be recorded and appended to the odour management system. The overall weekly trend should be observed and monitored so as to alert the operator of operational and process issues. As part of the stage one improvements, the existing biofiltration system media will be removed and cleaned to lower backpressure and reduce plugged flow. The air distribution system within the biofilter will be cleaned. Static pressure and temperature sensors will be installed.

- The airflow rate distribution survey suggests short-circuiting of air along the outer walls of each biofilter cell. During the stage one improvements of the existing biofiltration system, this can be engineered out with the addition of blanking plates along the inner walls of the biofilter. In addition, it would appear that air from OCS stream 1 and stream 2 enters separate biofilter bed cells. A provision should be put in place to allow for blending of both airstreams before entering the biofilter. This will

also assist with the buffering of inlet load as a result of the pasteurisation vessel emptying. This will be performed as part of the stage one improvements.

- The current sprinkling system installed over the existing biofiltration system requires upgrading. This system will need to allow for the addition of essential nutrients and minerals as part of the sprinkling liquor. The application rate should be automatically controlled and timed so as to ensure adequate moisture addition to each biofilter cell. As part of the study, it was noted that the upper layer of wood chip that was applied to the biofilter bed some time ago is rotten and covered with an excessive quantity of biofilm and polysaccharides. This gives the impression that the biofilter bed is adequately wet. This is not the case. Samples taken through digging deep (approx. 1m) into the bed to the LECA layer revealed dry media with significant quantities of solids attached. Moisture contents in the range of 22 to 31 per cent w/w basis were recorded. The ideal moisture content range would be 45 to 50 per cent w/w basis. During the stage one improvements, the existing biofilter bed will be removed and cleaned, with the top wood chip layer on the current system discarded and not replaced. In order to confirm its removal, investigation trial pits will be dug out to determine whether this is required. In addition, adequate sump collection will be put in place and the reengineered sprinkling system will allow for 10 per cent leachate from the biofilter to be reapplied to the surface of the bed (taking adequate precautions not to allow this leachate to become septic). The maximum droplet size of the sprinkling liquor should be no greater than 1mm diameter and provide equal loading coverage across the bed. Sufficient capacity will be incorporated into the engineering of the sprinkling and leachate collection system to take account of the proposed stage two biofilter system improvements.

- The current odour treatment capacity of the odour control system is approximately 100,000Am3/hr of odorous air. Based on the current building volume and minimum standards for ventilating such buildings, the required ventilation capacity will need to be increased up to a level of approximately 129,940Am3/hr (stage two biofilter system improvements). This provides two air-changes (AC) per hour in the intake/composting hall and three AC per hour for the maturation/pasteurisation hall. The existing scrubbers will provide treatment capacity for a maximum volume flow of 120,000Am3/hr (theoretical capacity, this will be confirmed during the stage one improvements) and since the fans are on variable speed drives, there is the possibility of increasing these to this level of treatment. The remaining 9,940Am3/hr can be blended with the exhaust air from the scrubbers on the inlet to the biofiltration

system. The existing effective biofilter bed volume is 984m^3 (excluding wood chip). During stage one improvements of the odour control system, the biofilter effective bed volume will be increased to 1,498m^3, thereby providing an effective true retention time of 38 seconds for a treatment volume of 100,000Am3/hr. This stage one improvement provides a total effective bed volume increase of 52 per cent over existing bed media volume which will lead to marked improvement in the exhaust odour threshold concentration for the existing system. This is achieved through increasing the effective bed height (from 2.3m to 3.5m), which is achievable using LECA media (since it has excellent structural integrity and porosity). These engineering works are relatively straightforward and can be completed during the stage one improvement. For stage two improvements, it is proposed that the air treatment volume should be increased from 100,000Am3/hr to 129,940Am3/hr and the biofilter increased in size from 1,498m^3 to an effective bed volume of 2,338m^3. This would provide a residence time of 45 seconds for this treatment volume. This can be achieved by providing two additional biofilter bed cells of approximate dimensions 6m W by 20 m L by 3.5 m H.

- Ventilation extraction grills should be adequately cleaned bi-monthly. All extraction grills positioned over dust generation activities such as shredding and screening should be closed up and/or moved to an area where dust loads are minimised. Locating grills over such dusty activities leads to the entrainment of dust loads into the extraction and odour control system, leading to blockage and failure. Extraction ductwork and extraction grills should be positioned within the building so as to ensure odorous gases are collected from low odour load areas to high odour load areas (for example, control the airflow rate profile across the building by inducing airflow profile from the front of the building towards the back of the building). Face velocities across grills should be designed to be less than 3 to 4m/s while duct velocities should be greater than 12m/s so as to prevent build-up of dust within the ductwork. This will be implemented as part of the stage one improvements.

- Site N has installed a 28m stack to aid with the dispersion of odours from the odour control system. Following a review of this report and the results of same, the exhaust odour limit on the upgrade odour control system will need to be no greater than 2,000 to 3,000 OU$_E$ m^{-3} in order to ensure no odour complaints as a result of odour emission from the exhaust stack. The current exhaust odour threshold concentrations are in the range of 49,490 to 65,246 OU$_E$ m^{-3}. During stage one improvements, the wet scrubbers will be refurbished and the existing biofiltration system effective height

will be increased from 2.3m to 3.5m. This will provide a 52 per cent increase in biofilter media volume over existing conditions. During the stage two improvements, two new additional biofilter cells would increase the biofilter media volume by an additional 840m^3. Following the stage one improvements, the odour control systems should achieve exhaust odour threshold concentrations of 2,000 to 3,000 OU$_E$ m^{-3} for a treatment volume of 100,000Am3/hr, while following the stage two upgrade the odour control system should achieve an exhaust odour threshold concentration of 2,000 to 3,000 OU$_E$ m^{-3} for a treatment volume of 129,940Am3/hr.

- Continuous monitoring of TOC was performed on the maturation / pasteurisation extraction ductwork in order to assess the impact of pasteurisation vessel emptying on the odour control system. During no emptying, the average TOC and temperature value recorded were 102.40mgC/Nm3 and 302K. Following opening of the pasteuriser and emptying of the pasteurisation vessel, the TOC value increased by 3.44 times to a value of 352mgC/Nm3. The temperature increased to a value of 313K. The values returned to near starting levels in approximately one hour with TOC and temperature values of 124.80mgC/Nm3 and 307K. This activity occurs approximately six times per day. Adequate buffering of this cyclic load can be achieved through the refurbished scrubbing system and pre-blending the inlet air to the biofiltration system. This will ensure a more consistent load on the inlet to the biofiltration system, which will minimise odour spike events. This will be considered as part of the stage one improvements that will be performed in the short term.

Building and containment system

- All areas within the composting plant, including all bunded areas, would benefit from adequate floor sloping and drains to prevent the pooling of leachate and waste water. Leachate pooling over prolonged periods of time can lead to significant odour release and contaminated surfaces will lead to the release of odours. In addition, all leachate holding tanks should be placed under slight negative pressure and all odorous air collected from these tanks directed to the odour control system for treatment. This will be considered as part of the stage one improvements that will be performed in the short term.

- The truck wash down area should be bunded so as to limit the area of contamination of the floor surface within the maturation/pasteurisation building. This should be designed so as to prevent the contamination of large areas of the building floor. This
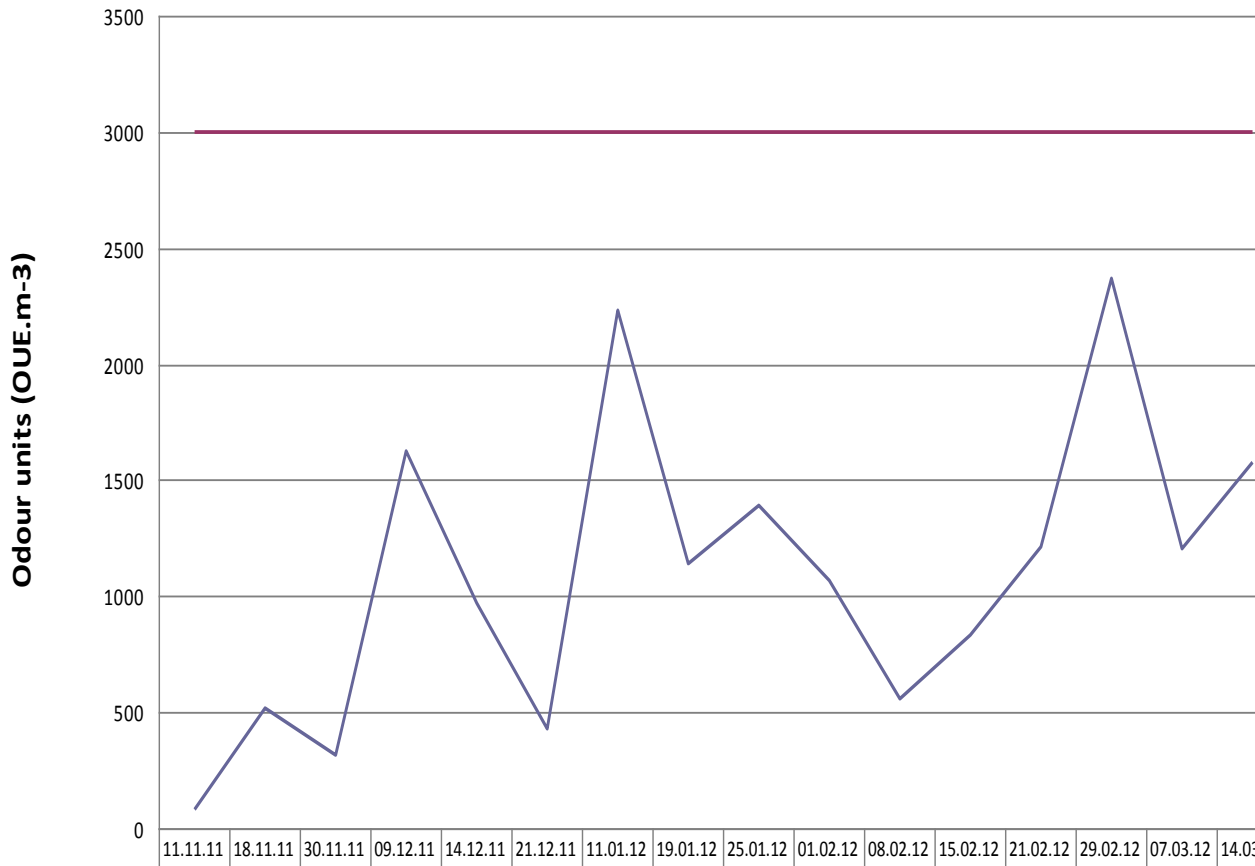
will be considered as part of the stage one improvements that will be performed in the short term.

