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Understanding biofilter performance and determining emission concentrations under operational conditions

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Executive Summary

As early as the 1990s, concerns were growing regarding the risks associated with the emission of bioaerosols. In the absence of dose response relationships in the community, the Environment Agency used a precautionary approach in the regulation of these sites in relation to the location and operation of composting plants, to minimise any potential health impacts from these sites and in particular open windrow sites. This together with an increased target for recovery of biodegradable waste and diversion from land fill resulted in a rise in the number of enclosed composting facilities operating in the UK.

Biofilters have been used as an abatement technology at biowaste plants primarily for odour removal, but also for the control of bioaerosols, for many years and over that time very little has changed in terms of the fundamental biofilter design criteria. Research over the past 20 years has led to a better understanding of the principles of operation of biofilters in relation to odour. However, there are still many gaps in the knowledge which need to be addressed if biofilters are to be designed to control all emissions and to perform efficiently.

This research project was commissioned by Sniffer on behalf of the UK Regulators together with industry representation. The project was carried out by a team led by the University of Leeds, in partnership with Odournet UK Ltd. The overall objective was to determine the extent to which abatement methods incorporating either open or enclosed biofilters reduce both bioaerosols and odour emissions from enclosed biowaste treatment operations. The research also attempted to answer the following questions:

1. What current technologies (e.g. combination of biofilter and scrubber) are being used throughout the UK biowaste industry to treat emissions?
2. What emission concentrations are being achieved by current technologies under operational conditions, and what rates of reductions relative to untreated emissions do these represent?
3. What design configurations and operating conditions (e.g. empty bed residence time, media type, moisture content, etc.) are required to ensure that maximum reduction rates are achieved, taking into consideration the different processes?
4. What is the degree of aerobicity/anaerobicity in existing, enclosed, biowaste treatment processes?
5. How significant of an impact does the degree of aerobicity/anaerobicity have on the levels and types of bioaerosol and odour emitted?
6. What impact does the ratio of aerobic to anaerobic activity at a site have on the site's overall environmental performance?
7. Which technology (or technologies) might be put forward as candidates for Best Available Techniques (BAT) for bioaerosol and odour abatement?

8. What final bioaerosol and odour concentrations are achievable by the candidate BAT(s) for each of the available, enclosed, biowaste treatment operations?

This research involved an initial review of the available literature pertaining to the performance of biofilters in their application to treat emissions from biowaste sites. This was followed by evaluation of the performance of biofilter systems at eight biowaste treatment sites in the UK, which was conducted over a period of one year. The findings of the research are primarily based on the data obtained during this phase of the study.

The sites were chosen to ensure that as large a range of different abatement system arrangements and process parameters as possible were captured. The study acknowledged the current position in the UK were the majority of abatement systems consist of open biofilters, although enclosed systems are increasingly applied at new, large scale biowaste facilities. The key variables that were considered were;

- whether the biofilter was open or enclosed,
- whether the abatement system included a scrubber or not,
- the type of biofilter media being used (e.g. woodchips, brash and granular peat),
- the biowaste type, and the treatment process being used.

The sites selected included two Eco Deco bio-drying systems, three in-vessel composting (IVC) tunnel sites, two enclosed windrow sites and one rotating drum system.

Sampling and analysis was undertaken for odour (using olfactometry), hydrogen sulphide, ammonia, Volatile Organic Compounds (VOCs) and the bioaerosols, *Aspergillus fumigatus*, total bacteria and gram negative bacteria. The techniques applied were standardised and delivered using accredited procedures where available.

It is important to note that all of the biofilters sampled as part of this study were observed to be in good condition and were well monitored. The media condition and particle size were generally good and the operational parameters of each system were within the ranges identified through review of relevant literature. As a result, the data obtained in terms of emissions and performance is likely to be representative of abatement systems that can be considered to be well designed, operated and maintained (Best Available). The results of this study do not therefore, allow conclusions to be drawn regarding the performance of abatement systems that are badly designed and operated or poorly maintained. Further sampling would need to be undertaken to determine the impact on the emission of odour and bioaerosols and removals that can be achieved by such systems.

The key findings of the study are as follows:

Emission of odour and bioaerosols from enclosed biowaste treatment facilities

1. The concentration of bioaerosols and odour in the process air varied from site to site and sometimes between visits to the same site. The data shows that there was no direct relationship between the type of waste being treated, or the treatment system being used and the concentration of bioaerosols or odour and odorous VOCs emitted. It would appear that the odour and bioaerosol concentration of process air is influenced by a complex interaction between specific process operating conditions, the waste types being handled, and the configuration of the air extraction and collection systems.
2. The process air comprised a complex mixture of chemical components that included; hydrogen sulphide; ammonia; a wide range of odorous VOCs including aliphatic hydrocarbons, alcohols, ketones; and organic sulphur compounds; organic acids; esters and terpenes. No direct correlations were identified between waste type, process type and the dominant chemical compound groups.
3. Overall the concentration of bacteria (total and gram negative) in the process air was significantly higher than the concentration of *Aspergillus fumigatus,* regardless of the treatment system being used and the type of waste being treated. There was no relationship, either positive, or negative between the concentrations of *Aspergillus fumigatus*, total bacteria, or gram negative bacteria.
4. From the data obtained during this study, it was not possible to identify a clear indicator for anaerobic/aerobic conditions from the perspective of a single or combination of easy to measure VOCs. Although indicators of anaerobic decomposition such as hydrogen sulphide and dimethyl sulphide were identified in the process air (Kissel et al, 1992; Homans & Fischer, 1992), their concentrations were relatively low and did not correlate with overall odour concentration. An apparent correlation between the concentration of ethanol and total VOCs and total odour was identified. However, further research incorporating a wider range of sites, including those with suboptimal process conditions may lead to a different conclusion and this is therefore recommended as an area for further study.

Emission of odour and bioaerosols from the abatement systems

1. The concentration of bioaerosols emitted from the abatement systems varied from site to site and also between visits to the same site. For all three bioaerosol markers, no relationship was found between the inlet and outlet concentrations. It would appear that for the sites sampled the concentration of bioaerosols being emitted from the abatement system, regardless of what system is employed, is independent of the concentration entering each system.

2. In contrast all the biofilters sampled were capable of maintaining a relatively stable odour emission concentration, which was independent of the variation in the process load as indicated by the inlet measurement. The study indicated that the concentration of air from well operated biofilters, as measured using olfactometry is likely to fall within the range of 200 to 5500 OU_E/m^3. All biofilters also appeared to have a beneficial effect on the character of the odour released and perceived offensiveness in comparison to the process odours.
3. More detailed analysis showed that the odour from biofilters comprised of a mixture of odorous components which include aromatic hydrocarbons, alcohols, ketones, aldehydes, reduced sulphur compounds, terpenes and organic acids. No direct correlations between overall odour and specific VOC compounds or compound groups were identified, implying that the overall odour concentration of air released from well operating biofilters is influenced by interactions between a variety of different odorous components. Hydrogen sulphide and ammonia do not appear to contribute significantly to the odour released from well operated processes and the biofilters treating process air. This is due to the fact that hydrogen sulphide is effectively removed and residual concentrations of ammonia do not significantly exceed its relatively high odour threshold.
4. A number of individual VOCs were identified in the outlet air that did not occur in the corresponding inlet sample. This included aromatic hydrocarbon, terpenes and reduced sulphur compound groups, such as dimethyl sulphide and dimethyl disulphide. The sulphur compounds may have been produced as a result of partial oxidation of other sulphur compounds, or areas of anaerobic activity within the biofilter media. The terpene compounds are likely to originate from the biofilter media, whilst the other VOCs may be generated as a result of biogenic reactions within the filter. The concentration of these compounds was however generally low and is not considered to be a limiting factor in the application of this technology.

Bioaerosol and odour removal efficiency

1. In terms of removal, all of the biofilters in this study achieved efficiencies in terms of total odour of between 69 to 94 %. The removal efficiency of ammonia and specific VOCs did however, exhibit significant variation from site to site. This is likely to be due to variations in the solubility of each compound and its amenity for absorption into, and oxidation within, the biofilm of the biofilter media, as well as the fact that some VOCs are generated within and by the media as described above.
2. The data showed that odour emission concentrations from open and enclosed biofilter systems were comparable indicating that enclosure of the biofilter had little impact on the overall concentration of odour, but may be affected by dispersal with stack height. The same is true for scrubbers. In some cases, the scrubber appears to increase the odour and VOC concentrations, which may be due to accumulation of organic matter

within the scrubber liquors. Scrubbers do however have a beneficial impact on ammonia removal, with efficiencies recorded of between 62% and 98% which may have a positive effect on the biofilter media efficiency.

3. In contrast, it appears that open biofilters performed significantly better than enclosed biofilters, with respect to their removal efficiency for *Aspergillus fumigatus*. Whilst enclosed biofilters produced the highest removals for total bacteria, it is not clear from this data set whether open, or enclosed biofilters are better for the removal of gram negative bacteria. The application of scrubbers (acid alone or acid and alkali in series) also appears to have beneficial effects in terms of reducing bioaerosols. This supports the view in the literature that acid scrubbers used in conjunction with biofilters achieve the best reductions (Aarnink *et al.,* 2005; Zhao *et al*., 2011). The biofilters in this study were particularly effective in reduction of *Aspergillus fumigatus*. They appeared to be less effective against bacteria and total bacteria in particular. This is different from the information presented by Seedorf and Hartung (2002), who found their scrubber system to be more effective against bacteria (53-90%) than fungi (13-68%).
4. In terms of the overall performance of the abatement systems for bioaerosols, the study indicates that the bioaerosol reduction efficiency was extremely variable from site to site and between visits to the same site. The same abatement system did not appear to be able to simultaneously achieve significant removals of *Aspergillus fumigatus*, total bacteria and gram negative bacteria.
5. The *Aspergillus fumigatus* removal efficiency of the biofilters appeared to be related to the inlet concentration, with poor removals at low inlet concentrations. The data suggested that biofilters may be consistently emitting *Aspergillus fumigatus* and that this appears to be observed when the inlet concentration is low. It may also mean that when using a biofilter alone or in conjunction with an upstream scrubber, it will not be possible to completely eliminate *Aspergillus fumigatus* from the air stream. Although not conclusive, the suggestion that biofilters are a constant source of *Aspergillus fumigatus* may advocate the use of downstream scrubbers to negate the net emission of *Aspergillus fumigatus* by the biofilter and improve the overall performance of the abatement system. This agrees with the findings of Ottengraf & Konings (1991) who stated that biofilters were net emitters when the inlet concentrations were low and were net reducers, when concentrations were higher in the inlet.

Impact of key design and operating parameters on odour and bioaerosol removal

1. The impact of biofilter media type varied between the different types of bioaerosols. The granular peat biofilters were extremely poor at reducing the concentration of *Aspergillus fumigatus.* However, they produced reasonable reductions in gram negative bacteria and significant reductions in total bacteria. Looking at the performance of woodchip, clay and brash biofilters there appeared to be little difference in the performance for both *Aspergillus fumigatus* and total bacteria. The performance of

woodchip biofilters for gram negative bacteria is extremely variable and the data shows very poor removals for the brash and clay biofilters.

2. In contrast to the bioaerosols, media type had little impact on the odour removal efficiency. Biofilters with each of the media types sampled (e.g. woodchip, peat, brash and clay aggregate) all achieved odour removal efficiencies in excess of 90%. Biofilters with a granular peat media did, however, appear to achieve the lowest ammonia removal efficiencies and the performance of the brash and woodchip biofilters was also generally good.
3. The key operating parameters of relevance to control of odours drawn from literature are residence time, moisture content, temperature (of process air and the biofilter media), media nutrient content, and pH. It was not possible to assess the criticality of these parameters in direct terms on odour emissions since the biofilters studied all fell within or close to the optimal range. However, evidence suggests that operating parameters for bioaerosol differ to odour. This reflects the consensus in the literature. For example, Ottengraf & Konings (1991) stated that impingement was a key mechanism in bioaerosol removal and that air velocity, biofilter media particle size and the size of the bioaerosols were the key factors.
4. The study has identified indicative ranges for the key operational parameters for odour removal that can be used for the basis of definition of BAT. Fundamentally, biofilters are considered to provide a viable solution for treatment of odourous gases from biowaste plants, providing they are designed to meet the emission characteristics that have been defined above in terms of total odour, monitored operated in accordance with these criteria. The application of a scrubber is a component of Best Available Techniques (BAT) where the concentrations of potential gases or toxic constituents such as, but not limited to, ammonia or hydrogen sulphide, may impact on biofilter performance. Scrubbers may also be required for control of temperature and particulate load. It is recommended that this is evaluated on a site by site basis during design and commissioning.

This study has generated some valuable data and provided a significant contribution to the knowledge surrounding the gaseous emissions from enclosed biowaste plants and the performance of abatement systems. However, some knowledge gaps and areas for further research are highlighted. These are presented below.

Areas for further research and evidence gaps:

1. Overall there continues to be a lack of good quality data regarding the concentration of bioaerosols in the air emitted from enclosed biowaste processes and biofilters emissions. This makes it extremely difficult to evaluate the performance of abatement systems and in particular biofilters for the control of bioaerosols. Existing data is

extremely variable due to the different sampling techniques that have been used, particularly for biofilter outlets. More sampling needs to be undertaken using robust, standardised sampling procedures, in order to provide a more comprehensive data set.

2. The study was not able to provide an insight into the effect of anaerobicity on the emission of odour or bioaerosols. Therefore, data is needed to investigate the impact of anaerobicity on odour and bioaerosol emissions and more specifically whether there are any relationships between specific VOCs / VOCs groups and odour that may serve as markers for anaerobicity / abnormal conditions.
3. This study has provided data on the performance of biofilters and scrubbers when used to treat air from a range of biowaste treatment process under 'normal' operation. More research is needed to investigate the performance of these systems in terms of their ability to treat the air emitted from biowaste processes that are operating under 'abnormal' conditions. This will help to define the operational limits for application of biofilter technology to composting processes and BAT
4. The apparent correlation between the concentration of ethanol and total volatile organic compounds and total odour requires further investigation.
5. Further research is required to evaluate the performance of biofilters with different media types (e.g. lava rock, organic media and activated carbon), or with combinations of different media or media mixes in terms of odour and bioaerosol emissions and removal.
6. The current literature contains contradictory information regarding the impact of biofilter design and operating parameters on odour, bioaerosol emissions and removal. The data provided in this study did not provide a clear picture of the impact of parameters, such as media moisture content, biofilter temperature, absorptivity, process air temperature and media porosity. Further research is needed to investigate the importance of these parameters in order to refine operational ranges and firmly define optimal conditions between optimal design and normal /abnormal biofilter operation.
7. The data obtained during this study, together with data available in the literature suggests that the mechanisms involved in the removal of odours and bioaerosols are different. This may imply that significant removals of odour and bioaerosols cannot be achieved simultaneously in a single biofilter system. Further research is needed to determine if a single biofilter can be optimised for the removal of bioaerosols and odour. Additional research should be carried out on the feasibility of using a two stage abatement system, with each stage optimised for the removal of odour or bioaerosols.
8. The performance of biofilters in terms of bioaerosol and in particular, *Aspergillus fumigatus* removal showed that biofilters may be net emitters. The impact of this is that at low inlet concentrations the removal efficiency is relatively low. Further research is needed to investigate the potential for net emission of bioaerosols from biofilters, both in terms of the overall concentration and also the individual species. This research

should also evaluate the potential for applying scrubbing post biofiltration to remove bioaerosols.

9. This report identified that there is a lack of information regarding the range of biowaste treatment options being used throughout the UK and also the abatement systems that are being employed. Therefore it would be beneficial to liaise with the biowaste treatment industry and attempts to compile a database regarding the current biowaste treatment options being used in the UK together with the abatement system currently being employed.

10. This research highlighted a great deal of variability in the performance of scrubbers for both odour and bioaerosol removal. This may have been due to the limited number of sites included in this study which employed scrubbers and biofilters. Therefore further work should be carried out to look specifically at the performance of scrubbers and also to determine whether for bioaerosols the scrubber liquor represents a significant source of bioaerosols and therefore adversely affects their performance. This may lead to the development of clear guidelines for the operation and maintenance of scrubbers for odour and bioaerosol removal. The research should encompass a range of different scrubber arrangements in terms of the liquid and the packing used and could also investigate the potential for the use of a downstream scrubber post-biofilter for effective bioaerosol removal.

11. The literature appears to be divided over the subject of ammonia toxicity within biofilters. Some authors have suggested that elevated ammonia loading rates can have a significant impact on the performance of a biofilter at composting sites due to the occurrence of ammonia toxicity leading to microbial inhibition, causing a reduction in the capacity of the biofilter to adsorb and decompose ammonia. However others have observed no ammonia toxicity effects even at relatively high ammonia concentrations, suggesting that even high initial levels of ammonia in exhaust gases may be removed effectively using biofiltration. The results from this study showed that ammonia removal was extremely variable and that the removal efficiency was not related to the inlet concentration. As a result further work is needed to establish whether biofilters are capable of achieving ammonia removal at elevated concentrations and whether ammonia toxicity is a factor affecting performance of biofilters. Work should also be carried out to determine the biological response to elevated ammonia concentrations to establish whether the microbial population within the media adapts to elevated ammonia concentrations or whether a specialised population is already in-situ.

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1.0 Introduction

In response to a Government commitment to reducing the amount of biodegradable waste entering landfills as part of the Landfill Directive (1999/31/EC), there has been a significant growth in the composting industry. It was estimated that in 2012 there were approximately 323 operational sites in the UK (WRAP, 2012). As early as the 1990s, concerns were growing regarding the risks associated with the emission of bioaerosols, in particular from open air composting plants.

Biofilters have been used in the waste industry for many years with varying degrees of success, as their initial designs were based on a fairly basic understanding of their method of operation. The principles of their design were relatively straightforward, using a specified air flow rate and an air retention time in the filter bed. Whilst the structural materials used for the filters might have become more sophisticated since then, and in the UK there is a move towards using emission stacks, the fundamental design criteria have changed very little.

Research over the past 20 years has led to a better understanding of the principles of design and operation of biofilters, together with the upstream and downstream processes needed to optimise their performance. However, there are still many gaps in the knowledge, which need to be addressed if biofilters are to be designed in a more rational way to efficiently remove the odours and emissions. Optimisation of the performance of biofilters, as an abatement technique, requires a developed understanding of the processes taking place within the biofilter, and a better pragmatic approach to designing biofilters, which can be applied to varying conditions found on waste treatment facilities and monitoring performance. This would enable risk based decisions on whether or not proposed designs and maintenance schedules ensure biofilters control emissions effectively.

The outcome of a recent study (Frederickson et al, 2013) suggested that knowledge gaps still exist and that more specific information is required, on the impact of upstream operating parameters and abatement system characteristics, on the emission of odour and bioaerosols. It was also suggested that an attempts should be made to determine if there is any relationship between odour and bioaerosol emissions, in order to establish the extent to which biofilters may be used to reduce the emission of odour and bioaerosols.

The overall objective of this research project was to determine the extent to which abatement methods, incorporating either open or enclosed biofilters, reduce both bioaerosols and odour emissions from enclosed biowaste treatment operations. The work carried out as part of this research project aims to provide the most complete answers currently possible to the following questions which were defined by Sniffer within the project brief:

1. What current technologies (e.g. combination of biofilter and scrubber) are being used throughout the UK biowaste industry to treat emissions?

2. What emission concentrations are being achieved by current technologies under operational conditions, and what rates of reductions relative to untreated emissions do these represent?
3. What design configurations and operating conditions (e.g. empty bed residence time, media type, moisture content, etc.) are required to ensure that maximum reduction rates are achieved, taking into consideration the different processes?
4. What is the degree of aerobicity/anaerobicity in existing, enclosed, biowaste treatment processes?
5. How significant of an impact does the degree of aerobicity/anaerobicity have on the levels and types of bioaerosol and odour emitted?
6. What impact does the ratio of aerobic to anaerobic activity at a site have on the site's overall environmental performance?
7. Which technology (or technologies) might be put forward as candidates for Best Available Techniques (BAT) for bioaerosol and odour abatement?
8. What final bioaerosol and odour concentrations are achievable by the candidate BAT(s) for each of the available, enclosed, biowaste treatment operations?

In order to be able to answer some of these questions, and to be able to attempt to recommend a joint Best Available Techniques (BAT) for bioaerosol and odour abatement, it was necessary to carry out an evaluation of the emission of odour and bioaerosols at a range of enclosed biowaste treatment sites. The overall objectives of the visits were:

- to undertake monitoring for odour and bioaerosols across the abatement system under different operating conditions;
- to determine the degree of aerobicity/anaerobicity of the process at the time of sampling using the plant operating data;
- to establish the process operations being undertaken at the time of sampling;
- to establish the design and operating parameters for the abatement system at the time of sampling;
- to determine the impact of upstream plant operating conditions on the emission of odour and bioaerosols;
- to determine the impact of abatement system design and operation on the performance of the system in terms of odour and bioaerosol removal.

The report contains an overview of the current literature relating to odour and bioaerosol abatement at enclosed biowaste treatment sites, details of the fieldwork undertaken as part of the project including site selection, and the sampling and analysis methods used and the results of the sampling undertaken at the biological waste management sites. This is then

followed by a discussion of those results, together with a comparison with what is already known in the literature. All this data is then used to put forward design and operational criteria for best practice application of biofilters for bioaerosol and odour abatement, and provide some information regarding the final bioaerosol and odour concentrations that may be achievable by the candidate BAT(s) for each of the available, enclosed, biowaste treatment operations.

2.0 Literature review

The following sections provide an overview of the literature relating to the emission of odour and bioaerosols from enclosed biowaste treatment sites. Published information is presented on the removal of odour and bioaerosols by biofilters and scrubber/biofilter combinations, and the emission concentrations that have been measured. The literature reporting on the results of full scale plant is limited, therefore this study provides a mix of papers and reports from both controlled laboratory and pilot scale.

It was acknowledged by Frederickson *et al* (2013) in their recent report that the literature evaluating bioaerosols and biofilters remains fairly sparse. To date very few papers, except perhaps Sanchez-Monedero et al (2003) have evaluated the condition of a biofilter (moisture content, media age etc.) in relation to its ability to remove bioaerosols and particulates.

The relative merits of full scale monitoring compared to laboratory and pilot scale experimental data was discussed in VDI3477 (2004). It suggested that data originating from laboratory scale experiments using biofilter bed volumes less than 1 m^3 are far too small to allow a scale-up. It added that experimental plants tend to be operated for only short periods of time. As a result they do not take account of the fact that the performance of a full-scale biofilter may change significantly in the course of its service life.

VDI3477 (2004) did acknowledge that laboratory-scale experiments are invaluable for conducting comparative studies and investigating the basic mechanisms. They also stated that they are unsuitable for establishing design and sizing criteria for full-scale plants. Valid results can only be obtained by field testing in pilot plants that process the actual waste gas stream to be treated. This was also acknowledged by Frederickson *et al* (2013) who stated that the variable nature of the removal efficiencies is often a feature of laboratory studies and can be misleading.

2.1 Odour and bioaerosol emissions from biowaste treatments sites and the impact of feedstock type and operating conditions.

Frederickson *et al* (2013) reported that the nature and concentration of odour compounds emitted during composting will be related to a variety of factors. These include the composition of the waste, the stage of composting and the temperature and aerobicity of the composting pile. This was supported by Pohle & Kliche (1996) who identified three stages in the aerobic composting process: the acid start stage; a thermophilic stage; and a cooling stage, and suggested that specific odorous compounds are associated with each stage.

Schlegelmich *et al* (2005) reported that in accordance to Krzymien *et al*. (1999), their experiment showed that critical odour concentrations are released mainly during the first 2–

3 weeks of the composting process. The odour concentration reaches its maximum after a week, and slowly starts to decrease to around 3000 OU_E/m^3, and even below 1000 OU_E/m^3 during the last 2 weeks of composting.

Frederickson *et al* (2013) found that very high odour concentrations are associated with in-vessel exhaust emissions. They obtained a range of high odour concentrations in exhaust gases with a maximum value of >2 million OU_E/m^3. They reported odour data of more than 6-8 million OU_E/m^3 from other sources. Pagans *et al* (2005) stated that the exhaust gases from composting are usually characterised by high flow rates and low pollutant concentrations, which conflicts with Frederickson *et al* (2013). These variations are likely to be due to the different designs of extraction system that are applied across the composting sector, and variations in feedstock.

Data obtained by the Odournet group, during a range of unpublished privately funded studies conducted between 2005 and 2013 at biowaste treatment and composting facilities across Europe indicate that the odour concentration varies significantly from site-to-site. The degree of variation was attributed to a complex range of factors, which include the configuration of the extraction systems, the type of composting process being used, the feedstock type and quality, and the air extraction rate. No direct correlations were identified between odour concentration and specific process types or feed stocks. Higher concentrations were observed in systems where air was extracted directly from the composting tunnels, as opposed to combined ventilation from waste reception and processing halls. Odour concentrations of between 1,512 OU_E/m^3 to 338,106 OU_E/m^3 were observed with a mean value of 12,854 OU_E/m^3 (n = 236) (unpublished). The same dataset also shows concentrations of ammonia from 0 to 97 mg/m^3 with a mean of 15 mg/m^3 (n=34); and concentrations of hydrogen sulphide from 0 to 4.2 mg/m^3, with a mean value of 0.3 mg/m^3 (n=44).

According to Liu *et al* (2009), odours are generated due to organic matter decomposition and anaerobic fermentation, especially when insufficient oxygen is available. Kissel *et al* (1992) agreed that under anaerobic conditions, biological oxidation of organic matter is incomplete, and may lead to the production of intermediate decomposition products such as methane, hydrogen sulphide and hydrogen gas. These may then be emitted in the gaseous form and can lead to odour problems. Epstein (1997) reported that even when emitted in low concentrations, reduced sulphur compounds may cause problems. This was attributed to their very low odour threshold values.

Homans and Fischer (1992) suggested that during the thermophilic phase anaerobic conditions due to incomplete or insufficient aeration will produce reduced sulphur compounds. Incomplete aerobic degradation will lead to the emission of alcohols, ketones, esters and organic acids. Shen *et al* (2011) also reported that aerobic conditions are a critical factor determining the discharge of unwanted emissions.

Williams *et al* (2013) found no consistent correlation between bioaerosols and odour and suggested that caution should be applied in drawing conclusions from a relatively limited dataset. They acknowledged that more data was needed before any conclusion could be drawn as to whether odour could be used as a proxy indicator for exposure to bioaerosols. This point was picked up by Frederickson *et al* (2013) who observed that 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.

According to Frederickson *et al* (2013), determining the relationship between specific chemical compounds and human olfactory response can be challenging, as odour perception varies on an individual basis. 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. They found that when the concentrations were lower (0.002-1ppm), the relationship became more complex and that only trimethylamine was observed to have a linear relationship to odour. There was a logarithmic relationship between ethylbenzene and dimethylsulphide and odour, but no relationship was found for p-cymene. They also reported that a linear relationship was observed between acetic acid and odour at concentrations between 0.1 and 50ppm, but none between ammonia and odour at concentrations ranging from 0.5 to 100ppm.

2.1.1 VOC emissions

Pagans *et al* (2006) studied the emission of VOCs produced during composting of different organic wastes using a laboratory scale composting process. They found that concentrations of VOCs in the composting exhaust gases for each waste type ranged from 50 to 695mg Total carbon per cubic metre (C/m^3), for the organic fraction of MSW (5:1 mix with bulking agent), and from 13 to 190mg carbon/m^3 for the same waste with a higher proportion of bulking agent (1:1). In comparison, they found that for raw sludge the VOC concentration ranged from 200 to 965mg carbon/m^3 and for anaerobically digested sludge the emissions ranged from 43 to 2900mg carbon/m^3. 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.

The literature contains a large number of articles in which the components of exhaust gases and in particular VOCs from biowaste treatment are reported. In many cases, the typical components are different and will depend on the waste being treated and the process parameters at the time of sampling. The data in Table 1 was presented by Komalis *et al* (2004) and shows the prevalent VOCs that were emitted from a range of different waste types under laboratory conditions using enclosed vessels and forced aeration. It can be seen that aromatic hydrocarbons and terpenes appear to be emitted during the composting of a range of waste types. On the other hand, alcohols and acids appear to be more waste specific.

Table 1 Prevalent VOCs emitted from a range of laboratory composting reactors (Komalis *et al* (2004)

Waste Type	Prevalent VOCs (listed in descending order of prevalence)
Partially composted MSW	Aromatic hydrocarbons, terpenes, ketones
Mixed paper	Aromatic hydrocarbons, alkanes, alcohols
Green waste	Terpenes, aromatic hydrocarbons, ketones, alkanes
Food waste	Sulphides, acids/esters, alcohols, terpenes
Paper/food waste	Aromatic hydrocarbons, alkanes
Paper/green waste	Acids, ketones, terpenes, aromatic hydrocarbons

Eitzer (1995) found that the primary VOCs released during the composting of MSW were aromatic hydrocarbons, D-limonene, chlorinated compounds and ketones. Pierucci *et al* (2005) looked at the biological treatment of MSW and found that the principle components in the effluent gas were terpenes, monocyclic arenes, alkanes, halogenated compounds and esters.

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 comprised terpenes (65 %), ketones (8 %), hydrocarbons (8 %), alcohols (7 %), esters (5 %), aldehydes (3 %) and sulphur compounds (3 %).

Liu *et al* (2009) reported that the predominant groups of chemicals emitted during the composting of MSW were alkylated benzenes, alkanes, alkenes, terpenes and sulphur compounds. Table 2 shows the typical maximum concentrations of selected compounds reported by Liu *et al* (2009).

Table 2 Maximum concentrations of VOCs emitted during the composting of MSW (Lui et al 2009)

Compound	Maximum Concentration (ug/m^3)
heptane	60
octane	80
nonane	666
n-decane	1061
Hexane	65
cyclohexane	54
Methyl-cyclohexane	4
Toluene	728
Ethylbenzene	4587
Xylene	8100
Ethyltoluene	917

These figures are similar to those reported by Komilis *et al* (2004) and Turan *et al* (2007). Liu *et al* (2009) also reported that alkenes and terpenes were detected in relatively low

concentrations during MSW composting, which is at odds with the findings of Komalis *et al* (2004), who found both in much higher concentrations. The higher concentrations were attributed to the presence of higher proportions of green waste in the MSW but may also be the result of different process operations.

According to Shen *et al* (2011), turning of piles of waste during composting, produces lower CH_4 and N_2O emissions, than the passive aeration of a static pile that has an assured aerobic environment. They reported that composting processes that utilise forced aeration produce even lower CH_4 and N_2O emissions, due to the provision of a more plentiful supply of oxygen. Previous research by the same author looked at the type of aeration pattern used (continuous or intermittent) and suggested that intermittent ventilation can reduce the emission of greenhouse gases. The authors surmised that the reason for this was the promotion of complete denitrification through intermittent aeration, thereby preventing the build-up and eventual emission of nitrous oxide.

2.1.2 Ammonia emissions

Frederickson *et al* (2013) reported that there have been very few published studies looking at the emission of ammonia from full size composting plants and therefore most ammonia emissions data has been obtained from laboratory-scale trials. They acknowledged that ammonia emission even under well-aerated conditions is normal, especially with highly biodegradable feedstock such as municipal solid waste.

Pagans *et al* (2005) 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. Beck-Friis *et al* (2001) found ammonia gas to be the main compound found in exhaust gases from composting, except for carbon dioxide.

According to Kissel *et al* (1992), when the C:N ratio is low, gaseous nitrogen compounds are released and conversely, when the C:N ratio is high, little gaseous nitrogen is released as most of it is incorporated into new microbial biomass.

Pagans *et al* (2006) suggested that temperature, pH, and initial ammonium content are the most important parameters affecting the amount of nitrogen emitted as ammonia. A high temperature and pH favour ammonia volatilization by displacing the NH_4^+/NH_3 equilibrium to ammonia. Table 3 shows the data they obtained and shows that the initial nitrogen concentration had a significant impact on ammonia emissions.

Table 3 Observed ammonia emissions during the laboratory scale composting of a range of feedstock (Pagans *et al*, 2006)

Waste type	Ammonia emission (g NH_3/kg dw)
Source separated organic fraction of MSW	0.32
Dewatered raw sludge	0.10
Dewatered anaerobically digested sludge	0.60
Slaughterhouse waste (high N concentration)	5.30
Partially hydrolysed hair (high N concentration)	20.7

According to Pagans *et al* (2006) ammonia emission under laboratory conditions was strongly dependent on process temperature. During the thermophilic stage (40-65°C), there was an exponential increase when process temperature increased. A linear correlation was found in the final mesophilic (20-40°C) stage. They suggested that this has implications for the operation of the composting process for the achievement of waste material sanitation. They also suggested that the high temperature sanitation stage [Animal By-Products Regulations (ABPR) temperature requirement depends on system being used], should take place after an initial lower temperature thermophilic stage.

Frederickson *et al* (2013) agreed with the findings of Pagans *et al* (2006). They stated that as temperature and pH increase, increased concentrations of ammonia gas will be produced. This will be stripped from the composting pile by high air flow rates subsequently emitted to air. The reason suggested was the higher solubility of ammonia gas at higher temperatures, which would increase emissions. Pagans *et al* (2005) observed that the highest concentration of ammonia corresponded with high composting temperature, showing an intimate relationship between the composting temperature and the ammonia emissions.

Grunditz and Dalhammar (2001) agreed but stated that high temperatures inhibit the nitrification process. They reported that the possibility for ammonia volatilisation is high during the high temperature phase of the composting process. This was supported by Beck-Friis *et al*. (2001) who observed that ammonia emissions started when there was a combination of thermophilic temperatures (> 45°C) and a high pH (~ 9).

Smet *et al*. (1999) reported ammonia concentrations up to 227mg/m^3 in the exhaust gases from composting. Elwell *et al* (2001), Kim *et al* (2009),Shen *et al* (2011), Hong *et al* (1998) and Osada *et al* (1997), all reported that increased aeration rates were associated with increased ammonia emissions. The higher the aeration rate, the lower the emission of nitrous oxide and methane, but the higher the emission rate of ammonia.

2.1.3 Sulphur compound emissions

According to Kissel *et al* (1992), under aerobic conditions, organic sulphur is oxidised almost entirely to sulphate. However, under anaerobic conditions, organic sulphur may be reduced and form potentially odorous volatile organic sulphur compounds. They report that even

when a composting pile is well aerated, there will inevitably be anaerobic pockets and that potentially odorous gases may be released from these microsites. In order to avoid such problems, they suggested that rapid continuous aeration should be provided. Homans & Fischer (1992) agreed that anaerobic conditions during thermophilic composting 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.

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 during mushroom composting. Liu *et al* (2009) reported that the high aeration rate resulted in the relatively low concentration of sulphur compounds detected during their pilot scale composting experiments.

2.1.4 Bioaerosol emissions

The literature review carried out by Frederickson *et al* (2013) identified that bioaerosols are likely to be primarily bacteria and gram-negative bacteria, and that a substantial proportion may be anaerobic. They found that a tunnel composting system, treating green waste and food waste, emitted bacteria at 3.75 x 10^5 cfu/m^3, gram negative bacteria at 1.81 x 10^5 cfu/m^3 and fungi at 4.2 x 10^4 cfu/m^3 (Table 4).

Table 4 emission concentrations of bacteria, gram negative bacteria and fungi from two in-vessel composting facilities (Frederickson et al, 2013)

Parameter	Site C	Site P*
Feedstock material	Source separated green waste and food waste	Green waste and food waste
System	Tunnels	Composting vessels
Aeration system	Forced negative aeration	No detail given
Bacteria (cfu/m^3)	2.82 x 10^5 – 3. 73 x 10^5	5.4 x 10^3 – 7.8 x 10^4
Gram negative bacteria (cfu/m^3)	6.72 x 10^4 – 1.81 x 10^5	1.08 x 10^4 – 1.8 x 10^4
Fungi (cfu /m^3)	9.6 x 10^3- 4.2 x 10^4	0 – 3.6 x 10^3

* The inlet gas stream consists of exhaust air from the composting vessel and the waste reception hall.

In comparison, another plant treating the same waste type using composting vessels emitted concentrations that were an order of magnitude lower. This may have been due to the fact that the air from site 'P' was not solely from the composting vessels, but also from the waste reception hall which may have contributed to the 'dilution' of the air from the composting vessels. The concentration of bioaerosols in the air from the waste reception area will vary depending upon the activities taking place, which may often be intermittent. For example, if fresh waste is being shredded, the concentration of bioaerosols will be significantly higher than they would be if the waste was not being shredded.

Fisher et al (2008) evaluated the concentration of fungi at an in-vessel biowaste treatment facility, although no further information was given regarding the waste type being treated or the composting system. They found that the highest numbers of mesophilic species were found in the loading area (10^4 and 10^7 cfu/m^3), followed by the compost pile hall (10^5 to 10^6 cfu/m^3). For the thermotolerant species a similar trend was observed, but the concentrations in the loading area were nearly as high as in the compost pile hall (10^5 to 10^6 cfu/m^3).

Table 5 shows data obtained from a study conducted in 2003 by Sanchez-Monedero *et al,* in which the concentration of bioaerosols was measured inside the composting hall during normal operations. There does not appear to be a relationship between the concentration of bioaerosols being emitted and either the waste type being treated, or the type of ventilation system/turning being used.

Table 5 Bioaerosol emission from full scale biowaste treatment plants (Sanchez-Monedero et al, 2003)

Waste type	Throughput (wet tons/yr)	Aeration system	A. fumigatus (cfu/m^3)	Mesophilic bacteria (cfu/m^3)
MSW, SS, GW	40000	Forced only	10^5	10^4
MSW, SS, GW	30000	Forced & turning	10^5	10^4
MSW, GW	30000	Forced & turning	10^3	10^5
MSW	76000	Forced & turning	10^2	10^5
SS, GW, FW	28000	Forced & turning	10^3	10^3
SS, GW	5000	Forced only by suction	10^5	10^4
GW, FW	1750	Forced only	10^4	10^3

Figure 1 shows data presented by Kummer and Theil (2008) on *Aspergillus fumigatus* concentrations in the inlet and outlet air to a number of biofilters. No further information was given regarding the process operations or feedstock materials. The concentration of *Aspergillus fumigatus* ranged from 10^2 to 10^5 cfu/m^3, with the majority between 10^4 and 10^5 cfu/m^3.

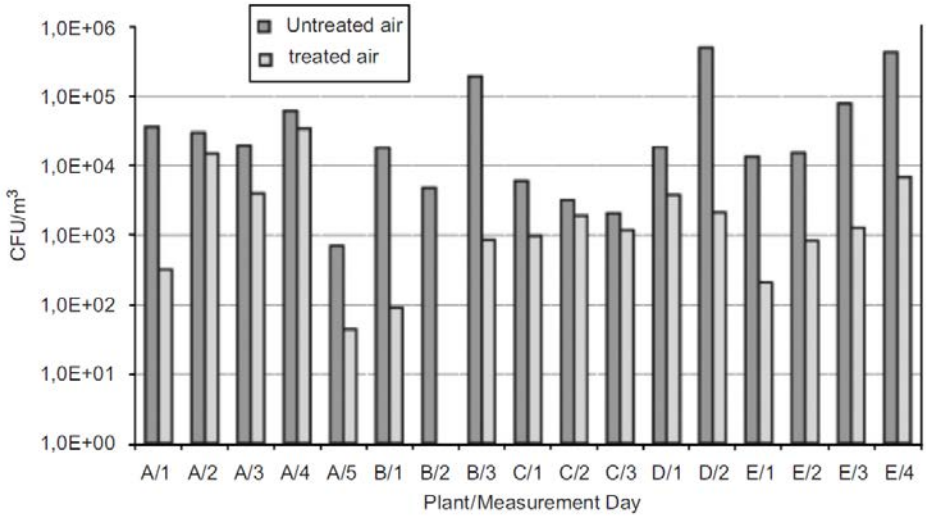

Figure 1 Biofilter inlet and outlet *Aspergillus fumigatus* concentrations at waste treatment facilities (Kummer & Theil, 2008)

2.2 The removal of odour and bioaerosols by biofilters or scrubbers and biofilters in combination

Guidance issued by DEFRA (2009) indicates that biofilters are widely used across a range of industries which generate "organic" odour, including sewage sludge installations, composting installations and pet food factories.

Kummer and Thiel (2008) suggested that biofilters have become successfully established because of their versatility and attractive economics. Frederickson *et al* (2013) suggested that 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.

According to Chung *et al* (2004) biofiltration is regarded as the best available control technology for treating air containing odorous compounds, since it is more cost effective and minimises the creation of secondary contaminated waste streams. Rosenfeld *et al* (2004) also reported that biofiltration was being recognised in the USA by state and air quality regulatory agencies as the best available control technology for treating odour.

VDI2590 (2008) reported that biofiltration is the most common technology for treatment of exhaust air from animal by-products processing plants in Germany. It suggested that current biofilter systems are characterized by an open design, organic filter media and exhaust air conditioning in an upstream spray humidifier with closed water circuit. This suggests that an open design is preferred despite the fact that Heining (1998) reported that enclosed biofilters promise higher efficiencies than open biofilters.

Biofiltration has been put forward as an effective control against odorous emissions (Mohseni & Allen, 2000; Rappert & Muller, 2005; Nevin & Barford, 2000) and many authors have suggested that biofiltration is effective for the elimination of a range of VOCs including ethylbenzene (Alvarez-Hornos *et al* 2008), benzene (Zilli *et al*, 2005), styrene (Jorio *et al*, 2000) and toluene (Rene *et al* 2005). Devinny *et al* (1999) stated that air-phase bioreactors (such as biofilters) can treat highly soluble and low molecular weight VOCs and inorganic compounds. They also said that low molecular weight aliphatic hydrocarbons such as methane, pentane and some chlorinated compounds are difficult to biodegrade.

VDI3477 (2004) reported that biofilters lend themselves to all waste gas cleaning applications involving air pollutants that are readily biodegradable. It also stated that process combinations such as chemical scrubber/biofilter are common practice. Inclusion of a chemical scrubber allows the concentration of pH-relevant exhaust air constituents such as H_2S and NH_3 to be reduced to a tolerable level of approx. 5mg/m^3 for the biofilter media and the microorganisms. Too high a level of these can result in acidification of the filter media and hence, unfavourable environmental conditions for the microorganisms.

A more cautious approach was taken by Colon *et al* (2009), who stated that since biofilters are intended primarily for odour control, there is a question of whether they can be regarded as an effective screen for particulates, and therefore bioaerosol reduction. This was echoed by Frederickson et al (2013), who questioned whether bioaerosol and odour removal in biofilters was mutually compatible.