- All large access doors on the facility building must be interlocked so as to prevent the opening of two or more doors at once. This will prevent wind tunnel effects on the building and the fugitive release of odours. Adequate sealing and flashing should be provided on all doorways. Pedestrian doors should not be left opened. This will be considered as part of the stage one improvements that will be performed in the short term.

- Examination of the effective negative pressure on the building suggests fugitive release of odours from the building may be occurring. Low negative and positive pressures were recorded on the downwind side of the building when wind speeds were at low breeze. Higher wind speeds will lead to greater fugitive release of odours from the facility buildings. This issue can be overcome through improved integrity sealing of the building using appropriate expanding foam application and improved extraction from the overall facility. This will minimise fugitive odour release and reduce the potential of odour detection in the downwind field. This will be considered as part of the stage one improvements that will be performed in the short term.

- An alternative extraction arrangement is recommended for the airlocks on the building. The existing arrangement is not optimal as the fitted fan is inducing high negative pressure within the airlock (-ive 31 to –ive 42Pa) and when the inner airlock door is opened, odorous air from the composting hall is being dragged into the airlock (negative pressure within composting hall is –ive 7 to –ive 11Pa). This will be considered as part of the stage one improvements that will be performed in the short term.

- Currently, there are fresh air intake grills positioned on the building. These allow makeup fresh air into the building which is removed by the odour control system. These grills should be fitted with mechanical actuated self-closing dampers which are controlled on the basis of building absolute static pressure. By providing a static absolute pressure limit of negative 15 to 20Pa on the building, the self-closing damper/lourve will close and open automatically so as to control the applied negative pressure on the building. This ensures that there is adequate negative pressure placed upon the building and that the fugitive release of odours from the building envelope is minimised. This will be considered as part of the stage one improvements that will be performed in the short term.

Management and procedures

- The odour management plan should be updated to include the following:

  o An odour control system process parameters verification procedure, including limit ranges which are to be audited by the operator on a weekly basis (for example static pressures on internal ductwork and process equipment, liquid distribution in the scrubbing systems and biofilter bed, bed moisture content and application, pH set points, oxidation reduction potential (ORP or Redox) set points, probe calibration procedures, and so on).

  o A waste acceptance procedure on methods of how to handle particularly odorous loads received at the facility.

  o A spillage and leachate management procedure and check sheet for the operating facility.

  o A spares check sheet to ensure adequate replacement parts and chemicals supplies are in stock at the facility.

  o A sump emptying protocol for dictating the frequency of scrubber sump emptying and dosing regime.

  o Vehicle acceptance and clean down procedures.

  o Door management procedures.

  o Building integrity testing procedures and frequency of the same.

  o On-site and off-site odour sniff and measurement procedures for auditing facility performance.

Chimney dispersion - odour bag analysis results compared to the target threshold

	11.11.11	18.11.11	30.11.11	09.12.11	14.12.11	21.12.11	11.01.12	19.01.12	25.01.12	01.02.12	08.02.12	15.02.12	21.02.12	29.02.12	07.03.12	14.03
Odour Units (OUE.m-3)	84	517	318	1628	967	432	2227	1139	1390	1068	557	835	1209	2372	1206	15
Target Threshold (OUE.m-3)	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	300

Site N odour bag analysis results.

9.2   Appendix B – Silsoe Odours Ltd case studies

SILSOE ODOURS Ltd

Building 42 WrestPark, Silsoe,
Bedfordshire, MK45 HP.

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REPORT
to
Open University

CASE STUDY DATA FROM BIOFILTERS
USED WITH IN-VESSEL COMPOSTING

3 July 2012

Produced by:-

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With thanks to RECOGEN Ltd

CASE STUDY DATA FOR BIOFILTERS USED WITH IN-VESSEL COMPOSTING

The following data was determined for samples collected from biofilters, generally of a mixed shredded wood type media, being used in conjunction with in-vessel composting facilities.

Considerations
The key reasons for acquiring the data were to determine the odour emission rate and also determine biofilter odour treatment performance. Due to the variables involved, it is necessary to exercise a degree of caution in the interpretation of the data, because the biofilter airflows in some instances were not uniform, the age and quality of the media was not determinable and the processes supplying air to the biofilters were not standardised. Furthermore, due to the cost limitations in taking samples, the data does not include multiple replicates.

Summary conclusions
The data shows that some processes place huge and inappropriate demands on the biofilters in terms of odour concentration and temperature. Though not given in the data presented, there was evidence in the extreme cases, that ammonia levels were high.

The data also shows that there has been no common basis for designing and sizing the biofilters, although there was evidence that the Environment Agency's H4 guidance 45 second contact time is commonly referred to.

Once-through biofilters generate high odour loadings and high temperature airflow to the biofilters. Air temperature of 60°C has been found. This, combined with saturated air and ammonia, means that even high wood content biofilters have been seen to be composting in situ.

Irrigation systems on some biofilters, combined with the composting effect, has caused the structure to fail and the biofilters to collapse in parts, increasing localised water logging from the irrigation or rainfall.

General recommendations
Based on the foregoing, we believe that biofilters must be more carefully designed in accordance with the required duty, and reference must be made to the air input quality.

The specification of media must include due consideration to structure, pore size, particle size, surface area, resilience, structural strength, resistance to degradation, as well as cost and availability.

Chipped or chunked wood that is screened and sized accordingly still has merit, and bark may be used in the upper layers where compression is not so great. However, peat and compost based biofilters are liable to slump, compact and degrade.

The new generation of LECA media systems have many useful characteristics, but care will be needed in regard to developing biomass and the maintenance of a wet environment on the LECA surfaces.

Biofilters are liable to the short-circuiting of airflow and should be sized accordingly, with greater attention to the floor area to depth aspect ratio. Depth is important to provide back pressure to give rise to uniform vertical airflow.
Biofilter plenums are also poorly designed and air short-circuiting has been noted where perforated pipe and wood oversize is used without properly formed void spaces.

The use of 'soakaway crates' to form the plenum has merit; it is durable, of open structure and is robust to take the vertical weight.

Harvested rainwater is ideal for irrigation, grey water may be useable but any form of effluent should be avoided else the biofilter itself becomes a source of odour.

Case studies

Case study #1 (2004) Rotary drum composter facility

Compost feedstocks inclusive of full cat 3 ABP waste food and food factory waste, including blood, meat and feathers.

Air off the process is directed through both acidic and alkaline wet scrubber tower systems prior to the biofilter.

Biofilter construction was with base of sleepers raised on blocks to form plenum, sidewalls of clay earth banks, or concrete panels. Inlet duct comprised 1.2m dia concrete underground pipe.
Biofilter media was mainly of wood chunks and shredded natural wood, with admixture of cockle shells.

Biofilter size and airflow as follows:

The biofilter measured 20m by 18m. The area was 360m^2.
Total airflow to the biofilter was 24.74 cu.m/sec.
The mean airspeed through the biofilter was calculated as 0.68722m/sec.
The depth of the biofilter (minus plenum) was 2.2m.
The air contact time (empty bed volume basis) through the biofilter was calculated as 32 seconds.