Weber and Hartmans (1995) also warned that although biofilters have been shown to provide a suitable technology for the treatment of contaminated air, fluctuations in the concentrations of the contaminants in the air can have a negative impact on their performance. This is thought to be the result of inactivation of the microbial population within the biofilter due to the toxic effects of high concentrations of certain contaminants and that this could be mitigated against by having an absorbent either before the biofilter, or incorporated into the biofilter media.

According to Leson & Winer (2012), experience in Europe suggests that biofiltration has economic and other advantages over existing air pollution control technologies when applied to air containing low concentrations of easily biodegradable pollutants. This was supported by Govind (199) and Paques (1997), who agreed that there is also an economic argument for the use of biofilters, since biofiltration investment and operating costs are lower than for thermal and chemical oxidation processes. According to Jager & Jager (1978), biofilters have comparatively low operating costs if used for the treatment of odours exhaust air from composting facilities for MSW.

2.2.1 Odour removal

The general capabilities of biofilters for odour removal are reported in various places in the literature, however literature specific to the composting sector is more difficult to find with most published studies focusing on the removal effectiveness of the technique in terms of specific compounds or VOCs, as presented below. Devinny 1999 raises an important point in relationship to removal efficiency as an indicator of performance, stating that percentage removal is not necessarily a good indicator of comparative performance between biofilters, since it is affected by a range of site specific variables that include flow, inlet load etc.

This point is clearly illustrated in the olfactometry data collected by the Odournet group from biowaste facilities across Europe (Odournet Group, 2013), which indicate that percent efficiency is strongly influenced by variations in the concentration of process air and the inherent odour generated from the media of the biofilter and microbial metabolism. The consolidated dataset of all the biofilter tests indicate a range in percent abatement of between -128% and 92%, with a mean of 76%. The dataset clearly indicates that poorly operating biofilters have the potential to be net generators of odours, and emphasises the importance of careful biofilter design and operational maintenance and monitoring.

Guidance published by SEPA (2010) suggests that biofilters can achieve odour removals of up to 95%, which agrees with the information provided by AfOR (2007), who also state that biofilters generally work at 85-95% odour removal, provided that they are proactively maintained. However, even if a system achieves such a relatively high level of odour removal the remaining emission may still be odorous and cause problems. According to Woodfield and Hall (1994), soil and peat biofilters can be >99% and 95% effective respectively, which agrees with the provided by Ricardo (2013) and the European Commission (2006), which also suggest 99% removal.

2.2.2 VOC removal

Rosenfeld *et al* (2004) set up a pilot scale system using two biofilters in series. Biofilter One consisted of bark & woodchips mixed with mature green waste compost, with a volume of 337m^3, an air flow rate of 82 m^3/min and a retention time (paper does not indicate if this is actual or empty bed) of 4.1 minutes. Biofilter Two consisted of bark & woodchips mixed with compost with a volume of 2407m^3, an air flow rate of 60 m^3/min and a retention time of 4 minutes. Their data (Table 6) shows that the removal of ammonia, dimethyl disulphide, formic acid and sulphur dioxide were very high. However, the same system failed to remove a significant portion of the incoming carbon disulphide or acetic acid even, with a combined retention time of more than 8 minutes.

Table 6 Removal of selected odour compounds using a two stage biofiltration system (Rosenfeld *et al*, 2004)

Compound	Reduction (%)
Ammonia	99
Dimethyl disulphide	91
Carbon disulphide	32
Formic acid	100
Acetic acid	34
Sulphur dioxide	100

Pinnette *et al* (1994) concluded that high levels of ammonium in their biofilter bed contributed to poor odour removal during start up, due to inhibition of biological populations by ammonium.

Ergas *et al* (1995) suggested that interactions between different VOC compounds will influence their biodegradation rates and that inhibition can occur when two or more compounds are present due to preferential uptake of one compound over another, or due to toxic interaction between compounds.

Liu *et al* (2009) reported that during their pilot scale experiments using a compost biofilter with a volume of 180 litres and an empty bed residence time of between 32 and 65 seconds, more than 90% removal efficiency was achieved for alkylated benzenes (except for benzene, 88% and toluene, 82%). They observed higher removal efficiencies for smaller molecular weight compounds e.g. hexane (>85%), pentane (>87%) and octane (>91%) compared to *n*-decane (10%) and nonane (64%). They also reported that the removal of sulphur compounds was high, at more than 99%. However, for terpenes the removal was much lower.

McNevin and Barford (2000) presented VOC removal rate data from various authors and this can be seen in Table 7. It is obvious from this data that the removal rate is dependent upon the VOC and that even the same VOC can have a different removal rate, as highlighted by Togna & Singh (1994) and Hodge & Devinny (1995), who quoted removal rates of 175 $g/m^3/hr$ and 29 $g/m^3/hr$ respectively for ethanol. The data presented by McNevin and Barford (2000) is lacking in additional information regarding the characteristics of the biofilter. It is therefore not possible to determine if there are variations in removal of VOCs, due to different design and operating parameters.

Table 7 Different VOC removals quoted by various authors as reported by McNevin and Barford (2000)

Biofilter	VOC	Removal rate	Author
compost, oyster shell & perlite	Non-methane HC	0.314 g/m^3/hr	Kapahi & Gross (1995)
compost, oyster shell & perlite	Benzene	0.13 g/m^3/hr	Ergas *et al* (1995)
No details given	VOC	20 g/m^3/hr	Knauf & Zimmer (1994)
No details given	Triethylamine	140 g/m^3/hr	Tang *et al* (1996)
No details given	Ethanol	175 g/m^3/hr	Togna & Singh (1994)
No details given	Ethanol	29 g/m^3/hr	Hodge & Devinny (1995)
No details given	Methyl ethyl ketone	121 g/m^3/hr	Deshusses *et al* (1995)
No details given	Printing solvents	80 g carbon/m^3/hr	Rothenbuhler *et al* (1995)

Ergas *et al* (1995) reported that they were able to consistently achieve more than 90% reduction in the concentration of difficult to degrade aromatic compounds. They also showed that the removal of benzene, toluene and xylene decreased when the residence time in the biofilter was reduced from 3 minutes down to 1 minute and this demonstrates that the removal of aromatics requires longer retention times. During their study, the inlet concentration of aromatics varied significantly but the removal efficiency of the biofilter was not affected.

Tunee (2011) investigated the removal of a range of VOCs using two different biofilters containing different media (Table 8). It can be seen that regardless of the type of VOC, the performance of the two biofilters was comparable. The largest difference in performance was seen for hydrogen sulphide, with a lower removal using the peat biofilter. However, even in this case the difference was only 6% and therefore may not be statistically significant.

Table 8 VOC removal using two different biofilters with different media types (Tunee, 2011)

VOC	Removal (%)	
	woodchip	peat
Benzene	94.2	92.3
Toluene	95.1	94.2
m-,xylene	95.4	95.2
o-xylene	93.8	93.9
Styrene	93.0	95.9
Isoprene	97.8	92.6
Ammonia	85.3	83.9
Chloroform	86.6	82.9
Hydrogen sulphide	91.4	85.4

The data presented by the European Commission (2006) can be seen in Table 9. It again does not include any details regarding the biofilter used. Therefore, it is not possible to determine the impact of biofilter design and operating parameters on its performance.

Table 9 Biofilter efficiency in treating mechanical biological treatment gas streams (European Commission, 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

Data presented by Devinny *et al* (1999) also includes the media used in the biofilters and in the case of selected VOCs shows the effect of the biofilter media on the elimination capacity of different biofilters (Table 10). For benzene, toluene, ethylbenzene and xylene (BTEX) the removal varies depending on the media used, with the highest elimination capacities observed for carbon coated foam, and the lowest removals for the same biofilter. In the case of dimethyl sulphide, the highest removal efficiencies were observed for wood bark (70 $g/m^3/h$), with values for the compost and compost/pine mulch being much lower, between 10-13 $g/m^3/h$. The largest variations were observed for methanol, with a compost biofilter achieving 18-70 $g/m^3/h$ and the compost/perlite mix achieving 301 $g/m^3/h$.

Nicolai and Janni (2001) observed that some VOCs can be produced as by-products of microbial oxidation in biofilters.

Table 10 Elimination capacity of common odorous compounds. (Devinny *et al* (1999).

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

2.2.3 Ammonia removal

Pagans *et al* (2005) suggested that biofilters can achieve a high degree of ammonia removal (95-98%) using a range of different media types, either organic or inorganic. According to research carried out by Classen *et al* (2000), Hong *et al* (2000) and Janni (1999), looking at the use of biofilters to treat swine and dairy building air, a biofilter is capable of achieving between 55% and 82% reduction in ammonia, which is lower than the figures quoted by Pagans *et al* (2005).

Pinette *et al* (1994) reported an ammonia removal rate of 1 g/m^3/hr for a biofilter containing compost, bark mulch and woodchip. This is significantly lower than the figures quoted by Kapahi and Gross (1995), who observed removal rates of 10.6 g/m^3/hr for a biofilter using a mixture of compost, oyster shell and perlite, which corresponded to a removal efficiency of 96.4%. In contrast, Bonnin *et al* (1994) found that the peat biofilter in their study was only capable of an ammonia removal rate of 0.2388 g/m^3/hr. However, this did correspond to a removal efficiency of 98.3%.

Liang *et al* (2000) reported that in his study a compost biofilter achieved ammonia removal efficiencies above 95%, with loads ranging from 0.33 to 16.25 mg NH_3/kg media/hr and an EBRT of between 31.8 to 78 seconds.

Studies carried out by Chung *et al* (2003) and Park *et al* (2002) on biofiltration of exhaust gases in composting facilities, indicated ammonia reductions of 98% for an average loading rate of 10,180 mgNH^3/ m^3/hr and an EBRT of 16 seconds.

Pagans *et al* (2005) reported ammonia removals for a laboratory scale biofilter, which was 0.2m in diameter, had a media depth of 0.23m and a volume of 0.0072m^3 with a volumetric loading rate of 0.69 m^3/m^3/min, and gas retention time of 86 seconds. In general as the loading rate increases, the elimination capacity for ammonia also increases (Table 11). However, this data shows that the loading rate appears to have no impact on the removal efficiency. For example efficiencies of over 90% were achieved at loading rates ranging from 846 to 7500 mg NH_3/m^3/hr.

Table 11 Ammonia removal efficiency of a laboratory scale biofilter using inlet gas from a range of feedstock (Pagans *et al*, 2005)

Gas source	Loading rate (mg NH_3/m^3/hr)	Elimination capacity (mg NH_3/m^3/hr)	Removal efficiency (%)
OFMSW (5:1)	846	829	98.9
OFMSW (1:1)	7500	7170	95.9
DS	6670	6580	99.4
AP (day 1-4)	67100	61300	89.5
AP (day 4-9)	37500	21700	46.7

Contradictory reports have been presented regarding the presence of inhibition, with Smet *et al* (2000) reporting no toxicity effect of ammonia even at ammonia concentrations up to 550 mg/m^3, whereas Baquerizo *et al* (2004) reported that a high concentration of free ammonia in the support media can strongly inhibit the biological activity of a biofilter.

Data collected from biowaste sites by the Odournet group (Odournet Group, 2013) indicated removal efficiencies for ammonia of up to 100%. In many cases, the concentration of ammonia emitted from the biofilters was below the lower limit of detection of the analytical technique employed.

2.2.4 Hydrogen sulphide removal

Data presented by McNevin and Barford (2000) illustrated the variability in the removal rates observed for hydrogen sulphide and quoted in the literature. Pinnette *et al* (1994) found a hydrogen sulphide removal rate of 2.361 g/m^3/hr for a biofilter containing compost, bark mulch and woodchip. In comparison Bonnin *et al* (1994) found a significantly higher removal rate of 10 g/m^3/hr for a biofilter containing peat, which corresponded to a removal efficiency of 99.9%. This in turn was significantly lower than the figure of 130 g/m^3/hr

quoted by Yang and Allen (1994) for a bench scale compost biofilter, which also corresponds to a removal efficiency of 99.9%. Brennan *et al* (1996) studied a bench scale peat biofilter and found a removal rate of 8.3 g/m^3/hr (99.9%), which is similar to that quoted by Bonnin *et al* (1994). The highest hydrogen sulphide removal rate was observed by Ergas *et al* (1995) who found that their compost, oyster shell and perlite biofilter removed 99.9% of the hydrogen sulphide which equates to a removal rate of 420g/m^3/hr.

According to Yang and Allen (1994) at loading rates of more than 150 g/m^3/hr the removal rate levelled off at approximately 130 g/m^3/hr, which implies that a maximum biological degradation rate had been reached. They also found that sulphate concentrations of more than 25 mg S/g dry compost inhibited the performance of their biofilter.

Data collected from biowaste sites by the Odournet group (unpublished) indicates removal efficiencies for hydrogen sulphide of up to 100%.

2.2.5 Bioaerosol removal

VDI3477 (2004) observed that to date bioaerosol emissions from biofilters have not been fully researched. Kummer and Thiel (2008) stated that as biofilters vary greatly in both design and operating conditions, it is difficult to make a general statement on their bioaerosol removal efficiency. Results from various studies suggest that the composting-specific microbiological parameters are retained in the biofilter even though the removal efficiency and the exit gas concentrations are subject to great variability (Schilling *et al*, 1999). However, they acknowledged that many of these measurements were not performed under standardised conditions (e.g., isokinetic sampling, concurrent clean gas and raw gas measurements) so that the results may not be representative.

Chung *et al* (2004) were also cautious when they stated that although the odour reduction capabilities of biofilters are considered promising the environmental risk associated with release of bacteria from these systems needs to be assessed. They suggested that the key factor affecting bioaerosol emission is the immobilisation efficiency. During their experiments using a pilot scale biofilter they found a range of microorganisms were released during the 90 day operation with concentrations up to 2.6 x 10^4 cfu/m^3, although they found no significant relationship between flow rate and bioaerosol concentration. Quoting a series of acceptable microbial air quality figures led them to conclude that the emissions they recorded were acceptable and therefore granular activated carbon (GAC) has the potential to be used as an effective biofilter media.

Ottengraf & Konings (1991) investigated the effect of a range of full scale biofilters on the concentration of bioaerosols (Table 12) and they reported that from their results biofilters were net emitters when the inlet concentrations were low and were net reducers when concentrations were higher in the inlet. They also noted that at low gas velocities the concentration of bacteria in the outlet was generally higher than that going in (i.e. net

emitters,) and there was a clear decreasing trend in outlet concentration at increased gas velocities.

Table 12 Bioaerosol emissions from a range of full scale biofilters (Ottengraf and Konings (1991)

Biofilter type	Media	Area (m^2)	Media height (m)	Gas flow rate (m^3/hr)	Bacteria (cfu/m^3)	Moulds (cfu/m^3)
Closed	Compost & polystyrene	24	1	9000	1750	1180
Open	compost	25	0.75	750	4780	600
Closed	Compost & polystyrene	14	1	3000	217	-278
Open	Peat & heather branches	300	1	60000	-10,000	30
Open	Peat & heather branches	225	1	30000	-7500	125
closed	Compost & polystyrene	20	1	8000	440	16

Sanchez-Monedero *et al* (2003) carried out bioaerosol sampling at seven full scale composting facilities treating a range of materials (Table 13). However, the quoted removal efficiencies and elimination rates in this paper must be treated with some caution since the sampling methodologies used were not standardised and in particular the biofilter outlet samples were taken by simply placing a 6-stage Andersen sampler approximately 40cm above the surface of the biofilter and no enclosure was used. As a result the biofilter emission concentrations will be underestimated due to the fact that the exhaust air coming directly from the biofilter will have been diluted by the ambient air. Therefore it is highly likely that the results presented here are an overestimation of the actual bioaerosol reductions achieved by the biofilters. The removals quoted range from 90% to more than 99% for *A. fumigatus* and between 39% up to 94.2% for mesophilic bacteria. The observed removal rates for mesophilic bacteria were extremely variable with very low rates observed for a compost/woodchip biofilter with media that was only 1 month old up to more than 94% for a peat biofilter.

Table 13 Results of bioaerosol sampling at a number of full scale biofilters treating exhaust air from enclosed biowaste treatment facilities. (Sanchez-Monedero *et al* 2003)

Waste type	Throughput (wet tons/yr)	Aeration system	Biofilter dimensions (m^2 x d)	Biofilter media	Age of media (m)	Air flow rate (m^3/hr)	Residence time (s)	*Aspergillus fumigatus*		Mesophilic bacteria	
								Rem (%)	Elimin rate (cfu/m^3/hr)	Rem (%)	Elimin rate (cfu/m^3/hr)
MSW, SS, GW	40000	Forced aeration only	1500 x 1.1	Compost, woodchip	12	165000	36	99.4	2.2×10^7	89.6	2.5×10^6
MSW, SS, GW	30000	Forced aeration & turning	700 x 2.4	Pine bark	18	70000	86	90.4	3.0×10^5	88.6	7.9×10^5
MSW, GW	30000	Forced aeration & turning	450 x 1.3	Compost, woodchip	12	50000	42	98.0	2.1×10^5	74.7	8.1×10^6
MSW	76000	Forced aeration & turning	400 x 1.3	peat	36	-	-	-	-	94.2	-
SS, GW, FW	28000	Forced aeration & turning	572 x 1.8	Compost, woodchip	1	100000	37	97.9	$4.65x\ 10^7$	39.1	2.2×10^5
SS, GW	5000	Forced aeration only by suction	110 x 1.2	Compost, woodchip	12	16000	29	99.3	1.1×10^7	68.1	2.2×10^6
GW, FW	1750	Forced aeration only	6.75 x 1	Compost, woodchip	12	250	97	98.7	4.4×10^5	71.9	2.2×10^5

SS – sewage Sludge, GW – Green waste, FW – food waste

Seedorf J & Hartung J (1999) reported that in their study the biofilter reduced the amount of mesophilic bacteria by 11% and 71% respectively, and the amount of thermotolerant fungi by 71%. The concentrations of endotoxin and mesophilic fungi in the clean air after the bioscrubber were 3.8 times and 2.7 times higher than in the air of the piggery respectively.

Martens *et al*. (2001) found a reduction potential for bacteria in half technical scale biofilter units between 70 and 95%, while much less reductions of only 11% were observed in a commercially operated biofilter at a pig house.

Seedorf J & Hartung J (2002) investigated the bioaerosol removal of a container based biofilter system incorporating an upstream water scrubber (Table 14). Their results show that there were differences in the reduction efficiency of the scrubber and the biofilter between sampling days in the same plant and that this was particularly pronounced for fungi.

Table 14 Bioaerosol reduction by a container based scrubber/biofilter system (Seedorf & Hartung, 2002)

Day	Reduction across scrubber (%)		Reduction across scrubber & biofilter	
	Bacteria	Fungi	Bacteria	Fungi
1	86.7	68.5	98.3	97.9
2	90.5	13.4	99.1	73.1
3	53.6	49.5	94.5	85.3
4	74.1	17.5	96.9	74.9
5	65.8	58.8	95.4	95.2

Fredrickson *et al* (2013) presented data from a range of publications in which the performance of full scale facilities were monitored (Table 15). It is clear that the sampling techniques used varied considerably from one study to another and included impingers, filters and impaction samplers. It is also apparent that the removal of bacteria and fungi varied significantly from one study to another. Fredrickson *et al* (2013) observed that as a general trend bacteria had lower removal efficiencies in some of the studies than fungi (as low as 11 to 30 % in some studies, but 90% or better in others). Fungi, where measured, appeared to have higher removal rates (from 49% through to 100%).

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.

Table 15 Scientific literature evaluating biofilter performance and bioaerosols (Frederickson *et al*, 2013)

Sampling method	Load rate into biofilter cfu m^{-3} or EU/ng m^{-3}	Media type	Bacteria removal efficiency (%)	Fungal removal efficiency (%)	Reference	Other points to note
Millipore impinger	Bacteria n.d. – 10^4 Mould n.d.- 302	Polystyrene, compost Peat-heather	Not specified	Not specified	Ottengraf & Konings, 1991	Used 'generalised media' to culture
Sampled particles	Not found	Not found	11-71	71	Seedorf & Hartung, 1999	Bioscrubber 22% efficiency quoted
Polycarbonate filters (total counts), glass fibre (endotoxin)	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	Martens *et al.*, 2001	Five different biofilter materials tested
AGI-30 impinger	10^6 bacteria, 10^3 fungi, 10-216 EU.	Wood shavings	90 ~92 endotoxin	73	Seedorf & Hartung, 2002	Dust 83%. Note 2 scrubbers in line
Six-stage Andersen sampler 1 min	2.7 x 10^2 to 2.2 x 10^5cfu m^{-3}	Coarse fraction compost, peat Pine bark & roots	40	90	Sanchez-Monedero *et al.*, 2003	Media as for AfOR. 78% AF 2.1µm+ 35% bacteria
AGI-30 impinger & polycarbonate filters (cfu)	1.0-4.2 x 10^7 biofilter inlet	Coke/compost and root wood Coconut fibre	58-80 99	90	Schlegelmilch *et al.*, 2005	Bioscrubbers (21% meso reduction, 77% for thermos)
Filters VDI 4252 /4253 gelatine & polycarbonate	1.0 x 10^8 'raw gas'	Not specified, only that it is 'wet' or 'dry' at stages	90-100	90-100	Haumacher *et al.*, 2005	Best results found for wet biofilter & non-thermplasma
AS-50 and PVC filters. Various agars, API strips, endotoxin	10^{5-6} bacteria and 10^{5-6} fungi inc. A. fumigatus	50% compost/peat only mix 40% compost/peat & 20% bentonite 40% compost/peat & 20% halloysite	100 GN17 endotoxin 100 GN 52 endotoxin 99.6GN11 endotoxin	Not tested	Tymczyna *et al.*, 2007	Dust removed at 82-87% efficiency in all three biofilter mixes

Sampling method	Load rate into biofilter cfu m^{-3} or EU/ng m^{-3}	Media type	Bacteria removal efficiency (%)	Fungal removal efficiency (%)	Reference	Other points to note
Exhaust gas passed via water	10 gram-negative (GN) bacteria, 11ng m-3 endotoxin, 0.9 mg m-3 dust (means)	Granule activated carbon	90-98	Not tested	Ho, K-L *et al.*, 2008	Same species at inlet and outlet
Andersen 10s & Sartorius MD8 gelatine filter	10^{5-6} TMC m-3 (total cells)	Shredded tree roots/ polypropylene, both with acid scrubbers	46-84 Andersen, 69-96 MD8	Not tested	(Zhao *et al.*, 2011)	Up to 93% particulates removed
PN-EN 13098:2007 using GilAir 5 and filters	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	Tymczyna *et al.*, 2011	Malt extract agar used for fungi. RH of biofilters 50-68%, temp 23C

Seedorf and Hartung (1999) applied a bioscrubber for the decontamination of air vented from a pig facility and found that it appeared to be an additional source of microbial pollution. Likewise, Martens *et al*. (2001), who studied biofiltration of the pig house air reported elevated numbers of microorganisms in the effluent air.

Several authors have commented on the selectivity of biofilters in terms of bioaerosol removal, with some suggesting that emissions from biofilters might be different from inputs with different species, as well as concentrations. 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.

Biofilter media usually contains more than 10^7 microorganisms/g that colonise the surfaces of the material. The permanent air flow through the biofilter can mobilise some of these attached micro-organisms as demonstrated for fungi by Rabe and Becker (2000). In extreme situations emission quantities may be higher than without a biofilter. From investigations on biofilter surfaces in composting plants it is known that the exhaust gas can contain twice the concentrations of fungi than were found in the inlet gas before the filter (Seedorf 2000).

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. Schlegelmilch *et al*. (2005) in particular stated that 'secondary emissions' were non-pathogenic, compared to biofilter inputs. On the other hand, Ho *et al*. (2008) reported the species between a biofilter inlet and outlet were considered 95% similar and the biofilter was thought to have no species selectivity.

2.3 The impact of biofilter design and operating parameters.

According to Morgan-Sagastume & Noyola (2006) three factors are the key to determining the performance of a biofilter filled with compost material and they are (i) the type of the filter media (including void fraction, particle size, moisture content, microbial diversity and nutrients), (ii) the prevailing conditions of gas flow inside the biofiltration unit (including superficial velocity, gas distribution, temperature and inlet pressure) and (iii) the substrate concentration, solubility and biodegradability. Schlegelmich *et al* (2005) agreed when they reported that the main parameters influencing the efficiency of biofiltration technology for the treatment of odorous emissions are the biofilter material and the type of biofilter used (open/enclosed).

It has been stated in the literature that for optimum growth and metabolic activity, micro-organisms rely on defined environmental conditions such as moisture, pH, oxygen content, temperature and nutrients and that these parameters must be controlled within narrow limits. As microorganisms are affected by changes in their environment, they may require some time for acclimation before developing their full activity after biofilter start-up, or

changes in the operating conditions. Therefore, although biofiltration can be a simple technology, its effectiveness relies on monitoring and then optimising several parameters that promote and maintain a healthy microbial community capable of degrading odorous compounds within the biofilm. 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.

It should be noted at this point that the majority of the work reported in the literature looking at the impact of biofilter design and operating parameters has focussed on the impact on odour and VOC removal and not bioaerosol removal. Since the mechanisms of odour/VOC (adsorption, oxidation and biodegradation) and bioaerosol (impaction) removals are completely different, it is likely that some of the biofilter design and operating parameters that are important in odour and VOC removal are not so critical when it comes to bioaerosol removal. This was acknowledged by Ottengraf & Konings (1991) who developed a model to describe the rate of microbial emission from biofilters and suggested that the mechanisms involved were very different to those associated with odour removal. The two mechanisms suggested were the capture of microorganisms by impingement on the media surface and the emission of microorganisms from the wet bio-layer surrounding the biofilter media particles. They reported that both mechanisms were affected by the air velocity, biofilter media particle size and the size of the bioaerosols.

Woodfield and Hall (1994) reported that the microbiological population within the biofilter must be kept viable and therefore water content, pH, nutrient level and temperature must be controlled within a relatively stable operational range. They also suggested that if the inlet gas stream contains a large amount of dust or fatty acids then it may be necessary to include a scrubber upstream of the biofilter to prevent the biofilter media from clogging. This would also help to pre-humidify the inlet air before entering the biofilter.

2.3.1 Media characteristics

According to Quigley *et al* (2004) the overall effectiveness of a biofilter is largely governed by the properties and characteristics of the support media, which include porosity, degree of compaction, water retention capabilities and its ability to host a microbial population. However, in reality although the selection of media should be based on all these parameters frequently only media with good biodegradation properties tend to be selected.

Alvarez-Hornos *et al* (2008) agreed and stated that one of the key factors affecting biofiltration performance is the characteristics of the biofilter media. Nicolia and Janni (2001) also suggested that biofilter media is critical in biofilter design and performance and that environmental and nutritional requirements for microbial growth (e.g. moisture, temperature and nutrients) must be considered in both the selection and management of the media.

Frederickson *et al* (2013) state that 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.

Leson and Winer (2012) commented that mineralisation of biofilter media over time will lead to compaction and increase in back pressure and that in open systems, this is usually improved by turning of the media after around 2 years of operation, and complete replacement of the media after another 1 to 2 years. This was also commented upon by Woodfield and Hall (1994) who said that depending upon the media type and its maintenance, over time it will start to decompose and compact, which will lead to an increase in pressure drop, a decrease in air flow and a loss of performance and as a result the media will need to be replaced.

According to Devinny *et al* (1999), the most important factors governing biofilter performance are media moisture content, pH and bed temperature, although they did acknowledge that other factors such as biofilter size, airflow distribution and packing material selection are important as they influence the lifetime of the media, or its performance. Table 16 presents typical (not optimum) biofilter operating conditions as presented by Devinny (1999).

Table 16 Typical biofilter operating conditions as presented by Devinny (1999)

Parameter	Typical value
Media height	1 – 1.5m
Area	1 - 3000 m^2
Air flow	50 – 300,000 m^3/hr
Surface loading	5 – 500 $m^3/m^2/hr$
Volumetric loading	5 – 500 $m^3/m^3/hr$
Bed void volume	50%
Mean effective gas residence time	15 – 60 seconds
Inlet pollutant concentration	0.01 - 5 g/m^3
Inlet odour concentration	500 – 50,000 OU/m^3
Operating temperature	15 – 30°C
Inlet air relative humidity	> 98%
Media moisture content	60%
Media pH	6 – 8
Typical removal efficiencies	60 – 100%

Colon *et al* (2009) conducted some monitoring of two full scale biofilters before and after the media was replaced (Table 17) and found that significant improvements in odour removal was achieved after the media was replaced after 4 years continuous operation.

Table 17 Effect of media replacement on the removal of odour in full scale 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)	3950–15800	3950–7900
Gas retention time (s)	25–98	26–52
VOC Loading rate (g C/m^3 biofilter/h)		
Old media	18.0	11.3
New media	22.8	34.4
VOC Elimination capacity (g C/m^3 biofilter/h)		
Old media	11.1	8.6
New media	17.1	27.0
VOC Removal efficiency (%)		
Old media	42	65
New media	74	71
Ammonia loading rate (g C/m^3 biofilter/h)		
Old media	2.68	1.25
New media	2.56	2.86
Ammonia elimination capacity (g C/m^3 biofilter/h)		
Old media	1.12	0.9
New media	2.04	2.52
Ammonia removal efficiency (%)		
Old media	41	74
New media	89	92

Sanchez-Monedero (2003) carried out monitoring of removals of *Aspergillus fumigatus* and mesophilic bacteria at a number of full scale biowaste treatment plants and although they did not comment directly, the data they provide (Table 18) includes the age of the media in the biofilters along with the percent removals calculated from their inlet and outlet data. It is likely that due to the sampling method used for the biofilter outlet samples that the overall removals are overestimates as commented on previously. It can be seen that there does not appear to be a clear relationship between the age of the media and the removal of *Aspergillus fumigatus*. The removal varied very little between 1-12 months, but there did appear to be a drop when the media was 18 months old. For the mesophilic bacteria the removal varied from biofilter to biofilter even at the same media age and the highest removal was found for the oldest media at 36 months and the lowest removal was found for the youngest media at only 1 month old.

Table 18 Influence of media age on the removal of Aspergillus fumigatus and mesophilic bacteria by biofilters (Sanchez-Monedero et al, 2003)

Age of media (months)	Removal (%)	
	Aspergillus fumigatus	Mesophilic bacteria
1	97.9	39.1
12	99.4	89.6
12	98.0	74.7
12	99.3	68.1
12	98.7	71.9
18	90.4	88.6
36	-	94.2

2.3.1.1 Moisture content

Williams and Miller (1992) reported that bed moisture content was the single most important parameter for biofilter viability and suggested that optimal moisture contents varied from 20 to 60%. They suggested that biological activity ceases if the moisture content of an organic material is too low; if it is too high this leads to anaerobic zones forming in the bed where oxygen required for bio-oxidation is depleted. Devinny et al (1999) agreed and added that lack of control of moisture content is the most common cause of poor biofilter performance. This view was supported by Frederickson *et al* (2013) who also stated that 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. They suggested that the optimum moisture content is 30-60% water, the optimum level of which is dependent on the support medium used.

According to VDI3477 (2004) when biofilter media is overly wet this will lead to water-logging and that under these conditions, the pores of the filter media are filled with water which block the gas flow. This not only affects the removal efficiency, but also leads to oxygen depletion and insufficient oxygen supply for the microorganisms. As a consequence, metabolic end products can be produced which are similar to those formed by decaying organic materials and have a very unpleasant smell.

Budwill and Coleman (1999) also commented on the importance of moisture content and suggested that if the media is too dry it will not support the establishment of a suitable microbial population and if it is too wet the porosity will be reduced and high back pressures will lead to reduced air flow.

According to Leson and Winer (2012), the moisture content of the inlet air to a biofilter should be controlled at 40-60% using humidification of the inlet air or spray irrigation on the surface of the biofilter. This is in agreement with Pinnette *et al* (1994), who reported a loss of biological degradation of odorous compounds when moisture content dropped below approximately 40% and also Mudliar *et al* (2010) who suggested optimum moisture content is 30-60 per cent water (by weight).

This is a slightly lower moisture content range to that quoted by Hong *et al* (2013) who suggested that biofilters operate most efficiently when the moisture content falls within the range 50-70%. This is in agreement with Ottengraf and Van den Oever (1983) who kept the moisture content in their biofilter between 50–70% and found that at lower water levels, the organic packing lost its microbial activity, while higher water content promoted the development of anaerobic zones in the bed.

Ergas *et al* (1995) found that when investigating the performance of a full scale biofilter the results improved when water was added to the filter media as the media moisture content was found to be well below 50%. They found that the removal of aromatic VOC and hydrogen sulphide increased dramatically and almost immediately when the moisture content was increased slightly from below less that 50% up to 55%.

Nicolia and Janni (2001) investigated the impact of the compost/woodchip ratio on the performance of their pilot scale experimental biofilter which had an air flow rate of 81.5 m^3/hr and an EBRT of 5 seconds. They investigated compost/woodchips mixtures containing 0% 10% 20% 30% 40% and 50% compost and found odour reductions of 67.5%, 67.2% 84.3% 82.6% 81.6% and 83.2% respectively. They also looked at the impact of moisture content at the different compost/woodchip ratios and found that at lower moisture contents the odour reduction improved as the percent compost increased. However, at higher moisture contents the percent compost had no effect on odour removal. During the same study the removal of hydrogen sulphide was unaffected by the percent compost at medium and high moisture contents and for low moisture contents little hydrogen sulphide removal was observed which would suggest that moisture content is the critical factor. For ammonia, the removal increased as the percent compost increased and also the higher the moisture content the higher the ammonia removal.

The importance of moisture content was considered by Lu *et al* (2002) who suggested that a pre-humidification system should be established to ensure the inlet air humidity is close to 100%. This agrees with VDI3477 (2004), which suggested that in order to maintain the required moisture content of the filter media, additional surface irrigation will be needed, regardless of the humidity and water saturation level of the waste gas feed. Depending on the type of media, a moisture content of between 40 % and 60 % is recommended.

Some biofilter media such as peat are hydrophobic and therefore they are difficult to moisten and Devinny *et al* (1999) also suggested that when common biofilter media are

allowed to dry out they become hydrophobic and therefore attempts to re-wet them may take some time.

Devinny et al (1999) discussed the importance of moisture content, however rather than suggesting optimum moisture content ranges they talked about field capacity, a concept more familiar to soil scientists. Field capacity is the point at which a porous material contains enough water so that any additional added water will drain away under gravity. They suggested that biofilters are typically operated at around 50% of the media field capacity. The moisture content at field capacity will vary depending on the biofilter media because of their different surface areas, affinities for water and pore size distribution. The field capacity of any particular porous material can be measured relatively easily by taking 100g of the biofilter media and placing it into a funnel which has a small piece of cotton wool fitted into its neck. The funnel is then placed over the top of a 100ml measuring cylinder and 100ml of water is added evenly over the surface of the media. After one hour, the volume of water retained by the media is calculated by difference to provide the % (vol/vol) field capacity. For example, if 45ml of water is in the measuring cylinder then 55ml has been retained by the media and therefore the field capacity is 55% vol/vol.

According to Woodfield and Hall (1994), moisture content is very important for maintaining a viable microbial population within the biofilter. They suggested that a daily visual inspection of the biofilter should be carried out in order to check for dry spots and/or channelling of the irrigation water of inlet gas stream. They stated that it is essential to keep biofilter material irrigated and that a peat/heather biofilter will work well when the moisture content is around 60%, although they also suggested that the exact figure is not too critical. If the media is allowed to dry out, it will cease to function and in the case of peat this can be a major problem as it is very difficult to re-wet. On the other hand excessive watering should also be avoided as it can lead to flushing out of the valuable microbial population from the media. They went on to say that while pre-humidification is a good idea, it cannot supply sufficient moisture to meet the total water requirements of the biofilter bed and that it is likely that surface irrigation will also be required.

2.3.1.2 Temperature

Devinny *et al* (1999) suggested that microbial activity and therefore the performance of a biofilter are strongly influenced by temperature. Each microbial species is adapted to a certain temperature range within which its reaction rates will be optimised. In general the metabolism of microorganisms reduces as the temperature decreases thereby reducing the rate at which contaminants are biodegraded. However, outside this range if the temperature rises too far, the microbes will reach a point at which their metabolic activity drops off rapidly. If the temperature drops too far below the optimum range the microbe's reaction rate will slow down and they will eventually become dormant and may die.

Different microbial species have a different maxima and range over which they operate effectively. If biofilters contained a single microbial species then the best strategy would be to operate at the optimum temperature for that species. However, in reality biofilters contain 100s or 1000s of different species and this varied microbial ecosystem will be more adaptable to changes in temperature. If the temperature changes suddenly, many of the species within the media will become inactive and the performance of the biofilter will drop dramatically. However, if that change in temperature is less significant, the efficacy of the biofilter may be affected, but is likely to recover. This is because some microbes within the biofilter will become acclimatised and will become the dominant species. Therefore, in their opinion the key issue is to avoid is a sudden change in temperature and fluctuating temperatures may cause problems.

According to Tunee (2011), most microorganisms operate efficiently at a temperature ranging from 15 to 30°C and the higher the temperature the higher the metabolic and hence biodegradation rate up to around 40°C. On the other hand the solubility of many compounds and adsorption rates decrease with increasing temperature. Tunee (2011) indicated that 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.

A number of authors have carried out experiments or monitoring of full scale facilities and come up with observations of the effect of temperature and recommendations for the most appropriate operating temperature for biofilters.

According to Hong *et al* (2013), biofilters operate most efficiently at a temperature of between 15 and 35°C and they reported that biofilter performance appears to drop when temperatures exceed 40°C. This was supported by Yoon and Park (2002), who stated that 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. They also concluded that rapid operating temperature changes should be avoided as this will result in microbial species becoming inactive, therefore resulting in a decline in treatment.

According to Leson and Winer (2012), a temperature of between 20 and 40 °C should be maintained in the inlet air to a biofilter. This was supported by Frederickson *et al* (2013) who stated that the microorganisms responsible for degrading odorous compounds within biofilms are strongly influenced by temperature and in order to achieve optimum microorganism performance within a biofilter it should be operating between 30 and 40°C.

Bohn (1992) found that low operating temperatures will enhance sorption of odorous compounds into the biofilm, but will slow down the microbial growth and that higher temperatures will have the reverse effect. He suggested that high performance for most odour removing applications occurs within a temperature range of 25–40°C.

Knauf and Zimmer (1994) found that the removal efficiency for organics decreased steadily as temperature of the exhaust increased and for a bark compost biofilter, removal efficiency dropped from 95 to 85% as temperature rose from 40 to 55°C.

Yang and Allen (1994) found that hydrogen sulphide oxidising bacteria present in their biofilter were most active in the temperature range 25–50°C and that the removal efficiency at a constant loading dropped markedly on either side of this temperature range.

Brennan *et al* (1996) found that removal rates for hydrogen sulphide in their biofilter decreased by over 50% when the ambient temperature decreased from 20–22°C down to 9-12°C. In contrast Pinnette (1994) found that once a biological population was established in their biofilter, odour removal above sludge composting facilities was not compromised at temperatures below 10°C.

Tunnee (2011) investigated the effect of temperature on biofilter VOC removals (Table 19) and found that for both the woodchip and peat biofilters the removal of VOCs reached a peak at 45°C and that either side of that temperature the removal dropped off. The author does not elaborate on whether the differences are the result of VOC degradation or changes in volatility.

Table 19 Effect of temperature on the removal of VOCs from two different biofilters with different media types (Tunee, 2011)

Temperature (°C)	Removal (%)	
	woodchip	peat
25	76	60
35	84	86
45	90	96
55	84	77
65	54	54

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 empty bed residence time set to 1.5 minutes and VOC inlet concentration to 92g/m^3. However, decreasing the empty bed residence time at 32°C caused a reduction in VOC removal efficiency to 81%. They also reported that a peat-packed biofilter had the highest VOC removal efficiency when biofilter temperature was set to 32°C (94%) and had an empty bed residence time of 1.5 minutes. They also showed that when the same peat biofilter was operated at only 25°C, empty bed residence time had to be increased to three minutes to get close to the removal efficiency (93%) achieved at 32°C with an empty bed residence time of 1.5 minutes. This demonstrated that achieving optimal VOC removal efficiency in their experiments was a balance between temperature and residence time.

2.3.1.3 pH

Leson and Winer (2012) suggested that since biofilters rely on microbial processes to achieve a reduction in key odorous compounds, and since most microorganisms prefer a specific pH range, changes in media pH can have an impact on their activity and therefore the efficiency of the biofilter as a whole. They also commented that the degradation of some compounds including sulphur and nitrogen containing compounds and chlorinated organics can lead to the production of acidic by-products leading to a drop in biofilter media pH. This is broadly in agreement with the views of McNevin and Barford (2000), who stated that biological metabolism is strongly dependent on pH and generally most biological growth occurs near a neutral pH and wide deviations from this will impair the efficiency of the biofilter.

Frederickson *et al* (2013) suggested that to promote a healthy microbial population within a biofilm and subsequent effective odour treatment, the pH of packing material should be neutral, around pH 6-8. This is similar to the pH ranges stated by several other authors including Hong *et al* (2013) who said that biofilters operate most efficiently at a pH in the range 6.5 – 7.5, and Eitzer (1989) who suggested that biofilter media should have a pH of between 7 and 8.

Unlike Kim *et al* (1998) and Smet *et al* (1996) who observed acidification of their biofilter which was accompanied by a decrease in removal efficiency due to pH inhibition of the biodegradation process, Liu *et al* (2009) did not observe any change in the pH of their compost biofilter media and they cite this observation as a justification for the use of compost based biofilters as an abatement technology for odour.

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).

Yang and Allen (1994) found that hydrogen sulphide removal efficiency in their biofilter decreased markedly at pH below 3.2, but was almost independent of pH at higher values.

Devinny et al (1999) takes a similar stance with pH as that reported previously for temperature as they state that the effects of biofilter pH and temperature are similar in several ways. As with temperature, each microbial species will thrive over a certain range of pH and will be inhibited or killed if conditions move outside that range. Rapid changes in pH will be detrimental to most species however a microbial ecosystem consisting of a large number of different species will adapt to slower changes in pH. According to Devinny et al (1999), most biofilters are designed to operate at pH 7 which is a neutral state. However, there are large numbers of microorganisms that thrive at pH conditions significantly higher or lower than this. The starting pH of different new biofilter media will vary from acidic media such as peat at pH 4-5, up to alkaline media such as activated carbon at pH 10. During the operating lifetime of the biofilter the pH of the media will tend to drop due to the generation of acids.