Raw exhaust gas quality prior to gas clean-up system

	Sampled 11:36	Sample 11:45	Sample 12:22	Mean
Inlet	551,948	379,429	429,425	**453,600**

Case study #1 Biofilter sampling results sampling 19 January

The following tables show the odour concentration results of the sampling surrounding the biofilter.

Sampling January 19th

Sample no.	Time taken	Position	RESULTS OU$_E$ m^{-3}
101	11:08	Off biofilter	653
102	10:55	Plenum	54,948
103	11:51	Plenum	84,161
104	12:00	Off biofilter	1,389
105	13:20	Off biofilter	669
106	13:10	Plenum	34,264

Case study #1 Biofilter sampling results sampling 2 February

Sampling 2 February

Sample no.	Time taken	Position	RESULTS OU$_E$ m^{-3}	Hedonic 'characterisation' of the odour as determined by members of the SRI odour panel.
201	9.48	Biofilter South	368	
202	10.13	Biofilter mid	446	
203	10.31	Biofilter North	336	Earthy x 6, Compost x6
204	10.41	Plenum	41,343	
205	11.00	Upwind	566	
206	11.25	Biofilter south	252	
207	11.32	Biofilter mid	368	
208	11.45	Biofilter North	229	Earthy x 5, Compost x 5, Sugary x 1
209	12.25	Biofilter mid	240	
210	12.45	Receptor gate/l'scape	793	
211	13.00	Yard	229	
212	13.20	Biofilter mid	199	Earthy x 5, Compost x 5, Rotten Cabbage x2, Chicken x 1, Sewage x 1

The GEOMEAN of the odour sampling for biofilter exhaust to air, taken over the two days equates to 392 OU/cu.m

Case Study #1 CONCLUSIONS - PROCESS EXHAUST DATA

The odour concentration GEOMEAN was 392 OU$_E$/cu.m.
The total airflow to the biofilter was; 24.74 cu.m/sec.
The biofilter area was 360m^2.
The odour emission rate was therefore 9698.08 OU$_E$ /sec

The specific odour emission rate (per unit area) was 26.939 OU$_E$ /sq.m. sec.

The odours off the biofilter were predominently characterised as earthy and compost.

Comment;
Due to financial issues, this facility is no longer in use and despite initial issues with odours, ultimately the process exhaust clean up system was improved and perfected, and as can be seen, the biofilter worked very well. One key was a change in the alkali scrubber so that hypochlorite was discontinued, because the downstream effect can 'kill' off the biofilter media microorganisms.

Case study #2 (2004) Rotary drum composter facility

Compost feedstocks inclusive of full cat 3 ABP waste food and food factory waste, but the majority being co-collected food and green waste from households.

Air off the process is directed through both acidic and alkaline wet scrubber tower systems prior to the biofilter.

Biofilter construction within a building comprised two tiers of biofilter media, with the air path leading from the plenum of the first, through the media and then to the plenum of the second.

The exhaust from the second tier biofilter led to an exhaust stack.

The composting processes generate exhaust gas, which is discharged to atmosphere through a very sophisticated gas clean-up system.

The two primary process exhausts each pass through ammonia scrubbers, comprising scrubber towers with recirculated acidified water scrubbing. The two exhausts from these are ducted to a transition duct and delivered to alkali scrubber towers for the removal of sulphides and other odorous gases.

Both secondary scrubbers then deliver the exhaust air to a transition duct and ultimately to two tiered horizontal biofilter beds comprising wood chip, bark and cockle shell mixture biofilter media. The scrubbed and filtered air off the biofilter discharges to atmosphere via an 8m tall, fan assisted exhaust stack.

The biofilters each measured approx 12m by 18m.
Total airflow to the biofilters was; ~20 cu.m/sec.
The depth of each biofilter (minus plenum) was 2.2m. Total volume 950 cu.m.
The air contact time (empty bed volume basis) through the biofilter was calculated as 47 seconds.

Results obtained from the various sampling points and at the sampling period duration were as shown in table below. The final exhaust (to atmosphere) concentrations are acceptable.

Case study #2 Summary of results for odour concentrations

Sample number	Source	Time taken	Sampling position	RESULTS $OU_E\,m^{-3}$	
1	Top exhaust	13:55	Pre top ex fan	**27,593**	Ideally should be less than this, however, shows marked (3X) reduction compared to plenum.
2	Lower exhaust	14:00	Pre lower ex fan	**13,617**	As above, working on reduced plenum with 2X reduction.
3	Top plenum	14:10	Plenum door	**87,772**	
4	Lower Plenum	14:30	Plenum door	**29,246**	Is either working on weaker input or scrubbers are more effective.
5	Ambient DW	18:00	SW corner of yard	**614**	With benefit of dispersion the odour levels at downwind end of site are now acceptable.
6	Process Hall	18:30	Adjacent fan intake	**29396**	Shows the variation in odour generated through the day, is much reduced when activity is less at end of day.

The biofilter media was fresh and may have accounted for the variable and unpredictable results.
These crude data serve to remind us that there are many variables. In this instance it was suspected that the upstream parts of the scrubbers were fouling the air being delivered to the biofilters; these were being overloaded, and being fresh did not have the capacity to perform.

Case study #3
(2008) Bunker type composter facility/bunker type biofilter

This facility is characterised as an 'open' topped composting bunker with downward vertical suction aeration to an under-floor system of extraction duct laterals, leading to the main extraction fan and exhausting to a biofilter.

The system operates with either 1, 2 or 3 bunkers of compost leading to the same extraction fan, each bunker having an electrical valve in its ductwork and the valves sequenced so that the bunkers operate under suction ventilation on a regime of, for example, 5 minutes on and 10 minutes off.

In some instances there are other bunkers with a similar fan system, supplying the same biofilter.
There was some evidence that the sequencing was not totally synchronised and on occasions, the air supplied to the biofilter would be doubled, and the biofilter overloaded.

Biofilter media comprised over-sized woody waste from screened composted green waste.

Biofilter 1: 12m x 8m x 2.4m = 230cu.m. Airflow to 1 was 1.8 cu.m/sec RT of 127 secs.
Biofilter 2: 20m x 6m x 3.0m = 360cu.m. Airflow to 2 was 1.5 cu.m/sec RT of 240 secs.
Biofilter 3: 40m x 4m x 2.5m = 400cu.m. Airflow to 3 was 3.17 cu.m/sec RT of 126 secs.

NOTE: The air quality into the biofilters was measured on a separate occasion as in the range 2,283,610 to 1,177,660 **OU_E m^{-3}, so assume approximately 2,000,000 OU_E m³.**

Case study #3 Results

Sample number	Source	Time taken	Process	Sampling position	Odour concentration, OU_E m^{-3}	Odour removal efficiency, %
2	Bio-Filter 1	10:34 - 10:42	Sanitisation	Top of filter bed	26,298	99.3
3	Bio-Filter 1	11:00 - 11:08	Sanitisation	Top of filter bed	8,079	
5	Bio-Filter 2	12:45 - 12:55	Maturation	Top of filter bed	6,868	99.6
6	Bio-Filter 2	13:05 - 13:14	Maturation	Top of filter bed	6,454	
8	Bio-Filter 3	14:00 - 14:10	Maturation	Top of filter bed	13,706	98.5
9	Bio-Filter 3	14:12 - 14:22	Maturation	Top of filter bed	68,735*	

* some short-circuiting suspected in biofilter media

Perhaps a key to the high odour removal efficiency in this case is the long residence times, between 2 and 4 minutes.

Case study #4
(2009) Bunker type composter facility/bunker type biofilter

This facility is characterised as an 'open' topped composting bunker with downward vertical suction aeration to an under-floor system of extraction duct laterals, leading to the main extraction fan and exhausting to a biofilter.

The system operates with either 1, 2 or 3 bunkers of compost leading to the same extraction fan, each bunker having an electrical valve in its ductwork and the valves sequenced so that the bunkers operate under suction ventilation on a regime of, for example, 5 minutes on and 10 minutes off.

In some instances there are other bunkers with a similar fan system, supplying the same biofilter.
There was some evidence that the sequencing was not totally synchronised and on occasions, the air supplied to the biofilter would be doubled, and the biofilter overloaded.

Biofilter media comprised over-sized woody waste from screened composted green waste

A session of odour and gas sampling was initiated. This was undertaken on two occasions, 10 September 2009 when the odour sampling and system checks were undertaken, and 23 September 2009 when various gas and system checks were undertaken (see section 4).

Odour sampling (10 September 2009)

Odour samples were collected from eight points within the site and one point upwind. Table 4 describes the rationale and details of the sampling points. Samples were evaluated remotely for odour concentration and the Silsoe odour panel were also asked for a description of the odour.