2.3.1.4 Nutrient content

Biofilters rely on the fact that microorganisms use the contaminants present in the inlet air for the energy and carbon that they provide. Therefore, biofilter performance relies on the presence of a microbial community which in turn relies on the availability of nutrients such as nitrogen, phosphorus and potassium (Devinny et al, 1999). This is supported by Frederickson *et al* (2013), who reported that microorganisms in a 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 nutrients.

Compost based media have the advantage that the required nutrients tend to be present naturally, whereas inorganic media such as activated carbon do not contain any inherent nutrient supply (Devinny et al, 1999). During operation of a biofilter it is important that operators maintain a continuing supply of nutrients.

Gribbins and Loehr (1998), as quoted in Devinny et al (1999), found that degradation rates within a compost/perlite biofilter were limited by the availability of soluble nitrogen and they suggested that the C:N ratio of the media should be maintained a more than 1:100. They also warned that leachate production should be minimised in order to reduce nitrogen losses from the media. Devinny et al (1999) commented that the figure quoted for C:N ratio was higher than previously reported, and suggested that the reason for this is that the significance of nutrient availability was previously unrecognised.

Hwang *et al* (2007) agreed when they suggested that despite the fact that compost based biofilter media contains significant concentrations of organic nitrogen and other micronutrients, nutrient depletion will still occur during long term operation. Williams (1995) and Heining *et al* (1995) suggested that an improper nutrient balance (e.g. due to the presence of too much grass) in the biowaste can lead to excessive VOC and ammonia emission.

The importance of nitrogen in biofilter performance was also highlighted by Morgenroth *et al* (1996), who found that hexane removal efficiency was improved significantly when nitrate was added to the biofilter media. Other researchers have reported that the injection of ammonia gas also increased VOC removal (Morales *et al*, 1998; Wu *et al*, 2006).

Zhu *et al* (2004) reported that biofilter performance depends not only on the availability of VOCs but also on the presence of oxygen and nutrients and substrate biodegradability.

In stark contrast VDI3477 (2004) reported that in odour abatement applications, the ability of the filter media to act as a nutrient and nutrient salt source plays only a minor role in determining performance.

Specific values to evaluate the nutrient content of media are currently absent from the literature. However, criteria to assess the health of biofilter media in terms of specified nutrients (ammonium, nitrate, nitrite sulphate) and related parameters (electrical conductivity) that have been developed on the basis of experience of Ghent University are summarised in Table 20 (personal communication).

Table 20 Criteria for assessing the health of biofilter media (personal communication from Olfascan]

Parameter	Indication of the quality of the biofilter media		
	Optimal	Intermediate	Negative
$NH4^{+}$-NOx-N	0.25 – 3.5 g/kg	3.5 – 5 and 0.15 – 0.25 g/kg	> 5 and < 0.15 g/kg
SO_4^{2-}	<1000 mg/kg	NA	>1000 mg/kg
Electrical conductivity	<1000 µS/cm	1000 – 3000 µS/cm	>3000 µS/cm

2.3.2 Design and operating parameters

In addition to the effects of biofilter media characteristics, there are also a number of operating parameters that can also have a significant impact. However, it is also acknowledged that media type and characteristics will have an impact on some of the key operating parameters.

2.3.2.1 Up-flow or down-flow design

Devinny et al (1999) reported, and Lu et al (2002) agreed, that down-flow operation in enclosed biofilters can offer advantages when it comes to moisture control. Drying out of media tends to occur as a result of either the introduction of unsaturated inlet air into the biofilter, or through the heat generated by microbial activity. Therefore, biofilter media will generally dry out on the inlet side of the bed as this is the first contact point for the 'dry' inlet air and the region of highest microbial activity (since contaminant concentration will also be at its highest). In down-flow biofilters, this will be on the top surface and any drying effect can easily be controlled through the use of surface spray irrigation. Conversely, in up-flow biofilters drying will occur at the bottom of the media bed where it is more difficult to modify moisture levels. However, there are also instances where an up-flow design has advantages and this is particularly true when the biodegradation of the contaminants in the inlet air leads to the production of acids. In an up-flow biofilter, acids will build up in the lower layers of the media bed and trickling water containing a pH buffer will allow the acids to be washed out easily. In comparison, if acids build up in the top layers of the media bed, as would be the case in a down-flow biofilter, the acids would be washed through the entire media depth.

2.3.2.2 Inlet air flow rate

Oxygen is vital to the operation of biofilters because most odour reducing microorganisms are aerobic. 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.

Devinny et al (1999) reported that oxygen limitation may occur in biofilters and that this may adversely affect biodegradation rates even if oxygen is not completely absent from the media. Poor air permeability through the biofilter due to compaction or ineffective air distribution are common causes of oxygen limitation and can lead to the formation of anaerobic pockets within the media that generate malodorous compounds.

Schlegelmilch *et al*. (2005) reported that air flow rate has a minor effect on the efficiency of removal of bioaerosols in a biofilter, and Zilli *et al*. (2005) concluded that velocity has no effect on emissions.

2.3.2.3 Contaminant loading rate

According to Devinny *et al* (1999), contaminant load, which is a measure of the mass of contaminant entering the biofilter, per unit time and per unit volume, has a major impact on biofilter performance. High loads may reduce removal efficiency, and media acidification may be experienced, together with excessive microbial biomass growth and subsequent blocking of the pores within the media. In comparison, biofilters operated at low loads may reach an optimal steady state. They stated that in practice, loads will vary, but that microbial based processes operate best at steady loads.

Swanson and Loehr (1997) and Moussavi *et al* (2009) reported that when referring to mass loading rate often an average value for the entire bed volume is reported. However, the plug-flow nature of biofilters causes most of the degradation to occur at the influent end, so deeper reaches of the biofilter receive smaller mass loads.

According to Devinny *et al* (1999), the performance of a biofilter in terms of elimination capacity can only ever be equal to or less than the mass loading rate. Under low load conditions, the elimination capacity is likely to be equal to the load and the system will therefore achieve 100% removal efficiency. However, if the load increases a point will be reached where the overall mass loading will exceed the overall elimination capacity of the system, and removal efficiencies of less than 100% will be observed.

Lui *et al* (2009) reported that during their pilot scale biofilter experiments total VOC removal efficiency ranged from 20-95%, with higher removal efficiencies when the inlet concentration of total VOCs were lower and therefore loading rates were lower. They went on to report that the elimination capacity of their biofilter increased with increasing inlet VOC loading rate, especially at the higher empty bed residence times. They also reported that for any given pollutant, the elimination capacity of the biofilter increased with

increased inlet loading rate, until a maximum was reached. They quoted a maximum VOC elimination rate of 17.5 g C/m^3/hr at a loading rate of 31.16 g C/m^3/hr. This agrees with the findings of Pagans *et al* (2007), who reported a maximum VOC elimination rate of 18.7 g C/m^3/hr in their pilot scale biofilter.

Some authors have suggested that the contaminant load, and in particular ammonia load, can have a significant impact on the performance of a biofilter at composting sites. Frederickson *et al* (2013) observed that 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. They went on to say that even moderate ammonia concentrations in the order of 45-100 mg NH_3/m^3 may contribute to microbial inhibition and decreased biofilter performance. VDI3477 (2004) indicates that the main risk posed by ammonia (and hydrogen sulphide) relates to their ability to modify the pH of the media and that concentrations as low as 5 mg/m^3 could have a detrimental effect on biofilter operation.

On the other hand Smet *et al*. (2000) found somewhat surprisingly 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.

2.3.2.4 Residence time

Residence time is a critical design and operating parameter, since it determines the length of time available for transfer of pollutants to the biofilter biofilm.

The residence time of the biofilter is typically presented in the form of Empty Bed Residence Time (EBRT) or true residence time (t). Empty bed residence time is calculated simply by dividing the empty volume of the bed by the air flow, whilst true residence time takes this one step further and also considers the porosity of the media applied. In principal, it reflects a better indicator for residence time since it considers the effect of the media (Devinney et al 1999). However, the use of EBRT tends to prevail in literature due to its ease of calculation and the fact media porosity values are rarely available.

According to BREF document published by the European Commission (2006), the residence time should be between 30 and 60 seconds, unless testing supports the use of shorter retention times. This is supported by the information provided by the draft Technical Guidance Note for anaerobic digestion facilities (Environment Agency 2013), which recommends that the residence time should also be between 30 - 60 seconds, but preferably nearer to 60 seconds.

Liu *et al* (2009) carried out pilot scale experiments on an upflow biofilter containing mature MSW compost material and reported that the removal efficiency for total VOCs was higher at higher empty bed residence times, due to the longer contact time between the

contaminated air and the biofilter media. At empty bed residence times of 32.5s, 40.5s and 65s they found VOC removal efficiencies of 20-84.8%, 31.9-82.7% and 49.8-95%, respectively.

Yang and Allen (1994) found that for gas phase residence times less than 23 seconds their biofilter removal rates suffered from resistance to transfer of hydrogen sulphide from the gas phase to the biofilm.

According to Leson and Winer (1991), typical residence times for commercial or industrial applications range from 25 seconds for the treatment of odour and low VOC concentrations, up to 60 seconds or more for high concentrations of VOCs.

Empty bed residence times need not be long for most odour compounds, but biofilters are typically designed to have empty bed residence times in the range of 15 to 60 seconds (Frederickson et al, 2013). According to Woodfield and Hall (1994), the residence time that is required to effectively abate an odour will depend upon the concentration and composition of the inlet odour. They suggested that as a rough guide, a minimum residence time of 30 seconds should be aimed for, or for high concentrations this should be increased to 50 seconds.

Once again, data presented by Sanchez-Monedero (2004) also includes the gas phase residence time for the biofilters they monitored (Table 21), although they did not comment on the data. This shows that for *Aspergillus fumigatus* the removal does not appear to be related to the gas phase residence time, and that within the range 29 to 97 seconds the removal remains in excess of 90%. For the mesophilic bacteria, again there does not appear to be a relationship with the highest (89.6%) and lowest (39.1%) removals being at gas phase residence times of 36 and 37 seconds, respectively. Further characteristics of the biofilters in this study and the inlet bioaerosol concentrations can be seen in Tables 5 and 13.

Table 21 Influence of gas phase residence time on the removal of *Aspergillus fumigatus* and mesophilic bacteria by biofilters (Sanchez-Monedero et al, 2003)

Residence Time (seconds)	Removal (%)	
	Aspergillus fumigatus	Mesophilic bacteria
29	99.3	68.1
36	99.4	89.6
37	97.9	39.1
42	98.0	74.7
86	90.4	88.6
97	98.7	71.9

Chen & Hoff (2009) suggest that empty bed residence times between 4 and 10 seconds should be sufficient for a biofilter designed to control odours and VOCs from various confined livestock facilities, provided the moisture content is controlled adequately.

Ergas *et al* (1995) reported results of some pilot scale experiments using a biofilter filled with a mixture of compost, perlite and crushed oyster shells treating exhaust air from a wastewater treatment facility. They looked at the effect of loading rate and EBRT on the removal of selected VOCs (Table 22). They found that for trichloromethane, dichloromethane, trichlorethane and tetrachloroethane the removal initially increased as the loading rate increased and EBRT decreased, but then dropped off when the loading rate increased further and the EBRT decreased further. However, the trend for benzene and toluene was different with an overall drop in removal rate as the loading rate increased and the EBRT decreased.

Table 22 Effect of loading rate and empty bed residence time on the removal of selected VOCs by a pilot scale biofilter as reported by Ergas *et al* (1995)

Compound	0.46 $m^3/m^2/min$ 120 seconds	0.7 $m^3/m^2/min$ 78 seconds	1.7 $m^3/m^2/min$ 32 seconds	1.8 $m^3/m^2/min$ 31 seconds
Trichloromethane	18	42	37	23
Dichloromethane	23	36	42	19
Trichlorethane	28	40	43	11
Tetrachloroethane	25	49	38	12
Benzene	77	48	51	9
Toluene	78	61	39	14

2.3.2.5 Media depth

Pilot scale research carried out by Hong *et al* (2013) investigated the impact of media depth in a woodchip biofilter on the removal of ammonia. Three biofilters were operated with media depths of 20cm, 40cm and 60cm. In terms of performance, the maximum inlet concentrations of ammonia were around 250 ppm and the exhaust concentrations were 130 ppm, 30 ppm and 10 ppm for the 20cm, 40cm and 60cm biofilters respectively, which corresponds to removals of 48% 88% and 96%, respectively.

The depths used by Hong et al (2013) are low compared to the data presented by Devinny et al (1999), who suggested that the media depth should be between 1m and 1.5m. This information agrees with VDI3477 (2004) in which it was stated that the depth of the biofilter bed will vary depending on the media type selected, and that in general the depth should not be less than 1m. It went on to suggest that for bark chips a large depth well in excess of 1.5m could be used, for root wood the depth should be at least 1.5m and that for a biofilter using the oversize material from green waste composting the depth should be between 1 and 1.5m. Information provided by Odour Services International Limited (personal

communication, 2014), suggested that a depth of between 3 and 3.5m can be used for woodchip if the fraction size is varied to prevent compaction. The media depth of biofilters constructed using inorganic media (e.g. lava rock) can also exceed 1.5m.

2.4 Odour and bioaerosol emissions from biofilters at biowaste sites.

The following section reports the values observed for bioaerosols and various odour compounds in the exhaust air from biofilters. However, this data needs to be treated with caution as the sampling methodology applied is not always stated explicitly and variations in the quality of data may occur due to methodologically variations. In some cases, as has been stated previously with regard to Sanchez-Monedero *et al* (2003), the sampling methodology may be such that the exhaust air becomes diluted with ambient air and therefore the concentration of bioaerosols quoted will not be representative of what is actually being emitted by the biofilter.

2.4.1 Odour and VOC emissions from biofilters

Defoer *et al*. (2002) measured both odour and chemical concentrations of 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 13,050 OU_E/m^3.

Sironi *et al* (2007) undertook sampling of exhaust air from the surface of biofilters using a fixed hood with a chimney and reported that the odour concentration from the biofilter was 53 OU_E/m^3.

A larger dataset collected by the Odournet group (unpublished) during a range of unpublished and privately funded studies conducted on biowaste composting facilities across Europe between 2005 and 2013, indicates that the concentration of odour from biofilters as determined by olfactometry ranged from 77 to 60,359 OU_E/m^3, with a mean value of 2,600 OU_E/m^3 (n=870). The highest concentrations of odour were measured from systems which had clear design issues or operational deficiencies in terms of media condition, as a result of breakthrough of untreated process air through the media due to channelling or excessively dry media and poor air distribution. All measurements were conducted using methods which isolate the biofilter off-gas from the effects of atmospheric dilution (i.e. by isolation of the biofilter using a sheeting method similar to that applied during this research).

Outlet concentrations of ammonia extracted from the same dataset indicated a range from 0 to 3.7 mg/m^3 with a mean value of 0.1 mg/m^3 (n=68), whilst hydrogen sulphide concentrations ranged from 0 to 0.3 mg/m^3 with a mean of 0.1 mg/m^3 (n=103). Elevated concentrations of ammonia and hydrogen sulphide did not appear to correlate with

elevated odour concentrations within this dataset, which implies that hydrogen sulphide and ammonia were not dominant contributors to the odour concentration of air released at the study sites.

Liu *et al* (2009) reported that during their pilot scale biofilter experiments the concentration of total VOC emitted by the compost media itself was negligible, which conflicts with the information provided by Pagans *et al* (2007) who suggested that poor VOC removal was observed due to emission of VOCs from the compost media itself.

Pagans *et al*. (2006) found that the mean VOC concentrations in the exhaust gas from their labs scale biofilters ranged from 55 to 295mg C/m^3 for the organic fraction of MSW (5:1 mix with bulking agent) and from 12 to 145mg C/m^3 for the same waste with a higher proportion of bulking agent (1:1). In comparison, they found that for raw sludge the VOC concentration ranged from 55 to 270mg C/m^3 and for anaerobically digested sludge the emissions ranged from 42 to 855mg C/m^3.

Pagans *et al* (2006b) studied the emission of VOCs produced during composting of different organic wastes using a laboratory scale composting process and 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.

DEFRA (2009) refers to a recommended EBRT of 45 seconds and states that biofilters can achieve odour concentrations as low as 200-500 OU_E/m^3.

2.4.2 Bioaerosol emissions from biofilters

Fredrickson *et al* (2013) reported that although many research papers have identified good removal efficiencies for bioaerosols via biofilters, there is some disagreement over whether the emissions of bioaerosols from biofilters in terms of the species present are in fact the same as the species in the inlet air to the biofilter. They also observed that in the studies that they looked at, it was not unusual to see higher concentrations of bioaerosols at the outlet than the inlet of a biofilter. Various explanations were put forward, such as biofilter materials being net emitters, anomalous results, air flow, growth within biofilters, and so on.

Hartikainen and Martikainen (1996) suggested that peat or partial peat biofilters can emit significant concentrations of bioaerosols during long term operation. 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.

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

Frederickson *et al* (2013) reported that despite very good removal efficiencies in some instances, concentrations released to the atmosphere are still elevated above background, and are often in excess of published guidelines particularly for total and gram-negative bacteria. However, such guidelines relate to the concentration at the nearest sensitive receptor and are not emission limits for biofilters.

If these absolute values are considered, then it is apparent that there are still issues to address, and that although the biofilters are demonstrating good removal efficiencies, the emissions to air for these parameters remain in excess of recommended values.

Figure 1 presented earlier in this report, shows data presented by Kummer and Theil (2008) on *Aspergillus fumigatus* concentrations in outlet air from a number of biofilters installed at waste treatments sites. No further information was given regarding the biofilter characteristics. The data shows that the outlet concentration of *Aspergillus fumigatus* at the 17 study sites ranged from a low of zero up to 10^4 cfu/m^3. Of those 17 sites the majority (12 of 17) had emission concentrations of 10^2 cfu/m^3 or 10^3 cfu/m^3.

The data presented by Frederickson et al (2013) (Table 23) shows the biofilter outlet concentration of bacteria, gram negative bacteria and fungi at two sites. The concentration of bacteria was consistently higher than either the concentration of gram negative bacteria or fungi. The lowest concentrations were found to be for the fungi with zero being detected in the outlet from both sites on occasion.

Table 23 Biofilter emission concentrations of bacteria, gram negative bacteria and fungi (Frederickson et al, 2013)

Parameter	Site C	Site P*
Biofilter Surface area (m^2)	231	No detail given
Biofilter media	Compost/woodchip	No detail given
Media age	I year	No detail given
Bacteria (cfu x $10^3/m^3$)	25.2 – 42	15.6 – 25.2
Gram negative bacteria (cfu x $10^3/m^3$)	0 – 0.6	1.2 – 6.0
Fungi (cfu x $10^3/m^3$)	None detected	0 – 1.2

Table 24 shows the data obtained by Sanchez-Monedero et al (2004) during their full scale plant monitoring. Due to the sampling method used it is likely that the concentrations quoted in this paper are low due to the potential 'dilution' of the sample with ambient air. It can be seen that the biofilter outlet concentration of *Aspergillus fumigatus* ranged from 10^2 to 10^3 cfu/m^3 (the majority were 10^2) and for mesophilic bacteria the concentrations tended to be an order of magnitude higher at between 10^3 and 10^4 cfu/m^3 with the majority at 10^3 cfu/m^3. There does not appear to be a relationship between the age of the media, air flow

rate and residence and the emission concentration of either *Aspergillus fumigatus* or mesophilic bacteria. However, without the actual data this cannot be confirmed.

Table 24 Biofilter emission concentrations of Aspergillus fumigatus and Mesophilic bacteria at full scale biowaste composting sites (Sanchez-Monedero et al, 2004)

Biofilter dimensions (m^2 x d)	Biofilter media	Age of media (m)	Air flow rate (m^3/hr)	Residence time (s)	Aspergillus fumigatus (cfu/m^3)	Mesophilic bacteria (cfu/m^3)
1500 x 1.1	Compost, woodchip	12	165000	36	10^3	10^3
700 x 2.4	Pine bark	18	70000	86	10^2	10^3
450 x 1.3	Compost, woodchip	12	50000	42	10^2	10^4
400 x 1.3	peat	36	-	-	10^2	10^3
572 x 1.8	Compost, woodchip	1	100000	37	10^2	10^3
110 x 1.2	Compost, woodchip	12	16000	29	10^2	10^3
6.75 x 1	Compost, woodchip	12	250	97	10^2	10^3

3.0 Current process options for the treatment of biowaste in the UK and for the treatment of emissions

It is difficult to get a clear picture of the current biowaste treatment options and odour and bioaerosol abatement technologies used in the biowaste industry in the UK, as there is no database that can provide all the required information. Therefore, the review presented in this section is based on the information available in the literature together with the experience of the authors.

3.1 Biowaste treatment options currently used in the UK

One of the key sources of information on the types of technologies currently used in the UK was the results of a survey of the UK organics recycling industry published by WRAP in 2012. The survey obtained responses from a total of 336 operating sites, which represented 74% of those contacted. The survey showed that composting continues to be the treatment option that processed the largest quantity of organic waste with a total of 5,850,000 tonnes of waste treated by composting (including IVC) in the UK in 2012.

The majority of inputs to the surveyed sites were separated green/garden waste at 63% of total inputs. Mixed food and green waste accounted for 26% of inputs, with separated food waste at 5% and 'other' material providing 6%; (examples of materials entered as 'other' are sewage sludge, wood, liquids, manure and sanitised material from other composting sites).

According to the WRAP survey, the majority of organic waste that was processed at composting sites in 2012 was conducted using open air windrow and this remains the most cost effective way of treating organic waste that is not animal by-product (ABP) within the UK.

The survey results show that 67% of sites operating in-vessel composting (IVC) facilities also utilised another technology and that of those sites, 74% operated these in series with the IVC system, 23% in parallel to and 3% in parallel and in series. In addition it was noted:

- Open air windrows were used at 81% of sites surveyed and at 57% of those sites the open air windrow system was used as the sole treatment system. At 24% of the sites it was used in series with, or in parallel to, another technology and in most cases the other technology was an in-vessel system.
- Those sites using only open air windrows, or open air windrows in parallel with another system, accounted for 68% of the total number of facilities, and together they received 54% of the inputs in 2012.
- In-vessel systems were employed at 22% of sites surveyed, with 8% of the sites employing solely in-vessel systems and 15% operating it in series, or in parallel to another technology.

In addition to this, the results of the WRAP survey also showed that covered windrows, aerated static piles and continuous block composting were used at 11% of the sites and accounted for only 2.5% of the total waste input. Another 5% of the sites surveyed were using technologies classed as 'other' e.g. deep clamp and thermophilic aerobic digestion, and processed 4% of total UK inputs.

Table 25 shows the proportion of each waste type that is treated by the different biowaste options in the UK according to the results of the WRAP survey in 2012. It can be seen that the majority of the food, mixed food and green waste in the UK is treated using in-vessel systems either alone, or in series with another technology. Most of the green wastes (and waste types described as 'other') are treated using open air windrows.

Table 25 Percent of incoming waste type treated by the different biowaste treatment options in the UK (WRAP, 2012)

	Food waste	Green waste	Mixed food & green waste	Other
IVC in series with another technology	36	8	47	9
IVC alone	25	7	52	5
Open air windrows	< 0.5	78	1	82
Covered windrows	0	1	0	<0.5
Aerated static piles	0	1	0	4
Continuous block	0	2	0	0
Other	38	31	<0.5	<0.5

In-vessel systems include a whole host of different types of technologies primarily designed to meet the requirements of the current Animal By-Products Regulations, (2011) in the UK. In the UK, as a result of the high capital cost of in-vessels systems in most cases the in-vessel system is only used to partly treat the waste with the remaining treatment being done using alternative 'cheaper' technologies (open windrow).

The WRAP survey does not provide any information as to the types of in-vessel system that are currently used in the UK. However, from the literature, information provided as part of this research project and the experience of the authors, it appears that the most widely used IVC technology is the tunnel system.

The survey shows that in 2012 there were a total of 30 mechanical biological treatment facilities in the UK treating approximately 2.52 million tonnes of waste. Feedstock sources were reported as almost exclusively from municipal sources (98%), with only a small volume coming from non-municipal sources. Table 26 shows the types of Mechanical Biological Treatment (MBT) processes operating in the UK and it can be seen that in 2012 the majority of the sites were using aerobic biodrying.

Table 26 Number of sites operating different MBT process options in the UK (WRAP, 2012)

Process Type	2010	2012
Aerobic biodrying	3	10
IVC alone	2	6
Anaerobic digestions alone	0	4
IVC with anaerobic digestion	2	2
Thermal treatment	1	0
Other	1	1

3.2 Current abatement systems used in the UK

Looking at the literature and the information provided as part of this project it would appear that the majority of the abatement systems currently used in the UK consist of an open biofilter on its own, although there is a growing trend towards use of enclosed biofilters, particularly at large scale waste processing facilities. Acid scrubbing is applied at some sites, upstream of both enclosed and open biofilters. To the authors' knowledge, only one site uses an acid scrubber and alkali scrubber in series prior to the biofilter. The combination of a biofilter and downstream carbon filter has also been used but this system is rare.

Table 28 shows the list of sites that were shortlisted for this project, and it is clear that most of the sites in this small sample operated an open biofilter only system, with a small number including a scrubber and an open biofilter. The number of enclosed biofilter systems was relatively small and only one site was operating with both an acid and alkali scrubber. The predominant air flow regime used in biofilters in the UK is an up-flow system regardless of whether the biofilter is open or enclosed. In terms of media type the main types used in the UK appears to be woodchip (this study) or compost woodchip mixtures (literature). Other media types that are used at a smaller number of sites include peat, brash, clay aggregate and other commercially available inorganic media. Table 27 contains a list (by no means exhaustive) of some of the biofilter media types that have been quoted in the literature.

Table 27 The range of biofilter media types quoted in the literature

Biofilter media	Author
Compost Compost & polystyrene Peat & heather branches	Ottengraf & Konings (1991)
Compost, woodchip Pine bark Peat	Sanchez-Monedero et al (2003)
Biochips Coconut fibre/peat Bark and wood 'Filter pellets' Biocompost	Martens et al (2001)
Wood shavings	Seedorf & Hartung (2002)
Coke/compost and root wood Coconut fibre	Schlegelmilch et al., 2005
50% compost/peat only mix 40% compost/peat & 20% bentonite 40% compost/peat & 20% halloysite	Tymczyna et al (2007)
Granule activated carbon	Ho, K-L et al., 2008
Shredded tree roots/ polypropylene, both with acid scrubbers	Zhao et al (2011)
Compost 40%, peat 40%, straw 20%	Tymczyna et al (2011)
Compost, oyster shell & perlite	Kapahi & Gross (1995), Ergas et al (1995)

Table 28 Details of the abatement system and biofilter at the sites shortlisted for this project

Site number	Biofilter configuration	Biofilter medium
1	1 enclosed biofilter	Woodchip
2	1 open biofilter	Woodchip
3	1 open biofilter	Woodchip
4	Unknown	Woodchip
5	Biofilter on each tunnel	Woodchip
6	2 acid scrubbers plus biofilter & 1 open biofilter on the reception hall	Pine wood chips with less than 10% bark
	Acid scrubber and open biofilter	Pine woodchips 30-60mm
7	Scrubber plus 2 biofilters on reception hall and compost process	Wood Bark
8	3 open biofilters on vessels & 2 open biofilters on maturation area	90% bark, 10% woodchip with added phosphate, urea & lime
9	1 open biofilter	Brash
10	Acid wash scrubber and 5 open biofilters	Granular peat
11	Acid wash scrubber & 3 biofilters on MSW stream & 2 on the GW stream	Granular peat
13	Acid and Alkali scrubbers plus 6 enclosed biofilters	Clay aggregate
14	Open biofilter	Unknown
15	Open biofilter	Unknown
16	2 open biofilters	Unknown
17	1 open biofilter	Unknown

4.0 Fieldwork – site selection and methodologies

4.1 Sampling sites

4.1.1 Site selection rationale

Given the overall aim of the research project, when selecting sites, it was important to ensure that as large a range of different abatement system arrangements and process parameters were captured. However, the number of sites that could be incorporated into the study was limited, so it was necessary to focus on the key variables. The key variables that were considered are:

- Open or enclosed biofilter arrangement;
- Whether the abatement system includes a scrubber or not;
- Biofilter media type;
- Composting process feedstock;
- Composting process type; and
- Composting process operating parameters (e.g. aeration system).

In addition to the variables outlined above, consideration was given to more practical factors, such as accessibility of the sampling points and previous experience of the site. One of the objectives of the research was to look at the impact of anaerobic conditions on the performance of the abatement systems, detailed process parameters, such as temperature/time profiles were required. Therefore consideration was given to whether the process was ABPR compliant as this will affect the amount of process data available.

4.1.2 Final list of sites

When choosing the sites to be included in the research project, the choice was more limited than anticipated, and it was not possible to incorporate a range of sites that includes all the biowaste treatment technologies, or all the abatement system configurations available. However, the final list of sites does reflect the current predominant biowaste treatment options and abatement systems currently use in the UK as highlighted in section 3.

Table 29 shows the details of the sites that were sampled as part of this research project. Overall, there were four enclosed biofilter sites and four open biofilter sites. Of the eight sites sampled, four of them had an acid scrubber as part of their abatement system. However, it should be noted that at site UOL08 the scrubber was not operational at the time of sampling. In terms of process operations, two of the sites were MBT plant operating bio-drying systems, whereas the remaining six were all composting plants. The in-vessel composting sites included three utilising tunnels, two with enclosed windrows and one

incorporating a rotating drum system. The next section of the report provides an overview of each of the sites.

4.1.3 Site descriptions

4.1.3.1 Enclosed biofilter sites

UOL01

Site UOL01 is a MBT facility taking primarily black bag (mixed MSW) waste – 1200 tonnes per week (approximately 6-8 tonnes of which is dog faeces). The local authorities bringing waste to the site are mainly on a fortnightly collection, which increases the amount of anaerobic material and potentially the occurrence of flies, especially in the summer months. The moisture content of the feedstock is understood to be generally around 42%. The site is located on an industrial estate, which includes a waste transfer station and there are neighbours virtually up to the site boundary on two sides, placing sensitive receptors in relatively close contact with the operation.

The process itself is undertaken in a single building which uses an Eco Deco biodrying system operating under negative pressure aeration (air is drawn down through the waste) through special concrete grids on the floor. In the biodrying process the biodegradable fraction is oxidised aerobically and the energy liberated as heat is used both for further drying the so-called dry fraction, and for thermally sanitising all the materials.

The system is housed in a single building, starting at the reception pit for all incoming wastes, where they are shredded and transferred by overhead crane to the bio-drying reactor. In this reactor the wastes are piled between 4.5 and 4.7 m and remain in the biodryer for around 12 -15 days.

The temperature is targeted to be 55^{o}C and is prevented from getting any higher using a feedback system, based on the temperature measured at the inlet to each of the extractor fans, which is a direct result of the temperature of the air passing inside the waste mass. A raising of the temperature of the waste in any bay, (measured on the air emitted from the bay itself) of at least 10°C with respect to the initial temperature measured at the moment of the depositing of the shredded refuse, indicates that the process is started. The process is estimated to reduce the waste mass by approximately 25%, with a target moisture level of less than 20%, before the overhead crane moves the dry material to the Refining Hall. The refining processes are designed to produce different fuel products for market.

Table 29 Details of site operations and abatement system

Parameter	UOL01	UOL02	UOL03	UOL04	UOL05	UOL06	UOL07	UOL08
Visits	2	1	2	1	1	3	2	1
Process	Eco-Deco bio-drying	2-stage enclosed windrows	Enclosed windrows	IVC rotating drums	Eco-Deco bio-drying	IVC Tunnels	IVC Tunnels	IVC Tunnels
Feedstock	MSW	Green waste MSW	Green waste MSW	Green waste & Food waste	MSW	Green waste & Food waste	< 50mm MSW	Green waste & Food waste
Waste throughput	1200 t/wk	60,000 t/yr		48,000 t/yr	75,000 t/yr		24,000 t/yr	35,000 t/yr
Aeration system	Forced	Forced	Forced		Forced	Forced	Forced	Forced
Abatement system	Enclosed biofilter	Acid Scrubber & Enclosed biofilter	Acid Scrubber & Enclosed biofilter	Acid and Alkali scrubber & Enclosed biofilter	Open biofilter	Open biofilter	Acid Scrubber & Open biofilter	Acid Scrubber & Open biofilter
Up-flow/Down-flow	Up	Up	Up	Up	Up	Up	Up	Up
Biofilter dimensions	55 m x 12m x 2.2m	GW 630m^2 x 2.24m deep. OGM 840m^2 x 2.24m^2	GW 630m^2 x 2.24m deep. OGM 840m^2 x 2.24m^2	6 filters @ 2 x 6m	55 m x 12m x 2.2m	5.7m x 2.2m	20m x 20m x 2m	18m x 6m x 1.5-2.1m
Biofilter surface Area (m^2)	660	840	840	12m^2 each	660	12.5	400	108
Media depth (m)	2.2	2.24	2.24	4.2	1.1	2.5	2m	2.1
Irrigation system		Daily wetting of surface using spray nozzles on a distribution grid	Daily wetting of using spray nozzles on a distribution grid. Wet scrubbers pre biofilter ensure high RH >90% of inlet air.	Rotating sprinklers	Sprinkler system	Atomiser spray system (same as for windrow)	Sprinkler system - automated	Sprinkler system which irrigates into the media at 0.5micron sized droplets. Achieve 60-65% moisture.

Parameter	UOL01	UOL02	UOL03	UOL04	UOL05	UOL06	UOL07	UOL08
Irrigation rate		Daily	Daily	On a timer 300mins on/off	Never on due to rain	Constant during dry months, never during wet months	~6m^3/day during dry months, never during wet months	2-5mins/2 hrs. Constant use. Approx. 1m^3 per filter per day.
Flow rate (m^3/s)	14.2	24.2	20.8 (GW) 29.1 (OGM)	7.4	14.3	0.7	8.7	9.7
Surface loading rate (m^3/m^2/hr)	77	104	119 (GW) 125 (OGM)	370	78	211	78	81
EBRT (s)	51	78	68 (GW) 65 (OGM)	41	51	43	84	71
Biofilter media	Woodchip & brash	Granular peat	Granular peat	Clay aggregate	Brash	Woodchip	Pine Woodchip <10% bark	Pine woodchips 30-60mm
Media Grading	n.a	-	-	-	Undulating	Flat	Flat	
Media containment	Good	-	-	-	Good	Good	Good	
Media age		-	-	-	-	-	12 months	18 months
Inlet temp (°C)	31-36	38	34 - 37	23	42-43	29-40	24 - 34	16
Flow Homogeneity	n.a	n.a.	n.a.	n.a.	good	n.a	Good	Good. Measured by client at base of media
Weed growth	n.a	-	-	-	Some	None	None	-
Particle size	-	-	-	-	Good	Good	Good	-
Scrubber pH	No Scrubber	-	-	Acid – 5, Alkali – 9.5	No Scrubber.	No Scrubber	Target of 4. Fluctuates 2-7	No Scrubber
Scrubber residence time	No Scrubber	-	-	Depends on fan speed – not monitored	No Scrubber.	No Scrubber.	Depends on fan speed – not monitored	No Scrubber.

The floor of the biodrying reactors is split into 23 sections, each served by its own fan, which discharges into a common duct before the air is forced into the biofilter. A further fan takes air from the head space in the main building and exhausts into the inlet manifold of the biofilter. The biofilter is an enclosed metal panelled structure with a plan area of 55m long by 12m wide and is approximately 2.2m deep. The flow of air through the biofilter is approximately 57,400m^3 per hour, which equates to approximately 3 complete changes of the air of the building cavity every hour. Air flow is balanced through the control of the fans that draws the air through the waste mass. The speed of these fans will vary depending upon the temperature of the waste mass, to ensure that drying is maximised and the temperature is kept within safe limits. Air entering the biofilter has a range of temperatures, with the age of the waste being the determining factor in temperature. The moisture of the airflow and the irrigation system helps to keep the biofilter moist, with the irrigation system manually activated, or set on a timer for the time and duration of operation.

The biofilter media is made up of screened composted green waste and woody material. The media is supplied in a single batch, sufficient to fill the whole biofilter, to ensure homogeneity in the characteristics of the media in the biofilter. The biofilter medium has an expected lifespan of seven years and according to the operator's Odour Management Plan, the expected performance in terms of odour removal, is that the biofilter will achieve greater than 90% destruction of odour for the first 10 months and 95% thereafter. The surface of the biofilter is enclosed and the exhaust air directed to a 17.7m high stack shown in Plate 1. Sampling from the inlet and outlet is shown in Plates 2 and 3.

Plate 1 Outlet stack from biofilter at Site UOL01

Plate 2 Sampling port in the inlet duct to the biofilter at Site UOL01

Plate 3 Sampling from the biofilter outlet duct at Site UOL01

UOL02

This facility began operation in 2010 and treats up to 225,000 tonnes of household waste every year. All waste is processed indoors and the incoming waste is received into two different receiving halls, depending on what type of waste is being delivered (garden & kitchen waste and residual waste). Garden and food waste is delivered directly into a dedicated composting facility.

Approximately 170,000 tonnes per year of municipal waste passes through the entire plant. However, the amount of waste passing through the composting plant is much lower at only 60,000 tonnes per year through the green waste composting process. Overall there are two waste streams in separate composting halls, one municipal waste and one green waste and food.

Each waste type stream is processed in one large reactor of 14 windrows followed by a second reactor with 14 windrows. The waste is fed into the start of the first reactor and the windrows are turned daily so that the compost is gradually migrated to the discharge end of the reactor. Composted material is then removed from the discharge end of the first rector, tromelled, and then fed into the start of the second reactor, which is also turned daily. The temperature of the exhaust air is monitored continuously and the ABPR requirements are 55°C for at least 12 hours in the compost.

The abatement system consists of an acid wash scrubber to reduce/remove ammonia, with a two level spray system and enclosed granular peat biofilters, all of which are 2.24m deep, with a plenum corridor along the length of the centre of the biofilter bed, with regular side ports feeding to the underside of peat support trays.

There are three biofilters on the municipal waste stream (840m^2) and two biofilters on the green waste stream (630m^2). The municipal waste biofilters also treat air from various parts of the waste handling facility including building air, in addition to the composting forced air system. The green waste biofilters treat air from the green waste composting hall in addition to the composting forced air system. The municipal waste biofilters treat approximately 95,000 - 100,000m^3/hr and the green waste biofilters treat around 75,000 m^3/hr. The surface of the biofilters is wetted daily using spray nozzles on a distribution grid.

UOL03

Overall the site operations at UOL03 are the same at that described for UOL02 in the previous section. The only additional information to note is that the media in the three municipal waste biofilters were replenished between March and June 2012 after approximately 18 months service. The green waste biofilters were put into operation in January 2011 and their expected service life is between 5 and 7 years.

UOL04

At the time of writing this report, the information regarding site operations and abatement at this site were very limited. The fully enclosed in-vessel composting facility was acquired by the operator in 2009 and the facility has a throughput capacity of approximately 48,000 tonnes per year. The facility utilises an advanced biological treatment process to convert biodegradable material into high grade compost. The composting process incorporates accelerated composting in primary composting vessels (PCVs), which are slow rotating, large steel drums 24m long and 4.5m wide. Conditions are optimum for composting with temperatures typically at 45-50˚C. Shredded waste is loaded at one end and moves down the vessel for approximately 3 to 4 days, before it is unloaded onto screens, separating oversized waste for re-shredding and re-composting.

All the waste handling and treatment activities take place inside a single fully enclosed building. Upon delivery waste material enters the reception area and is then placed into windrows and turned each day for 4 days prior to loading into primary composting vessels. Waste material remains in the primary composting vessels for 3-4 days, before being screened and discharged into the secondary composting vessels (SCVs), for a minimum time of 135 minutes, at a minimum temperature of 71°C, an ABPR requirement. This is a batch process where time and temperatures are recorded using electronic probes, which transmit data to the site control computer.

After being removed from the composting vessels, the material is then formed into small windrows. These windrows are then routinely turned for approx. 12-14 days, moving down the Process Building towards the Dispatch Airlock. The aim of this composting process is to achieve a target process loss figure of 20%.

All the composting activities take place in two large composting halls. The vents feed separate scrubbing systems comprising an acid, then alkali scrubber. The scrubbers then feed into a lightweight expanded clay aggregate biofilter. The headspace above the biofilter is then vented naturally through the main stack.

4.1.3.2 Open biofilter sites

UOL05

This site is a MBT facility for up to 75,000 tonnes per year of municipal waste. The site is almost identical to that at UOL01 in terms of the process operating information. The main difference relevant to this project is that the biofilter is open to atmosphere rather than enclosed (See plate 4). The surface of the biofilter is made up of shredded wood on top of a layer of 'brash' (term used by site staff) and the exhaust air goes straight to atmosphere. Plates 5 and 6 show the sampling being undertaken from the inlet duct and from the surface of the biofilter.

Plate 4 The open biofilter at UOL05, showing the surface of the biofilter and the arrangement of the inlet duct.

Plate 5 Sampling from the inlet duct to the open biofilter at UOL05

Plate 6 Sampling of the open biofilter at UOL05

UOL06

This in-vessel composting site is located adjacent to a large garden centre and nurseries also under the ownership of the operator. The site has two distinct process streams; an open windrow system which takes green waste, and an in-vessel composting system which processes green waste and food waste. On arrival at the site, the feedstock is shredded within 24 hours and mixed with oversize material from previous batches in order to ensure that the C:N ratio and the bulk density are optimised. In general 10 tonnes of feedstock is mixed with 3 tonnes of oversize material. Once mixed, a compost accelerator additive is added at approximately 20 litres per 200 tonnes of feedstock.

The in-vessel system comprises of eight composting tunnels that are 22m long, 5.7m wide and 4.5m high. Each takes approximately 200 to 250 tonnes of a mixture of food wastes and green waste, which is piled 2.5 to 3 m high in each tunnel. The vessels use a positive aeration system where air is blown through the floor of the tunnels and through the composting mass of waste.

The plant is ABPR compliant and the sequence of composting is that the waste is kept at 60^{o}C for two days in the first phase tunnels before being moved to the outside windrowing area for phase 2. Each tunnel has 6 temperature probes installed to monitor the temperature and the data from these is fed to the control room computer. The air flow into the waste is controlled by the temperature feedback data and only when the temperature has remained at 60°C for 2 days will the tunnel be vented and the waste removed. The total

time in the tunnels including the initial heating phase, 2 days at 60°C and the venting and cooling stage is around 7 days. Following composting, the material is screened and the various products separated and the oversize rejects are used to back mix into either the incoming raw material or the low oxygen piles in the windrows to improve the structure.