Case study #4 Odour sampling points 10 September 2009

Ref.	Biofilter/location	Odour sample location/time	Purpose
S1	Air Off Biofilter B	When the fans from Vessels 3 and 4 were operating.	To determine air quality from off the biofilter.
S2	Air Into Biofilter B	Air from Vessel 8.	To determine the quality of air from the **primary process.**
S3	Air Into Biofilter B	Air from Vessel 4.	To determine the quality of air from the **primary process.**
S4	Air Off Biofilter B	When the fan from Vessel 8 was operating.	To determine air quality from off the biofilter, but when a different vessel was being ventilated.
S5	Air Off Biofilter D	When the system was aerating Bay W3.	To determine air quality from off the maturation biofilter.
S6	Air Into Biofilter D	When the fan from Bay W3 was operating.	To determine the quality of air from the **maturation process.**
S7	Shredder	Near to the shredder discharge point.	To determine the extent of the odour from this source.
S8	Upwind	Extreme north of site.	To gain information regarding the background within this locality.
S9	Effluent Compound	Low down within the surface	To investigate if the water

		water storage compound.	storage compound was a significant source.

Case study #4 Odour sampling results of the odour concentrations and odour descriptions.

Ref.	Biofilter/location	Odour concentration, 10.3 OUE/m³	Description of smell
S1	Air Off Biofilter B (3+4)	623,700	Compost, organic, plastic bin
S2	Air Into Biofilter B (8)	2,283,610	Rubbish bin on a hot day, rotting bleach, rotting organic material
S3	Air Into Biofilter B (3+4)	1,177,660	Disinfectant, medical/hospital
S4	Air Off Biofilter B (8)	161,802	Beetroot leaves, compost, plastic bin
S5	Air Off Biofilter D	50,920	Cheesy, sweaty feet, rotting aniseed
S6	Air Into Biofilter D	30,591	Dried fruit, dates
S7	Shredder	60,903	Earthy with chlorine, rotting food
S8	Upwind	294	Fat, crisps, cucumber oily
S9	Effluent Compound	354	Same as S8 but stronger.

Airflows during sampling

During the sampling session, the pressures and airspeeds within the ducts were measured and have been converted into volumetric airflows at Table below.

Case Study #4 Air pressures, velocities and volumetric airflows in the ducts at Stanton

	Suction pressure	Blown pressure	Total pressure	Airspeed	Airflow in 250mm duct
	mm	mm	Pa	m/sec	cu.m/hr
Fan 3	270	220	4802	13	2291
Fan 4	230	234	4547	11	1940
Fan 7/8	400	112	5018	6.1	1078
Fan D	358	6	3567	8.3	1474

Note: 1mm H_2O equates to 9.8Pa

### Airflow arrangements for the primary process biofilter B

The air to biofilter B ran in a sequence to ventilate vessels 3, 4, 7 and 8, with each having approximately 10 to 15minutes of run time and then being dormant while the other vessels are cycled. The program that controls this is based on a percentage run time; for example, 45 per cent of a 30-minute cycle. The precise time of each fan starting is not pre-determined and becomes out of sequence (skipped) when the vessel is being loaded or unloaded.

During the sampling, the recording of the fan run-times revealed that the fans extracting air from the vessels 3 and 4 ran simultaneously. The two fans (F3 and F4) supply air to the biofilter at the same time. Vessels 7 and 8 share the same fan (F7/8), but employ butterfly valves to enable sequencing. Vessels 1 & 2 and 5 & 6 are on separate systems supplying biofilters C and A respectively.

An illustration of the system associated with biofilter B is shown below.

***Case Study #4 Schematic of the Fan and duct systems associated with Biofilter B***
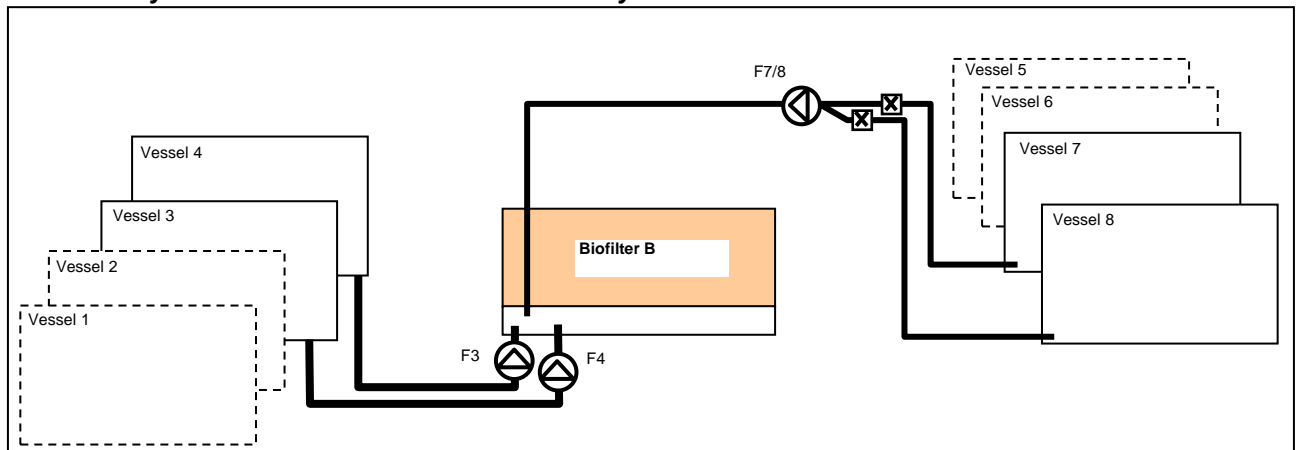
Based on table 5, the combined airflow to biofilter B when both fans 3 and 4 were operating, would have been 4231cu.m/hr; that is, four times that for when the Fan 7/8 was operating.

Biofilter characteristics

On the morning of the odour sampling, the preceding night temperature had been low and the air was still cool ~6°C. Air off the biofilter was near saturation and warm, consequently as it left the biofilter surface, the water vapour due to condensation formed a 'fog' of water droplets that were clearly visible. It was clear that the air from the biofilter was not uniformly distributed, but was more concentrated towards the duct entry end, giving rise to higher air-speeds.

This suggested that the biofilter media had either settled or deteriorated and/or that the air plenum under the media was not providing uniform distribution of the air throughout the whole area of the biofilter (see Figure 3).There are a number of reasons for this, but ultimately the solution shall be to overhaul and restore the biofilter to proper operation.

Figure 3: Illustration of non-uniform airflow from the biofilter.
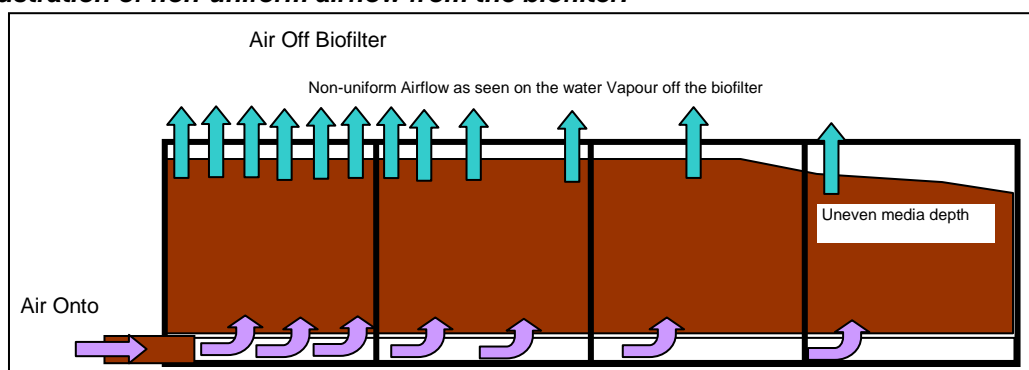
Discussion of odour sample results – Biofilter B

The results of the samples evaluated provide useful information regarding key aspects of the site. Samples S1 to S4 relate to biofilter B. Table 7 reproduces this data in a simple format. The airspeeds are based on uniform flow through the biofilter. Given the evidence of non-uniform flow, the actual contact time may be as low as 25 per cent of the values given.

Case study #4 : Biofilter B – performance summary

		Biofilter performance for Vessels 3+4		Biofilter performance for Vessel 8
Air OFF	OU_E m^{-3}	623,700		161,802
Air ON	OU_E m^{-3}	1,177,660		2,283,610
Odour Reduction	OU_E m^{-3}	553,960		2,121,808
Odour Removal Performance %		47%		93%
Air Upflow	m^3/hr	2291 + 1940 = 4231		1078
Air Upflow speed	m/sec	0.0122		0.0031
Air Contact time	sec.	163		641

The odour descriptions serve to confirm that the panel are able to detect that composting type odours are present. It is possible that the smell of plastic may be attributed to the ductwork. The generality of the descriptions are regarded as non-pleasant odour types, however, to some people the use of the word 'compost' is a near neutral description and similar to earthy or green vegetables. Use of the words bleach and medical, may be attributed to disinfectants used on the site.

Discussion of odour sample results – Biofilter D

The results of the samples S5 and S6 relate to biofilter D, which is associated with maturation Bays 1 to 5, on the west side of the yard. The airspeeds are based on uniform flow through the biofilter. However, the media is clearly of varying depth and appears shallow in some places, suggesting that deterioration and slumping or compaction has occurred.