The exhaust air from the eight tunnels is ducted into 4 biofilters housed in metal roll-on-roll-off containers approximately 5.7m long and 2.2m high as shown in Plate 7. The exhaust air from tunnels 1 to 4 goes into biofilters 3 and 4 and that from tunnels 5 to 8 goes into filters 1 and 2. The exhaust air enters the plenum chamber beneath the biofilter via a 315 mm diameter flexible connection pipe, the yellow pipe shown in Plate 8.

Plate 7 Photograph showing the biofilters at UOL06

The incoming air to the biofilter was sampled from a port in a section of pipe inserted in the yellow feed pipe, as shown in Plate 8. The surface of the biofilter was covered with a plastic sheet, sealed along both sides and at one end (see Plate 9), with the exhaust samples being taken from the end of the container where the plastic sheet was left open.

Plate 8 Inlet duct to biofilter 4 at UOL06

Plate 9 Plastic sheet covering the whole surface of the biofilter at UOL06

UOL07

This site is an ABPR compliant site taking the less than 50mm fraction of black bin waste from an MBT process. The material is mixed with oversize material from the in-vessel system and material that has undergone maturation. Typically this is mixed in a 2:1 ratio (oversize: maturation material). Each load of feed material from the MBT process is then mixed in a ratio of 4:1 with the oversize/maturation material prior to be loaded into the in-vessel system.

The site uses a two stage tunnel system with each of the tunnels programmed to achieve 60°C for 2 days to comply with the APBR requirements. The double ended tunnels are in two sets of 10, with 10 tunnels in Barrier One and 10 tunnels in Barrier Two. The material spends 14 days in Barrier One and 14 days in Barrier Two. Feed material is loaded into the tunnels with a total of approximately 156 tonnes per tunnel. The process is controlled automatically and for any tunnel to be classed as 'passed' and able to be transferred to the Barrier Two tunnel, the temperature of all probes must be maintained above 60°C for 48 hours at one point during the time the material is in the tunnel.

In terms of the air extraction from the tunnels, the phase 1 and phase 2 tunnels each have their own separate extractor fan drawing air into a manifold taking air from the headspace of each tunnel. The discharge from each of these fans goes through an acid scrubber containing 77% sulphuric acid before the air is forced into the plenum chamber beneath each biofilter. The biofilter is approximately 20m long, 20m wide and 2m deep and is filled with pine wood chips with less than 10% bark. The biofilter media was installed in 2011 and has an expected lifespan of 3 years. The moisture content of the media is controlled using an automatic spray system. Plates 10 and 11 show the sampling arrangement for the inlet duct and from the surface of the biofilter.

Plate 10 The biofilter inlet duct at UOL07

Plate 11 Sampling sheet on the outlet of the biofilter at UOL07

UOL08

This site treats 35,000 tonnes of waste per year, which is primarily kerbside collected green and food waste together with very small amounts (>1%) of commercial food waste. The waste is processed in five tunnels which are filled sequentially and the waste typically spends 5 to 7 days in the tunnels. The waste in the tunnels is aerated using forced aeration and each vessel has independent recirculation and extract fans.

The abatement system consists of four biofilters, each 18m long, 6m wide and between 1.5 and 2.1m deep. The biofilters contain pure pine woodchips of approximately 30-60mm particle size. The biofilters are split into 2 systems which are identical and run in parallel using 2 biofilters per system, again in parallel. Air from the tunnels is mixed with air from the sheds before splitting and entering two biofilters (system 1 and 2). The air exiting each biofilter is combined before entering the stack. Air enters the biofilters through a plenum and ventilated floor. At the time of sampling, the media was approximately 18 months old and has an estimated lifespan of between 3 and 5 years. The surfaces of the biofilters are irrigated through a timed manifold. The abatement system also contains an acid multipack tower scrubber with plastic media; however this was not in use and at the time of sampling air was being diverted from going through the scrubbers.

4.2 Sampling and analysis methods

4.2.1 Scope

The scope of the monitoring conducted at the study sites was as follows:

- Determination of odour concentration in terms of European odour units by olfactometry.
- Determination of the concentration of odour relevant compounds, which included hydrogen sulphide, ammonia and other volatile organics.
- Determination of the concentration of *Aspergillus fumigatus*, total bacteria and gram negative bacteria.

The monitoring was conducted by collecting samples from the air entering and leaving each stage of the abatement system at each site. Samples were collected simultaneously for each determinant over a period of 30 minutes. A total of three samples were collected consecutively at each sampling location with an interval between each consecutive sample of no more than 30 minutes. Where possible, samples were collected simultaneously at each location in the abatement system e.g. scrubber inlet, biofilter inlet and biofilter outlet, to enable the results to be directly compared.

The one exception to this approach was site UOL07, where access problems prevented direct collection of a sample from the inlet to the scrubber. The initial plan at this site was to evaluate the performance of the scrubber by sampling the outlet of the scrubber with the scrubber switched on and off. However, this approach relied upon the assumption that the inlet air stream remains constant in terms of the concentration of odour and bio-aerosols throughout the entire sampling period, which was later proved not to be the case. Determination of the performance of the scrubber at this site was therefore not possible.

Both sites UOL02 and UOL03 consisted of two parallel waste streams, green waste and MSW. At UOL02 only the green waste stream was sampled and at UOL03 both waste streams were sampled on consecutive days.

Due to the arrangement of the abatement system and the air flows at UOL08 samples were taken from the biofilter stage 1 inlet, biofilter stage 2 inlet, biofilter outlet 1, biofilter outlet 2 and a biofilter combined outlet. In order to determine the concentration of bioaerosols entering the abatement system and to calculate the removal efficiency of the abatement system a mean inlet concentration was calculated from the Stage 1 and 2 inlet data.

All sampling was carried out by Odournet UK Ltd, Northumbrian Water Scientific Services (NWSS) and Leeds University using accredited methods, where available.

In addition to odour and bioaerosol sampling, media samples were collected from the biofilters at all of the open biofilter sites to enable the ‘health’ of the biofilter to be assessed.

Further details of the techniques applied to collect and analyse samples are provided in the sections below.

4.2.2 Sampling of odour and odour relevant compounds from ducts and stacks

The collection of samples for olfactometry analysis was conducted using UKAS accredited procedures (UKAS Testing Laboratory No. 2430) by Odournet UK Ltd at all sites. Samples collected from the ducts and release stacks at enclosed biowaste sites using the lung principal of sample collection, by drawing a sample through a sample probe and line into a clean Nalophane™ bag, in accordance with the requirements of BS EN 13725 (2003). Samples were pre-diluted with odourless nitrogen, where necessary, to eliminate the risk of condensation of water within the sample line or sample bag, and to ensure that the integrity of the samples were maintained for subsequent sensory and chemical analysis.

- Hydrogen sulphide sampling was conducted at the open biofilter sites by Odournet UK Ltd using non-isokinetic sampling and collection onto a charcoal tube to the procedural requirements of BS EN 13649. Hydrogen sulphide sampling at the enclosed biofilter sites was conducted by Northumbrian Water Scientific Services using method APA11.
- Ammonia sampling was conducted at the open biofilter sites by Odournet UK Ltd using procedures based on NIOSH 6016 method to enable determination of ammonia concentration direct from the odour sample bag. Analysis for ammonia at the enclosed biofilter sites was undertaken by Northumbrian Water Scientific Services was conducted using an impinger based method BS EN 14791.

Samples for subsequent analysis of odour relevant Volatile Organic Compounds was conducted by drawing air from the odour bag onto a sorbent tube using procedures based on BS EN 13649.

4.2.3 Sampling of bioaerosol from ducts and stacks

Isokinetic sampling of bioaerosols from ducts and stacks was undertaken by either Odournet UK Ltd (open biofilter sites) or Northumbrian Water Scientific Services (enclosed biofilter sites).

This was carried out using the methods outlined in the German standard VDI 4257 part 2 entitled "*Bioaerosols and biological agents' emission measurement: sampling of bioaerosols and separation in liquids*." Bioaerosol samples were collected by sampling a representative volume of air from the duct using isokinetic sampling methods. The air was drawn into impingers containing saline solution, which were then sealed and transported to the analysis laboratory under temperature controlled conditions.

4.2.3 Sampling of odour and bioaerosol from open biofilters

The procedure for sampling odour and bioaerosols from the outlet of open biofilters was developed to optimise the collection of data that can be considered representative of the biofilter as a whole, where it is was not possible to fully enclose the filter, or sample all locations for practical reasons (i.e. due to the size of the filter), or for reasons of excessive cost.

The protocol drew on guidance published by VDI 3880 and Odournet's existing UKAS accredited biofilter odour sampling procedures. The procedure involved an initial survey of the filter to determine air flow patterns and the degree of flow homogeneity over the bed surface, the results of which were used to identify sampling locations. Sampling was then conducted by isolating selected areas of the filter from the dilution effects of the atmosphere using an inert plastic 'tent'. Full details of the procedure were as follows:

1. The biofilter was inspected visually to review media condition and characteristics of water vapour release across the bed surface.
2. The biofilter was divided into a grid of equal squares or sub sections. The number of sub sections was determined depending upon the size of the biofilter. As a starting point, biofilters of 100 m^2 or less should be divided into 4 equal subsections. For larger biofilters, an additional sub section should be added per additional 100m^2 of area.
3. A 1 m^2 flow hood (see Figure 2) was used to measure the flow from each sub section. The metal flow hood was placed onto the surface of the biofilter and sealed using plastic sheeting weighed down with biofilter media, as can be seen in the photograph below. Once in place the air leaving the biofilter would flow out through the chimney of the hood.
4. The velocity of the air was measured using Odournet's UKAS accredited flow measurement procedures (based upon ISO 10780) using either a pitot tube and micro-manometer (for velocity measurements > 5 m/s) or a thermal anemometer (for velocity measurements < 5 m/s).
5. The results of the flow survey were used to characterise the biofilter into different flow areas. Flows within a factor of 2 were considered to be homogenous.

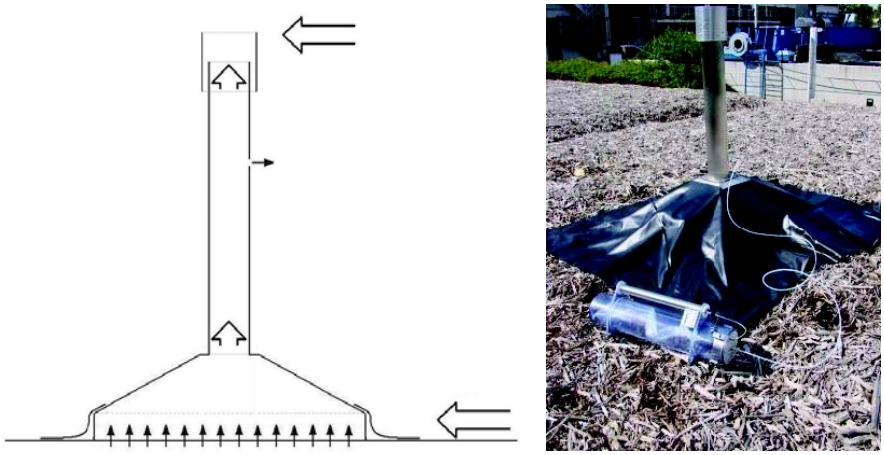

Figure 2 Flow measurement hood

Once the flow survey had been carried out, the odour and bioaerosol sampling was carried out as follows:

1. A sample sheet was deployed across the surface of the biofilter to facilitate collection of odour and bioaerosol samples from the biofilter surface. The sample sheet was standardised to 4m x 10m (area 40 m^2). This size was determined on the basis of practical implications in covering the biofilter and the size of sheeting currently commercially available.
2. The sheet was deployed to achieve coverage of a minimum of 10% of the surface of the biofilter. This target coverage can be achieved either by use of a single sheet (for smaller biofilters with an area <400 m^2), or by moving the sheeting across the surface of the biofilter to different locations for larger biofilters (i.e. with an area >400 m^2), subject to the results of the flow survey.
3. Positioning of the sheet was determined on the basis of the flow survey results. Where the outlet flow of the biofilter was judged as heterogeneous (i.e. if the difference in measured flow velocities in the grid subsections varied by a factor of >2), the sample sampling sheet was moved across the biofilter after collection of each paired odour / bioaerosol sample to enable coverage of areas of the media with different flow characteristics. Where the outflow was judged to be homogeneous across the filter, the sheet was left in one position and all three sets of samples were collected from this position, subject to achieving the minimum coverage levels specified in point 2.
4. The sheet was secured and sealed around three sides using biofilter material and was left open at one end. The location of the open end was determined from the prevailing wind direction (Plate 12).

Plate 12 Sampling from biofilter outlet using plastic sheeting

Once the sheet was in position on the surface of the biofilter the odour sampling tube and the bioaerosol impinger were mounted on a tripod or metal spike approximately 0.5m inside the open end of the sheet and approximately 0.3m above the surface of the biofilter. The inlet to the impinger and odour sampling tube were placed so that they were facing the direction of flow of biofilter outlet air beneath the sheet (Figure 3)

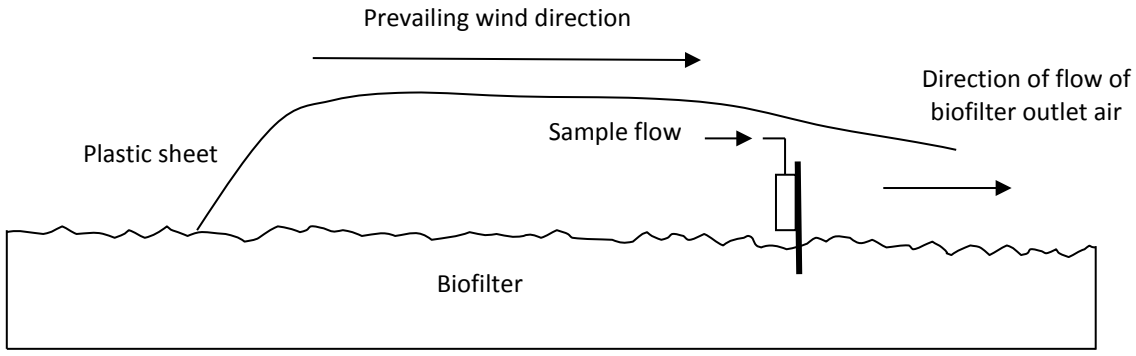

Figure 3 Sampling arrangement for open biofilters

Sampling for odour and odour relevant compounds was then conducted from beneath the sheet, using the method described in section 4.2.3.

Sampling of bioaerosols from the outlet of open biofilters was undertaken using AGI-30 impingers containing saline solution. Samples were taken at a constant flow rate of 12.5 l/min using a 12v pump. The flow was measured using a standard flow meter mounted

downstream of the impinger. After sample collection the impingers were sealed and transported to the analysis laboratory under temperature controlled conditions.

4.2.4 Odour analysis techniques

The following analysis techniques were applied:

- Olfactometry analysis was carried out in accordance with BS EN 13725 to determine the odour concentration of the samples in European odour units (OUE/m3). Character assessment of the odours was also carried out using in-house standardised odour wheel and was conducted immediately prior to determination of the odour concentration of each sample in accordance with BS EN 13725. At the same time, a subjective assessment of the relative unpleasantness of the odour was conducted on the basis of the panel's perception.
- Hydrogen sulphide analysis was conducted by Odournet UK Ltd using non-isokinetic sampling and collection onto a charcoal tube, to the procedural requirements of BS EN 13649, with subsequent analysis by an external laboratory (NWSS applied method APA11).
- Ammonia analysis was conducted using a NIOSH 6016 method to enable determination of ammonia concentration direct from the odour sample bag (Odournet UK Ltd). Analysis for ammonia undertaken by NWSS was conducted using a method based on BS EN 14791.
- Gas Chromatography – Mass Spectroscopy (GC-MS) analysis was conducted to identify and quantify the concentration of volatile organic compounds in each set of samples. The analysis was conducted using a Gas Chromatography – Mass Spectrometry Analyser equipped with a thermal desorption unit (TD-GC-MS) which has been set-up specifically for the determination and quantification of odorous compounds. Compounds were identified by manual examination of the chromatograph against an in-house database by experienced odour specialists. The lower limit of detection of the system was in the order of 10 ug.

4.2.5 Bioaerosol analysis

Analysis of the saline samples was conducted by the Open University microbiology laboratory within 24 hours of collection. The culture and enumeration was carried out according to the standard procedure laid out in the AfOR protocol (2009), '*A standard protocol for the monitoring of bioaerosols at open composting facilities'.* The methods used for analysis are as follows:

- *Aspergillus fumigatus* was cultured on Malt Extract Agar supplemented with Penicillin G (Na^+ salt) (20,000 units/l) and Streptomycin sulphate (40,000 units/l) and incubated at 40°C for 2 days.

- Total bacteria was cultured on half strength nutrient agar supplemented with 100mg/l of Cycloheximide and incubated at 37°C for 2 days.
- Gram negative bacteria was cultured on Mac Conkey Agar supplemented with 200mg/l of Cycloheximide and incubated in the dark for between 3 and 7 days.

4.2.6 Biofilter media sampling and analysis

Analysis of the biofilter media was also undertaken to determine its characteristics in terms relevant to sustaining effective microbial growth (i.e. moisture content, pH, electrical conductivity, amount of ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), sulfate (SO_4^{2-}) and phosphate (PO_4^{3-}). Sampling was conducted by collecting representative samples of between 0.5 to 1 kg of the media from across the surface of the biofilter.

5.0 Results

The following sections present the results that were obtained from the site sampling fieldwork that was undertaken and is presented in such a way as to address the questions that were presented in the introduction.

5.1 Review of the condition of open biofilters

The open biofilters that were available for the study were site UOL05, UOL06 and UOL07. The biofilters were all composed of woodchip media, or combinations of woodchip and brash, and designed using either a plenum chamber, or a network of distribution pipes below the bed.

In general terms, all of the biofilters were observed to be in good condition. The media condition and particle size were good and there was no visual evidence of drying, or significant weed growth. All of the filters were well graded apart from UOL05, which had a slightly undulating surface. Containment of the media was generally good and the flow distribution from all filters, where access was available, indicated a homogeneous flow of air through the media. The results of the media analysis conducted on the open biofilters are presented in Table 30.

Review of the table indicates that pH of the media ranged from 6.6 to 8.1 and the moisture content from 63.6 to 71.8%. Nitrite, nitrate and ammonium exhibited some variation across the sites with ranges from ranged from 5 – 170, 11 – 1423 and 7 to 550 mg/kg respectively. Sulphate levels ranged from 20 to 540 mg/kg. The electrical conductivity ranged from approximately 42 to 664 µS/cm

Table 30 Biofilter media analysis

Site	Electrical Conductivity [µS/cm]	NH_4^+-N [mg/kg]	NO_2^-N [mg/kg]	NO_3^-N [mg/kg]	NH_4^+-NO_x^-N [mg/kg]	SO_4^{2-} [mg/kg]	Moist Cont (%)	pH
UOL05 (23.07.13)	531	450	35	1423	1.908	205	66.5	6.9
UOL05 (08.10.13)	460	550	5	410	0.965	540	71.8	7.0
UOL06 (14.08.13)	42	35	5	11	0.0505	145	71.8	6.8
UOL06 (19.09.13)	151	192	65	120	0.3768	35	63.6	8.1
UOL06 (15.10.13)	664	515	170	521	1.206	65	71.7	6.6
UOL07 (02.10.13)	206	146	15	190	0.35	35	68.3	6.6
UOL07 (12.11.13)	44	7	10	34	0.051	20	69.4	6.6

From the perspective of the biological health of the media in each biofilter to sustain microbial growth, the results of the analysis were generally positive. The electrical conductivity, pH and % dry solids of all media samples collected were within the intermediate to optimal range to support a healthy population as indicated in Table 31 below.

Table 31 Suggested criteria for assessing biofilter media health (personal communication, 2013)

Parameter	Indication of the quality of biofilter media		
	Optimal	Intermediate	Negative
EC (µS/cm)	< 1000	1000 – 3000	> 3000
NH_4^+-NO_x-N	0.25 – 3.5	3.5 – 5 and 0.15 – 0.25	> 5 and < 0.15
SO_4^{2-}	<1000 mg/kg	NA	>1000 mg/kg
Moist Cont (%)	60 - 75	75 - 80 and 50 - 60	> 50 and < 80
pH	6 – 8	5 – 6 and 8 -9	< 5 and > 9

The NH_4^+-NO_x-N analysis of the media samples did however, highlight some potential deficiencies in samples collected from UOL06 and UOL07. This would suggest some potential for inhibition in growth of microbes at this site.

5.2 Impact of upstream waste type, process configuration and operating parameters on the emission of bioaerosols and odour in the inlet to the abatement system

The following section presents the individual bioaerosol, odour and VOC concentrations in the inlet air to the abatement system at each site, and attempts to identify the impact of the upstream site process configuration, and plant operating parameters on emission concentrations. The data is presented as a series of bar charts and the full bioaerosol and odour data is presented in Appendix 2 and 3 at the back of this report. In each of the charts, the data is presented as a mean of the three samples taken, and the error bars represent the maximum and minimum concentration, which give an indication of the variability in the samples.

5.2.1 Aspergillus fumigatus

Figures 4, 5 and 6 show the concentration of *Aspergillus fumigatus*, total bacteria and gram negative bacteria in the exhaust air from the different sites arranged by site. Appendix 2 contains figures showing the same data arranged according to waste treatment system type and by waste type.

The sites sampled as part of this research included two Eco Deco biodrying sites (UOL01 and UOL05), two enclosed windrow sites (UOL02 and UOL03), one rotating drum site (UOL04)

and three tunnel composting sites (UOL06, UOL07 and UOL08). It can be seen in Figure 4 and Table 32 that the concentration of *Aspergillus fumigatus* in the inlet air to the abatement systems varies considerably from one site to another. It also appears that there is no relationship between the concentration of *Aspergillus fumigatus* emitted and the composting or biodrying system being used (Figure 20 in Appendix 2). This may be due to the fact that at some sites the air entering the abatement system is a mixture of process air and air from other areas of the site. Ancillary activities involving the agitation of waste material (e.g. shredding) will have a large impact on the concentration of bioaerosols. Because such activities may be intermittent they may have a big impact but over a limited time period.

The highest concentration of *Aspergillus fumigatus* was found at UOL08 where the abatement system is fed with air taken from the composting tunnels and from the waste reception area. The mean concentration of 25,780 cfu/m^3 was more than seven times higher than the concentration at UOL01, which was the next highest. It appears that the high concentrations of *Aspergillus fumigatus* at UOL08 are not typical of the other tunnel composting sites sampled (Figure 20 in Appendix 2).

At UOL06 the mean concentrations were between 1,776 and 2,970 cfu/m^3 and at UOL07 the concentration varied from 9 to 500 cfu/m^3. The variability at UOL07 between sampling visits could not be attributed to any difference in the process operations taking place. The variability at UOL06 between sampling visits was attributed to variations in the tunnel operations. During the first two visits the tunnels were full and the material was being maintained at temperatures above 60°C for ABPR compliance. On the third visit the material in the tunnels had achieved its ABPR time temperature requirements and all the tunnels were being vented, ready for being emptied. As a result the ventilation rate was higher and may account for the lower concentration of *Aspergillus fumigatus.* It is not clear whether this is a result of the higher ventilation rate producing a 'dilution' effect, or because the material has undergone a 'pasteurisation' stage, which may or may not have inactivated a proportion of the *Aspergillus fumigatus* in the waste material in the tunnels.

The Eco Deco biodrying sites (UOL01 and UOL05) exhibited a great deal of variation in the inlet concentration of *Aspergillus fumigatus* between visits. Both sites discharge air from the waste reception and biodrying areas to the abatement system. The concentration of bioaerosols will be a function of the activities taking place within the building, e.g. loading and unloading of waste and also emission of bioaerosols from the waste. Drying of the waste material during the process may lead to higher numbers of bioaerosols being stripped from the material by the air passing through it. The concentration of *Aspergillus fumigatus* at UOL01 varied between visits from 794 to 3,393 cfu/m^3 and at UOl05 it varied between 1,927 and 3,154 cfu/m^3. The variability at UOL05 could not be attributed to differences in process operation. A higher airflow at UOL01 observed during the second may account for the higher concentration of *Aspergillus fumigatus* in the air. If the higher flow rates are indicative of higher aeration rates in the material in the biodrying bays, this may suggest

that more *Aspergillus fumigatus* is being stripped out of the material by the higher volumes of air passing through it.

At the two enclosed windrow sites (UOL02 and UOL03), air entering the abatement system comes from a single building housing the waste reception area and the aerated windrows. The green waste stream at UOL02 was sampled on one occasion and the green waste and MSW streams at UOl03 were sampled on consecutive days. The concentration of *Aspergillus fumigatus* at UOL03 were comparable on the two days, despite the fact that the samples were taken from different air streams coming from very different waste streams. In comparison the concentration at UOL02 was much lower at only 399 cfu/m^3. Differences in air flow rates were observed on the green waste streams at UOL02 and UOL03 and on this occasion lower concentrations of *Aspergillus fumigatus* at UOL02 were associated with higher air flow rates.

UOL08 uses a rotating drum system housed in a single building together with the static windrows. The air from the whole building is sent to the abatement system. This is the only site where the waste is not actively aerated at any stage in the treatment process by passing an air stream through the waste. Aeration is augmented by agitating the material by turning the windrows, or by the rotating drum. The mean concentration of *Aspergillus fumigatus* in the inlet air from site UOL04 were extremely low at only 11 cfu/m^3.

Looking at the upstream processes in terms of the waste being treated (Figure 25 in Appendix 2), it is not possible to establish any clear relationship between the type of waste being treated and the concentration of *Aspergillus fumigatus* being emitted. For example, at UOL02 and UOL03 the concentration was different despite using the same system to treat the same waste type (Figure 4 and Table 32). In addition at UOL03 comparable concentration of Aspergillus fumigatus were emitted from the green waste and MSW waste streams. Comparing the sites treating green waste/food waste mixtures using tunnel systems the concentration of *Aspergillus fumigatus* being emitted varies significantly from 1,776 cfu/m^3 at UOL06 to more than 25,000 cfu/m^3 at UOL08.

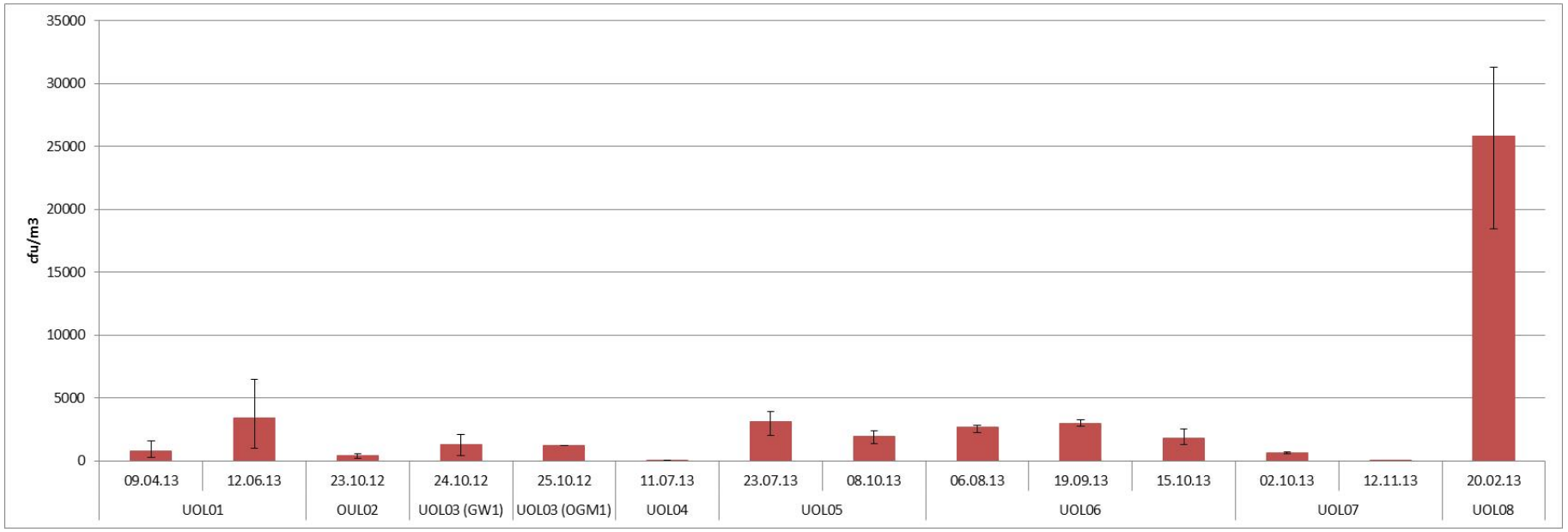

Figure 4 *Aspergillus fumigatus* concentration in the inlet air to the abatement system at the different sites.

Table 32 Mean, maximum and minimum *Aspergillus fumigatus* concentrations in the inlet air to the abatement system at the different sites

Site	UOL01		OUL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09.04.13	12.06.13	23.10.12	24.10.12	25.10.12	11.07.13	23.07.13	08.10.13	06.08.13	19.09.13	15.10.13	02.10.13	12.11.13	20.02.13
Mean	794	3393	399	1327	1233	11	3154	1927	2656	2970	1776	624	9	25780
Max	1622	6516	582	2119	1233	33	3896	2429	2850	3283	2574	701	12	31267
Min	262	1044	208	459	1233	0	2032	1376	2268	2758	1290	543	7	18473

5.2.2 Total bacteria

Figure 5 and Table 33 show the concentration of total bacteria emitted at the eight sites arranged according to site. Figures 23 and 26 in Appendix 2 show the same data arranged according to process type and waste type. It is apparent from the data that regardless of the waste being treated, and the system being used, the concentration of total bacteria is significantly higher than those for *Aspergillus fumigatus* and that this is true for all the sites sampled.

Once again, the highest concentration was found for the tunnel system at UOL08 (111,644 cfu/m^3), although it was not as significant as observed for *Aspergillus fumigatus*. A comparison with the other tunnel composting systems suggests that this high concentration is not typical of that produced by other tunnel systems. Site UOL07 had a maximum concentration of 55,233 cfu/m^3 for the others the maximum observed concentration was less than 20,000 cfu/m^3. At UOL06 the concentration varied over the three visits, with a lower concentration observed during the final visit when the air flow rate was higher.

The concentration of total bacteria at the Eco Deco biodrying sites (UOL01 and UOL05) varied between visits. The mean concentrations at UOL01 were 14,293 and 43,260 cfu/m^3 and at UOL05 they were 25,118 and 14,744 cfu/m^3. The overall trends at the two sites mirrored those observed for the *Aspergillus fumigatus* and in the case of UOL01 may also be related to the variation in the air flows coming from the waste handling and treatment building.

The two enclosed windrow sites treating green waste (UOL02 and UOL03) showed similar concentrations of total bacteria at 9,784 cfu/m^3 and 10,453 cfu/m^3 respectively. The concentration emitted from the MSW stream at UOL03 was higher at 10,453 cfu/m^3.

Finally, the rotating drum system at UOL04 had a significantly higher concentration of total bacteria compared to the concentration of *Aspergillus fumigatus* discussed in the previous section. It was found to be one of the highest emitters of total bacteria at 25,828 cfu/m^3.

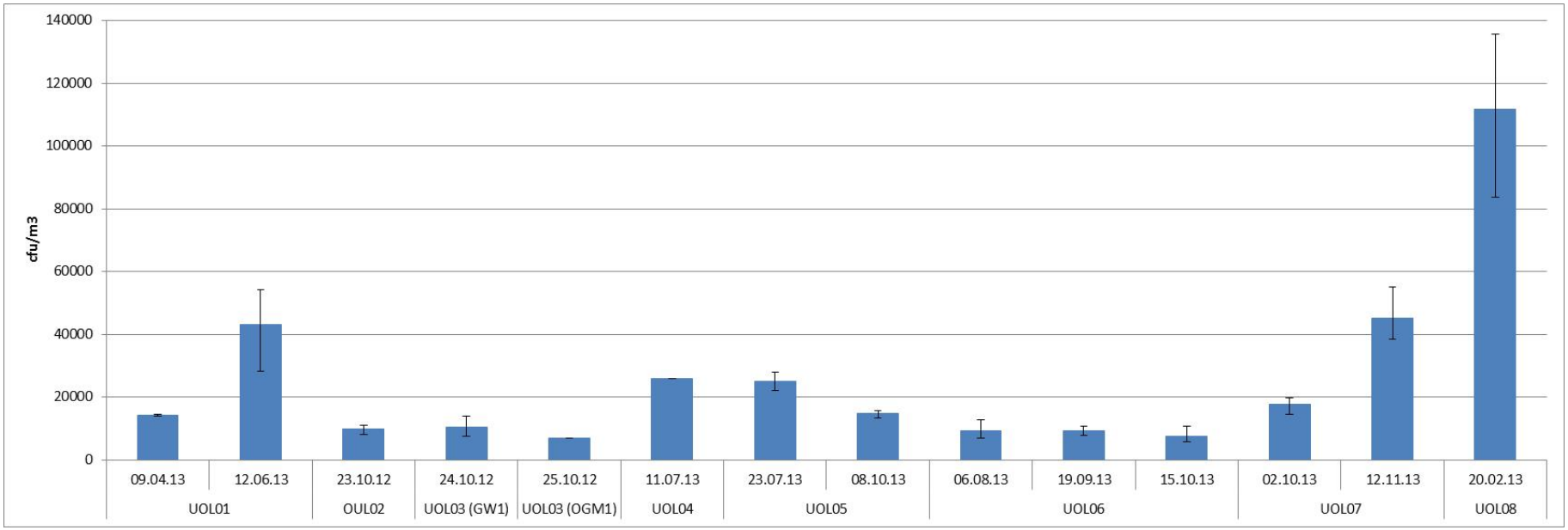

Figure 5 Total bacteria concentration in the inlet air to the abatement system at the different sites

Table 33 Mean, maximum and minimum total bacteria concentrations in the inlet air to the abatement system at the different sites

Site	UOL01		OUL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09.04.13	12.06.13	23.10.12	24.10.12	25.10.12	11.07.13	23.07.13	08.10.13	06.08.13	Date	09.04.13	12.06.13	23.10.12	24.10.12
Mean	14293	43260	9784	10453	7101	25828	25118	14744	9158	9161	7681	17860	45251	111644
Max	14630	54175	11014	14009	7101	25828	27821	15706	12701	10633	10618	19870	55233	135654
Min	13855	28199	8219	7514	7101	25828	22272	13480	6958	7786	5728	14515	38406	83751

5.2.3 Gram negative bacteria

Figure 6 and Table 34 show the concentration of gram negative bacteria emitted by the eight sites sampled arranged according to site. Figures 24 and 27 in Appendix 2 show the same data arranged according to process type and waste type. The data shows that the emission profiles for gram negative bacteria are very different from those for *Aspergillus fumigatus* and total bacteria with different sites emitting high and low concentrations.

The highest concentration of gram negative bacteria was observed at UOL07 (33,685 cfu/m^3) and this site also showed significant variation between visits. In comparison, the emission from the other tunnel systems were much lower with a maximum of 6,857 cfu/m^3 at UOL06 and 16,820 cfu/m^3 at UOL08.

The emissions from the Eco Deco biodrying sites (UOL01 and UOL05), which use the same treatments system and same waste type, varied between site and also between visits. The concentrations at UOL01 were significantly higher at 9,957 and 16,355 cfu/m^3 compared to 4,046 and 2,833 cfu/m^3 at site UOL05. The variability at site UOL01 follows the same trend as that observed for the other two bioaerosols, with a higher concentration associated with a higher air flow rate.

The concentration of gram negative bacteria in the exhaust air from the two enclosed windrow sites (UOL02 and UOL03) treating green waste were comparable at 3,704 and 3,568 cfu/m^3. The samples taken from the MSW stream at UOL03 were much lower at only 2,464 cfu/m^3.

The lowest concentrations of gram negative bacteria were observed in the exhaust air from the rotating drum system at UOL04, which treats a mixture of green waste and food waste. The mean concentration was only 746 cfu/m^3.

A comparison between the different sites in terms of the fraction of the total bacteria that were gram negative reveals an extremely variable picture. There is no relationship between the types of waste being processed, or the type of treatment system being employed and the proportion of gram negative bacteria emitted. For example at the biodrying plants the proportion of bacteria that were gram negative varied from 12% at UOL05 up to 98% at UOL01. The tunnel systems were equally variable with the lowest proportion of gram negative bacteria observed at UOL08 and the highest at UOL06. Overall, the smallest fraction of gram negative bacteria was seen at UOL04 where they represented less than 1% of the total bacteria. The data also shows that the proportion of gram negative bacteria emitted is not related to the type of waste. For example the green waste emitted 0.9% up to 85%, the green waste/food waste sites emitted 24% to 60% and the MSW sites emitted 12% to 98%.

Regression analysis carried out on the bioaerosol data showed that there was no relationship (positive or negative) between any of the bioaerosols in the inlet samples.

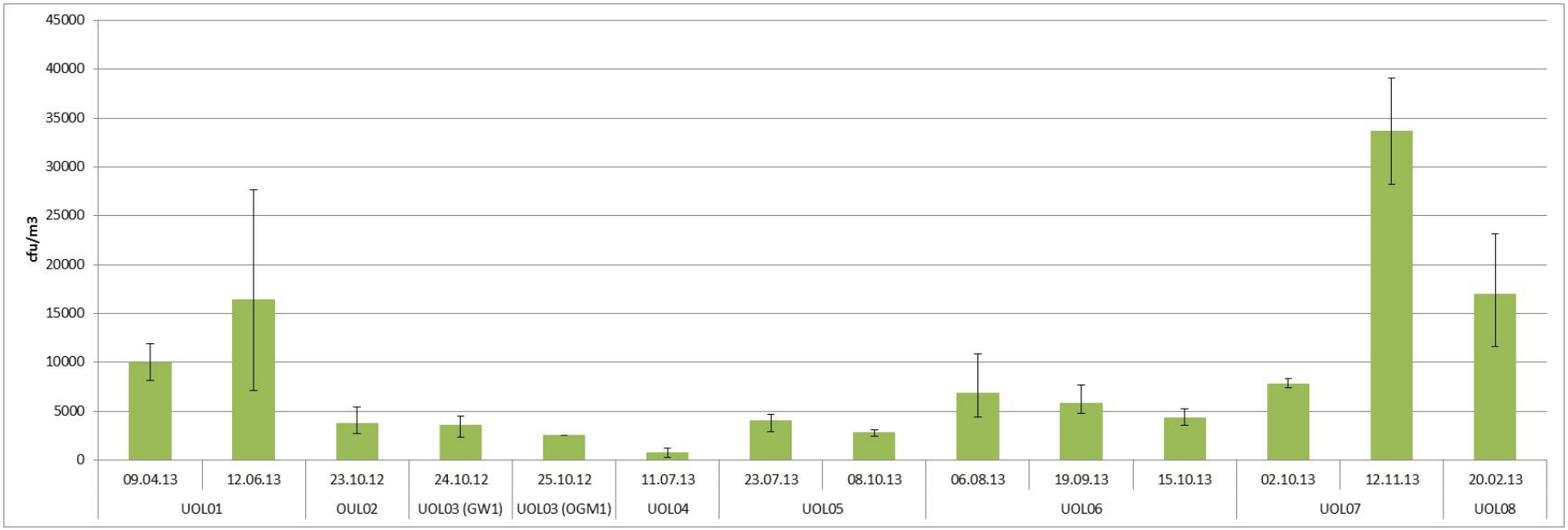

Figure 6 Gram negative bacteria concentration in the inlet air to the abatement system at the different sites

Table 34 Mean, maximum and minimum gram negative bacteria concentrations in the inlet air to the abatement system at the different sites

Site	UOL01		OUL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09.04.13	12.06.13	23.10.12	24.10.12	25.10.12	11.07.13	23.07.13	08.10.13	06.08.13	Date	09.04.13	12.06.13	23.10.12	24.10.12
Mean	9957	16355	3704	3568	2564	746	4046	2833	6857	5820	4317	7753	33685	16920
Max	11891	27694	5386	4480	2564	1233	4704	3095	10843	7679	5212	8360	39137	23152
Min	8112	7129	2734	2345	2564	233	2859	2468	4374	4785	3558	7407	28246	11642

5.2.4 Odour

Figure 7 and Table 36 show the concentration of odour in the exhaust air from the different sites arranged by site. It can be seen that the mean odour concentration of air released from the composting process varied significantly across the sites studied, ranging from 5,000 OU_E/m^3 to 145,000 OU_E/m^3. Variations in concentration were noted both between sites and between sample visits to the same site.

Table 35 shows the data obtained from the analysis of the olfactometry data by process type and the data indicates that there is little evidence of a direct influence of process on odour concentration.

Table 35 Summary of mean odour concentration of process air by process type

Site	Process type	Feedstock	Geometric mean odour concentration [OU_E/m^3]		
			Visit 1	Visit 2	Visit 3
UOL01	Biodrying	MSW	10796	36437	
UOL05	Biodrying	MSW	29950	16573	
UOL06	IVC tunnels	Green / food	145311	13057	4856
UOL07	IVC tunnels	MSW	8685	12345	-
UOL08	IVC tunnels	Green / food	17453	-	-
UOL03	Enclosed windrow	Green (visit 1) and MSW (visit 2)	13892	22778	-
UOL02	Enclosed windrow	Green and MSW	58422	-	-
UOL04	IVC rotating drum	Green / food	9040	-	-

For the sites utilising tunnels systems (sites UOL06, UOL07 and UOL08), the odour concentration ranged from 4,856 OU_E/m^3 to 145,000 OU_E/m^3, with an overall mean concentration of 33,617 OU_E/m^3. The data obtained from site UOL06 indicated that the odour concentration in the process air varied substantially despite comparable feedstock and processing conditions observed during visit 1 and 2. A 25% variation in the air flow was noted between these two visits; however, this may be associated with the uncertainty of the flow measurement method and would not account for the large difference in odour concentrations detected. During the third visit, the tunnels were being vented to cool the material following completion of the ABPR cycle, and it is plausible that the lower concentration of air detected on this visit was influenced by this process cycle.