Despite the fact that the odours above the filter are not very noticeable (walk round review) the results suggest that the biofilter performance is poor, and the odour descriptions and values suggest that the biofilter is contributing to odours in the airflow.

Case study #4 Biofilter D – performance summary

		Biofilter performance for mat. bays W 1-5	
Air OFF	OU_E m^{-3}	50,920	Cheesy, sweaty feet, rotting aniseed
Air ON	OU_E m^{-3}	30,591	Dried fruit, dates
Odour Reduction	OU_E m^{-3}	-20,329	
Odour Removal Performance %		-66%	
Air Upflow	m^3/hr	1474	
Air Upflow speed	m/sec	0.0073	
Air Contact time	sec.	274	

Case Study #4 PROCESS AIR QUALITY

Additional research regarding air quality from the primary processes.

Given the values for odour contained within the air being sent to the biofilters, it was considered worthwhile to investigate the air quality to determine and confirm that the composting processes were operating aerobically and effectively.

Case study #4 Results

The results reveal that the process is clearly aerobic and the oxygen levels are high (compared to some operating regimes where O_2 levels are allowed to drop to 9 per cent or less). The results reveal that the air within the compost process from vessels 3

and 4 contains higher levels of oxygen than that from the enclosed vessels 5 and 8. This is a function of the design; that is, when aeration takes place for vessels 1 to 4, fresh air is drawn into the process, whereas when aeration takes place for the enclosed vessels 5 to 8, air from within the vessel is drawn into the process. Other explanations may be in regard to the fan capacity, tonnages being aerated, depth of material and fan cycle times.

For the vessel 4 data, figure 5 provides an illustration of an aeration period from start to end. This shows how the duct air from the previous cycle is purged with stale process air, causing a slight drop in oxygen being sensed at the fan, followed by a steady climb in oxygen content as the fresh air is entrained into the compost and dilutes the CO_2 levels being exhausted.

Figure 4 provides an illustration of the oxygen control being undertaken on vessel 4. The aeration is begun when the O_2 level has dropped to 16.2 per cent and is restored back up to 17.5 per cent. Figure 5 shows the compost in vessel 8 is in the peak of its cycle and the oxygen levels are being maintained at a lower value, but still above 12 per cent.

Research has shown that the composting process can tolerate oxygen levels down to 5 per cent O_2 before the process 'stalls' due to lack of oxygen for respiration.

Case study #4
Oxygen profile during aeration of vessel 4.
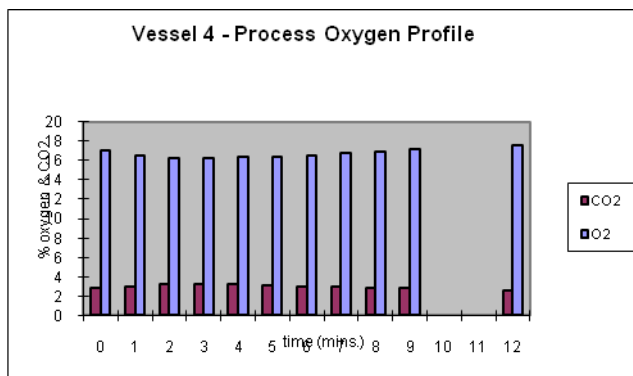
Oxygen profile during aeration of vessel 8.
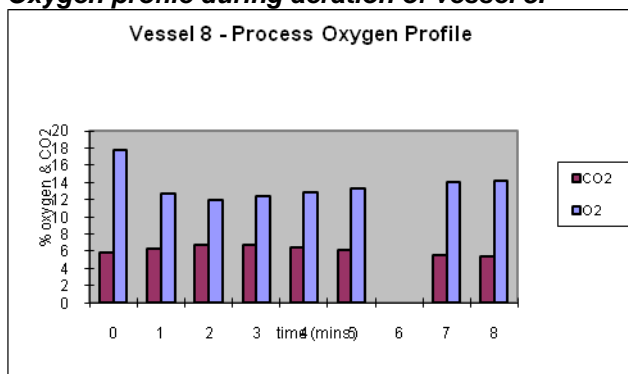
Case study #5
(February 2011) Bunker type composter facility/bunker type biofilter
In-vessel Composting
The vessels (tunnels) are provided with air ducts in the floor, and a system of air ducts and pipes that suction ventilate the compost using powerful suction pressure fans mounted on the roofs of the tunnels. Air from these fans is ducted to biofilter 1. Monitoring of temperatures, air quality and material moisture content enables aerobic compo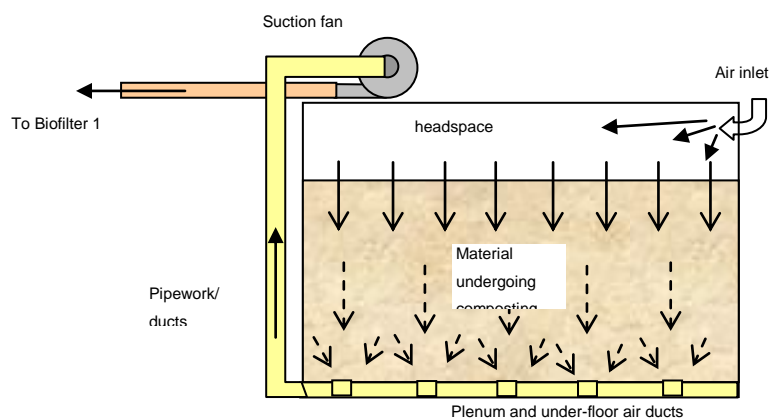sting to continue until the material is properly sanitised according to Defra Animal Health and BSI PAS100 requirements.

Case study #5 Diagram to show suction ventilation process

Compost maturation
Once the material in the tunnels has achieved its target temperatures and residence times, it is out-loaded from the tunnels and stored in the maturation bays for stabilisation and maturation. The bays are again provided with under-floor ducts and a suction ventilation system that discharges air to either biofilter 2 or 3.

These bays are exposed to the environment and may be kept well-ventilated as temperatures are less critical and a fall in temperature is useful as it aids the progress of the fungi that work in the latter stages of maturation of carbonaceous material (similar to what happens on the forest floor).
Stabilisation is complete when the microbial respiration has reduced to levels sufficient for the material to pass PAS100 (the BSI standard for quality compost) testing.

The performance of the primary composting process biofilter was evaluated by taking air samples of the air at the inlet to the biofilter and the air exhausting from the surface of the biofilter.

The methodology used is summarised at Appendix 3.

The samples were evaluated by Silsoe Odours Ltd, a UKAS accredited laboratory that specialises in this work. The results for odour concentration are shown below at Figure 3.

Case study #5 Silsoe Odours results

COMMERCIAL - IN CONFIDENCE

SILSOE ODOURS Ltd
Building 42 Wrest Park, Silsoe, Bedfordshire, MK45 4HP.
Olfactometric measurements for: Recogen Corby on 22 February 2011

UKAS TESTING
0609

Results:

Table 1: Results for Corby odour samples analysed on 22 February 2011

Time Analysed	Sample No.	Sample Source and Position	Odour Panel Threshold ou_E m^{-3}	Pre-dilution	Odour concentration of the sample ou_E m^{-3} (including pre-dilution)
10:04	20110222 C1	Top of Bio filter 1, Primary vessel	163	9:1	1,630
10:34	20110222 C2	Input air from IVC's	855	10,010:1	8,558,550

Biofilter media comprised mixed woody compost oversize and shredded softwood and chipped bark

The airflow to the biofilter during sampling was measured (hot wire anemometer) as 990cu. m/hr

NOTE:
The composting system that utilises the single pass airflow means that the air being directed to the biofilter is directly off the process and of high odour concentration, high temperature and saturated.

It has also been found that the ductwork can, when the process becomes drier, cause dust to settle within the plenum of the biofilter; leading to poor airflow characteristics and short circuiting of the biofilter.

Case study #6
(June 2010) Bunker type composter facility/bunker type biofilter
In-vessel composting
The vessels (tunnels) are provided with air ducts in the floor, and a system of air ducts and pipes that suction ventilate the compost using powerful suction pressure fans mounted on the roofs of the tunnels. Air from these fans is ducted to biofilters. Biofilter media comprised mixed woody compost oversize and shredded softwood and chipped bark.

Table 1: Results of odour measurements on 23 June 2010.

	Sample No.	Sample source and position	Odour concentration of the sample OU_E m^{-3} (including pre-dilution)	Removal efficiency, %	
	20100623 C1	Off biofilter 1	6,331	99.9	
	20100623 C2	Into biofilter 1	6,472,466		
	20100623 C3	Off biofilter 2	5,007	99.6	
	20100623 C6	Into biofilter 2	1,369,368		
	20100623 C4	Off biofilter 3	343	83.2	
	20100623 C5	Into biofilter 3	2,048		

The assessors were asked to describe the odour of each sample as soon as they were able to recognise it at above the detection threshold.

	Compost	Earthy	Cereals/biscuits	Pungent	Bleach	Rotting cabbage	Manure	Medical	Rotten eggs	Smoky	Chicken manure	Woody/musty	Grass cuttings	Sewage	Cooked meat
C1	3	5		2	1			1							
C2 Inlet	1	1		2	1	1	1	1	1				1	1	1
C3	4	3		1	1			2							1
C6 Inlet	2	3		1	1	1		1							1
C4		2	1		3	1	1							1	
C5 Inlet	3	3			1		1								1

Case Study #7
(September 2010) Bunker type composter facility/bunker type biofilter
In-vessel composting
The vessels (tunnels) are provided with air ducts in the floor, and a system of air ducts and pipes that suction ventilate the compost using powerful suction pressure fans mounted on the roofs of the tunnels. Air from these fans is ducted to biofilters. Biofilter media comprised mixed woody compost oversize and shredded softwood and chipped bark.

This document provides an evaluation of the biofilter odour treatment and release. This report does not present multiple replicates but does provide a good indication of odour levels at the facility.

Odours.
The replicate sampling from biofilter 3 reveals some variation over the biofilter surface area. The biofilter performances calculated as 89 per cent odour reduction for both biofilters 1 and 3 are in accord with industry targets.

Biofilter airflows for biofilter 1 and 3 were 5 and 5.6cu.m/sec respectively.
And sizes approximately 3m x 12m x 2.4m deep in each case.

Case study #7 Results of odour measurements on 17 September 2010

Time analysed	Sample no.	Sample source and position	Odour concentration of the sample (including pre-dilution) OU_E m^{-3}	Odour removal efficiency	Air residence time, s
13:17	20100917 W1	Biofilter 1 Top	845	89%	17.2
13:43	20100917 W2	Biofilter 1	7,966		
12:16	20100917 W4	Biofilter 3 Top	1,063	89%	15
12:58	20100917 W5	Biofilter 3 Top	418		
13:31	20100917 W6	Biofilter 3	6,680		

Case study #7 Results of odour descriptions on 17 September 2010

The assessors were asked to describe the odour of each sample as soon as they were able to recognise it at above the detection threshold.

	Compost	Earthy	Cereals/biscuits	Pungent	Bleach	Rotting fruit	Manure	Medical	Rotten eggs	Smoky	Chicken manure	Woody/musty	Grass cuttings	Sewage
W1	3	2		1	2			1	1				1	1
W2 Inlet	1	2			1	1	1	3	1					
W4	4	3			2					1		1		
W5	3	4			2			1		1			1	
W6 Inlet	3	4		1	2	1	1		1		2			

These biofilters performed well despite short air residence times. However the inlet odour concentrations were much lower than in the other case studies.

It is interesting to note that the odour characteristics change with pungent, rotting fruit, and manure odours being absent from the biofilter 'top' samples and present in the inlet samples.

**Case study #8
(October 2010) Bunker type composter facility; Enclosed bunker biofilter**

This facility comprises a small scale bunker type composting process, based on green waste that is admixed to food waste (kerbside caddy collected) and composted in bunkers and moved between each bunker to provide aeration, mixing and movement in accordance with ABPR.

The biofilter services the air space within the overall building.
The biofilter is delivered air via the blower.

The blower/fan operates at 2500 to 3000cu.m per hr airflow and can work at a combined suction and exhaust pressure of 300mm water gauge.

The biofilter media was specified to provide maximum surface contact of air to wood-based particles, without fine particle sizes that lead to degeneration and clogging of the media. The upper one metre of the biofilter media comprises chipped bark; this is to enable good moisture dispersion across the filter media and in the damp form, to provide an overall layer of increased air resistance to help ensure uniform airflow across the full area of the biofilter.

An assessment was undertaken 28 October 2010, when samples of air were taken from the inlet and exhaust of the biofilter both at a time of increased activity in the facility and during a time of low activity. During the movement of compost in process, the odour concentration within the building is elevated, however, the biofilter was shown to provide an efficiency of 90 per cent during this time, reducing the odour

concentration from **31,610 OU$_E$ m^{-3}** (air sampled from the air duct **prior** to the biofilter) to **3,252 OU$_E$ m^{-3}** (air sampled from the exhaust duct **after** the biofilter).

When the site had been inactive for more than two hours, the odour concentration was lower, and the odour removal of the biofilter produced a correspondingly lower odour output.

Samples of air were taken from the inlet and exhaust of the biofilter at a time of during the movement of compost in-process; that is, at a time when the odour concentration within the building was elevated.

Later, after the conditions in the building had been allowed to settle down, two further samples were taken. The results were reported as follows:

Sample no.	Process conditions	Description	OU$_E$ m^{-3}
A	Immediately after compost movement within the building.	Air sampled from the air duct **prior** to the biofilter.	31,610
B	Immediately after compost movement within the building.	Air sampled from the exhaust duct **after** the biofilter.	3,252
C	After a settlement period had elapsed. No materials being handled.	Air sampled from the air duct **prior** to the biofilter.	13,580
D	After a settlement period had elapsed.	Air sampled from the exhaust duct **after** the biofilter.	3,052

The assessors were asked to describe the odour of each sample as soon as they were able to recognise it at above the detection threshold.

Case study #8 Odour characteristics

	Compost	Earthy	Cereals/biscuits	Pungent	Bleach	Rotting fruit	Manure	Smoky	Chicken manure	Refuse	Grass cuttings
A	2	2	3	1		3	1		1		
B	3	1	2	2	1	2			1		1
C	4	1	1			3	2				
D	3	2	3	1	1	2			1		

Case study #9
(September 2011) IVC composter facility; Open bunker biofilter

To assess the performance of the biofilter and the emission rate from the biofilter, surface samples were collected in triplicate from the inlet fan duct and from a sheeted biofilter surface. The IVC was composting mixed green and food waste.

The inflated sheet covering the biofilter surface; odour samples were collected of the escaping air.

On the first day, when the IVC was being emptied and filled, the air entering biofilter from the IVC and the composting building had a mean odour concentration of 46,588 OU_E m^{-3} and the air leaving the biofilter had a concentration of 42,077 OU_Em^{-3} resulting in an **odour removal efficiency of 9.7 per cent** and an odour emission rate of 351,678 OU_E/s.

On the second sampling day, when the IVC was not being emptied and filled, the air entering biofilter from the IVC and composting building had a mean odour concentration of 45,885 OU_E m^{-3} and the air leaving a concentration of 46933 OU_E m^{-3}, resulting in an **odour removal efficiency of -2.3 per cent** and an odour emission rate of 244,623 OU_E/s. The lower emission rate is a result fan flow rate being reduced by having three of the six vent inlets closed.

The main reason for the low odour removal efficiency was the complete lack of irrigation of the wood chip biofilter material. The site manager commented that they had plenty of rain in that part of the country. The residence time was also short at 35 seconds.

Case study #9 biofilter dimensions

Biofilter dimensions	
Length	14.3
Width	9.3
Area	133
Depth	2
Nominal volume	266.0
Mean residence time, seconds	35.5

Case study #10
(July 2009) Tunnel type composter facility; Open bunker biofilter

This facility processed primarily green waste from kerbside and tidy tip sources.

The floor ventilated tunnels vented surplus air through a scrubber before the biofilter. The biofilter material was mainly 'oversize' material.

We collected triplicate samples from the inlet and outlet air of the biofilter using the sheet method to cover the biofilter surface in order to obtain a representative sample of the exhaust air. We measured the airflow rate into the biofilter and calculated the odour emission rate from the biofilter and the biofilter efficiency.

Case study #10 Biofilter performance

Sample source and position	Odour concentration of the sample $OU_E\,m^{-3}$ geometric mean	Air flow rate, m^3/s	Emission rate $OU_E\,s^{-1}$	Biofilter efficiency, %	Biofilter volume, m^3	Residence time, s.
Outlet	2921	11.2	32681	74	439	39
Inlet	11400					

9.3   Appendix C - Examples of selected UK biofilter suppliers and odour consultants

Odour Services International Ltd.

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OSIL TECHNOLOGIES

LavaRok® Biofiltration...

OSIL LavaRok systems are biological filters using pumice stone as support material on which the micro-organisms grow in the form of a thin bio-film.

The bacteria are key to the performance of the system. These have been optimised and years of empirical research, including live pilot trials and full scale studies have allowed us to optimised the strains of bacteria used for various applications. We work closely with our microbiology partners at the school of applied sciences at **Wolverhampton University** and **Biosystems Europe** to ensure that we always have the best combination of bacteria and the correct nutrient supplements (if required) for our wide ranging projects.

- Very Low Maintenance.
- Low Running Costs.
- 25 year Operational Life.
- High Performance.
- Non-Hazardous By-Product.
- Versatile Contaminant Treatment.
- High Porosity.
- High Pour Volume.
- Excellent Liquor Retention.