The mean odour concentration of air measured at UOL07 and UOL08, which also employ tunnel systems, were 14,401 and 17,453 OU_E/m^3 respectively. Although the mean concentrations at UOL07 and UOL08 are of the same order of magnitude, it is important to note that the design and configuration of the ventilation systems and the rate of extraction

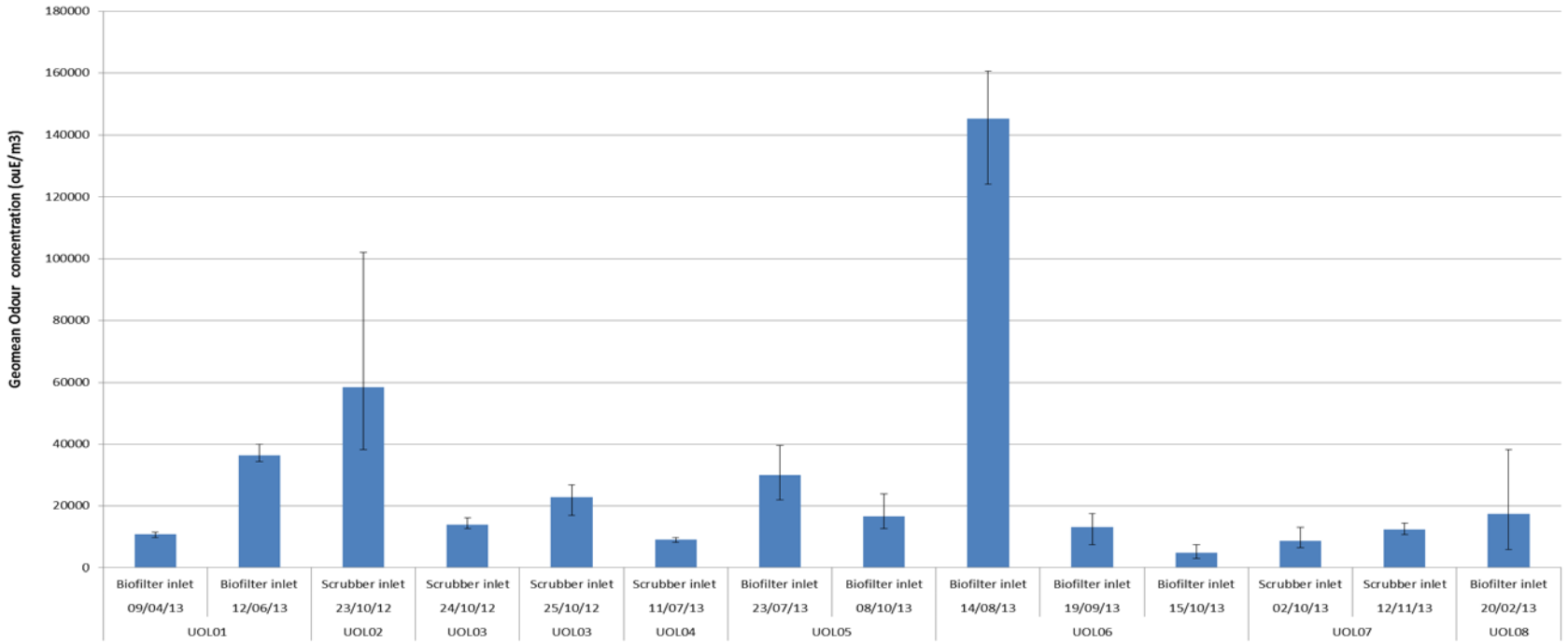

Figure 7 Mean odour concentration measured in process air at the different sites

Table 36 Mean, maximum and minimum odour concentrations measured in process air at the different sites

Site	UOL01		UOL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09/04/13	12/06/13	23/10/12	24/10/12	25/10/12	11/07/13	23/07/13	08/10/13	14/08/13	19/09/13	15/10/13	02/10/13	12/11/13	20/02/13
Location	Biofilter inlet	Biofilter inlet	Scrubber inlet	Scrubber inlet	Scrubber inlet	Scrubber inlet	Biofilter inlet	Biofilter inlet	Biofilter inlet	Biofilter inlet	Biofilter inlet	Scrubber inlet	Scrubber inlet	Biofilter inlet
Geomean	10796	36437	58422	13892	22778	9040	29950	16573	145311	13057	4856	8685	12345	17453
Max	11577	39956	102106	16137	26724	9683	39539	23892	160512	17494	7440	13033	14401	38234
Min	9749	34284	38247	12684	16949	8176	21919	12656	124146	7448	3046	6502	10789	5925

of air vary substantially between these sites. The sites also treat different types of waste so any similarity in odour levels may be coincidental.

Table 35 shows that for the Eco Deco biodrying sites, the mean odour concentrations in the process air ranged from 10,796 – 36,436 OU_E/m^3 (UOL01) and 16,573 – 29,905 OU_E/m^3 (UOL05). Operational conditions on each day were similar for both site visits, as were the waste types. The odour concentrations are therefore likely to be associated with variations in onsite activities at the time of sampling (e.g. material handling activities in the reception hall; status of individual tunnels).

For the enclosed windrow sites, the mean odour concentrations in the process air were 13,000 UO_E/m^3 and 23,000 UO_E/m^3 for UOL03 (treating green and MSW waste respectively), and 58,000 for UOL02 (treating green waste). Bearing in mind that the design and operation of each site were broadly comparable, the data implies significant differences in odour concentration can occur even when treating the same waste type with the same process. Although the composting of MSW at UOL03 appears to generate more concentrated odour, there is insufficient data to assess whether the material type is a dominant influencing factor for odour between sites. For the IVC rotating drum (UOL04), the concentration of odour was 9040 OU_E/m^3.

In terms of the perceived odour quality or character, review of Table 37 indicates that common descriptors are applied to all sites (i.e. compost). Waste type smells were positively identified in all sites treating municipal waste and the green and food waste fraction is also clearly identified in sites UOL02, UOL03 (visit 1) and UOL04. Ammonia type odours were also clearly detected in sites UOL01, UOL02, UOL03 and UOL05. The perceived unpleasantness of the odours were generally described as high, albeit on a relatively simple and subjective scale.

Table 37 Summary of the odour character of the process air

Site	Process Type	Feedstock	Odour Character (subjective)	Perceived unpleasantness (subjective)
UOL01	Biodrying	MSW	Waste, ammonia, compost	High
UOL05			Waste, ammonia, putrid	High
OUL06	IVC Tunnels	Green/Food	Rotten food, compost	High
OUL07		MSW	Waste, ammonia, compost, fishy	High
OUL08		Green/Food	Rotten food, compost	High
OUL03	Enclosed windrows	Green (visit 1) and MSW (visit 2)	Grass, woody, compost (visit 1). Waste, spoiled food, ammonia, compost	Moderate to high
OUL02		Green/MSW	Compost, waste, spoiled food, ammonia	High
OUL04	IVC Rotating drum	Green/Food	Compost, spoiled food, solvent, grass	High

5.2.5 Ammonia, hydrogen sulphide and volatile organic compounds

Figure 8 and Table 38 show the ammonia data for the sites sampled and shows that concentrations vary considerably from <0 mg/m^3 (<LLOD) up to 67 mg/m. The highest concentrations were detected at the two enclosed windrow sites (UOL02 and UOL03) treating MSW. No trends were identified between the ammonia concentration and odour concentration measured in the process air.

In comparison, the hydrogen sulphide data (Figure 8 and Table 38) shows that the concentrations detected in the process air were below the limit of detection of the analytical method employed at five of the eight sites sampled (UOL02, UOL03, UOL04, UOL05 and UOL06). Where hydrogen sulphide was detected, the concentrations ranged from approximately 0.15 mg/m^3 to 12.3 mg/m^3, although with the exception of UOL01, the concentration remained at or below 1 mg/m^3. The cause of the elevated concentrations of hydrogen sulphide at UOL01 (9.8 and 12.3 mg/m^3) could not be identified. Overall the concentration of hydrogen sulphide in the process air does not appear to be linked to process type or feedstock type.

The VOC analysis (Table 39) shows that the process air generated from the composting operations comprises a complex mixture of odorous components including aromatic, aliphatic and cyclic hydrocarbons, alcohols, ketones, aldehydes, esters, reduced sulphur compounds and terpenes. The composition of the air generated from the process appears to exhibit substantial variation from site to site and between sampling visits, both in terms of the individual odorous VOCs identified and their detected odour concentration.

The compounds detected above their odour threshold are identified in Table 40. The table presents the ratio between the measured concentration and the odour threshold value of each component and provides an insight into the main potential contributors to process odour at each site. A review of the data indicates that the highest concentration/odour threshold value ratios were linked to sulphur compounds (hydrogen sulphide, dimethyl sulphide), the aldehyde 3-methylbutanal, the ketone 2,3-butanedione and the ester ethylbutanoate, all of which were detected at concentrations of between 2 to 4 orders of magnitude above their odour threshold value.

The overall results from this study indicate that neither the process, nor the waste type, appear to have a significant impact on the chemical composition of the odour from composting processes. This result suggests that the overall odour concentration of air from composting processes is likely to be influenced by a complex interplay of the component odorous components which may exhibit additive, reductive and synergistic effects at a sensory level. This is expected to a large degree and reflects the findings of Odournet's experience and with other environmental odours, which comprise of a mixture of different odorous chemical components at different odour concentrations.

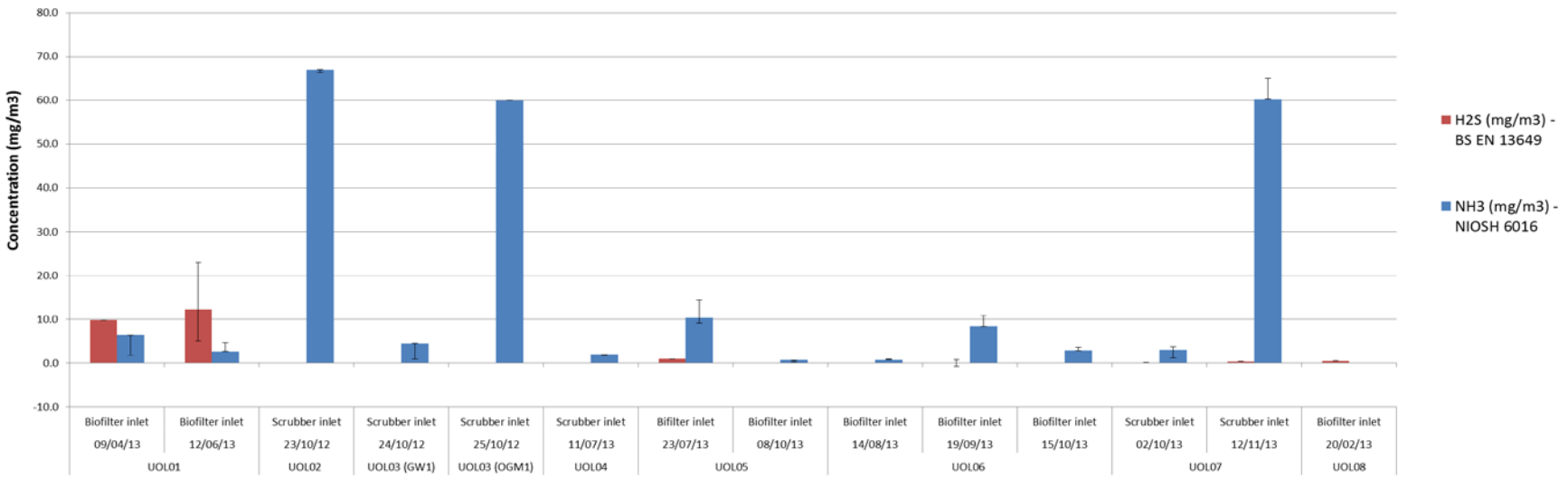

Figure 8 Mean hydrogen sulphide and ammonia concentration measured in process air at different sites

Table 38 Mean, maximum, and minimum hydrogen sulphide and ammonia concentrations measured in process air at the different sites

Site	UOL01		UOL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09/04/13	12/06/13	23/10/12	24/10/12	25/10/12	11/07/13	23/07/13	08/10/13	14/08/13	19/09/13	15/10/13	02/10/13	12/11/13	20/02/13
H2S														
Mean	9.8	12.3	<LLOD	<LLOD	<LLOD	<LLOD	1.0	<LLOD	<LLOD	<LLOD	<LLOD	0.2	0.4	0.75
Max	N/A	23.0	N/A	N/A	N/A	N/A	1.8	N/A	N/A	N/A	N/A	0.3	0.6	N/A
Min	N/A	5.1	N/A	N/A	N/A	N/A	0.3	N/A	N/A	N/A	N/A	<LLOD	0.25	N/A
NH3														
Mean	6.5	2.7	67.0	4.5	60.0	2.0	10.4	0.7	0.8	8.40	2.9	3.0	60.2	<LLOD
Max	N/A	4.6	N/A	N/A	N/A	N/A	14.4	0.7	1.0	11.	3.7	3.8	65.0	N/A
Min	N/A	0.9	N/A	N/A	N/A	N/A	6.8	0.7	0.7	7.10	2.5	2.5	55.6	N/A

Table 39 Inlet VOC concentrations(µg/m^3) detected identified by compound group concentration

VOC compound group	UOL01 09/04/13	UOL01 12/6/13	UOL02 23/10/12	UOL03 (GW1) 24/10/12	UOL03 (OGM1) 25/10/12	UOL04 11/07/13	UOL05 23/7/13	UOL05 8/10/13	UOL06 14/8/13	UOL06 19/9/13	UOL06 15/10/13	UOL07 2/10/13	UOL07 12/11/13	UOL08 20/02/13
	Biofilter Inlet	Biofilter inlet	Scrubber inlet	Scrubber inlet	Scrubber inlet	Scrubber inlet	Biofilter inlet	Biofilter inlet	Biofilter inlet	Biofilter inlet	Biofilter inlet	Bio inlet (scrub off)	Bio inlet (scrub off)	Biofilter inlet
Aromatic hydrocarbons	10275	7076	3017	1247	6941	451	4366	8498	3587	1520	309	91	353	333
Cyclic Hydrocarbons	3462	7415	1286	2094	2903	151	4614	4972	3168	1436	371	137	203	74
Aliphatic Hydrocarbons	7199	24776	10272	7085	10401	1126	16175	14506	352	1848	30	202	560	28
Alcohols	7245	49040	164242	2704	28029	42693	33748	22856	31798	6870	1721	8082	141	28736
Esters	n/d	2076	5915	83	419	5563	3180	6747	5727	1421	37	380	151	10063
Ketones	12105	25758	31558	8172	22309	8870	24740	10844	34473	6294	920	849	412	6633
Aldehydes	2109	3672	2509	833	2596	461	1541	1602	2776	496	129	n/d	301	168
Chlorinated compounds	189	1136	2560	3284	737	173	651	487	129	637	n/d	n/d	23	n/d
Organic S-compounds	n/d	434	2289	2338	2297	220	807	1288	2986	2848	2092	2316	539	230
Furans	n/d	1542	1227	111	1753	40	1057	2104	546	329	85	102	n/d	n/d
Ethers	261	n/d	356	324	61	101	51	123	129	79	n/d	n/d	n/d	33
Terpenes	7244	14114	6728	9932	6760	2357	7926	9223	50178	40771	9898	1820	524	12459
Organic nitrogen compounds	n/d	n/d	921	n/d	397	n/d	85	262	204	n/d	n/d	72	95	n/d
Organic acids	n/d	1066	3697	156	n/d	193	16882	26	992	39	173	n/d	410	173
Total	50089	138104	236577	38363	85603	62399	115824	83537	137046	64588	15765	14051	3712	58926

Table 40 Ratio of concentration to odour threshold value (OTV) for specific VOCs

Group Inlets (OTV RATIO)	Compound	UOL01 9/4/13	UOL01 12/6/13	UOL 02 23/11/12	UOL03 (GW1) 24/10/12	UOL03 (OGM1) 25/10/12	UOL04 11/7/13	UOL05 23/7/13	UOL05 8/10/13	UOL06 14/8/13	UOL06 19/9/13	UOL06 15/10/13	UOL07 02/10/13	UOL07 12/11/13	UOL08 20/02/13
		Biofilter inlet	**Biofilter inlet**	**Scrubber inlet**	**Scrubber inlet**	**Scrubber inlet**	**Scrubber inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet (scrub off)**	**Biofilter inlet (scrub off)**	**Biofilter inlet**
Inorganic	Ammonia	6	3	63	4	56	2	10	1	1	8	3	3	57	
	Hydrogen sulphide	16897	21207					1724					259	655	1293
Aromatic hydrocarbons	styrene	1	2	2		2		2	2						
	toluene	4													
	propylbenzene			2		4		3	12					2	
	1-methylethylbenzene		2			2		1	2						
	1-ethyl-3-methylbenzene	2	7			3			4						
	1-ethyl-4-methylbenzene		7	3		4		3	5						
	1-ethyl-4-methylbenzene					4									
	1,2,4-trimethylbenzene					2									
	decahydronaphtalene					40									
	decane		1												
Alcohols	ethanol	3	42	119	1	25	22	21	14	13	2	1	6	31	18
	2-butoxyethanol	1													
	1-propanol		10	125		8	32	14	9	30	4		6	9	24
	2-methyl-1-propanol		8	25		2	16	9	14	16	4		4	6	7
	1-butanol		1	16			27	13					6	2	4
	2-butanol		2	11		1	8	4	2	3				4	4
	3-methyl-1-butanol		94	60			106	113	93	146	33			13	39
	1-hexanol						4								1
	phenol			26	4										
	methanethiol				800										
Esters	ethylbutanoate										310	95	111		
	ethylacetate			1					2					2	
	1-methylpropylacetate							9	3	5				5	
	butylacetate		2	5				1	1						
	ethylpropionate							4	6	2			1	7	
	1-methylpropylacetate														5
	ethylpropionate														2
	propyl-2-methylpropanoate														1
	methylbutanoate							3		14					7
	ethylbutanoate		1031	1311				1422	993	2642				679	3205
	ethyl-3-methylbutanoate									573					607

Group Inlets (OTV RATIO)	Compound	UOL01 9/4/13	UOL01 12/6/13	UOL 02 23/11/12	UOL03 (GW1) 24/10/12	UOL03 (OGM1) 25/10/12	UOL04 11/7/13	UOL05 23/7/13	UOL05 8/10/13	UOL06 14/8/13	UOL06 19/9/13	UOL06 15/10/13	UOL07 02/10/13	UOL07 12/11/13	UOL08 20/02/13
		Biofilter inlet	**Biofilter inlet**	**Scrubber inlet**	**Scrubber inlet**	**Scrubber inlet**	**Scrubber inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet (scrub off)**	**Biofilter inlet (scrub off)**	**Biofilter inlet**
	propylbutanoate							1		4					5
	methyl-3-methylbutanoate									7					2
	2-methylpropyl-3-methylbutanoate														1
	methylpentanoate									14	3				
	ethylpentanoate									404	87			34	441
	propylpentanoate									7	1				6
Ketones	2,3-butanedione	18589	22789	24461	556		3289	12414	5559	1201	354			350	
	2-butanone	1	6	7	1	5	3	7	3	16	1		0	1	2
	2-pentanone		4	8		3	2	7	4	5	2				12
	2-heptanone	5	19	16		4	2	9	7						4
	2-hexanone									3					3
	2-heptanone									5	2			2	
	2-propenal				1										
Aldehydes	acetaldehyde		155	175	48	694	57	52	26	67		4		21	15
	2-methylpropanal	308													
	2-methyl-2-propenal					2				1					
	3-methylbutanal		1620									205		85	
	butanal				22	38		24	28	69	6	6		7	
	3-methylbutanal	745		405	63	458	263	1129	1134	3207	769			85	191
	pentanal							64	60						
	hexanal	486	386		74		40	336	332	36	18			12	
	heptanal	226	247	174	61			111	113		14				
	nonanal	204	331	198	51		22	145	149	16	13			45	
	decanal	68	78	134	45		3								3
	tetrachloroethylene				1										
Sulphur	dimethylsulfide		211	454	1240	405			560	2833	2672	2092	1116	1798	218
	dimethyldisulfide		25	182	110	192			60	9	9		88	144	1
Terpenes	alpha-pinene	3	7	3	26	5	1		6	122	85	27	1	4	23
	beta-pinene	2	3							6	6	2		1	3
	limonene	29	54	27	15	29	10		35	88	60	15	7	23	32
Amines	trimethylamine			11513		3263			1287					65	
Organic acid	acetic acid		71	158	10						3	12			6
	propanoic acid			40											1
	2-methylpropanoic acid														2

Group Inlets (OTV RATIO)	Compound	UOL01 9/4/13	UOL01 12/6/13	UOL 02 23/11/12	UOL03 (GW1) 24/10/12	UOL03 (OGM1) 25/10/12	UOL04 11/7/13	UOL05 23/7/13	UOL05 8/10/13	UOL06 14/8/13	UOL06 19/9/13	UOL06 15/10/13	UOL07 02/10/13	UOL07 12/11/13	UOL08 20/02/13
		Biofilter inlet	**Biofilter inlet**	**Scrubber inlet**	**Scrubber inlet**	**Scrubber inlet**	**Scrubber inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet**	**Biofilter inlet (scrub off)**	**Biofilter inlet (scrub off)**	**Biofilter inlet**
	butanoic acid			864											36
	3-methylbutanoic acid														32

5.2.6 Summary

Based on the data on the bioaerosol, odour and VOC concentrations in the exhaust air from the waste treatment sites sampled, a number of observations can be made:

- The bioaerosol concentrations in the process air ranged from 9 to 25,780 cfu/m^3 for *Aspergillus fumigatus*, 7,101 to 111,644 cfu/m^3 for total bacteria and 746 to 33,685 for gram negative bacteria. The mean values across all visits were around 3,290, 25,095 and 8,509 cfu/m^3 respectively.
- From this data there is no relationship between the type of waste or the treatment system and the concentration of bioaerosols or odour emitted. It would appear that it is a function of a complex mix of specific process operating conditions and waste characteristics at the time of sampling.
- From this data it is not possible to determine if the different waste treatments systems, or the type of waste being treated, produce a typical bioaerosol or odour emission profile.
- The impact of air flow rates on the concentration of bioaerosols varies from site to site. At UOL06 higher airflows reduced the concentration of bioaerosols and at UOL01 they increased the concentration.
- Overall the concentration of total bacteria is significantly higher than the concentration of *Aspergillus fumigatus,* regardless of the treatment system being used and waste being treated.
- The fraction of the total bacteria that are gram negative is extremely variable and does not appear to be related to the treatment system being used, or the waste being treated.
- From this data there is no relationship, either positive or negative between the concentrations of *Aspergillus fumigatus*, total bacteria or gram negative bacteria in the inlet to the abatement system.
- The odour concentration of the process air across the study sites ranged from approximately 5,000 OU_E/m^3 to 145,000 OU_E/m^3, with a mean value across all visits of around 29,000 OU_E/m^3.
- The odour descriptors applied to describe the character of the odour were relatively consistent across the sites and correlations were evident between the type of waste processed for sites handling food, green waste and MSW. The perceived offensiveness of the odours were described as moderate to high.
- The concentration of odour in the air extracted directly from the tunnels at UOL06 and UOL07 was broadly of the same order of magnitude as found at sites where air was extracted from a combination of processing areas (e.g. tunnels and waste hall), with the exception of visit 1 to UOL06 where the mean concentration of odour measured was approximately an order of magnitude higher.
- The concentration of hydrogen sulphide in the process air was generally low (<LLOD of the technique employed to 1 mg/m^3) across seven of the eight sites studied. The one

exception was UOL01, where the concentration was approximately one order of magnitude higher.

- The concentration of ammonia in the process air ranged from <LLOD of the analysis technique employed to 67 mg/m^3 across all sites, with a mean of 17.6 mg/m^3. The highest concentrations (>60 mg/m^3) were detected in the process air from the enclosed windrow systems at UOL03 treating MSW.
- The process air generated from all the composting operations comprised a complex mixture of odorous components which include aromatic, aliphatic and cyclic hydrocarbons, alcohols, ketones, aldehydes, esters, reduced sulphur compounds and terpenes. The dominant compound groups identified by mass in the process air from all sites were aliphatic hydrocarbons, alcohols, ketones and terpenes.
- The VOCs detected in the air do illustrate some general patterns across the processing sites. Aliphatic hydrocarbons make up a relatively high proportion of the VOCs detected in the process air at sites treated MSW waste. Terpenes are present in the process air streams of all sites, but are elevated at most of the sites treating green waste.
- A wide range of odorous compounds were detected in the process air above their odour threshold value, which varied to some degree from site to site. The compounds detected with the highest concentration/ odour threshold value ratios were sulphur compounds (hydrogen sulphide, dimethyl sulphide, dimethyl disulphide), aldehydes (3-methylbutanal, hexanal, heptanal, nonanal, decanal), the ketone 2,3-butanedione, the ester ethylbutanoate and the amine triethylamine, all of which are detected at concentrations of between 2 to 4 orders of magnitude above their odour threshold value. No specific correlations were identified between individual compounds, or compound groups, and odour concentration.

5.3 Emission concentrations of bioaerosols and odour from the abatement systems at the different biological waste treatment sites

The following section presents the individual bioaerosol, odour and VOC concentrations in the outlet air from the biofilters, in order to identify the outlet concentrations that are being achieved by the abatement systems at the different sites. It is important to note that the bioaerosol data presented in Figures 9, 10 and 11 shows a degree of variability between replicate samples as indicated by the error bars. This implies that there is a high degree of measurement uncertainty, which may lead to variable results. Therefore, it is clear that more data is needed in order to be able to further develop our understanding of the performance of abatement systems.

5.3.1 Aspergillus fumigatus

Figure 9 and Table 41 show the concentration of *Aspergillus fumigatus* in the exhaust air from the abatement systems at the different sites. Overall the concentrations ranged from 0 to 1,337 cfu/m^3. The lowest concentrations were found at UOL07 with a maximum of 6 cfu/m^3 during the second visit. The concentrations in the exhaust air from the abatement system at UOL04 were also extremely low at only 11 cfu/m^3. Both sites achieved a very low emission concentration of *Aspergillus fumigatus* using different abatement systems. At UOL07 the system comprises of an acid scrubber followed by an open biofilter and at UOL04, the system is an acid scrubber, followed by an alkali scrubber, then an enclosed biofilter.

The highest concentrations of *Aspergillus fumigatus* were found at UOL01 on the 12th June 2013 with a concentration of 1,337 cfu/m^3. The abatement system at this site consists of an enclosed biofilter alone.

The data shows that generally the concentration of *Aspergillus fumigatus* in the exhaust air is not determined by the abatement system being used. For example the enclosed biofilters produced an exhaust concentration of between 672 and 1,337 cfu/m^3 and the open biofilters produced an exhaust concentration of between 578 and 1,067 cfu/m^3. The emission concentrations at the sites with a scrubber and enclosed biofilter ranged from 11 and 724 cfu/m^3 and those with an acid scrubber and open biofilter ranged from zero to 963 cfu/m^3. Site UOL04 which has an acid and an alkali scrubber before the biofilter, achieved very low concentrations of *Aspergillus fumigatus,* although not as low as UOL07, which has only an acid scrubber prior to its open biofilter.

5.3.2 Total bacteria

Figure 10 and Table 42 show the concentration of total bacteria in the exhaust air from the abatement systems at the different sites. The data shows that at all the sites, the concentrations are significantly higher than the concentrations previously observed for *Aspergillus fumigatus*. The concentrations from the different abatement systems ranged from 515 to 61,541 cfu/m^3. Out of the 14 days on which sampling was undertaken, on only 5 days was the concentration of total bacteria below 10,000 cfu/m^3, and on only 1 day was it less than 1,000 cfu/m^3.

The lowest concentrations were found at UOL02 and UOL03. At UOL02, the concentration was 515 cfu/m^3 and at UOL03 it was 926 cfu/m^3. These sites were the only ones at which the concentration of total bacteria was under 1,000 cfu/m^3. Both sites achieved a very low emission concentration of total bacteria using a system comprising an acid scrubber, followed by an enclosed biofilter.

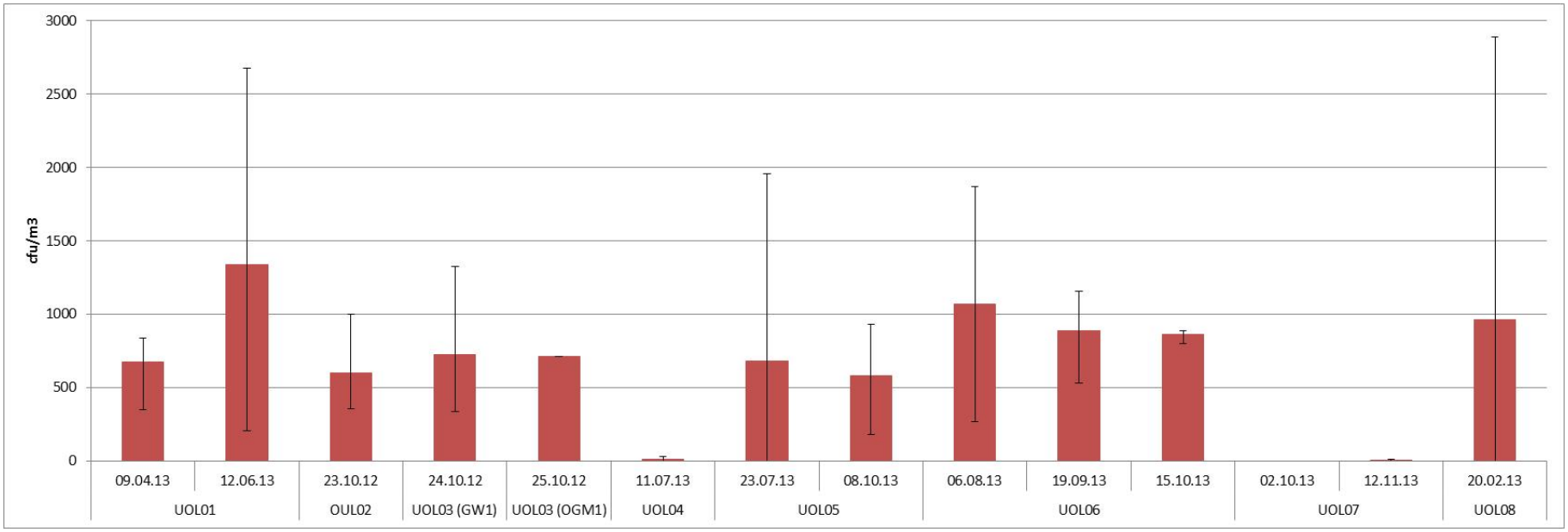

Figure 9 Emission concentration of *Aspergillus fumigatus* from the abatement system at the different sites.

Table 41 Mean, maximum and minimum *Aspergillus fumigatus* emission concentrations from the abatement system at the different sites

Site	UOL01		OUL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09.04.13	12.06.13	23.10.12	24.10.12	25.10.12	11.07.13	23.07.13	08.10.13	06.08.13	19.09.13	15.10.13	02.10.13	12.11.13	20.02.13
Mean	672	1337	599	724	713	11	682	578	1067	889	859	0	6	963
Max	834	2678	1000	1326	713	33	1956	933	1867	1156	889	0	11	2890
Min	350	208	355	335	713	0	0	178	267	533	800	0	0	0

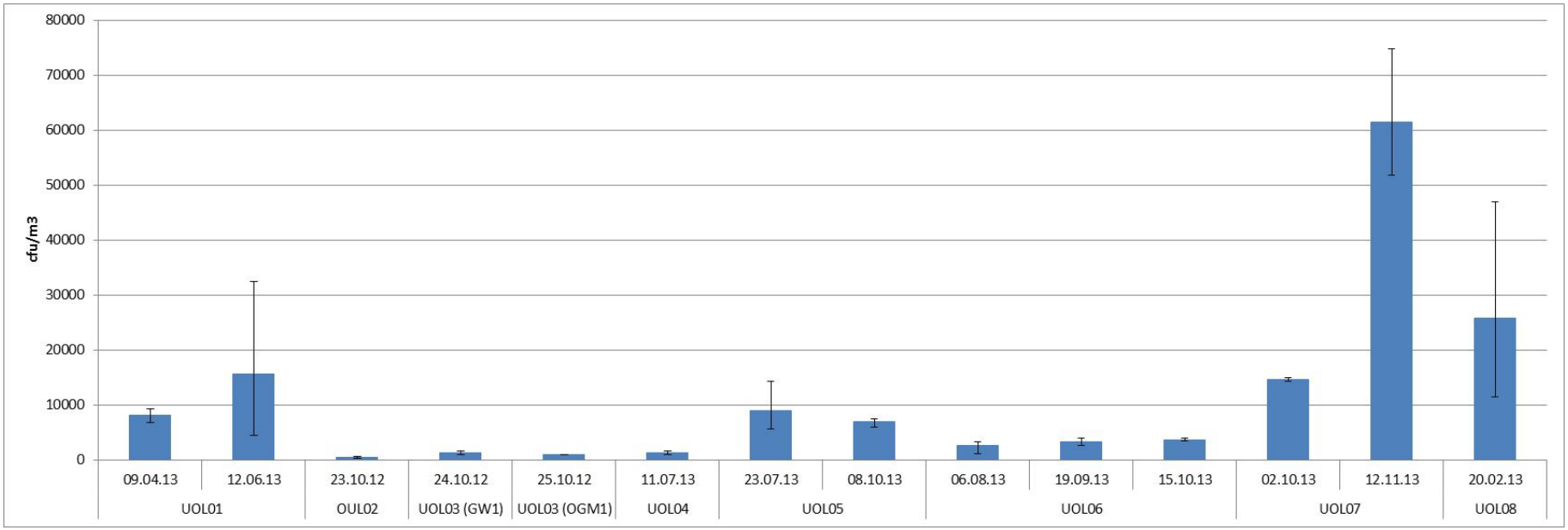

Figure 10 Emission concentration of total bacteria from the abatement system at the different sites.

Table 42 Mean, maximum and minimum total bacteria emission concentrations from the abatement system at the different sites

Site	UOL01		OUL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09.04.13	12.06.13	23.10.12	24.10.12	25.10.12	11.07.13	23.07.13	08.10.13	06.08.13	Date	09.04.13	12.06.13	23.10.12	24.10.12
Mean	8172	15580	515	1312	926	1348	9007	6937	2578	3319	3704	14726	61541	25790
Max	9376	32540	719	1633	926	1595	14311	7467	3378	4000	3911	14933	74844	46965
Min	6795	4547	237	899	926	1022	5600	5956	1067	2667	3467	14311	51822	11557

The highest concentrations of total bacteria were found at UOL07 which had an extremely high concentration of 61,541 cfu/m^3. The abatement system at this site consists of an acid scrubber, followed by an open biofilter. The other site with the same abatement system was UOL08 and this site also had a high concentration of 25,790 cfu/m^3. These two sites were the only sites with an emission concentration of total bacteria above 25,000 cfu/m^3.

The data shows that the type of abatement system being used may have an impact on the emission concentration of total bacteria. The lowest concentrations were found in the exhaust from the systems with an acid scrubber and enclosed biofilter; the highest concentrations were from the systems with an acid scrubber and open biofilter. Of the systems that do not include a scrubber, the situation is a little vague as the concentrations achieved by the enclosed biofilter only systems, range from 8,172 to 15,580 cfu/m^3 compared to 2,578 to 9,007 cfu/m^3 for the open biofilter systems.

Section 5.3.1 will look more closely at the detailed characteristics of the biofilters and scrubbers, and evaluate the removal efficiency of the different systems overall, and the scrubber and biofilter individually.

5.3.3 Gram negative bacteria

Figure 11 and Table 43 show the concentration of gram negative bacteria in the exhaust air from the abatement systems at the different sites. Overall it can be seen that the concentrations are higher than those for *Aspergillus fumigatus,* but lower than those for total bacteria. The data shows that the concentrations ranged from 144 cfu/m^3 to 35,911 cfu/m^3. Out of the 14 days on which sampling was undertaken, on 6 occasions the concentrations were below 1,000 cfu/m^3, and on a further 7 occasions they were below 10,000 cfu/m^3. On one occasion the concentration was in excess of 35,000 cfu/m^3.

The lowest concentrations were found at UOL04 where the concentration was 144 cfu/m^3. The abatement system at this site consists of an acid scrubber, followed by an alkali scrubber, followed by an enclosed biofilter. The highest concentrations were found at UOL07, with a very high concentration of 35,911 cfu/m^3. The abatement system at this site consists of an acid scrubber, followed by an open biofilter.

The data shows that the impact of the type of abatement system on the concentration of gram negative bacteria in the exhaust air is inconclusive. For example, the enclosed biofilters produced an exhaust concentration of between 5,106 and 7,155 cfu/m^3 and the open biofilters produced an exhaust concentration of between 415 and 5,212 cfu/m^3. The emission of gram negative bacteria from enclosed biofilters ranged between 144 and 324 cfu/m^3, and for those with a scrubber and an open biofilter, concentrations ranging from 2,085 to 35,911 cfu/m^3.

An attempt was made to determine if there was a relationship between the concentration of bioaerosols entering the abatement system and the concentration in the exhaust air. For

all three bioaerosol types, no relationship was found between the inlet and outlet concentrations. It would appear that for the sites sampled as part of this research project, the concentration of bioaerosols being emitted from the abatement system, regardless of what system is employed, is independent of the concentration entering. Looking at those systems where there is only a biofilter (open or enclosed), no relationship exists between the inlet and outlet concentration of *Aspergillus fumigatus* and total bacteria. However, with gram negative bacteria there is a positive relationship (r^2 = 0.75). In this case, it would appear that the higher the inlet concentration of gram negative bacteria, the higher the outlet concentration.

5.3.4 Odour

Figure 12 and Table 44 show the concentration of odour in the exhaust air from the abatement systems at the eight sites sampled during this project. Review of the results shows that the geometric mean odour concentration of the air released from the biofilters ranged from 212 OU_E/m^3 to 5,516 OU_E/m^3.

The highest mean concentration of odour of 5,515 OU_E/m^3 was measured in the exhaust air from the abatement system at UOL02 (acid scrubber followed by granular peat enclosed biofilter). The lowest mean concentration of odour of 212 OU_E/m^3 was measured in the exhaust air from the abatement system at UOL04 (acid scrubber, followed by an alkali scrubber and an expanded clay aggregate media enclosed biofilter).

With the exception of UOL01 and UOL06 on the 15th October, the geometric mean odour concentration of the air released from the biofilters remains relatively constant between sampling visits. This indicates that in general terms, the biofilters sampled appear to be capable of maintaining a relatively stable odour emission rate, which is independent of the variations in process load indicated by the inlet measurements. This is particularly notable for UOL06 where inlet odour concentrations differed by a factor of 10 between sampling on the 14th August 2013 and the 19th September 2013, yet the outlet odour concentrations remained relatively stable at 4,927 OU_E/m^3 and 4,378 OU_E/m^3 respectively.

Looking at the data in terms of the type of abatement system applied (summarised in Table 45), it is evident that the range of odour concentrations measured from enclosed biofilters (UOL01 to UOL04 and UOL08) was broadly comparable to those measured from open biofilters (UOL05 to UOL07) i.e. 212 to 5,516 OU_E/m^3 and 985 and 4,927 OU_E/m^3 respectively. The results indicate that enclosure of the biofilter appears to have little noticeable effect on the overall performance of the technique, from the perspective of outlet concentration.

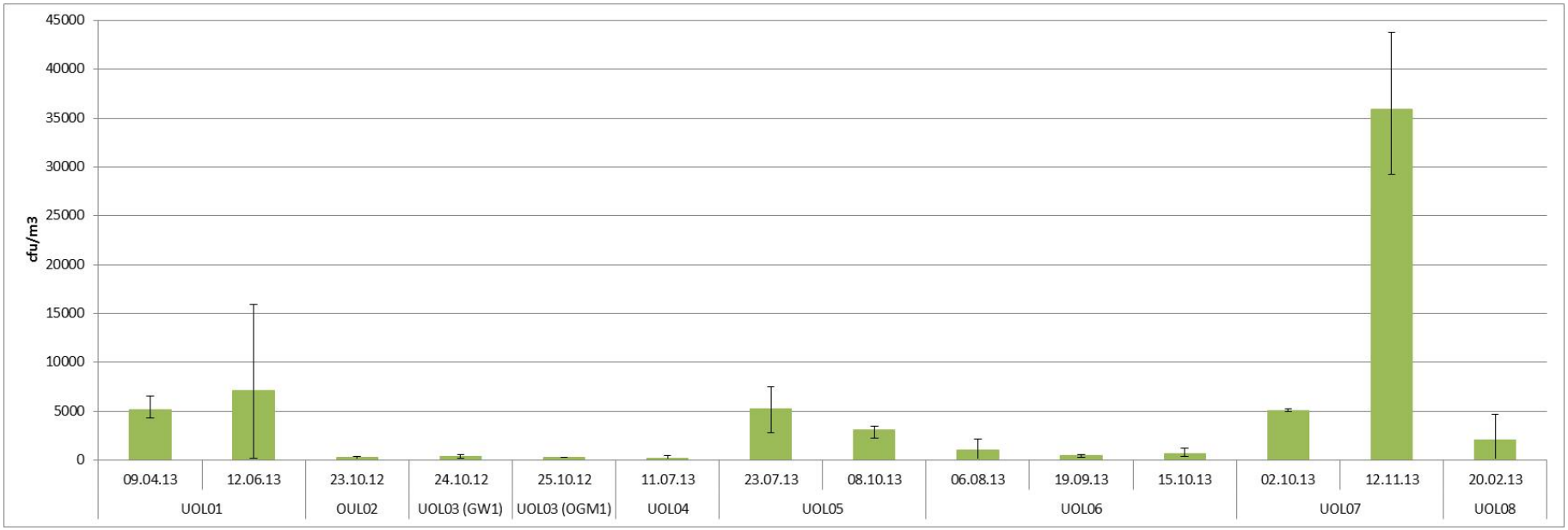

Figure 11 Emission concentration of gram negative bacteria from the abatement system at the different sites

Table 43 Mean, maximum and minimum gram negative bacteria emission concentrations from the abatement system at the different sites

Site	UOL01		OUL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09.04.13	12.06.13	23.10.12	24.10.12	25.10.12	11.07.13	23.07.13	08.10.13	06.08.13	Date	09.04.13	12.06.13	23.10.12	24.10.12
Mean	5106	7155	247	324	244	144	5215	3037	1037	415	652	5096	35911	2085
Max	6528	15916	387	503	244	433	7467	3467	2133	533	1244	5244	43822	4712
Min	4259	204	118	171	244	0	2756	2267	0	267	356	4978	29244	0

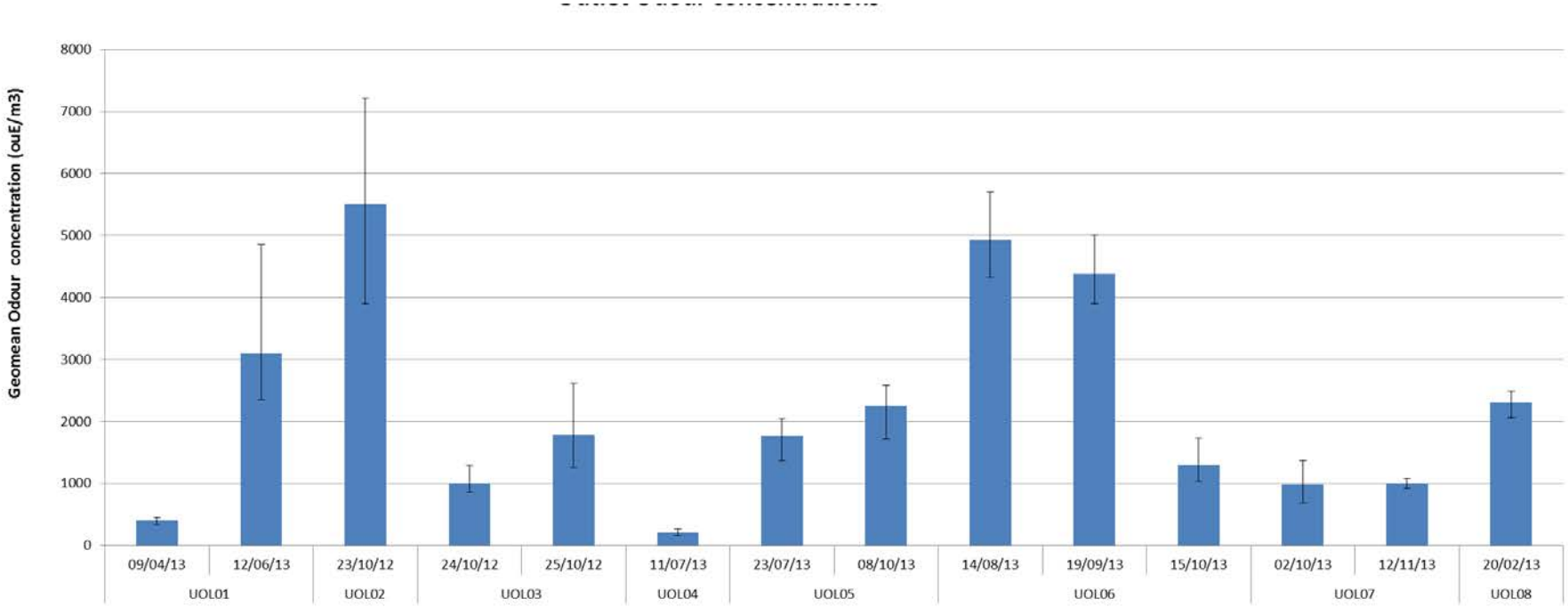

Figure 12 Emission concentration of odour (ou_E/m^3) from the abatement systems at the different sites

Table 44 Geomean, maximum and minimum odour emission concentrations (ou_E/m^3) from the abatement systems at the different sites.