OSIL TECHNOLOGIES

CuCarb® Dry Media System...
Flexibility to meet your needs.

OSIL offers a comprehensive range of activated carbon, impregnated carbon, oxidising alumina media, and hybrid, multi-media filters.

An OSIL dry media filter may be used as a stand-alone filter for polishing a another primary technology odour control unit discharge or as a stand alone treatment system. All our dry media filters require no operator intervention and provide guaranteed odour control performance.

Each filter is tailored to treat the contaminant odours. We can offer systems to treat H_2S, mercaptans, organic sulphides, ammonia, amines, and VOCs in any combination, and can also provide a guarantee of outlet odour concentration in ou_E/m^3.

Designed and built to BS4994 and fully compliant with WIMES 8.05, OSIL's dry media filters offer assured performance at a competitive price.

Mónashell

Air & Odour Abatement System for the Municipal, Utility and Industrial Markets

http://www.anua.co.uk/air-and-odour-abatement (accessed 20/03/12)

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The Mónashell Biofiltration System from Anua is a unique patented technology, which allows for the biological treatment of airstreams.

Biofiltration is a biological process whereby microorganisms are immobilised on a filtration media, converting captured pollutants from an air stream into harmless, nonodourous by-products.

Mónashell is a natural biological system that utilises shells coated with a blend of specifically selected microorganisms with an ability to control variation in pH by neutralising the acid by-products. This allows for the treatment of high levels of H_2S and reduced sulphur compounds. The process is also assisted by optimum pH ranges on the surface of the packing, which enhances capture and breakdown of low solubility organic sulphide compounds such as Alkyl Sulphides and Mercaptans.

Mónashell Typical System Performance*

Compounds	Concentration Range	Minimum Removal Efficiency
Odour	1,000 – 400,000 OU_E/m³	85 – 99%
VOC	1 – 200 MgC/m³	50 – 80%
Hydrogen Sulphides	1 – 200 ppm	95 – 99%
Ammonia**	1 – 30 ppm	95 – 98%
Organic Sulphides	1 – 15 ppm	95 – 98%

*Specific guarantees will be agreed on each individual project depending on agreed criteria.
** High levels of ammonia will require increased supply of irrigation water

Anua also have two enhanced Mónashell offerings.

- Mónashell Dual pass for use on persistent, low solubility VOCs.

- Mónashell EBF for the biological treatment of difficult industrial emissions containing high levels of VOC, H_2S and organic sulphur groups VOCs.

Mónashell Typical Dual Pass System Performance*

Compounds	Concentration Range	Minimum Removal Efficiency
Odour	$1,000 - 400,000\ OU_E/m^3$	90 – 99.5%
VOC	$1 - 200\ MgC/m^3$	70 – 85%
Hydrogen Sulphides	1 – 200 ppm	99 – 99.5%
Ammonia**	1 – 100 ppm	98 – 99%
Organic Sulphides	1 – 100 ppm	98 – 99%

The Mónashell Dual Pass Additional Advantages

- High odour removal efficiencies
- High elimination capacity on H_2S organic sulphides
- Primary and polishing stages in single unit reduces cost
- Configured as duty/duty or duty standby for maintenance

Mónashell Typical EBf System Performance*

Compounds	Concentration Range	Minimum Removal Efficiency
VOC	$100 - 1,200\ MgC/m^3$	50 – 90%
Hydrogen Sulphides	100 – 2,000 ppm	99 – 99.99%
Organic Sulphides	50 – 200 ppm	98 – 99.9%

The Mónashell EBf Additional Advantages

- Ability to treat high levels of VOC, H_2S and organic sulphides
- Environmentally friendly alternative to thermal treatment
- Strong performance on wide range of compounds
- Adaptability and flexibility of operation

Mónafil

Air & Odour Abatement System for the Municipal, Utility and Industrial Markets

http://www.anua.co.uk/air-and-odour-abatement

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The Mónafil technology is a biofiltration system utilising specialised patented peat media as a capture and support medium to treat air emissions.

Biofiltration is a biological process whereby microorganisms are immobilised on a filtration media, converting captured pollutants from an air stream into harmless, nonodorous by-products. Mónafil is an enhanced organic media biofiltration process employing a patented manufactured media which is inoculated with specific microbiological cultures, dependent on the nature and range of compounds in the air stream.

The media is processed, to enhance it's physical and chemical properties, in order to achieve optimum air treatment performance in terms of:

- Removal efficiency
- Reduced footprint
- Optimised effective contact
- Minimum pressure loss
- Enhanced media life

Every Mónafil system is designed to best meet the client's specific requirements and to provide the optimum odour abatement solution.

Mónafil at Work

Contaminated air is captured and ventilated to the inlet of our Monafil organic media biological filter.

As air passes through the filter, the chemical contaminants are captured by a combination of adsorption, absorption and chemisorption into the water on the surface of the filter where an active biofilm oxidises and breaks down the odorous compounds.

An irrigation system is employed intermittently on a once through basis to maintain the moisture content of the media and to wash out and remove oxidation by-products.

Treated air passes directly to atmosphere on open biofilter or to an outlet Plenum on enclosed systems where in general it passes to a stack for final dispersion.

Mónafil Typical System Performance*

Compounds	Concentration Range	Minimum Removal Efficiency
Odour	5,000 – 100,000 OU$_E$/m³	90 – 98%
VOC	1 – 150 MgC/m³	70 – 85%
Hydrogen Sulphides	1 – 30 ppm	95 – 98%
Ammonia**	1 – 30 ppm	95 – 98%
Organic Sulphides	1 – 15 ppm	90 – 95%

*Specific guarantees will be agreed on each individual project depending on agreed criteria.

** High levels of ammonia will require increased supply of irrigation water

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Biofilters
The medium level odour control solution

Used as a stand-alone package, or in combination as part of a DryCat system, ERG's biofilter provides trouble-free odour control for small to medium sized sewage treatment plants.

Filled with either calcified woodchip or peat and heather, all from renewable sources, ERG's biofilters have been refined and optimised over the years to offer outstanding value for money and simple operation. They require no storage of chemicals on site and need only a water or filtered final effluent supply and a drain connection.

Specially selected bacteria colonize the substrate media within the biofilter housing and there digest the odour-causing compounds, which typically include H_2S, mercaptans, organic sulphides and ammonia. The optimised environment for bacterial activity is maintained by regular, controlled irrigation.

Designed and built to BS4994 and fully compliant with WIMES 8.05, ERG's biofilter systems offer assured performance and competitive costing.

All our systems are custom-designed for the odour control duty required, and include a biofilter housing and irrigation system, biomedia, air extraction fan and ductwork, and electrical control panel.
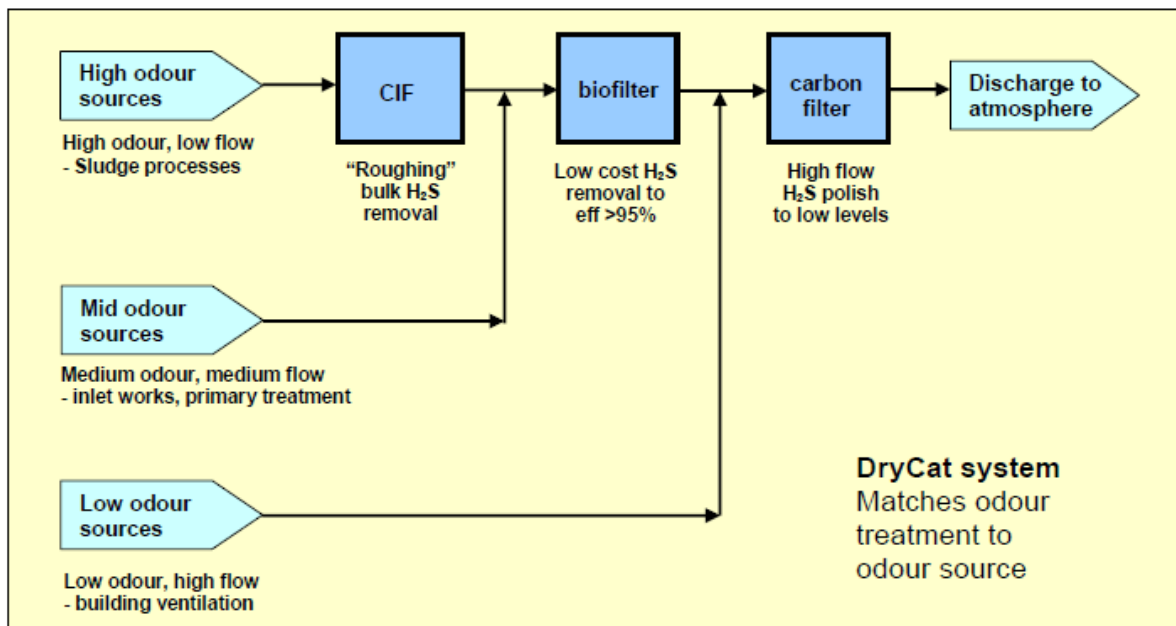
Key benefits

- Removal efficiencies of >98% for H_2S and >95% for other odours.