Site	UOL01		UOL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09/04/13	12/06/13	23/10/12	24/10/12	25/10/12	11/07/13	23/07/13	08/10/13	14/08/13	19/09/13	15/10/13	02/10/13	12/11/13	20/02/13
Geomean	402	3102	5516	1004	1782	212	1756	2255	4927	4378	1299	985	1004	2308
Max	448	4854	7222	1290	2611	259	2048	2580	5699	5009	1728	1367	1085	2483
Min	337	2350	3894	861	1255	163	1367	1722	4334	3899	1033	683	912	2062

Table 45 Mean odour, hydrogen sulphide and ammonia concentration of air released from biofilters by site

Site	Biofilter type		Geometric mean odour concentration [ou_E/m^3]			Mean hydrogen sulphide concentration [mg/m^3]			Mean ammonia concentration [mg/m^3]		
		ERBT	Visit 1	Visit 2	Visit 3	Visit 1	Visit 2	Visit 3	Visit 1	Visit 2	Visit 3
UOL01	Enclosed woodchip and brash	51	3102	402	-	<LLOD	<LLOD	-	0.88	<LLOD	-
UOL02	Enclosed granular peat	78	5516	-	-	<LLOD	-	-	1.5	-	-
UOL03	Enclosed granular peat	68 (GW)	1004 (GW)	1782 (MSW)	-	<LLOD	<LLOD	-	0.86 (GW)	0.74 (MSW)	-
UOL04	Enclosed lightweight expanded clay aggregate	65 (OGM)	212	-	-	<LLOD	-	-	<LLOD	-	-
UOL05	Open brash	41	1756	2255	-	<LLOD	<LLOD	-	1.16	0.42	-
UOL06	Open woodchip	51	4927	4377	1299	<LLOD	<LLOD	<LLOD	<0.1	0.52	0.37
UOL07	Open pine woodchip	43	985	1004	-	<LLOD	<LLOD	-	<0.1	<0.1	-
UOL08	Open pine woodchip	84	2308	-	-	<LLOD	-	-	<LLOD	-	-

A similar picture is evident from the odour concentrations measured from systems with and without a scrubber (Table 45). The application of a scrubber (either acid scrubber alone, or an acid and alkali scrubber in series) has little influence on the overall performance of the biofilter system from an odour emission perspective, at the sites studied. This result is not particularly surprising bearing in mind the lack of any apparent relationship between the inlet odour concentrations at the biofilters and the odour concentration at the outlet.

In terms of odour character, the descriptors applied to describe odours from the biofilter systems at each site are presented in Table 46 below. It is evident from the descriptors applied that there is little evidence of the breakthrough of process air at any of the sites. The perceived unpleasantness of the odours were consistently described as moderate to low which indicates, albeit in relatively subjective terms, that that biofilters were successful in reducing the unpleasantness of the odours relative to the process air.

Table 46 Summary of the odour character of the air emitted from the biofilters

Site	Media type	Feedstock	Odour character (subjective)	Perceived unpleasantness (subjective)
UOL01	Woodchip and brash	MSW	Earthy. wood, pine	Moderate to low
UOL02	Granular peat	Green and MSW	Earthy. wood, pine	Moderate to low
UOL03	Granular Peat	Green (visit 1) and MSW (visit 2)	Earthy, musty, peat	Low / moderate
UOL04	Clay aggregate	Green / food	Musty, old compost	Moderate to low
UOL05	Brash	MSW	Earthy, woody, musty	Moderate to low
UOL06	Woodchip	Green / food	Earthy, bark, musty	Moderate to low
UOL07	Pine woodchips	MSW	Bark, earthy, woody, very faint solvent	Moderate
UOL08	Pine woodchips	Green / food	Woody, very faint solvent	Moderate

Analysis of the relationship between the odour concentration and media type and empty bed residence time, indicates there are no significant correlations at any of the sites studied as part of this project (Figure 13).

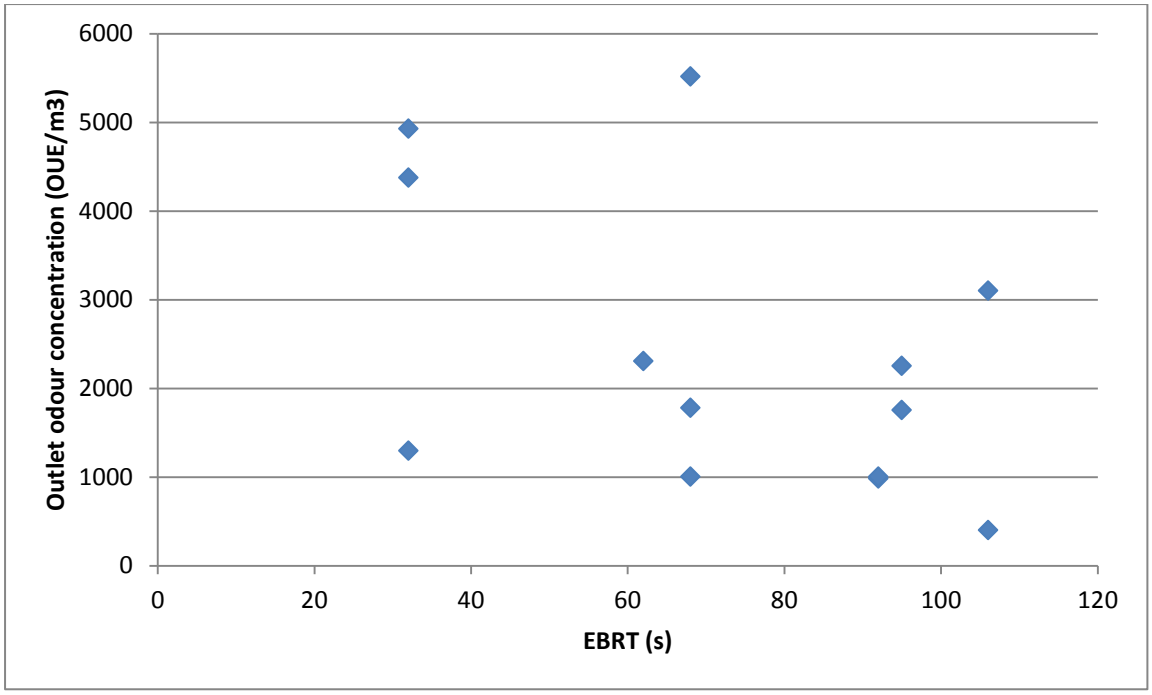

Figure 13 Relationship between EBRT and outlet odour concentrations

5.3.5 Ammonia, hydrogen sulphide and volatile organic compounds

Figure 14 and Table 47 show the concentration of hydrogen sulphide and ammonia in the exhaust air from the abatement systems at the different sites. Table 48 shows the concentration of the main VOC compound groups present in the exhaust air from the abatement systems, and presents the ratio between the measured concentration of individual components and their respective odour threshold values.

Review of the data indicates that the hydrogen sulphide concentrations detected in the air released from the biofilters were below the limit of detection of the analytical method employed on all but one occasion (UOL01 on the 9th April 2013). The presence of elevated concentrations of hydrogen sulphide (7.5 mg/m^3) in the air released from site UOL01, which equates to approximately 13,000 times its odour threshold, is however clearly inconsistent with the low odour concentration result obtained using olfactometry during the same visit (402 OU_E/m^3). This may be due to the fact that the hydrogen sulphide was not measured simultaneously with odour at this site, or due to analytical/sampling error. It has therefore been excluded from further analysis.

It can therefore be tentatively concluded that hydrogen sulphide does not have a significant influence on the odour concentration of the biofilters sampled during this study. It is interesting to note that the hydrogen sulphide concentration released from the abatement

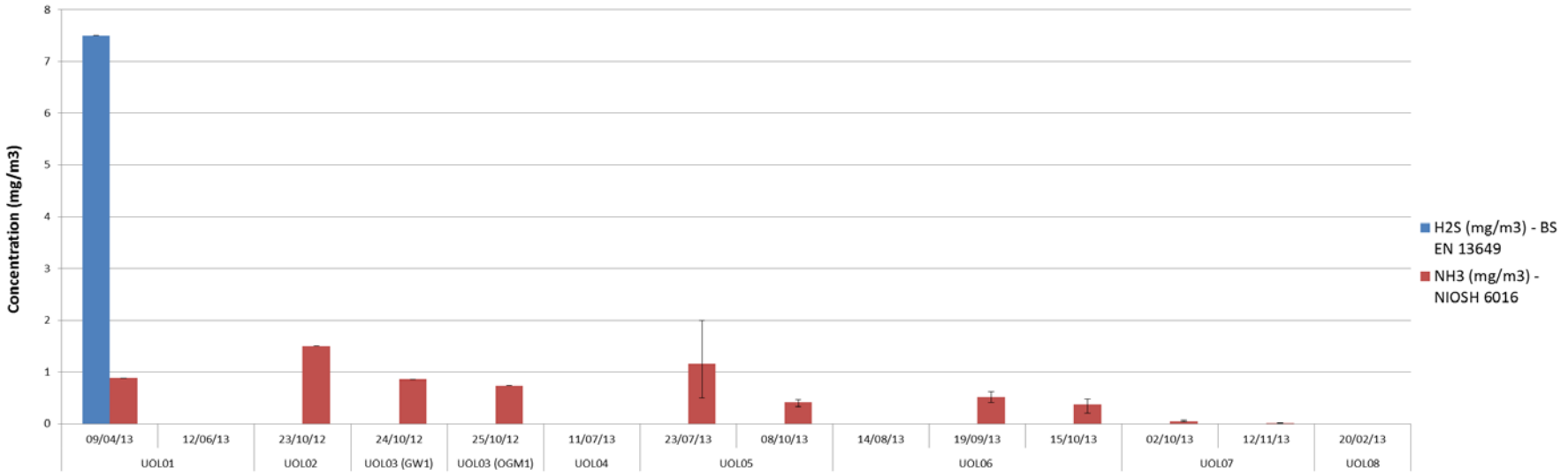

Figure 14 Emission concentration of H_2S and NH_3 from the abatement systems at the different sites

Table 47 Mean, maximum and minimum H_2S and NH_3 emission concentrations from the abatement system at the different sites

Site	UOL01		UOL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09/04/13	12/06/13	23/10/12	24/10/12	25/10/12	11/07/13	23/07/13	08/10/13	14/08/13	19/09/13	15/10/13	02/10/13	12/11/13	20/02/13
H2S														
Mean	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD
Max	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Min	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
NH3														
Mean	0.88	<LLOD	1.50	0.86	0.74	<LLOD	1.16	0.42	<0.1	0.52	0.37	<0.1	<0.1	<LLOD
Max	N/A	N/A	N/A	N/A	N/A	N/A	2.00	0.47	<0.1	0.61	0.48	<0.1	<0.1	<LLOD
Min	N/A	N/A	N/A	N/A	N/A	N/A	0.53	0.33	<0.1	0.41	0.20	<0.1	<0.1	<LLOD

system does not show any correlation with the concentration of organo sulphide compounds such as dimethyl sulphide or dimethyl disulphide (discussed below). This could be due to the differences in solubility, which makes hydrogen sulphide much more amenable to removal by absorption.

A review of the ammonia data indicates that the mean concentration in the air released from the biofilters ranges from <LLOD to 1.5 mg/m^3, and varies both between sites and sample visits. The lowest concentrations of ammonia (<LLOD) were found in the exhaust air at UOL01 (12th June 2013), UOL04, UOL06 (14th August 2013), UOL07 (12th November 2013) and OUL08 (20th February 2013). The highest mean concentration of ammonia of 1.5 mg/m^3 was found in the exhaust air from the abatement system at UOL02.

A review of the VOC results (Table 48) indicates that the exhaust air from all of the abatement systems comprises a mixture of chemical components, which include aromatic hydrocarbons, alcohols, ketones, aldehydes, reduced sulphur compounds, terpenes and organic acids; which vary in concentration from site to site and between sample visits.

Table 49 indicates that the compounds with the highest concentration/odour threshold value ratio detected in the outlet air were sulphur compounds (dimethylsulphide, dimethyl disulphide), aldehydes (acetaldehyde, nonanal, heptanal, decanal); terpenes (alpha-pinene, beta-pinene, limonene); ketones (2,3-butanedione, 2-heptanone); alcohols (2-methyl-1-propanol and 3-methyl-1-butanol) and aromatic hydrocarbons (decahydronaphtalene). It is therefore probable that the odour from biofilters serving composting processes is likely to be influenced to some extent by all of these components, although no direct correlations were identified (through regression analysis) with the odour concentration, in terms of odour units. This finding again illustrates the complexity of predicting the sensory response to odours using individual chemical components, and the widely accepted view that the sensory response to odour does not follow a linear relationship to specific chemical compounds when they occur in a mixture.

A review of the data in Table 49 indicates that in eight of the fourteen datasets (UOL03, UOL05, UOL06, UOL07 [visit 1] and UOL08), between 50 and 75% of the total concentration/ odour threshold value ratio of the outlet air was attributed to dimethylsulphide and dimethyl disulphide. This would suggest that these substances potentially have a more dominant influence on odour than the other compounds detected. It is interesting to note that although ammonia is present in the off-gas in two of the biofilter at mg/m^3 levels, the high odour threshold values of these compounds means that its contribution to the odour from a sensory perspective is likely to be very limited.

The odorous compounds detected in the biofilter off-gas are likely to originate from a combination of partial breakthrough through the media; partial oxidation of more complex chemicals within the filter; biogenic generation within the biofilter; and the release of volatile components from the wood chip media (i.e. the terpenes). The influence of these mechanisms is discussed in more detail in the next section.

Analysis of the data (using regression analysis) by abatement system type, media type and critical operating parameters such as empty bed residence time, moisture content etc. indicate no specific correlations, which confirms the complex nature of biofilter odour generation and removal.

Table 48 Emission concentration of VOC (compound groups) from the abatement system at the different sites ug/m^3)

	UOL01 09/04/13	UOL01 12/6/13	UOL02 23/10/12	UOL03 (GW1) 24/10/12	UOL03 (OGM1) 25/10/12	UOL04 11/07/13	UOL05 23/7/13	UOL05 8/10/13	UOL06 14/8/13	UOL06 19/9/13	UOL06 15/10/13	UOL07 2/10/13	UOL07 12/11/13	UOL08 20/02/13
Aromatic hydrocarbons	4977	2037	4584	167	3254	187	2901	5066	262	57	69	256	864	189
Cyclic Hydrocarbons	901	4229	2520	484	1987	86	3898	4292	140	54	n/d	495	392	51
Aliphatic Hydrocarbons	224	9587	9028	361	5732	249	8142	7003	151	47	19	438	1110	65
Alcohols	510	216	12300	109	556	346	926	523	n/d	165	82	n/d	13957	126
Esters	n/d	n/d	119	4	n/d	20	n/d	401	n/d	n/d	n/d	n/d	2235	15
Ketones	1299	192	11387	345	767	118	3070	1639	n/d	56	n/d	41	1903	379
Aldehydes	383	106	647	168	395	76	n/d	n/d	23	63	26	85	240	17
Chlorinated compounds	2988	998	1272	231	766	121	607	270	n/d	n/d	n/d	31	66	n/d
Organic S-compounds	n/d	326	1996	440	272	85	308	1114	700	1299	973	762	2721	210
Furans	n/d	n/d	1471	55	924	n/d	131	1105	191	123	n/d	n/d	385	n/d
Ethers	n/d	n/d	223	45	192	n/d	494	76	26	n/d	n/d	n/d	n/d	15
Terpenes	79	2600	6052	2481	3081	110	3905	5968	2140	3854	411	280	4519	8960
Organic nitrogen compounds	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	48	n/d	n/d	56	12
Organic acids	n/d	n/d	n/d	81	n/d	n/d	118	n/d	n/d	n/d	n/d	n/d	700	18
Total	11361	20290	51599	4971	17926	1398	24499	27457	3633	5766	1580	2389	29148	10057

Table 49 Emission concentration of VOC (individual compounds) identified above their odour threshold value. Ratio of concentration to odour threshold value is presented.

Group Outlets (OTV RATIO)	Compound	UOL01 09/04/13	UOL01 12/6/13	UOL02 23/11/12	UOL03 (GW1) 24/10/12	UOL03 (OGM1) 25/10/12	UOL04 11/07/13	UOL05 23/7/13	UOL05 8/10/13	UOL06 14/8/13	UOL06 19/9/13	UOL06 15/10/13	UOL07 2/10/13	UOL07 12/11/13	UOL08 20/02/13
		Biofilter outlet	Biofilter outlet	Biofilter outlet	Biofilter outlet	Biofilter outlet	Biofilter outlet	Biofilter outlet	Biofilter outlet	Biofilter outlet	Biofilter outlet	Biofilter outlet	Biofilter outlet (scrub on)	Biofilter outlet (scrub on)	Biofilter outlet
Inorganic	Ammonia	1		1	1	1		1							
	Hydrogen sulphide														
Aromatics	styrene			1				1	1						
	toluene	3													
	decahydronaphtalene		122						90	3			13		
	propylbenzene		2	2		2		2	8						
	1-methylethylbenzene					1		1							
	1-ethyl-3-methylbenzene		3	3		4		2	3						
	1-ethyl-4-methylbenzene			2				2	3						
Alcohols	ethanol			8											
	1-propanol			8											
	2-methyl-1-propanol			6					2		3	82			
	3-methyl-1-butanol			19											
	phenol				1	4								2	
Ketones	2,3-butanedione			383											
	2-butanone			3				1	1						
	2-pentanone			3											
	2-heptanone			10											
Aldehydes	acetaldehyde			96	28	34					3	11			
	heptanal			58	8										
	nonanal	73	53	96	8	83	12			4				11	
	decanal	25		38	6	24	7								
Sulphur	dimethylsulfide			480	265	169			683	593	1245	973			157
	dimethyldisulfide		36	137	16				33	6			75		3
Terpenes	alpha-pinene		2	3	8	2			4	5	9				17
	beta-pinene			1					1						2
	limonene		10	24	3	12			21	2	2		1	2	20
Organic acid	acetic acid				5									21	1

5.3.6 Summary

Based on the data on the bioaerosol and odour concentrations in the exhaust air from the abatement systems at the sites sampled as part of this study a number of observations can be made:

- All of the abatement systems sampled during this study were capable of achieving a low emission concentration of bioaerosols and odour.
- The outlet concentration from the biofilters ranged from 0 to 1,337 cfu/m^3 for *Aspergillus fumigatus*, 515 to 61,541 cfu/m^3 for total bacteria and 144 to 35,911 cfu/m^3 for gram negative bacteria.
- Overall, the concentration of bioaerosols and odour in the exhaust air from the abatement system varies from site to site and appears to be independent of concentration entering, and also independent of the type of abatement system being used.
- The concentration of total bacteria in the exhaust air from the abatement systems is significantly higher than the concentration of *Aspergillus fumigatus* and gram negative bacteria.
- The outlet concentration of odour from biofilters falls within the range of 212 to 5,516 OU_E/m^3.
- The descriptors used to describe the character of the odours released from the biofilter were generally consistent across all sites (i.e. earthy, woody, musty). Descriptors that could be attributed to the waste types being processed were not identified. The perceived unpleasantness of the odours released ranged from moderate to low on a subjective scale.
- There are no apparent correlations between empty bed residence time, media type and outlet odour concentration.
- Installation of a scrubber does not appear to have any direct influence on the outlet odour concentration of air from biofilters tested.
- The odour from biofilters comprises a mixture of odorous components which include: aromatic hydrocarbons, alcohols, ketones, aldehydes, reduced sulphur compounds, terpenes and organic acids.
- The odour released from the biofilters is influenced by the interaction of a variety of odorous sulphur compounds, aldehydes, ketones, terpenes, alcohols and aromatic hydrocarbons.
- Dimethyl sulphide and dimethyl disulphide yield the highest concentration/odour threshold value ratios for five of the eight sites sampled.
- Hydrogen sulphide concentration does not appear to be a significant component of biofilter off-gas, from a sensory perspective, for the biofilters tested.

- The emission concentration of ammonia shows variation between sampling visits and sample sites.
- There does not appear to be any correlation between media type, abatement system design and measured ammonia in the sites studied.
- Ammonia does not appear to contribute significantly to the odours released from the biofilters tested from a sensory perspective, due to its relatively high odour threshold.

5.3 Bioaerosol and odour removal efficiency of the different abatement systems

5.3.1 Aspergillus fumigatus

Figure 15 and Table 50 show the removal efficiencies for the abatement system at the eight sites sampled, including individual removal efficiencies for the scrubber and biofilter, where appropriate (not UOL07). It can be seen that across the full abatement system, the removal efficiency of *Aspergillus fumigatus* ranged from an increase in concentration of 57%, up to 100% removal. Of the 14 sampling events, on two occasions an increase in *Aspergillus fumigatus* was observed across the abatement system and on six occasions a removal in excess of 50% was observed.

Looking at the overall abatement system the highest removal efficiency was found at UOL04, where 100% of the *Aspergillus fumigatus* entering the system was removed. At this site the abatement system consists of an acid scrubber followed by an enclosed biofilter.

At sites UOL01 and UOL02, the concentration of *Aspergillus fumigatus* in the exhaust air from the abatement system was higher than that entering, and increases of 46% and 57% were found respectively. At UOL01 the system is an enclosed biofilter and at UOL02 it is an acid scrubber followed by an enclosed biofilter. Therefore the highest and lowest removal efficiencies were found at sites with the same abatement system arrangement, but different biofilter media types.

It is not possible to determine the impact of an upstream scrubber on the overall performance of the abatement systems. This is due to the fact that the study did not have similar sites (in terms of biofilter media, empty bed residence time etc.) with and without a scrubber. However, it is possible from the data obtained during this study, to evaluate the performance of the scrubber alone. The data shows that all of the scrubbers sampled were capable of achieving a reduction in the concentration of *Aspergillus fumigatus* (Table 51). The average removal ranged from 34% at UOL02, up to 100% removal at UOL04.

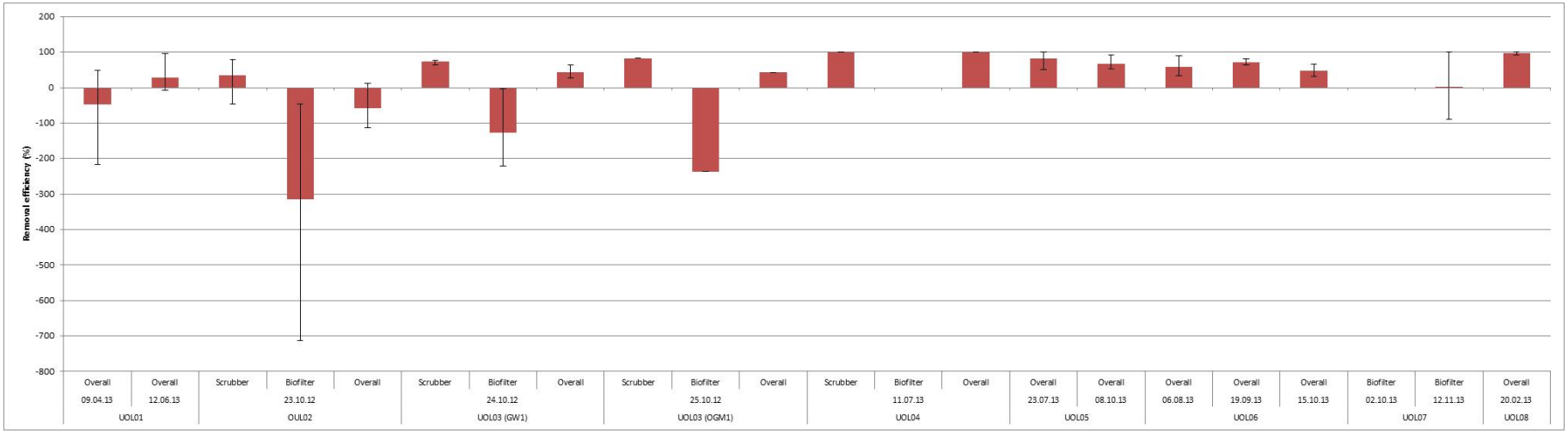

Figure 15 Mean removal efficiency for *Aspergillus fumigatus* of the abatement system at the different sites.

Table 50 Mean, maximum and minimum *Aspergillus fumigatus* removal efficiencies of the abatement system at the different sites

Site	UOL01		OUL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09.04.13	12.06.13	23.10.12	24.10.12	25.10.12	11.07.13	23.07.13	08.10.13	06.08.13	19.09.13	15.10.13	02.10.13	12.11.13	20.02.13
Mean	-46.3	29.0	-57.4	42.7	42.2	100.0	82.4	66.8	59.4	70.5	48.1	-	0.5	96.9
Max	48.6	96.8	12.6	63.6	42.2	100.0	100.0	92.7	90.6	80.7	65.5	-	100	100.0
Min	-217.2	-7.6	-113.0	27.0	42.2	100.0	49.8	52.8	34.5	64.8	27.2	-	-90.1	90.8

Looking at the inlet *Aspergillus fumigatus* concentrations, it does not appear that the performance of the scrubber is influenced significantly by the inlet concentration. The highest removal efficiency was seen for the acid and alkali scrubber system at UOL04, which had in inlet concentration of only 11 cfu/m^3, and the lowest removal was observed for the acid scrubber at UOL02, which had in inlet concentration of 399 cfu/m^3. This might suggest that the inlet concentration does play a role; however at UOL03, which also uses an acid scrubber, excellent removals of 73% and 83% were obtained at the inlet (*Aspergillus fumigatus* concentrations of 1327 cfu/m^3 and 1233 cfu/m^3 respectively).

Taking the data on the biofilters on their own, and comparing the performance of the open and enclosed biofilters, shows that based on the available data from this study, the open biofilters appear to perform significantly better than the enclosed biofilters, in terms of the removal of *Aspergillus fumigatus*. Of the four enclosed biofilters that were sampled, only one of them, on one occasion, was found to achieve any reduction in the concentration of *Aspergillus fumigatus* and that was the one at UOL01 on the 12th June 2013. All the other enclosed biofilters showed an increase in the concentration of *Aspergillus fumigatus* of between 46% and a massive 315%. It was not possible to evaluate the performance of the biofilter at UOL04 because no *Aspergillus fumigatus* was detected in the inlet air. The performance of the open biofilters sampled as part of this study was variable; however all of them achieved a reduction in the concentration of *Aspergillus fumigatus.* The lowest removal of only 0.3% was observed for the biofilter at UOL07 and the highest removal of 97% was observed at UOL08.

Analysis of the data for all the biofilters suggests that there may be a positive relationship between the removal efficiency for *Aspergillus fumigatus* and the concentration in the inlet air. The highest removal was observed for UOL08, which achieved a 97% reduction with an inlet concentration of almost 26,000 cfu/m^3. The biofilters that were found to be significant net emitters of *Aspergillus fumigatus*, UOL02 and UOL03 (GW and MSW), both had low inlet concentrations of 183, 372 and 212 cfu/m^3. Although not conclusive, this may suggest that biofilters are consistently emitting *Aspergillus fumigatus* and that this can only be observed when the inlet concentration is low. It may also mean that when using a biofilter alone, or in conjunction with an upstream scrubber, it will not be possible to completely eliminate *Aspergillus fumigatus* from the air stream. This also has implications regarding the use of upstream scrubbers and might support the use of scrubbers downstream of a biofilter. For example if an upstream scrubber is performing effectively and significantly reducing the concentration of *Aspergillus fumigatus,* the subsequent emission of *Aspergillus fumigatus* from the biofilter may adversely affect the overall effectiveness of the abatement system. However, if the scrubber is positioned downstream of the biofilter this may negate the net emission of *Aspergillus fumigatus* by the biofilter and improve the overall performance of the abatement system.

Looking at the performance of the biofilters in terms of the media type shows that those that have a granular peat media performed very badly (UOL02 and UOL03) and were the

biofilters that created a significant increase in the concentration of *Aspergillus fumigatus* in the exhaust air. Of the remaining biofilter, one was filled with 'brash' material, one was filled with light weight expanded clay aggregate and the rest were woodchip. Llittle if any difference was observed in the performance of these types. With the exception of the woodchip biofilter at UOL01 on the 9th April 2013, all of them achieved a reduction in the concentration of *Aspergillus fumigatus*. It was not possible to evaluate the performance of the clay aggregate biofilter at UOL04 because 100% removal was achieved by the scrubber systems prior to the biofilter.

Table 51 shows the characteristics of the eight biofilters together with their removal efficiencies for *Aspergillus fumigatus*. It can be seen that in terms of the surface loading rates, the highest was UOL04 with a surface loading rate of 370 $m^3/m^2/hr$, but since no *Aspergillus fumigatus* was detected in the biofilter inlet air, the performance cannot be evaluated. The lowest surface loading rate was 77 $m^3/m^2/hr$ at UOL01 and the performance of this biofilter was variable, with a 29% reduction during one visit and a 46% increase during the second visit. The empty bed residence times were within the range of 41 to 84 seconds, with the highest at UOL07 and the lowest at UOL04. The highest *Aspergillus removals* were observed at an EBRT of 71 seconds and a surface loading rate of 81 $m^3/m^2/hr$. Overall, regression analysis carried out on the data showed no relationship between the removal efficiency of the biofilters for *Aspergillus fumigatus* and the air flow rates, empty bed residence times or the surface loading rate.

The concern over the 'health of the biofilters at UOL05 and UOL06 did not adversely affect the performance of these biofilters, as they achieved up to 71% and 82% removals respectively. There does not appear to be any significant relationships (regression analysis) between the media characteristics and the removal of *Aspergillus fumigatus* with r^2 values of -0.668, 0.617 and 0.686 for nutrient content, moisture content and pH respectively.

Table 51 Characteristics of the biofilters at the eight sites and the *Aspergillus fumigatus* removal efficiencies achieved by the biofilter (black text) and the scrubber (blue text).

Site	Biofilter type	Scrubber	Flow rate (m^3/s)	Surface loading rate ($m^3/m^2/hr$)	EBRT (s)	Media type	Age of media	Biofilter 'health'	Removal efficiency
UOL01	Enclosed	No	14.2	77	51	Woodchip & brash	-	Good	-46% & 29%
UOL02	Enclosed	Yes	24.2	104	78	Granular Peat	-	-	-316% (34%)
UOL03	Enclosed	Yes	20.8 (GW 29.1 (OGM)	119 (GW) 125 (OGM)	68 (GW) 65 (OGM)	Granular Peat	-	-	- 128% (73%) -236% (83%)
UOL04	Enclosed	Yes	7.4	370	41	Light weight expanded clay aggregate	-	-	- (100%)
UOL05	Open	No	14.3	78	51	Brash	-	Slightly dry on the 8th October 2013	67% & 82%
UOL06	Open	No	0.7	211	43	Woodchip	-	Slight nutrient deficiency on the 06.08.13 and 19.09.13	48%, 59% & 71%
UOL07	Open	Yes	8.7	78	84	Pine Woodchip < 10% bark	12 months		0.3%
UOL08	Open	No	9.7	81	71	Pine woodchip 30-60mm	18 months		97%

5.3.2 Total bacteria

Figure 16 and Table 52 show the removal efficiencies for total bacteria of the abatement system at the eight sites sampled, including individual removal efficiencies for the scrubber and biofilter, where appropriate. Across the full abatement system the removal efficiency of total bacteria ranged from an increase in concentration of 35%, up to 95% removal. Of the 14 sampling events, on only one occasion was an increase in total bacteria observed across the abatement system and on four occasions a removal in excess of 80% was observed.

Looking at the overall abatement system, the highest removal efficiency was found at UOL02, where 95% of the total bacteria entering the system were removed. This was closely followed by UOL04, where 94% of the total bacteria were removed. Both these sites have an abatement system consisting of a scrubber followed by an enclosed biofilter. At UOL02 the scrubber system is a single acid scrubber, whereas at UOL04 the scrubber system is an acid scrubber followed by an alkali scrubber.

Site UOL07 was the only site where the concentration of total bacteria in the exhaust air from the abatement system was higher than that entering and an increase of 35% was observed on the 12th November 2013. At UOL07 the system is an acid scrubber followed by an open biofilter. It can be seen therefore that both the highest and lowest removal efficiencies were found at sites in which a scrubber is combined with an open or enclosed biofilter rather than a biofilter alone.

The enclosed biofilter only systems achieved reductions of between 43% and 52%. In comparison the open biofilter only systems achieved a slightly higher range of removal efficiencies of between 49% and 76%. On no occasion was an increase in concentration observed from the biofilter only systems, either open or enclosed.

Taking the data for the scrubbers alone shows that the performance was extremely variable from one site to another (Table 53). The scrubber at UOL02 and UOL04 achieved average reductions in the concentration of total bacteria of 43% and 61% respectively. In contrast the scrubbers at UOL03, both on the green waste and the MSW stream, led to an increase in the concentration of total bacteria in the outlet air stream of 42% and 34% respectively.

Looking at the inlet total bacteria concentrations it does not appear that the performance of the scrubber is influenced significantly by the inlet concentration. The highest removal efficiency was seen for the acid and alkali scrubber system at UOL04, which had in inlet concentration of almost 26,000 cfu/m^3. The acid scrubbers at UOL03 (GW and MSW) performed very badly and net increases of 42% and 34% were observed with inlet concentrations of 10,453 cfu/m^3 and 7101 cfu/m^3 respectively. This data might suggest that the higher the inlet concentration, the better the scrubber performance. However, a 43% reduction was observed at UOL01 at an inlet concentration of 9,784 cfu/m^3. Therefore at comparable inlet concentrations the performance of the acid scrubbers at UOL02 and UOL03 were extremely variable. Once again it is not clear from the available data why there is a significant difference in the performance of the scrubbers at the different sites.

Taking the data on the biofilters on their own, and comparing the performance of the open and enclosed biofilters, shows that based on the available data from this study, the enclosed biofilters appear to perform slightly better than the open biofilters. The removal efficiency of the enclosed biofilters ranged from 43% up to 90%, compared to a maximum of 76% for the open biofilters. Only one site failed to achieve any reduction across the biofilter and that was site UOL07, which was an open biofilter. Unlike the *Aspergillus fumigatus* data, a regression analysis carried out on this data does not show a relationship between the removal efficiency of the biofilter and the inlet concentration. The highest removals (90%) were achieved at UOL03, when the inlet concentration was 13,452 and 9,539 cfu/m^3. A net increase of 35% was observed at UOL07, when the inlet concentration was 45,655 cfu/m^3. This may suggest that when the inlet concentration of total bacteria is high the performance of the biofilter is affected, however a removal of 52% was achieved by the biofilter at UOL01 at an inlet concentration of 43,260 cfu/m^3.

Looking at the performance of the biofilters in terms of the media type shows that those that have a granular peat media performed very well (UOL02 and UOL03) and were the biofilters that achieved some of the highest removals, at 84% and 90% respectively. The lightweight clay aggregate biofilter at UOL04 also performed very well, with a removal efficiency of 84%. The performance of the brash and woodchip biofilters were very similar, with the exception of the open woodchip biofilter at UOL07, which was the only biofilter which produced an increase in the concentration of total bacteria. Table 53 shows the characteristics of the eight biofilters together with their removal efficiencies for total bacteria. It can be seen that the poorest performing biofilter and the only one producing a net increase in total bacteria was the one at UOL07, which had the highest empty bed residence time and an average surface loading rate. In contrast the best performance was observed at UOL03, at which the surface loading rate and empty bed residence time were in the middle of the range observed during this study. Identical removal efficiencies were observed at UOL02 and UOL04, despite the fact that the surface loading rates and empty bed residence times were very different. This variability in performance relating to biofilter operating parameters is backed up by the results of regression analysis, which found no relationship between total bacteria removal efficiencies and air flow rate, surface loading rate or empty bed residence time.

As was observed previously for *Aspergillus fumigatus* the low moisture and nutrient content of the biofilter media at UOL5 and UOL6 respectively appeared to have very little impact on performance.

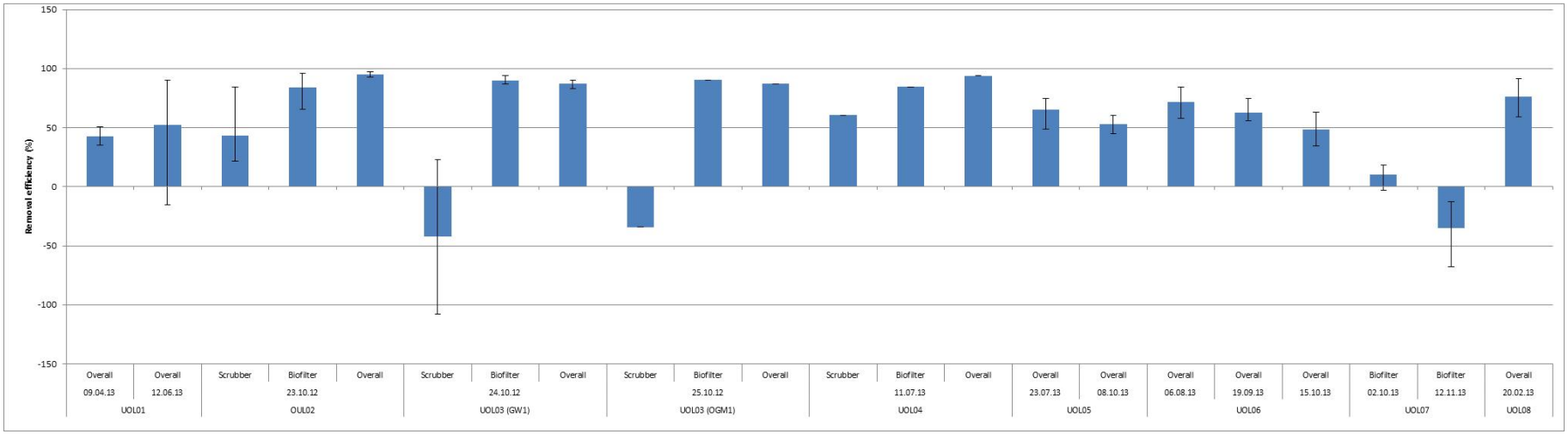

Figure 16 Mean removal efficiency for total bacteria of the abatement system at the different sites.

Table 52 Mean, maximum and minimum total bacteria removal efficiencies of the full abatement system at the different sites

Site	UOL01		OUL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09.04.13	12.06.13	23.10.12	24.10.12	25.10.12	11.07.13	23.07.13	08.10.13	06.08.13	13.09.13	15.10.13	12.06.13	23.10.12	24.10.12
Mean	43.0	52.4	94.9	87.1	87.0	93.8	65.1	52.7	72.0	62.9	48.7	10.3	-34.6	76.1
Max	51.0	90.4	97.1	90.0	87.0	93.8	74.9	60.4	84.7	74.9	63.2	18.5	-11.5	91.5
Min	34.9	-15.4	92.9	83.4	87.0	93.8	48.6	45.2	57.9	55.9	34.8	-3.1	-67.6	59.3

Table 53 Characteristics of the biofilters at the eight sites and the total bacteria removal efficiencies achieved by the biofilter (black text) and the scrubber (blue text).

Site	Biofilter type	Scrubber	Flow rate (m^3/s)	Surface loading rate ($m^3/m^2/hr$)	EBRT (s)	Media type	Age of media	Biofilter 'health'	Removal efficiency
UOL01	Enclosed	No	14.2	77	51	Woodchip & brash	-	Good	43% & 52%
UOL02	Enclosed	Yes	24.2	104	78	Granular Peat	-	-	84% (43%)
UOL03	Enclosed	Yes	20.8 (GW) 29.1 (OGM)	119 (GW) 125 (OGM)	68 (GW) 65 (OGM)	Granular Peat	-	-	90% (-42%) 90% (-34%)
UOL04	Enclosed	Yes	7.4	370	41	Light weight expanded clay aggregate	-	-	84% (61%)
UOL05	Open	No	14.3	78	51	Brash	-	Slightly dry on the 8th October 2013	53% & 65%
UOL06	Open	No	0.7	211	43	Woodchip	-	Slight nutrient deficiency on the 06.08.13 and 19.09.13	49%, 63% & 72%
UOL07	Open	Yes	8.7	78	84	Pine Woodchip < 10% bark	12 months		-35% & 10%
UOL08	Open	No	9.7	81	71	Pine woodchip 30-60mm	18 months		76%

5.3.3 Gram negative bacteria

Figure 17 and Table 54 show the removal efficiencies for the abatement system at the eight sites sampled including individual removal efficiencies for the scrubber and biofilter, where appropriate. It can be seen that across the full abatement system the removal efficiency of gram negative bacteria ranged from an increase in concentration of 66% up to 93% removal. Of the 14 sampling events, on three occasions an increase in gram negative bacteria was observed across the abatement system and on seven occasions a removal in excess of 80% was observed.

Looking at the overall abatement system, the highest removal efficiencies were found at UOL02, UOL03 and UOL06 (19th September 2013), where 93%, 91% and 92% of the gram negative bacteria entering the system were removed. The abatement systems at UOL02 and UOL03 are the same with an acid scrubber and enclosed biofilter at both sites, whereas at UOL06 the abatement system consists of an open biofilter alone. The abatement systems at UOL05 (both visits) and UOL07 (23rd October 2013 only) produced a net increase in gram negative bacteria of 25%, 6% and 66% respectively. At UOL05 the abatement system is an open biofilter only and at UOL07, it is an acid scrubber followed by an open biofilter.

The enclosed biofilter only system, achieved a reduction of up to 67%. In comparison, the open biofilter only systems, at UOL06 and UOL08 achieved excellent removal efficiencies of between 83% and 92%. However as stated earlier, the open biofilter only system at UOL05 did not perform well, with an increase in the concentration of gram negative bacteria being observed on both occasions the system was sampled. Taking the data for the scrubbers alone (Table 55), shows that the performance of the scrubbers was variable from one site to another. All the scrubbers achieved a reduction in the concentration of gram negative bacteria. The scrubber at UOL04 achieved the highest reduction efficiency of 68% compared to 38% at UOL02 and UOL03 (MSW) and only 13% at UOL03 (GW). The impact of the inlet gram negative bacteria concentration is unclear. The highest removals were found when the inlet concentration was lowest at only 745 cfu/m^3. However, identical removal efficiencies (38%) were observed at inlet concentrations of 3,704 cfu/m^3 and 2,564 cfu/m^3. The lowest removal efficiency was 13% at an inlet concentration of 3,568 cfu/m^3. Once again it is not clear from the available data why there is a significant difference in the performance of the scrubbers at the different sites. As with *Aspergillus fumigatus* and total bacteria, the highest reduction in gram negative bacteria was achieved at UOL04, where the scrubber system is an acid scrubber followed by an alkali scrubber.

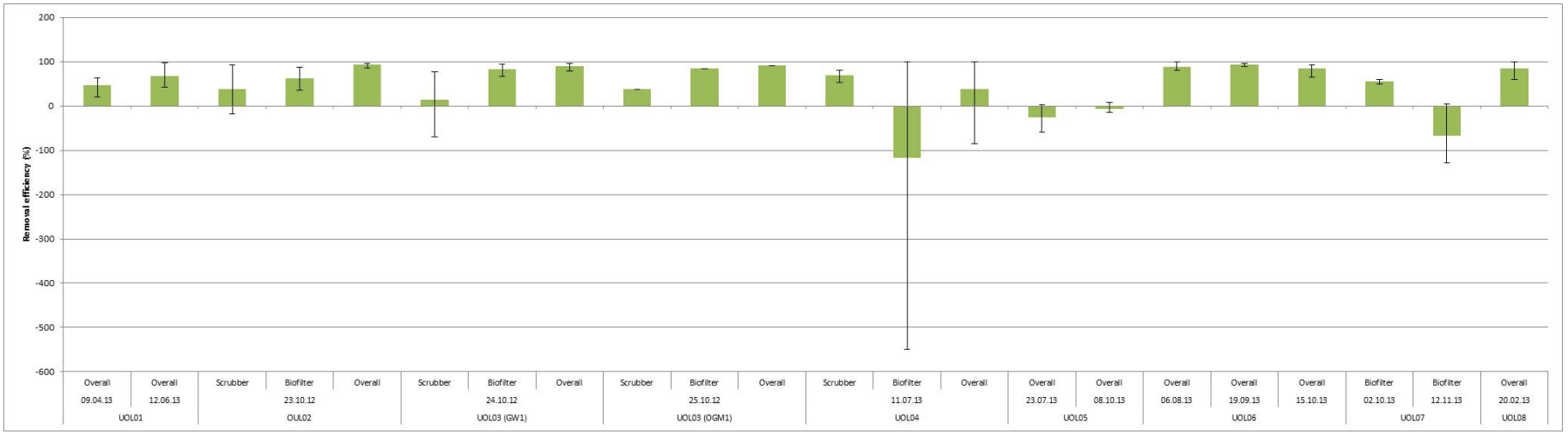

Figure 17 Mean removal efficiency for gram negative bacteria of the abatement system at the different sites.

Table 54 Mean, maximum and minimum gram negative bacteria removal efficiencies of the abatement system at the different sites

Site	UOL01		OUL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09.04.13	12.06.13	23.10.12	24.10.12	25.10.12	11.07.13	23.07.13	08.10.13	06.08.13	19.09.13	15.10.13	12.06.13	23.10.13	24.10.12
Mean	45.9	67.4	92.5	89.0	90.5	38.1	-24.5	-6.3	87.4	92..2	83.2	54.9	-65.6	84.3
Max	64.2	97.1	96.1	96.2	90.5	100.0	3.6	8.2	100.0	96.5	93.2	60.1	-3	100.0
Min	19.5	42.5	85.8	78.6	90.5	-85.7	-58.7	-15.1	80.3	75.1	65.0	49.2	-12	59.5

Looking the data on the biofilters on their own (Table 55) and comparing the performance of the open and enclosed biofilters shows that, based on the available data from this study, there is very little difference in the performance of the open and enclosed biofilters. Both the open and enclosed biofilters had occasions when the concentration of gram negative bacteria increased across the biofilter and the maximum removal efficiencies of the open and enclosed biofilters were 92% and 85% respectively. Analysis of the data shows that there is no relationship between the removal efficiency of the biofilter and the inlet gram negative bacteria concentration. The highest removal (92%) was achieved at UOL06 (19th September 2013), when the inlet concentration was 5,820 cfu/m^3. In contrast a net increase across the biofilter of 117% was observed at UOL04 when the inlet concentration was 222 cfu/m^3. This might suggest that when the inlet concentration of total bacteria is low, the performance of the biofilter is affected. However, a net increase of 66% was observed across the biofilter at UOL07 at an inlet concentration of 23,307 cfu/m^3.

Looking at the performance of the biofilters in terms of the media type shows that those that have a granular peat media performed reasonably well (UOL02 and UOL03), with maximum removals of 62% and 85% respectively. The performance of the woodchip biofilters was quite variable, with one at UOL07 producing an increase in the concentration of gram negative bacteria. The remaining woodchip biofilters performed well with removal efficiencies of between 46% and 92%. The lightweight clay aggregate biofilter at UOL04 performed very badly and on the day sampling was undertaken produced a 117% increase in the concentration of gram negative bacteria. The performance of the brash biofilter was also poor with increases in the concentration of gram negative bacteria of 25% and 6% on the two occasions it was sampled.

Table 55 shows the characteristics of the eight biofilters together with their removal efficiencies for gram negative bacteria. Regression analysis performed on the data shows no relationship between key design and operating parameters such as air flow rates, surface loading rates and empty bed residence time and the removal efficiency for gram negative bacteria. The poorest biofilter performances were observed at UOL04 and UOL07 (23rd October 2013), which had the lowest and highest empty bed residence times respectively.

The concern over the 'health of the biofilters at UOL06 did not adversely affect the performance of the biofilter; however the nutrient deficiency at UOL05 may be a factor in the poor performance. Having said that the performance of the same biofilter on the 23rd July 2013 was much worst despite the fact that on this occasion no issues with the 'health' of the biofilter were observed.

Table 55 Characteristics of the Biofilters at the eight sites and the gram negative bacteria removal efficiencies achieved by the biofilter (black text) and the scrubber (blue text).

Site	Biofilter type	Scrubber	Flow rate (m^3/s)	Surface loading rate ($m^3/m^2/hr$)	EBRT (s)	Media type	Age of media	Biofilter 'health'	Removal efficiency
UOL01	Enclosed	No	14.2	77	51	Woodchip & brash	-	Good	46% & 67%
UOL02	Enclosed	Yes	24.2	104	78	Granular Peat	-	-	62% (38%)
UOL03	Enclosed	Yes	20.8 (GW) 29.1 (OGM)	119 (GW) 125 (OGM)	68 (GW) 65 (OGM)	Granular Peat	-	-	83% (13%) 85% (38%)
UOL04	Enclosed	Yes	7.4	370	41	Light weight expanded clay aggregate	-	-	-117% (68%)
UOL05	Open	No	14.3	78	51	Brash	-	Slightly dry on the 8th October 2013	-25% & -6%
UOL06	Open	No	0.7	211	43	Woodchip	-	Slight nutrient deficiency on the 06.08.13 and 19.09.13	83%, 87% & 92%
UOL07	Open	Yes	8.7	78	84	Pine Woodchip < 10% bark	12 months		-66% & 55%
UOL08	Open	No	9.7	81	71	Pine woodchip 30-60mm	18 months		84%

5.3.4 Odour

Figure 18 and Table 56 show the odour removal efficiencies for the abatement systems at the sites sampled as part of this study, including removal efficiencies for the scrubber (shown in brackets) and the biofilter where appropriate. Odour removal efficiencies are only shown for the biofilter at UOL07, as sampling could not be carried out simultaneously at the inlet and outlet of the scrubber; consequently it was not possible to determine true abatement efficiency.

It can be seen that across the biofilters, the mean odour removal efficiency (as determined on the basis of odour unit data) ranged from 64% up to 98%. Across the scrubbers the mean removal efficiency of odour ranged from an increase in odour concentration of 31%, up to 37% removal.

The highest biofilter odour removal efficiency was found at UOL04, where 98% of the odour entering the biofilter was removed. This was closely followed by UOL06 on 14th August 2013 (97%). UOL04 has an enclosed biofilter with expanded clay aggregate media, whilst UOL06 has an open biofilter with woodchip media. The lowest odour removal efficiency was also found at UOL06 on 19th September 2013, where 64% of the odour entering the biofilter was removed.

The mean odour removal efficiency across the biofilters shows some variation between sampling visits and this is particularly notable for the biofilter sampled at UOL06, where the odour removal efficiency ranged from 64% to 97%. These variations in percentage removal across the sites can be partly attributed to inlet concentration. For example, the highest removal efficiency at UOL06 (97%) was achieved with an inlet concentration of 145,311 OU_E/m^3 and the lowest removal efficiency (64%) at an inlet concentration of 13,057 OU_E/m^3. At UOL05, a removal efficiency of 94% was achieved with an inlet concentration of 29,950 OU_E/m^3 whilst a removal efficiency of 86% was achieved with a lower inlet concentration of 16,573 ou_E/m^3.

This influence of inlet odour concentration on percentage removal indicates that removal efficiency is not always a good indicator of biofilter performance. Comparison of the concentration of the odour emitted from the biofilter to performance levels typical of the technology, is therefore a more useful approach to evaluate the odour removal effectiveness of an individual biofilter.

Review of the data by abatement system and media type (Table 57) indicates that these factors do not appear to have any significant influence on odour removal efficiency. For example, the highest removal efficiencies of 98% and 97% were achieved by both an enclosed and open biofilter respectively. Biofilters with each of the media types sampled (e.g. woodchip, peat, brash and clay aggregate) all achieved odour removal efficiencies of >90%.

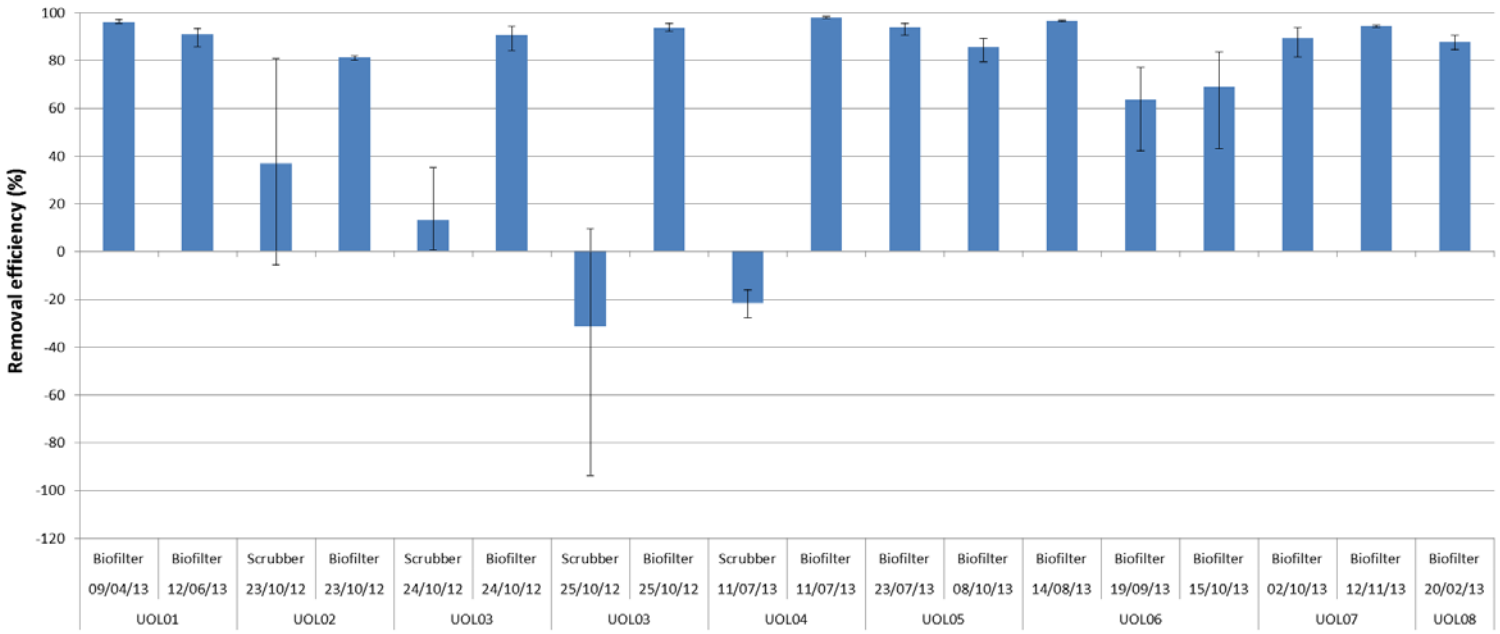

Figure 18 Mean removal efficiencies (%) for odour of the abatement systems at the different sites

Table 56 Mean, maximum and minimum odour removal efficiencies (%) of the abatement system at the different sites

Site	UOL01		UOL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09/04/13	12/06/13	23/10/12	24/10/12	25/10/12	11/07/13	23/07/13	08/10/13	14/08/13	19/09/13	15/10/13	02/10/13	12/11/13	20/02 /13
Location	Biofilter	Biofilter	Biofilter (scrubber)	Biofilter (scrubber)	Biofilter (scrubber)	Biofilter (Scrubber)	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter
Mean	96	91	81 (37)	91 (13)	93 (-31)	98 (-21)	94	86	97	64	69	89	94	88
Max	97	93	82 (81)	94 (35)	96 (10)	98 (-16)	96	89	97	77	84	94	95	90
Min	96	86	80 (-5)	84 (1)	92 (-94)	98 (-28)	91	80	96	42	43	81	94	85

Review of the data for the scrubbers on their own shows that the mean removal efficiency of odour ranged from an increase in odour concentration of 31% up to 37% removal. The performance of the scrubbers was variable from one site to another, with two of the four scrubbers producing an increase in the concentration of odour. The scrubbers at UOL03 (OGM) and UOL04 were the worst performing with increases in odour of 31% and 21% respectively. This may be explained by the build-up of odorous contaminants in the scrubber and scrubber liquors. The scrubbers at UOL02 and UOL03 (GW) achieved reduction efficiencies of 37% and 13% respectively. It is not clear from the data available why there is a significant difference in the performance of the scrubbers at the different sites. Looking back at the inlet odour concentrations, it does not appear that scrubber performance is influenced appreciably by the concentration of the process air.

In broad terms, the data indicates that the application of a scrubber has a limited or no effect on the overall odour concentration in the air presented to the biofilters, or biofilter performance in odour unit removal terms. It is understood that the scrubbers at the sampling sites are not specifically designed for the removal of odour and it is likely that the scrubbers which achieve a reduction in odour concentration do so via the removal of the soluble components in the airstream. Some of the scrubbers produced an increase in odour concentration. Plausible reasons for this could be the odour of the chemicals used within the scrubbers, the breakdown of larger compounds within the scrubber to a range of smaller VOCs or odour resulting from the condition of the scrubber (i.e. the scrubber media may require cleaning).

Table 57 Characteristics of the biofilters at the eight sites and the odour, H_2S and NH_3 removal efficiencies achieved.

Site	Biofilter type	Flow rate (m^3/s)	Surface loading rate ($m^3/m^2/hr$)	EBRT (s)	Media type	Age of media	Biofilter 'health'	Odour Removal efficiency Biofilter (scrubber)	H2S Removal efficiency Biofilter (scrubber)	NH3 Removal efficiency Biofilter (scrubber)
UOL01	Enclosed	14.2	77	51	Woodchip & brash	-	Good	91-96%	100%	86-100%
UOL02	Enclosed	24.2	104	78	Granular Peat	-	-	81% (37%)	-	58% (95%)
UOL03	Enclosed	20.8 (GW 29.1 (OGM)	119 (GW) 125 (OGM)	68 (GW) 65 (OGM)	Granular Peat	-	-	91-93% (13- - 31%)	-	24-49% (62-98%)
UOL04	Enclosed	7.4	370	41	Light weight expanded clay aggregate	-	-	98% (-21%)	-	80% (-70%)
UOL05	Open	14.3	78	51	Brash	-	Slightly dry on the 8th October 2013	86 - 94%	100%	41-90%
UOL06	Open	0.7	211	43	Woodchip	-	Slight nutrient deficiency on the 06.08.13 and 19.09.13	64% - 97%	-	86-100%
UOL07	Open	8.7	78	84	Pine Woodchip < 10% bark	12 months		89-94%	100%	100% (100%)
UOL08	Enclosed	9.7	81	71	Pine woodchip 30-60mm	18 months		88%	-	100%

5.3.5 Ammonia, hydrogen sulphide and volatile organic compounds

Figure 18 and Table 58 show the hydrogen sulphide and ammonia removal efficiencies for the abatement systems at the sites sampled, including removal efficiencies for the scrubber (shown in brackets) and the biofilter where appropriate. Table 59 shows the removal efficiencies of the main VOC compound groups present in the exhaust air from the abatement systems. Table 60 presents the removal efficiencies of individual components. Again, both tables present removal efficiencies for the scrubber (shown in brackets) and the biofilter.

The hydrogen sulphide data indicates that if the potentially anomalous result obtained from UOL01 is removed, all of the biofilters appear to be effective at removing hydrogen sulphide to levels below the limit of detection of the analysis technique (0.1 mg/m^3).

For ammonia, all of the biofilters tested achieved a reduction in ammonia concentration. However the removal efficiencies varied considerably from site to site, ranging from 24% removal at UOL03 (OGM), to 100% removal at UOL01 on 12th June, UOL06 on 14th August, UOL07 on 12th November and UOL08 on 20th February 2013. The removal efficiency also shows variation between visits. Review of the inlet NH_3 concentrations indicates that the variation in removal efficiency does not appear to correlate to inlet concentration. For example a removal efficiency of 90% was achieved at UOL05 on 23rd July with an inlet concentration of 10.4 mg/m^3, but only 41% removal efficiency with an inlet concentration of 0.71 mg/m^3. Conversely at UOL06 a 100% removal efficiency was achieved on 14th August with an inlet concentration of 0.80 mg/m^3, but only an 86% efficiency with an inlet concentration of 2.89 mg/m^3.

For the scrubbers, the mean ammonia removal efficiency ranged from an increase of 70% to 98%. The highest removal efficiencies were measured at UOL03 (OGM) and UOL02 at 98% and 95% respectively, where the inlet ammonia concentrations were relatively high (>60 mg/m^3). The lowest removal efficiency was measured at UOL03 (GW) on 24th October 2012 at 62%, where the inlet ammonia concentration was 4.5 mg/m^3.

The data indicates that scrubbing appears to have beneficial effect on ammonia and can achieve good removal efficiencies, reducing ammonia down to concentrations of <5 mg/m^3 prior to the biofilter. In comparison, removal efficiencies across the biofilters were more variable ranging from 24% up to 100% removal.

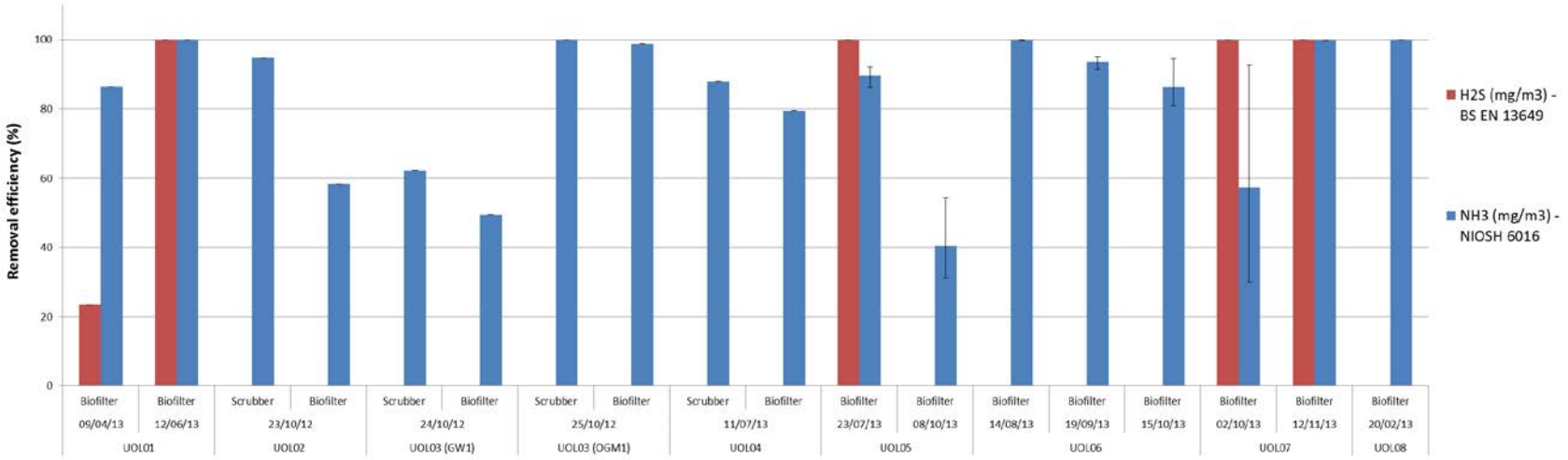

Figure 19 Mean removal efficiencies (%) for H2S and NH3 of the abatement systems at the different sites

Table 58 Mean, maximum and minimum H_2S and NH_3 removal efficiencies (%) of the abatement system at the different sites

Site	UOL01		UOL02	UOL03 (GW1)	UOL03 (OGM1)	UOL04	UOL05		UOL06			UOL07		UOL08
Date	09/04/13	12/06/13	23/10/12	24/10/12	25/10/12	11/07/13	23/07/13	08/10/13	14/08/13	19/09/13	15/10/2013	02/10/13	12/11/13	20/02/13
Location	Biofilter	Biofilter	Biofilter (scrubber)	Biofilter (scrubber)	Biofilter (scrubber)	Biofilter (scrubber)	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter
H2S														
Mean	100	100	-	-	-	-	100	-	-	-	-	100	100	100
Max	N/A	100	N/A	N/A	N/A	N/A	100	N/A	N/A	N/A	N/A	100	100	N/A
Min	N/A	100	N/A	N/A	N/A	N/A	100	N/A	N/A	N/A	N/A	100	100	N/A
NH3														
Mean	86	100	58 (95)	49 (62)	24 (98)	88 (-70)	90	41	100	94	86	100	100	-
Max	N/A	100	N/A	N/A	N/A	N/A	92	54	100	95	95	93	100	N/A
Min	N/A	100	N/A	N/A	N/A	N/A	86	31	100	91	81	30	100	N/A

Comparing the performance of the open and enclosed biofilters shows that, based on the available data from this study, there is generally no difference in hydrogen sulphide or ammonia removal performance. Looking at the performance in terms of media type shows that those that have a granular peat media (UOL02, UOL03 (GW) and UOL03 (OGM)) achieved some of the lowest ammonia removals at 58% 49%, and 24% respectively. The ammonia removal performance of the brash and woodchip biofilters was generally very good.

Table 57 shows the characteristics of the eight biofilters together with their removal efficiencies for odour, H_2S and NH_3. Review of the data appears to indicate that the characteristics of the abatement system do not generally appear to influence the H_2S or NH_3 removal efficiencies of the biofilters.

Review of Table 59 indicates that the removal efficiency of the main chemical groups exhibits significant variation from site to site. A number of compound group concentrations were reduced by up to 100%. However, the individual removal efficiencies of specific VOCs (Table 60) varied considerably indicating that some components are easier to remove than others, which can be expected since the removal efficiency is likely to be influenced strongly by the solubility of each compound and its amenity for absorption into and oxidisation within the biofilm of the biofilter media.

Taking the data for biofilters only, it appears that good individual compound removal efficiencies are generally seen for alcohols, esters, organic acids, and a number of compounds from the aldehyde and ketone groups.

It is evident from examination of Table 60 that a number of individual volatile organic compounds were identified in the outlet air that did not occur in the corresponding biofilter inlet sample. This occurs with a number of compounds in the reduced sulphur, aromatic hydrocarbon, alcohol, aldehyde and terpene compound groups. Looking at the reduced sulphur compound groups, dimethyl sulphide appears to have been generated in the outlet air from UOL05 (an open biofilter with brash media), whilst dimethyl disulphide was generated in the outlet air of UOL01 and UOL08, both of which are enclosed biofilters with woodchip media. These compounds may have been produced as a result of partial oxidation of other sulphur compounds, or areas of anaerobic activity within the biofilter, which could lead to the generation of sulphides.

In the aromatic hydrocarbon group, decahydronapthalene appears to have been generated in UOL01 (an enclosed woodchip biofilter) and UOL05, UOL06 and UOL07 (all open woodchip biofilters). Generation of this compound was only identified for biofilters with woodchip media.

Table 59 Removal efficiency % of VOC (compound groups)

	UOL01 09/04/13	UOL01 12/6/13	UOL02 23/10/12	UOL03 (GW1) 24/10/12	UOL03 (OGM1) 25/10/12	UOL04 11/07/13	UOL05 23/7/13	UOL05 8/10/13	UOL06 14/8/13	UOL06 19/9/13	UOL06 15/10/13	UOL07 2/10/13	UOL07 12/11/13	UOL08 20/02/13
	Biofilter	Biofilter	Biofilter (scrubber)	Biofilter (scrubber)	Biofilter (scrubber)	Biofilter (scrubber)	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter
Aromatic hydrocarbons	52%	71%	35% (-135%)	77% (41%)	53% (0%)	50% (18%)	34%	40%	93%	96%	78%	42%	35%	43%
Cyclic Hydrocarbons	74%	43%	36% (-204%)	72% (18%)	36% (-7%)	43% (-1%)	16%	14%	96%	96%	100%	53%	38%	31%
Aliphatic Hydrocarbons	97%	61%	44% (-57%)	67% (85%)	58% (-30%)	73% (17%)	50%	52%	57%	97%	37%	72%	41%	-136%
Alcohols	93%	100%	92% (5%)	93% (44%)	98% (-1%)	99% (3%)	97%	98%	100%	98%	95%	100%	62%	100%
Esters	n/a	100%	99% (-83%)	96% (-10%)	100% (-599%)	100% (24%)	100%	94%	100%	100%	100%	100%	61%	100%
Ketones	89%	99%	75% (-43%)	95% (19%)	97% (1%)	99% (-10%)	88%	85%	100%	99%	100%	99%	39%	94%
Aldehydes	82%	97%	71% (12%)	2% (79%)	84% (8%)	82% (7%)	100%	100%	99%	87%	80%	65%	-6%	90%
Chlorinated compounds	-1481%	12%	39% (19%)	35% (89%)	52% (-119%)	47% (-32%)	7%	45%	100%	100%	n/a	-100%	23%	n/a
Organic S-compounds	n/a	25%	36% (-35%)	83% (-9%)	84% (27%)	38% (37%)	62%	13%	77%	54%	53%	85%	30%	8%
Furans	n/a	100%	39% (-96%)	74% (-92%)	51% (-7%)	100% (15%)	88%	47%	65%	63%	100%	100%	13%	n/a
Ethers	100%	0%	39% (-2%)	66% (59%)	28% (-339%)	100% (6%)	-859%	38%	80%	100%	n/a	n/a	n/a	55%
Terpenes	99%	82%	45% (-63%)	76% (-4%)	61% (-18%)	95% (12%)	51%	35%	96%	91%	96%	94%	25%	28%
Organic-nitrogen compounds	n/a	0%	100% (51%)	n/a	n/a (100%)	n/a	100%	100%	100%	-100%	n/a	n/a	31%	-100%
Organic acids	n/a	100%	n/a (100%)	-100% (100%)	100% (-100%)	n/a (100%)	99%	100%	100%	100%	100%	n/a	-100%	90%
Total	77	85	80 (-10)	81 (33)	81 (-9)	98 (4)	79	67	97	91	90	96	52	83

Table 60 Removal efficiency % of VOC (individual compounds) identified above their odour threshold value.

Group % removal	Compound	UOL01 9/4/13	UOL01 12/6/13	UOL02 23/11/12	UOL03 (GW1) 24/10/12	UOL03 (OGM1) 25/10/12	UOL04 11/7/13	UOL05 23/7/13	UOL05 8/10/13	UOL06 14/8/13	UOL06 19/9/13	UOL06 15/10/13	UOL07 2/10/13	UOL07 12/11/13	UOL08 20/2/13
		Biofilter	Biofilter	Biofilter (Scrubber)	Biofilter (Scrubber)	Biofilter (Scrubber)	Biofilter (Scrubber)	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter	Biofilter
Inorganic	Ammonia	86%	100%	58% (95%)	49% (62%)	24% (98%)	80% (8-70%)	90%	41%	100%	94%	86%	100%	100%	100%
	Hydrogen sulphide	100%	100%	-	-	-	-	100%	-	-	-	-	100 %	100 %	100%
Aromatic hydrocarbons	styrene	100%	79%	53% (-72%)		69% (-6%)		63%	50%						
	toluene	25%													
	decahydronaphtalene		-100%						-100%	-100%			-100%		
	propylbenzene		-100%	39% (-84%)		55% (-3%)		32%	36%				100%		
	1-methylethylbenzene		100%			27% (7%)		-3%	100%						
	1-ethyl-3-methylbenzene	100%	61%			38% (-68%)		-100%	25%						
	1-ethyl-4-methylbenzene		100%	47% (-50%)		100% (-3%)		45%	46%						
	1,2,4-trimethylbenzene					46% (10%)									
	decane		84%												
	2-methyl-1,3-butadiene			100%(-100%)											
Alcohols	ethanol	85%	100%	91% (25%)	73% (100%)	100% (31%)	100% (4%)	100%	99%	100%	100%	100%	100%	99%	100%
	2-butoxyethanol	100%													
	1-propanol		100%	94% (-18%)		100% (-100%)	100% (0%)	100%	100%	100%	100%		100%	100%	100%
	2-methyl-1-propanol		100%	80%(-24%)		100% (-236%)	100% (10%)	100%	86%	100%	22%	-100%	100%	100 %	100%
	1-butanol		100%	100% (-72%)			100% (15%)	100%					100	100%	100%
	2-butanol		100%	97% (-99%)		100% (-165%)	100% (-2%)	95%	96%	100%				100%	100%
	3-methyl-1-butanol		100%	91% (n/a)	100% (n/a)	100%(-100%)	100% (-12%)	100%	100%	100%	100%			100%	100%
	1-hexanol			100%(-100%)			100% (-11%)								100%
	phenol			100% (-61%)	-20% (76%)									-100%	
	methanethiol				100% (33%)										
Esters	ethylbutanoate										100%	100%	100		
	ethylacetate			100% (-68%)					98%					100%	
	propylacetate			100%(-100%)											
	1-methylpropylacetate							100%	100%	100%				100%	100%
	butylacetate		100%	100% (-21%)		100%(-100%)		100%	100%						
	ethylpropionate							100%	100%	100%			100%	100%	100%
	propyl-2-methylpropanoate														100%
	methylbutanoate							100%		100%					100%
	ethylbutanoate		100%	100% (-29%)	100% (n/a)	100%(-100%)		100%	100%	100%			100%	100%	100%
	ethyl-3-methylbutanoate									100%					100%
	propylbutanoate			100%(-100%)				100%		100%					100%
	methyl-3-methylbutanoate									100%					100%
	2-methylpropyl-3-methylbutanoate														100%
	methylpentanoate									100%	100%				

	ethylpentanoate									100%	100%		100%		100%
	propylpentanoate									100%	100%				100%
Ketones	2,3-butanedione	100%	100%	95% (70%)	100% (57%)	100%(-100%)	100% (63%)	100%	100%	100%	100%				
	2-butanone	100%	100%	72% (-78%)	n/a (100%)	100% (12%)	100% (-31%)	91%	81%	100%	100%		100%	98%	100%
	2-pentanone		100%	77% (71%)		100% (-55%)	100% (-16%)	100%	100%	100%	100%				100%
	5-methyl-2-hexanone					100%(-100%)									
	2-heptanone	100%	100%	66% (-80%)		100% (-523%)	100% (17%)	100%	100%	100%	100%		100%	100%	100%
	2-hexanone									100%					100%
	2-propenal				n/a (100%)										
Aldehydes	acetaldehyde		100%	34% (17%)	77%(-147%)	74% (81%)	100% (-13%)	100%	100%	100%	-100%	10%	100%	100%	100%
	2-methylpropanal	100%			100%(-100%)										
	2-methyl-2-propenal					100% (66%)				100%					
	butanal				100% (81%)	100% (-34%)	100% (-100%)	100%	100%	100%	100%	100%		100%	
	3-methylbutanal	100%	100%	100% (12%)	100% (36%)	100% (-216%)	100% (33%)	100%	100%	100%	100%	100%		100%	100%
	pentanal							100%	100%			100%	100%		
	hexanal	100%	100%		n/a (100%)	100%(-100%)	100% (35%)	100%	100%	100%	100%		100%	100%	
	heptanal	100%	100%	28% (54%)	22% (83%)			100%	100%		100%		100%		
	nonanal	64%	84%	29% (84%)	24% (79%)	36%(-100%)	26% (28%)	100%	100%	71%	100%		100%	-100%	
	decanal	64%	100%	n/a (100%)	-100% (100%)	56%(-100%)	10% (-133%)						100%	100%	100%
	tetrachloroethylene				n/a (100%)										
Sulphur	dimethylsulfide		100%	-100% (100%)	82%(-14%)	-100% (100%)	100% (75%)	54%	-22%	79%	53%	53%	100%	68%	28%
	dimethyldisulfide		-46%	55% (-55%)	85% (0%)	100% (10%)	26% (8%)	75%	44%	28%	100%		100%	88%	-50%
Terpenes	alpha-pinene	100%	74%	41% (-76%)	71%(-3%)	51% (-6%)	n/a (100%)	42%	38%	96%	89%	99%	100%	80%	26%
	beta-pinene	100%	100%	46%(-100%)				100%	-100%	95%	100%	100%		100%	19%
	limonene	100%	82%	46% (-62%)	84%(-3%)	64% (-10%)	94% (11%)	57%	39%	98%	96%	99%	96%	90%	37%
Amines	trimethylamine			n/a (100%)		n/a (100%)			100%				96%	100%	
Organic acid	acetic acid		100%	n/a (100%)	-100% (100%)	100%		99%			100%	100%		29%	81%
	propanoic acid							100%						79%	100%
	2-methylpropanoic acid														100%
	butanoic acid													100%	100%
	3-methylbutanoic acid					100% (-100%)		100%							100%
	Hexanoic acid													-18	

The terpene beta-pinene appears to have been generated in the outlet air from UOL05. Beta-pinene is a plant based compound with a pine-like odour. UOLO5 is an open biofilter with brash media and the beta-pinene is likely to originate from the media itself. The data also indicates that terpenes generally have low removal efficiencies across a number of the biofilters sampled and it is likely that this is also due to the generation of terpenes by the media.

Looking at the data in terms of abatement system, the addition of a scrubber does not appear to have any impact on the removal efficiency of VOCs by the biofilters, and the concentration of some VOCs appears to increase through the scrubber (e.g. alcohols and terpenes at UOL02) at a number of sites. This may be due to either the partial oxidation of a number of compounds by the scrubbers or possibly volatilisation of compounds from the scrubber liquors.

The strong correlation between alcohols present in the exhaust air at concentrations higher than their corresponding OTV (e.g. ethanol, propanol), and a number of aldehydes and ketones (i.e. acetaldehyde, 2-butanone) in the outlet air (presented in the correlation analysis in Annex X), indicates that partial oxidation is likely to play a role in the apparent generation of compounds by the abatement systems.

5.3.6 Summary

Based on the data from this study the performance of the abatement systems in terms of bioaerosol reduction efficiency is extremely variable and the same abatement system does not appear to be able to achieve significant removals of *Aspergillus fumigatus*, total bacteria and gram negative bacteria.

- The removal efficiencies for *Aspergillus fumigatus*, total bacteria and gram negative bacteria are extremely variable from one site to another and also in some cases at the same site on different days.
- All the scrubbers sampled were capable of achieving reductions in the concentration of bioaerosols and were particularly effective against *Aspergillus fumigatus*.
- Overall scrubbers appear to be less effective against bacteria and total bacteria in particular.
- The performance of the two stage acid and alkali scrubber system at UOL04 appeared to be more effective than the acid scrubber alone, regardless of the bioaerosol type.
- In contrast the study of the performance of the scrubbers in terms of odour removal was extremely variable from one site to another and overall the operation of a scrubber appears to have limited or no effect on the odour concentration in the air stream.
- The performance of a scrubber in terms of the removal efficiency for *Aspergillus fumigatus*, total bacteria and odour appears to be independent of the concentration in

the inlet. In contrast, for gram negative bacteria, the performance may be influenced by the inlet concentration.

- In general it appears that open biofilters perform significantly better than enclosed biofilters with respect to their removal efficiency for *Aspergillus fumigatus*. In contrast, for total bacteria, enclosed biofilters produced the highest removals. It is not clear from this data set whether open or enclosed biofilters are better for the removal of gram negative bacteria.
- The odour removal efficiency across the biofilters sampled in this study shows some variation between sampling visits. The odour removal efficiency does not always appear to be a good indicator of biofilter performance and should be evaluated in combination with other biofilter performance indicators, such as odour emission concentration.
- The *Aspergillus fumigatus* removal efficiency of the biofilters in this study appears to be related to the inlet concentration with poor removals at low inlet concentrations. The data suggests that biofilters may be consistently emitting *Aspergillus fumigatus* and that this can only be observed when the inlet concentration is low. It may also mean that when using a biofilter alone or in conjunction with an upstream scrubber it will not be possible to completely eliminate *Aspergillus fumigatus* from the air stream.
- Although not conclusive, the suggestion that biofilters are a constant source of *Aspergillus fumigatus* may advocate the use of downstream scrubbers to negate the net emission of *Aspergillus fumigatus* by the biofilter and improve the overall performance of the abatement system.
- The removal efficiency of total and gram negative bacteria by biofilters does not appear to be related to the inlet concentration. In contrast, odour removal by biofilters does appear to be influenced by the odour concentration going in.
- The performance of granular peat biofilters is dependent upon the type of bioaerosol. They appeared to be extremely poor at reducing the concentration of *Aspergillus fumigatus.* However, in contrast they produced reasonable reductions in gram negative bacteria and significant reductions in total bacteria.
- There appears to be little difference in the performance of woodchip, clay and brash biofilters for both *Aspergillus fumigatus* and total bacteria. The performance of woodchip biofilters for gram negative bacteria is extremely variable and the data shows very poor removals for the brash and clay biofilters.
- In contrast, the type and characteristics of the abatement system appears to have little impact on the odour removal efficiency. Biofilters with each of the media types sampled (e.g. woodchip, peat, brash and clay aggregate) all achieved odour removal efficiencies in excess of 90%.

- Key design and operating parameters such as air flow rate, surface loading rate, empty bed residence time, media nutrient and moisture contents and pH appear to have no impact in the removal efficiency of bioaerosols.
- The data indicates that all but one of the biofilters sampled during this study were effective at reducing the hydrogen sulphide concentrations to below the limit of detection of the analysis technique.
- The ammonia removal efficiency shows variation between visits and does not appear to correlate to inlet concentration. The ammonia removal efficiency across the scrubbers ranged from an increase of 70% to 98%, and across the biofilters the removal efficiency ranged from 24% up to 100% removal. Overall there appears to be no difference in performance between the NH_3 removal efficiency of enclosed and open biofilters.
- Biofilters with a granular peat media appear to achieve the lowest ammonia removal efficiencies and the performance of the brash and woodchip biofilters was also generally good.
- The characteristics of the abatement system do not appear to influence the hydrogen sulphide or ammonia removal efficiencies of the biofilters.
- The removal efficiency of VOCs exhibits significant variation from site to site. A number of compound group concentrations were reduced by up to 100%. However, the individual removal efficiencies of specific VOCs varied considerably indicating that some components are easier to remove than others.
- The removal efficiency will depend upon the solubility of each compound and its amenity for absorption into and oxidation within the biofilm of the biofilter media.
- A number of individual VOCs were identified in the outlet air that did not occur in the corresponding inlet sample, particularly prevalent with the aromatic hydrocarbon, terpene and reduced sulphur compound groups.
- The sulphur compounds may have been produced as a result of partial oxidation of other sulphur compounds, or areas of anaerobic activity within the biofilter, which lead to the generation of sulphides.
- In this study the addition of a prescrubber does not appear to have any impact on the removal efficiency of VOCs by the biofilters, and at most sites the concentration of a number of VOCs appears to increase through the scrubber, but may be related to age and rate of replenishment of the scrubber solution itself.
- Terpene compounds are likely to originate from the biofilter media.