- Capable of treating gas flows from 200m³/hr up to 20,000m³/hr.

- Compact, neat rectangular modular design manufactured from GRP.

- Easily controllable spray system for optimal bio-media humidification.

- Robust fully enclosed housing capable of withstanding up to 4000Pa negative pressure if necessary. Easy to remove roof for maintenance or media change.

- Up-gradeable performance by addition of CIF pre-treatment or carbon filter polishing.

- Inexpensive bio-media with proven longevity.

- Filter housing can be supplied in any colour.

ERG's DryCat System for Odour Control

Unit operations – the building blocks

The DryCat System comprises at least two of the three basic "building block" equipment items. In all cases, the equipment selection and sizing is matched to the site requirements.

- Catalytic Iron Filter (CIF)
    - rusting iron media removes H_2S in one or two stages to efficiencies of 50-80%
    - used for bulk removal of high H_2S loads (50-500ppm) in small gas flows (typically less than 3,000m^3/hr)
    - ideal for treating highly odorous air flows from sludge tanks, sludge presses, imported/exported sludge pumping stations
- Biofilter
    - cost effective method of removing H_2S to good efficiency from medium air flows
    - traditional peat and heather technology – well proven
    - cheap to install and operate
    - protected from damaging peak H_2S loads by the CIF
    - assured outlet H_2S concentration by carbon filter
    - ideal for treating medium-odour air from preliminary and primary treatment areas
- Impregnated carbon filter
    - caustic impregnated carbon to polish H_2S to <50ppb and mercaptans to <100ppb
    - guaranteed boundary levels in ppb H_2S or OU/m^3
    - cheap to run as the majority of the H_2S is removed by the upstream CIF and biofilter
    - bed life designed to suit site requirements, typically >1year
    - ideal for treating general ventilation air from process buildings

High odour sources → CIF → biofilter → carbon filter → Discharge to atmosphere

High odour, low flow - Sludge processes

"Roughing" bulk H_2S removal

Low cost H_2S removal to eff >95%

High flow H_2S polish to low levels

Mid odour sources

Medium odour, medium flow - inlet works, primary treatment

Low odour sources

Low odour, high flow - building ventilation

DryCat system
Matches odour treatment to odour source

Case study - Rothesay STW

Flowrate = 12,500m^3/hr air, inlet H_2S concentration = peak 135ppm, average 60ppm, guaranteed stack H_2S concentration = 300ppb, design H_2S removal efficiency = 99.2%
The DryCat System was installed for approx 75% capital cost of a wet chemical scrubber.
The DryCat System operating cost is estimated at £9k/year, compared to a wet chemical scrubber (using caustic and bleach) operating cost estimated at £23k/year, a saving of £14k/year or 60%.

9.4   Appendix D - Example of biofilter media supplier

Melcourt Industries Ltd

Melcourt Biofiltration Media Technical Information Summary

	Melcourt Biofil® Medium	Melcourt Biofil® Coarse	Melcourt Filter Bark™ Medium	Melcourt Filter Bark™ Coarse	Melcourt Calcified Seaweed	Melcourt Bioshells®
Main constituent	Wood	Wood	Pine Bark	Pine Bark	Seaweed	Shells
Origin	British	British	European	European	European	British
Nominal particle size range	5 – 40 mm	15 – 100 mm	15 – 75 mm	50 – 125 mm	1–5 mm	20 – 30 mm
Wood content	>85%	>85%	<5%	<5%	n/a	n/a
Dust & fines	Minimal	Minimal	Minimal	Minimal	n/a	<5%
pH	4.5 – 6.0	4.5 – 6.0	4.5 – 6.0	4.5 – 6.0	8.5	6.0 – 8.0
Bulk density range	250 – 310kg/m³	250 – 300kg/m³	180 – 240kg/m³	200 – 250kg/m³	910 – 950kg/m³	525 – 575kg/m³
Quality range	Deluxe	Deluxe	Deluxe	Deluxe	Deluxe	Deluxe
Minimum effective depth	1000 mm	1000 mm	1000 mm	1000 mm	500 mm	300 mm
Settlement factor	15-25%	15-25%	15-25%	15-25%	1-3%	n/a
FSC certified	Yes	Yes	Yes	Yes	n/a	No
Durability (see note below)	3 years+	4 years+	3 years+	4 years+	8 years+	2 years+
Available as:						
Loose bulk	Yes	Yes	Yes	Yes	Yes	Yes
Polythene sacks	Yes	Yes	Yes	Yes	Yes	Yes
Bulk bags	Yes	Yes	Yes	Yes	Yes	Yes

Durability: This is a guide only as aggressive odours, management and maintenance of the filter will effect the media's life.

Liability: Products in the Melcourt Biofilter range are processed to be used as media in filters handling organic odours and have been tried in a range of conditions over several seasons. However, as Melcourt has no control over the circumstances surrounding the use of their products, the company cannot accept liability for every eventuality.

All values given in the Product Specification are typical. However, some variation may occur from time to time. Melcourt Industries Ltd reserves the right to alter the specification without notice, for the purpose of product improvement.

Typical applications
Installation type

Comprehensive technical data for all our products at www.melcourt.co.uk

Installation type						
Open-top tank/ vessel <1m deep	✓		✓		✓	
Open-top tank/ vessel >1m deep	✓	✓	✓	✓	✓	
Enclosed tank/ vessel <1m deep	✓		✓		✓	✓
Enclosed tank/ vessel >1m deep	✓	✓	✓	✓	✓	✓
Odour intensity	Low – Medium	Low – Medium	Low – Medium	Low – Medium	Low	High
Air volume	100 – 100,000m³/hr	100 – 100,000m³/hr	100 – 100,000m³/hr	100 – 100,000m³/hr	0 – 100,000m³/hr	100 – 100,000m³/hr

Association for Organics Recycling

FSC

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Glossary

Empty bed residence time: relates the flow rate to the size of the biofilter. It is defined as the empty bed filter volume divided by the air flow rate:

$$EBRT = \frac{V_f}{Q}$$

Where EBRT = empty bed residence time (seconds, minutes); V_f = filter bed volume (m^3); and Q = air flow rate $(m^3\ h^{-1})$. EBMT overestimates the actual treatment time.

True residence time: defines the expected actual time a parcel of air will remain in the biofilter, accounting for porosity. It is defined as the total filter bed volume multiplied by the bed porosity of the filter media, divided by the air flow rate:

$$\tau = \frac{V_f \times \theta}{Q}$$

Where τ = true residence time (seconds, minutes); θ = porosity (volume of void space/volume of filter material); and Q = air flow rate $(m^3\ h^{-1})$.

Surface (or volumetric) loading: defines the amount of air that is being treated. Surface loading rate is defined as the volume of gas per unit area of filter material per unit time (e.g. $m^3\ m^{-2}\ h^{-1}$). Volumetric loading rate is defined as the volume of gas per unit volume of material per unit time (e.g. $m^3\ m^{-3}\ h^{-1}$).

$$Surface\ loading = \frac{Q}{A}$$

$$Volumetric\ loading = \frac{Q}{V_f}$$

Where Q = air flow rate $(m^3\ h^{-1})$; A = filter area (m^2); V_f = filter bed volume (m^3).

Mass loading: is the mass of the contaminant entering the biofilter per unit area or volume of filter material per unit time (e.g. grams per m^2 or m^3):

$$Mass\ Loading\ (surface) = \frac{Q \times C_{Gi}}{A}$$

$$Mass\ Loading\ (volumetric) = \frac{Q \times C_{Gi}}{V_f}$$

Where Q = air flow rate (m^3 h^{-1}); C$_{Gi}$= inlet concentration (g m^{-3}), A = filter area (m^2), V$_f$ = filter bed volume (m^3).

Removal efficiency and elimination capacity: describe the performance of a biofilter. Removal efficiency is the fraction of the contaminant removed by the biofilter, expressed as a percentage:

$$Removal\ efficiency = \frac{C_{Gi} - C_{Go}}{C_{Gi}} \times 100$$

Where C$_{Gi}$= inlet concentration (ppm, g m^{-3}); C$_{Go}$ = outlet concentration (ppm, g m^{-3}).

Elimination capacity is the mass of contaminant degraded per unit volume of filter material per unit time. This calculation allows for a direct comparison of the results of different biofilter systems. Typical units for elimination capacity are grams per m^3:

$$Elimination\ capacity = \frac{(C_{Gi} - C_{Go}) \times Q}{V_f}$$

$$Elimination\ capacity = Volumetric\ mass\ loading \times Removal\ efficiency$$

Where C$_{Gi}$= inlet concentration (ppm, g m^{-3}); C$_{Go}$ = outlet concentration (ppm, g m^{-3}); Q = air flow rate (m^3 h^{-1}); V$_f$ = filter bed volume (m^3).

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