5.4 The degree of aerobicity and anaerobicity in enclosed biowaste treatments systems and the impact on the levels and types of bioaerosols and odours emitted

5.4.1 Evaluation of the aerobic to anaerobic ratio of the sites sampled using direct indicators

There are a number of direct and indirect approaches that could potentially be used to evaluate the anaerobicity of the composting processes. The presence of anaerobic indicators such as methane within the air coming out of the composting vessels is one of the direct indicators that can be used. Despite being an aerobic process overall, most composting masses are likely to have anaerobic sites where methane and other anaerobic compounds can be formed. The composition of source materials along with process management issues such as aeration, mechanical agitation, moisture control and temperature regime are the most important factors controlling methane emissions (Amlinger *et al* 2008). Some of that methane will be oxidised, but in many cases it is possible to find methane in the exhaust gases from the compost mass regardless of whether the process is using windrows or forced aeration systems. However, in most cases the amount released from the compost is low (Manios *et al* 2006, Amlinger *et al*, 2008). The energy released from anaerobic activity is small relative to that from aerobic activity and on occasions when the former represents a high proportion of the biological activity this is related to a slow increase in temperature within the mass. All the sites included in this monitoring programme showed a rapid rise to their respective control temperatures indicating low levels of anaerobic activity.

Compost is used in some of the poorer parts of the world to oxidise methane coming from landfill sites thus reducing the impact of greenhouse gas emissions. In that case the required loading rate for effective oxidation is considerably less than that found with conventional biofilters. (Amlinger et al 2008). As a result, once released from the composting mass we would not expect significant oxidation of methane in the biofilters.

5.4.2 Evaluation of the aerobic to anaerobic ratio of the sites sampled using indirect indicators

As with the direct indicators, there are a range of indirect indicators that may be used effectively to determine the presence of anaerobic sites within a compost mass of material. One indirect approach is to obtain data regarding the time temperature profiles of the compost within the vessels, to determine how it deviates from the expected 'aerobic' profile. The aerobic activity of the microorganisms within the feedstock releases the energy to heat the mass of material and if this is insufficient, due to the presence of extensive areas of anaerobicity, then the rate at which the temperature of the composting mass elevates is extended.

If the time temperature profiles indicate that there are issues with the time taken to reach temperatures of 55-60°C, then the bulk density becomes an important parameter as it helps to determine whether the supply system for the air was at fault, or whether bulk density is such that it is preventing air getting through the mass of composting material. Another parameter that would also be an indicator of potential anaerobic issues would be the moisture content, which is a key factor affecting the bulk density of the material. At low moisture contents, bulk density is unlikely to be an issue, as high moisture content is a key contributing factor to high bulk densities.

Therefore in summary, the approach taken in order to assess the aerobic/anaerobic ratio at the sites sampled was to examine the time temperature profiles to determine the time taken to reach temperatures of 55-60°C. If this is taking place within one or two days, this would indicate that there are no issues with significant anaerobic activity within the composting material. If the time temperature profiles indicate that the time taken to reach 55-60°C is excessive, then more information would be requested on the moisture content and bulk density of the feed material prior to it being loaded into the vessels.

UOL01

At the time of writing this report no time temperature data was available. However, the process operating information suggests that the moisture content of the feedstock at UOL01 is around 40% and therefore it is unlikely at such low moisture content, for there to be any issues with the bulk density of the material. Therefore, it is anticipated that the time temperature data will indicate that the material reached 55-60°C within a matter of a couple of days.

UOL05

The time temperature data for UOL05 shows the date the material was put into the bays and the current temperature that it is achieving. By looking at the age of the material and its current temperature, it is possible to determine how quickly the temperature of the material rose and therefore if there are any concerns regarding the anaerobicity of the material.

It can be seen from the data for the 23rd July 2013 that the age of the material in the bays ranged from less than 1 day to approximately 23 days. Bays 1 to 4 were complete and were in the process of being emptied. Bays 5 to 24 were full and the material was undergoing bio-drying. Bay 25 was being filled and the remaining bays were empty and ready to be filled with fresh feedstock.

The material in bays 5 to 25 has been in the system for between 1 and 19 days and looking at the data in more detail, the material in bays 21-24 had been in for less than 3 days, and

the temperatures in the exhaust air were already between 30°C and 52°C. The temperatures in the exhaust carrying the air from material that has been aerating for more than 5 days were generally in excess of 50°C. The temperatures in the exhaust vents can be related directly to the temperature of the air inside the mass of material, as the air is drawn down through the material and into vents, in which it is carried to the biofilter.

The data for the 8th October shows that bays 1 to 18 and bays 26-28 were full with material from 1 day to 17 days old. Again looking at the data in more detail, the material in bays 16-18 had been in the system for less than 4 days and temperatures are above 50°C. This may indicate that the material on this occasion has undergone a very rapid temperature increase when placed inside the bays, which in itself would suggest that the material does not show significant signs of anaerobic activity.

UOL06

The time temperature profiles for the material present in the tunnels on the 19th September are typical of the time/temperature profiles observed for all the tunnels during the site visits. All four tunnels were full and that the time spent in the tunnels was 6 days for tunnel 1, 10 days for tunnel 2, 18 days for tunnel 3 and 19 days for tunnel 4. Looking at the time temperature profiles in all the tunnels the temperature of the material increased rapidly when placed into the tunnels. In all the tunnels, the temperature of the material was in excess of 60°C and in the case of tunnel 2, in excess of 70°C within 24 hours. This data would suggest that the material is unlikely to contain areas of significant anaerobic activity that would inhibit the material from self-heating rapidly. Discussion with the site operator revealed that they will use the time/temperature profile, and in particular the rate of temperature increase in a new batch of waste, as an indicator of the 'health' of the batch. Occasionally a batch will be removed from a tunnel and re-mixed if it becomes obvious that the temperature is not increasing at a quick enough rate. The operator believes that the most common reason for the failure of a batch of waste to self-heat, is a high bulk density and the problem is usually resolved when the batch has been removed and remixed.

UOL07

Discussion with the site operator at UOL07 regarding the detail process operations revealed that when the feedstock (< 50mm fraction from an MBT plant) arrives at site, it is mixed with coarsely shredded green waste. The mix ratio is usually 5 parts feedstock and 1 part green waste and that as a general rule, this is sufficient to ensure that the bulk density is in the correct range, to ensure the process proceeds effectively. If the moisture content of the feedstock is higher than normal the mix ratio is reduced to 4:1. Once mixed the material is loaded into the tunnels on top of a layer of coarse green waste at the base of the tunnels.

The waste spends 2 weeks in Barrier One, which consists of 10 tunnels and another 2 weeks in Barrier Two (another 10 tunnels) after which, a minimum of 4 weeks is spent in maturation windrows.

The cycle of stages in the two barriers is a heat up period, a pre-composting stage, a hygienisation stage, a composting stage and finally a cool down period. During the pre-composting stage, the temperature in the material is allowed to increase up to approximately 50°C and is prevented from increasing any further through the introduction of fresh cool air through the material. After the pre-composting stage, the fresh air supply is shut off and the exhaust air from the tunnels is recirculated, and the material allowed to self-heat up to temperatures of around 60-65°C. In addition to the temperature monitoring, the tunnels are also fitted with oxygen sensors on the exhaust air. If the oxygen concentration in the exhaust air falls below 12%, the fresh air supply is automatically switched on. Looking in detail at the time/temperature profiles for the material and in particular, the time taken to self-heat at the start of the pre-composting stage and the hygienisation stage, should indicate if there are potential issues with the aerobic/anaerobic status of the material.

The data provided for the in-vessel composting system at UOL07 at the time of sampling on the 2nd October 2013 comprises of the status of the material in the tunnels in terms of the stage that they are at in the process, the date the material was placed into the tunnels and the average temperature within the material. The data shows that for the 10 tunnels in Barrier One, four were venting therefore indicating that the material had achieved the time/temperature requirements of the ABPR and awaiting removal into Barrier Two tunnels. The data shows that the temperatures within the material even during the composting stage, when the material had been in the tunnel for more than 8 days, were below 60°C. The material in tunnel 7 had been in the tunnel for 7 days (Table 61) and was still classed as being in the pre-composting stage, with an average temperature of only 53°C. Finally the material in tunnel 8 had been in the system for 3 days and had only managed to achieve an average temperature of 43°C.

Table 61 Process data for UOL07 on the 2nd October 2013.

Tunnel	Date filled	Residence time (d)	Process stage	Average Temp (°C)
4	19.09.13	14	Composting	56.4
5	25.09.13	8	Composting	51.3
6	25.09.13	8	Hygienisation	65.2
7	26.09.13	7	Pre-composting	53.7
8	30.09.13	3	heating	43.8

Although the information is limited there may be indications that the material is taking an excessive amount of time to reach the temperatures required of the ABPR and that this may be indicative of issues with the aerobicity of the material. However, further information on

the moisture content and bulk density of the material will be required before this can be confirmed.

During the visit on the 12th October additional operating data was obtained and this information can be seen in Appendix 6. The most important piece of information is the time/temperature profile shown in the first graph, which is typical of the profiles observed in the majority of the tunnels. It is clear that the material self-heats from ambient temperatures up to approximately 50°C within 30-40 minutes. Also apparent is the fact that when allowed to self-heat prior to hygienisation, the rise from 50°C up to around 65°C takes place within 30 minutes. This information would suggest that most batches of material show a typical aerobic behaviour and would not suggest that significant issues exist with respect to anaerobicity.

Discussion with the plant operator also revealed that as with site UOL06, the time/temperature data is used by the operator to determine the 'health' of a batch of waste. On occasion a batch of waste is removed from a tunnel and remixed, or recombined with additional green waste, if the operating data suggests that the material is not self-heating sufficiently quickly and that the temperature requirements will not be met.

Examination of the time/temperature profile for the batch of waste in tunnel 16 at UOL07 on the 12th November 2013 suggested that the waste has failed to reach the threshold temperature of 50°C prior to the pre-composting stage, despite the fact that the waste had been in the tunnel for four hours. On its own this may not indicate a problem; however the plant operating data also shows a high pressure on the ventilation system and that very little air was passing through the mass of material. The operating data showed that the fans were struggling to aerate the material, the fresh air fan was running at maximum and the operator had to override the control on the fresh air fan to avoid damaging the motor. This suggests that the bulk density of the material is too high and the operator was intending to remove the material from the tunnel and recombine it with addition coarse green waste. The presence of this overly dense and under-aerated material in the tunnel at the time of sampling on the 12th November may indicate that anaerobic zones may have been present in the material and that that this may affect the emissions in the inlet to the abatement system, particularly with respect to odour compounds.

The impact of this potential anaerobicity at UOL07 will be discussed in detail in section 6.4 in terms of the odour being emitted from the site and whether this indicates any potential anaerobic indicators were being emitted.

6.0 Discussion

The following sections contain a discussion of the data obtained from the sampling undertaken as part of this research project, together with the information available in the literature, within the context of the original questions identified in the introduction.

6.1 Review of odour and bioaerosol emissions from biowaste treatment facilities

According to the literature, the composition and concentration of odour emission from biowaste treatment facilities will vary and will primarily depend upon the type of waste being treated, and the stage at which the composting process is at (Frederickson et al, 2013; Pohle & Kliche, 1996). This was echoed by Schlegelmich *et al* (2005) and Krzymien *et al*. (1999) who suggested that high concentrations of odour are released during the first two weeks of the composting process. This is important for in-vessel systems, which tend to be used for the first two weeks of the composting process.

The emitted odour concentrations quoted in the literature vary from Pagans et al (2005) who stated that although flow rates are high the odour concentration tends to be low, to Frederickson et al (2013) who quoted figures of > 2million OU_E/m^3. The data from this study shows odour concentrations vary from site to site and also at the same site on different days. Overall odour concentrations ranged from 5,000 to 145, 000 OU_E/m^3, which are much lower than the figures quoted by Frederickson et al (2013). However, they are well within the figures quoted in the literature review from the large data set compiled by Odournet Group based on a range of unpublished privately funded studies conducted between 2005 and 2013 at biowaste treatment and composting facilities across Europe. The range quoted from this data was between 1,512 UO_E/m^3 to 338,106 UO_E/m^3, with mean values of 12,854 UO_E/m^3 (n = 236) (Odournet Group, 2013).

Although some authors have suggested that the odour emitted during the composting process is related to the waste type, the sensory data from this study does not support this conclusion. However, it should be borne in mind that the measured odour concentrations in process air will have been affected by the configuration of the air extraction systems serving each abatement system. This study found an odour concentration range of 13,892 – 58,422 OU_E/m^3 for sites treating green waste, 8,685 - 36,437 OU_E/m^3 for MSW and 4,856 - 145,311 OU_E/m^3 for a mixture of food waste and green waste.

Several authors have suggested that the composition of the exhaust air from biowaste treatment facilities in terms of the VOCs that are present also varies depending upon the waste type being treated (Pagans *et al*, 2006; Komalis *et al,* 2004; Eitzer, 1995; Pierucci *et al*, 2005; Defoer *et al*, 2002; Liu et al, 2009). The data from all these authors, together with the data from this study, can be seen in Table 62. Some VOCs are detected in the exhaust air regardless of the waste being treated including ketones and terpenes.

Table 62 Predominant VOCs detected in the exhaust air from waste treatment facilities.

Waste type	Compounds	Author
MSW	Aromatic hydrocarbons, terpenes & ketones	Komalis *et al* (2004)
MSW	Aromatic hydrocarbons, D-limonene, chlorinated compounds & ketones	Eitzer (1995)
MSW	Terpenes, monocyclic arenes, alkanes, halogenated compounds & esters	Pierucci *et al* (2005)
MSW	Alkylated benzenes, alkanes, alkenes, terpenes & sulphur compounds	Liu et al (2009)
MSW	Alcohols, ketones, aliphatic hydrocarbons, terpenes & aromatic hydrocarbons	This study
Green waste	Terpenes, aromatic hydrocarbons, ketones & alkanes	Komalis *et al* (2004)
Green waste	Terpenes, ketones & aliphatic hydrocarbons	This study
Food waste	Sulphides, acids/esters, alcohols & terpenes	Komalis *et al* (2004)
Green waste/Food waste	terpenes, ketones, hydrocarbons, alcohols & esters	Defoer *et al* (2002)
Green waste/food waste	Terpenes, alcohols, ketones, esters & organic sulphur compounds	This study

On the other hand it appears that some compounds, such as sulphur compounds, are present predominantly in the exhaust air from facilities treating food waste or food waste in combination with green waste. The data from this study shows that the concentration of VOCs varies significantly from site to site and also between sampling visits to the same site. It also appears that the limited data set from this study shows less discrimination between the different waste types being treated and the predominant VOCs present in the exhaust air.

Most authors agree that ammonia is an important emission compound even when the composting material is well aerated. This is particularly important when the waste material has a low C:N ratio (Pagans *et al*, 2005; Frederickson *et al*, 2013; Beck-Friis *et al,* 2001). Pagans *et al* (2005) and Frederickson *et al* (2013) both suggested that high temperatures during the composting process lead to high emission concentrations of ammonia. Other authors have commented that an important factor is the aeration rate, with higher aeration rates leading to increased ammonia emission concentrations (Elwell *et al*, 2001; Kim *et al*, 2009; Shen *et al*, 2011; Hong *et al*, 1998; Osada *et al*, 1997). The data from this study does not support this observation as there appears to be no relationship between inlet air flow rate and ammonia concentrations. This may be due to the fact that the authors above have observed a relationship between the aeration rate of the composting material and the ammonia emission, whereas the air flow data presented in this report is the air flow measured in the inlet duct to the abatement system. It is also important to note that inlet air samples were taken from the inlet duct immediately upstream of the abatement system and depending on the site, the inlet air may be a mixture of air from different areas of the facility (Table 63). As a result it may not be possible to determine relationships between air flow rates and ammonia emissions, for example when the source of the exhaust air is not limited to the air from the composting vessels.

Table 63 Exhaust air source for sites sampled in this study

Site	Source of exhaust air
UOL01	Air from whole biodrying hall including the waste reception area
UOL02	Air from the whole composting hall plus other areas of the facility
UOL03	Air from the whole composting hall plus other areas of the facility
UOL04	Air from whole composting hall
UOL05	Air from whole biodrying hall including the waste reception area
OUL06	Air from tunnels only
OUL07	Air from tunnels only
UOL08	Air from the tunnels and also the sheds

In terms of the overall ammonia concentration, the literature is limited as far as actual data is concerned, with the only quoted figure, 227 mg/m^3, presented by Smet et al (1999). In comparison, the ammonia concentrations found during this study, range from the detection limit up to a high of 67 mg/m^3. This is much lower than the figure quoted by Smet et al (1999).

Kissel et al (1992) reported that even if the composting process is aerobic, there will still be anaerobic pockets within the composting mass and that these may produce odorous sulphur compounds. Lui et al (2009) suggested that high aeration rates will result in the low sulphur compound emission rates. During this study the concentration of hydrogen sulphide ranged from below the detection limit, up to a high of 12 mg/m^3 (UOL01). For the majority of sites, apart from UOL01, the concentration was below 1 mg/m^3. However, organo sulphur compounds (in particular dimethyl sulphide) were detected in the process air at most of the waste sites, at concentrations between 0.2 and 2.8 mg/m^3. The data from this study did not support the observation of Noble et al (2001), who found a close correlation (r2=0.90) between the sum of the concentrations of hydrogen sulphide and dimethyl sulphide, and odour concentrations of the emissions from mushroom composting. The lack of such a correlation in this case is most likely to be due to the differences in feedstocks used in mushroom composting processing (i.e. high quantities of gypsum), compared to the biowaste sites included in this study, which lead to the generation of much higher concentrations of hydrogen sulphide and dimethyl sulphide.

The information available in the literature relating to the concentration of bioaerosols measured at full scale biowaste treatment facilities is rather sparse, and the data that is available needs to be treated with caution due to significant variations in the sampling locations and the sampling techniques used (e.g. non-isokinetic sampling). Frederickson *et al* (2013) suggested that the exhaust air from in-vessel system will contain primarily bacteria and gram negative bacteria. This observation is borne out in the data from this study, which shows that regardless of the process, or the waste being treated, the concentration of total bacteria and gram negative bacteria is higher than that of *Aspergillus fumigatus* (Table 64).

It also shows that the concentration of *Aspergillus fumigatus* is extremely variable from site to site and that it will vary even if there is no reported change in the plant operating conditions.

Table 64 Exhaust air bioaerosol concentrations

System	Waste	Concentration (cfu/m^3)		Author
Various	GW/FW	Bacteria Gram negative bacteria Fungi	$5.4 \times 10^3 – 3.7 \times 10^5$ $1.1 \times 10^4 – 1.8 \times 10^5$ $0 – 4.2 \times 10^4$	Frederickson et al (2013)
-	-	Mesophilic bacteria	10^5 - 10^6	Fisher et al (2000)
Various	Various	Aspergillus fumigatus Mesophilic bacteria	10^2 - 10^5 10^3 - 10^5	Sanchez- Monedero et al (2003)
-	-	Aspergillus fumigatus	10^2 - 10^5	Kummer & Theil (2008)
Various	Various	Aspergillus fumigatus Total bacteria Gram negative bacteria	$9 - 3.3 \times 10^3$ $7.2 \times 10^3 – 2.5 \times 10^4$ $7.5 \times 10^2 – 8.5 \times 10^3$	This study

It can be seen that overall the bioaerosol concentrations measured during this study were lower than those quoted in the literature. The concentrations of *Aspergillus fumigatus* and gram negative bacteria concentrations measured during this study were generally two orders of magnitude lower than the figures quoted in the literature, with a maximum value of 10^3 compared to 10^5 for both. The concentrations of bacteria were only one order of magnitude lower at 10^4 compared to a figure of 10^5 quoted in the literature.

There is no information in the literature regarding the impact of upstream operating parameters on the concentration of bioaerosols, and during this study the situation was rather confusing. For example, the impact of higher airflow rates on the concentration of *Aspergillus fumigatus* varied with an increase at one site and a decrease at another site.

Overall, according to the data from this study, the concentration of bioaerosols appears to be independent of the type of biowaste treatment system being used and also the type of waste being treated. It also appears that there is no relationship between the concentrations of the individual bioaerosols being emitted.

6.2 Review of emission concentrations and rates of reduction achieved by biofilters

Many authors have suggested that biofilters or systems incorporating scrubbers and biofilters are effective for odour reduction (Kummera and Thiel, 2008; Chung *et al*, 2004; Rosenfeld *et al*, 2004; Mohseni & Allen, 2000; Rappert & Muller, 2005; Nevin & Barford, 2000). Devinny et al (1999) and others, provides specific maximum capacities for a number of specific compounds that can be used to assess the overall capability of biofiltration in terms of removal of the specified chemical. These elimination capacities are not however relevant biofilters in odour treatment applications for compost odour (including those

studied in this case), since the concentration of VOCs present in process air are well below the stated values and typically fall in the micro to milligram per cubic meter concentration range.

Overall, the data obtained during this study, shows that odour removal efficiencies ranged from 64% up to 98% depending upon the site. This data range is lower than that quoted by AfOR (2007), who had a range of 85-95% and also the figure of 95% quoted by SEPA (2010). The study also shows that the performance of upstream scrubbers was extremely variable, with net increases in odour of -37% and removal efficiencies of 37%.

The odour removal efficiencies not only vary from site to site, but can also vary on different days at the same site. A key observation from this study is that the performance of the abatement system appears to be influenced by the inlet odour concentration, with a reduction in removal efficiency at lower inlet odour loads. This is likely to be due to the fact that the media in biofilters generates its own odour, which presents a limiting factor in terms of the overall removal performance that the biofilter can achieve. VDI3477 (2004) supports this observation, and states that the odour released from biofilters comprises a combination of odorous volatile compounds that are generated through biodegradation of crude gas components (i.e. a function specific biogenic odour) and release of odorous volatiles from the surface of the media itself (e.g. terpenes from woodchip) which vary depending upon the media used. VDI3477 (2004) goes on to state that the biogenic odour generated during breakdown of crude gas is independent of the media being used and is more likely to be influenced by microbial density. It is possible that odours are also generated as a result of the degradation of the media material with age.

In terms of odour emissions from biofilters, the data in the literature is rather sparse, with figures of 390-13,050 OU_E/m^3 quoted by Defoer *et al*. (2002) and 53 OU_E/m^3 quoted by Sironi *et al* (2007). In comparison, the mean outlet odour concentration observed during this study ranged from 212-5516 OU_E/m^3, and the data suggests that the outlet concentration is unlikely to fall between the 200-500 OU_E/m^3 range quoted by DEFRA (2009). Overall, some of the key observations from this study are that at most of the sites sampled, the concentration of odour in the biofilter outlet air remains consistent from one visit to another, and that overall biofilters are capable of maintaining a stable odour emission rate, regardless of the variation in inlet odour concentration.

The data from this study relating to VOCs shows that the removal efficiencies vary from site to site and that some compounds groups are more easily removed, as evidenced by the close to 100% removal for esters, alcohols and organic acids. A similar picture is also seen for individual VOCs, with some apparently more easily removed than others. A comparison between the data quoted by the European Commission (2006) and the data generated in this study (Table 65), shows that for most of the VOC groups the data are consistent. Ergas *et al* (1995) reported that they were able to consistently achieve more than 90% reduction in the concentration of difficult to degrade aromatic compounds, which also fits with the data from this study. This study also observed that there was no relationship between the

inlet concentration and removal efficiency for aromatics, and that even if the inlet concentration varied significantly, it did not affect the removal efficiency.

Table 65 Comparison of removal efficiencies for selected VOCs

Substance (group)	European Community (2006)	This study
Aldehydes, alkanes	75	Aldehydes -6 to 100 Alkanes -136 to 97
Alcohols	90	62-100
Aromatic hydrocarbons	80	34-96
Non-methane volatile organic compounds	83	52-98
Odour	95 - 99	64-98

One important observation from this study is that the VOCs observed in the outlet air from the biofilter are not necessarily the same ones that were observed in the inlet gas stream. This would suggest that some compounds are generated within the biofilter media and in the case of this study, those compounds appear to be reduced sulphur compounds, aromatics, alcohol, aldehydes, ketones and terpenes. This contradicts the findings of Liu et al (2009), but confirms the observations made by Pagans et al (2007), which indicated that poor percentage VOC removal was observed due to emission of VOCs from the compost media itself.

Rosenfeld *et al* (2004) found that during their study the two stage biofiltration system was capable of significant reductions in a range of odour compounds, but that acetic acid removal proved problematic even at high residence times. However, in this study no carbon disulphide or acetic acid was detected in either the inlet or outlet air above odour threshold, although trace amounts were detected in the offgas at UOL07 and OUL08. In addition the sites sampled as part of this study had residence times much lower than those quoted in their study, however most sites achieved almost 100% removal of many VOCs.

The data from this study shows that biofilters are capable of high removal efficiencies for ammonia and hydrogen sulphide, but that the performance in terms of ammonia is variable from site to site and also for at the same site on different days. The literature indicates that although hydrogen sulphide removal can vary to a degree, removal efficiency generally exceeds > 99.9% (Ergas et al, Bonnin et al & Yang and Allen, 2012). All the data in this study corroborates this as 100% removal was achieved in almost all cases. For ammonia, removal efficiencies ranged between 24 - 100%. The scrubbers generally performed better, with removal efficiencies of between 62 - 98%. This is not surprising as the scrubbers have been specifically designed for ammonia removal and the concentration of ammonia in the process air at sites fitted with scrubbers tended to be significantly higher than those sites with biofilters only.

In terms of the actual emission concentrations for hydrogen sulphide and ammonia, there is very little data provided in the literature and hence the discussion is based primarily on what was found during this study. Overall, the data from this study shows that the concentrations of ammonia and hydrogen sulphide in the outlet air from the abatement system were low, ranging from below the limit of detection of the monitoring technique applied to 1.5 mg/m^3. At some sites the concentration of outlet ammonia was variable between sampling visits and at some sites the variability in outlet ammonia concentration appeared to be a result of variations in the ammonia load entering the abatement system. The present data also shows that there is no relationship between the outlet ammonia and hydrogen sulphide concentration, and the odour concentration.

Overall, the removal of bioaerosols from the sites sampled as part of this study were extremely variable, both from site to site, and also from one visit to the next (at the same site in some cases). This is in agreement with Schilling et al (1999) who also stated that the removal efficiency and outlet concentrations of bioaerosols vary greatly. The data available in the literature shows a great deal of variability (Tables 13, 14 and 15). It is extremely difficult to compare the data obtained during this study to that presented by other authors due to differences in the bioaerosol measured, the sampling techniques, as well as the range of abatement system design and operating parameters.

The bioaerosol removal data presented in the literature has been collated and is presented in Table 66.

Table 66 Bioaerosol removal efficiencies across the entire abatement system

Bioaerosol	Removal (%)	Author
Aspergillus fumigatus Mesophilic bacteria	90.4 – 99.4 39.1 – 94.2	Sanchez-Monedero et al (2003)
Mesophilic bacteria Fungi	11 – 71 71	Seedorf and Hartung (1999)
Bacteria Fungi	94.5 – 99.1 73.1 – 97.9	Seedorf and Hartung (2002)
Bacteria Fungi	70 – 95 49 - 90	Martens et al, 2001
Bacteria Fungi	58 – 80 90	Schlegelmilch et al., 200
Bacteria Fungi	90-100 90-100	Haumacher et al, 2005
Bacteria	90-98	Ho et al, 2008
Aspergillus fumigatus Total bacteria Gram negative bacteria	-57 – 100 -34 – 95 -57 - 93	This study

What is immediately apparent from the table is that all the data presented in the literature shows a reduction in bioaerosols concentration across the abatement system. In stark contrast the data obtained in this study shows extreme variability, and in all the bioaerosols measured, there were instances where significant increases in concentration were observed across the abatement system. What is also apparent is that the maximum bioaerosol removal efficiencies observed in this study are broadly in agreement with the ranges quoted in the literature.

Chung et al (2004) reported that the potential for bioaerosol emission from biofilters should be investigated and Ottengraf & Konings (1991) and Seedorf (2000) also raised the issue of a net increase in the concentration of bioaerosols across biofilters. Frederickson et al (2013) also observed that it was not unusual to see higher concentrations of bioaerosols at the outlet than the inlet of a biofilter and various explanations were put forward, such as biofilter materials being net emitters, anomalous results, and growth within biofilters. During this study the full scale biofilters were capable of significant reductions in the concentration of bioaerosols (Table 67). However, on occasion there were net increases across the biofilter and this was not limited to any single bioaerosol type or biofilter type.

Table 67 bioaerosol removal efficiencies achieved by the biofilters sampled during this study

Bioaerosol	Removal Efficiency (%)	
	Enclosed Biofilter	Open biofilter
Aspergillus fumigatus	-46% - 29%	48% - 82%
Total bacteria	43% - 52%	48% - 72%
Gram negative bacteria	46% - 67%	-24% - 87%

Ottengraf & Konings (1991) reported that from their results biofilters were net emitters when the inlet concentrations were low and were net reducers when concentrations were higher in the inlet. It can be seen that for this study (Tables 51, 53 and 55) this was also the case for *Aspergillus fumigatus*, but not for total or gram negative bacteria.

Ottengraf & Konings (1991) also reported that at low gas velocities the concentration of bacteria in the outlet is generally higher than that going in (i.e. net emitters). This is not the case for the biofilters sampled during this study (Tables 51, 53 and 55). UOL06 consistently achieved good removals of *Aspergillus fumigatus* (70%), total bacteria (72%) and gram negative bacteria (87%), despite the fact that the inlet air flow rate was the lowest at only 0.7 m^3/s.

Ottengraf & Konings (1991) also stated that as air flow rates into a biofilter increase, the emission rate of microorganisms within the biofilter increase and that the capture rate is highly affected by the gas velocity. During this study this was not found to be the case as sites UOL02 and UOL03 had the highest air flow rates and emitted 599 and 713-724 cfu/m^3

Aspergillus fumigatus, 515 and 926-1312 cfu/m^3 total bacteria and 247 and 244-324 cfu/m^3 of gram negative bacteria. Compared to site UOL06, which had the lowest air flow rates and emitted 859-1,067, 2,578-3704 and 415-1,037 cfu/m^3 of *Aspergillus fumigatus*, total bacteria and gram negative bacteria respectively. This fits with the observations of Chung *et al* (2004) who found during their study that there was no significant relationship between flow rate and bioaerosol concentration.

Table 68 Bioaerosol emission concentrations from abatement systems – data from the literature and from this study

System	Concentration (cfu/m^3)		Author
Compost/woodchip biofilter	Bacteria Gram negative bacteria Fungi	$2.5 \times 10^4 – 4.2 \times 10^4$ $0 – 6.0 \times 10^2$ none detected	Frederickson et al (2013)
No detail given	Bacteria Gram negative bacteria Fungi	$1.5 \times 10^4 – 2.5 \times 10^4$ $1.2 \times 10^3 – 6.0 \times 10^3$ $0 – 1.2 \times 10^3$	
Compost/woodchip biofilter	*Aspergillus fumigatus* Mesophilic bacteria	$10^2 – 10^3$ $10^3 – 10^4$	Sanchez-Monedero et al (2003)
Pine bark biofilter	*Aspergillus fumigatus* Mesophilic bacteria	10^2 10^3	
Peat biofilter	*Aspergillus fumigatus* Mesophilic bacteria	10^2 10^3	
No detail given	*Aspergillus fumigatus*	$0 - 10^4$	Kummer & Theil (2008)
Various	*Aspergillus fumigatus* Total bacteria Gram negative bacteria	$0 – 1.3 \times 10^3$ $5.2 \times 10^2 – 6.1 \times 10^4$ $1.4 \times 10^2 – 3.6 \times 10^4$	This study

Table 68 shows the concentration of bioaerosols emitted from different abatement systems based on data obtained from the literature and from this current study. It can be seen that the *Aspergillus fumigatus* concentrations found during this study fit within the range reported by Kummer & Theil (2008) and are generally lower than the range quoted by Sanchez-Monedero et al (2003). The concentration of total bacteria observed during this study generally fall below the range quoted by Frederickson et al (2013). However, the maximum concentration observed in this study are similar to the maximum observed in their study. Overall, the concentration of gram negative bacteria observed during this study are slightly higher than those observed by Frederickson et al (2013) and have a lower range of values.

Frederickson et al (2013) pointed out that the current Environment Agency guidance for bioaerosol emission concentrations at open windrow compost sites are 1000 cfu/m^3 for bacteria, 500 cfu/m^3 for *Aspergillus fumigatus* and 300 cfu/m^3 for gram negative bacteria.

If these figures were applied to the emissions from the biofilters sampled as part of this study, then it can be seen that the concentration of total bacteria, on only 2 out of the 14 sampling days, was below 1000 cfu/m^3. On only 3 out of the 14 sampling days, the *Aspergillus fumigatus* emission concentrations fell below 500 cfu/m^3. For gram negative bacteria, the concentration was below 300 cfu/m^3, on only 3 of 14 sampling days.

Therefore it is apparent that the concentration of bioaerosols emitted from abatement systems consisting of biofilters only, or biofilters and scrubbers, regularly exceed the concentrations that are permissible for open windrow systems. This agrees with what Frederickson *et al* (2013) reported, that despite very good removal efficiencies in some instances, concentrations released to the atmosphere are still elevated above background, and are often in excess of guidelines which have been defined for ambient air. However, it should also be stressed that the bioaerosol concentration measurements carried out during this study were taken in an enclosure, directly over the surface of the biofilter, and therefore capture the concentration in the air as it leaves the biofilter. However, the permissible concentrations quoted for open windrow systems are those that would be measured at the nearest sensitive receptor. It is not known what impact the bioaerosols leaving the abatement systems in this study would have on the concentrations at the nearest sensitive receptor.

6.3 Review of biofilters design and operation to maximise odour and bioaerosol reduction.

The majority of the work reported in the literature in relation to the impact of biofilter design and operating parameters has focussed on the impact on odour and VOC removal, and not bioaerosol removal. There is very little information regarding the impact of biofilter design and operation on either the removal efficiency for bioaerosols, or the emission concentrations. The only comment found in the literature refers to the potential impact of air flow rates and media particle size on the removal of bioaerosols, which is consistent with the view that the main mechanism for bioaerosol removal is impingement. It should be noted however that although there are a large number of comments in the literature regarding 'optimum' design and operating parameters, there is a lack of actual performance data to support this. Many authors have expressed opinion and quoted figures, but in many cases they do not refer to actual full scale, pilot, or laboratory scale results to back this up.

On the other hand, there is a large amount of literature relating to the impact of biofilter design and operation on the removal of odour. This includes media characteristics, residence times and inlet contaminant concentrations. Again, this is to be expected since the mechanism for odour, VOC, ammonia and hydrogen sulphide removal, is dependent upon the effectiveness of transfer into the biofilm and the subsequent action of the microbial population, within the biofilter media. The removal efficiency and the outlet emission concentration will therefore rely on the activity of those microorganisms, which in

turn relies on a favourable environment in which they can grow and maintain their metabolic activity.

The key biofilter design and operating parameters quoted in the literature as important for optimising the performance of biofilters tend, therefore, to be those that facilitate optimal microbial growth and metabolism, such as moisture content, pH, nutrient availability and temperature; together with those that optimise the absorption of the target compounds such as temperature, moisture content, residence time, air flow rate and contaminant concentration.

Table 69 shows the design and operating parameters of the biofilters sampled as part of this study compared to the suggested ranges quoted in the literature. It should be noted at this point that design and operating parameter data, such as empty bed residence time, operating temperature and air flow rate are available for most of the sites sampled, however, the more detailed media characteristics, such as moisture content, pH and nutrient content are only available for sites UOL05, UOL06 and UOL07 and therefore the data set in extremely limited.

Table 69 Comparison of the design and operating parameters for the biofilters sampled during this study and the values quoted in the literature

Parameter	**Literature**	**This study**
Area (m^2)	1 - 3000	12-840
Air flow (m^3/hr)	50 – 300,000	2520 – 104,760
Surface loading (m^3/m^2/hr)	5 – 500	77-370
Empty bed residence time (s)	15 – 60	41-84
Operating temperature (°C)	15 – 40°C	16-43
Media pH	6 – 8	6.6 - 8.1
Media moisture content (%)	20 - 70	63 - 72

It can be seen that for most of the parameters listed, the biofilters in this study fall within the suggested ranges. This makes it difficult to comment on the impact of design, on the performance of the biofilters that fall outside the recommended design and operating ranges, for some of the key parameters. Only the empty bed residence times, moisture content, pH and temperature of some of the biofilters in this study fall outside the recommended range quoted in the literature. For EBRT, three out of the nine biofilters sampled had significantly longer residence times, between 71 and 84 seconds. For moisture content and pH, this only included one site and in each case the actual values were only slightly outside the 'optimum' range.

Table 70 shows the detailed design and operating parameters, and the performance data for the abatement system and the biofilter, at the eight sites sampled in this study. It will be referred to in the following sections.

Table 70 Overall Abatement system design and operating characteristics and bioaerosol, odour, Hydrogen sulphide, ammonia and total VOC emission concentrations and removal efficiencies (overall abatement system = black text, biofilter = red text, scrubber = blue text)

Parameter	UOL01	UOL02	UOL03	UOL04	UOL05	UOL06	UOL07	UOL08
Abatement system	Enclosed biofilter	Acid Scrubber & Enclosed biofilter	Acid Scrubber & Enclosed biofilter	Acid & Alkali scrubber & Enclosed biofilter	Open biofilter	Open biofilter	Acid Scrubber & Open biofilter	Acid Scrubber & Open biofilter
Biofilter media	Woodchip & brash	Granular peat	Granular peat	Clay aggregate	Brash	Woodchip	Pine Woodchip <10% bark	Pine woodchips 30-60mm
Up-flow/Down-flow	Up	Up	Up	Up	Up	Up	Up	Up
Biofilter surface Area (m^2)	660	840	840	$12m^2$ each	660	12.5	400	108
Media depth (m)		2.24	2.24	4.2	1.1	2.5	Min 6ft	1.6 – 2.1
Media age		-	12 months		-	-	12 months	18 months
Flow rate (m^3/s)	14.2	24.2	20.8 (GW) 29.1 (OGM)	7.4	14.3	0.7	8.7	9.7
Surface loading rate ($m^3/m^2/hr$)	77	104	119 (GW) 125 (OGM)	370	78	211	78	81
EBRT (s)	51	78	68 (GW) 65 (OGM)	41	51	43	84	71
Inlet temp (°C)	31 - 36	38	34 - 37	23	42-43	29 - 40	24 - 34	16
Electrical Conductivity [µS/cm]	-	-	-	-	459 - 531	41 - 663	44 - 206	-
NH4+-N [mg/kg]	-	-	-	-	450 - 550	35 - 515	7 -146	-
NO2—N [mg/kg]	-	-	-	-	5 -35	5 -170	10 - 15	-
NO3—N [mg/kg]	-	-	-	-	410 - 1423	10.5 - 521	34 - 189	-
NH4+-NOx—N [mg/kg]	-	-	-	-	0.965 1.908	0.0505 – 1.206	0.051 – 0.35	-
SO4 2- [mg/kg]	-	-	-	-	205 - 540	35 - 145	20. - 35	-
Moisture content (%)	-	-	-	-	66.5 – 71.8	63.6 – 71.8	68.3 – 69.4	-
pH	-	-	-	-	6.9 -7.0	6.6 – 8.1	6.6	-
Aspergillus fumigatus removal	-46 & 29	-57	42 & 43	100	67 & 82	47, 59 & 71	(0.3)	97

Parameter	UOL01	UOL02	UOL03	UOL04	UOL05	UOL06	UOL07	UOL08
efficiency (%)		(-316) (34)	(-128 & -236) (73 & 83)	(-) (100)				
Aspergillus fumigatus emission concentrations (cfu/m^3)	672 - 1337	599	713 - 724	11	578 - 682	859 - 1067	0 - 6	963
Total bacteria removal efficiency (%)	43 & 52	95 (84) (43)	87 & 87 (90 & 90) (-42 & -34)	94 (84) (61)	53 & 65	49, 63 & 72	-35 & 10	76
Total bacteria emission concentration (cfu/m^3)	8172 - 15580	515	926 - 1312	1348	6973 - 9007	2578 - 3704	14726 - 61541	25790
Gram negative bacteria removal efficiency (%)	46 & 68	93 (62) (30)	89 & 91 (83 & 85) (13 & 38)	38 (-117) (68)	-25 & -6	83, 87 & 92	-66 & 55	84
Odour removal efficiency (%)	91 - 96	81 (37)	91 & 93 (13 & -31)	98 (-21)	86 - 94	64 - 97	89 - 94	88
Odour emission concentrations (OU_E/m^3)	402 - 3102	5516	1004 - 1782	212	1756 - 2255	1299 - 4927	985 - 1004	2308
Hydrogen sulphide removal efficiency (%)	100	-	-	-	100	-	100	100
Hydrogen sulphide emission concentrations (mg/m^3)	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD	<LLOD
Ammonia removal efficiency (%)	86 -100	58 (95)	24-49 (62-98)	80 (-70)	41 - 90	86 -100	100	100
Ammonia emission concentrations (mg/m^3)	<LLOD – 0.88	1.5	0.74 -0.86	<LLOD	0.42 – 1.16	< 0.1 – 0.52	< 0.1	<LLOD
Total VOC removal efficiency (%)	77-85	80	81	98	67-79	90-97	52-96	83
Total VOC emission concentrations (mg/m^3)	11361 - 20290	51599	4971 - 17926	1398	24499 - 27457	1580 - 5766	2389 - 29148	10057

6.3.1 Media characteristics

As was observed for media moisture content, there are a number of authors who have reported that the performance of biofilters was affected by the temperature of the biofilter media. Yang and Allen (1994) reported that the bacteria responsible for the oxidation of hydrogen sulphide, operated best at a temperature range between 25°C and 50°C and that outside that range, the removal efficiency for hydrogen sulphide drops off. They also reported that VOC removals in their peat biofilter were higher at 32°C than they were at either 25°C or 45°C. This is at odds with the situation reported by Tunnee (2011) who looked at the performance of a woodchip and a peat biofilter and found that VOC removal peaked at 45°C, and that either side of this the removal decreased. Brennan et al (1996) observed that removal rates for hydrogen sulphide decreased by more than 50%, when the temperature range changed from 20-22°C down to 9-12°C.

Hong et al (2013) observed that biofilter performance dropped off at temperatures above 40°C. This corroborates the observation of Knauf and Zimmer (1994) who reported that for a bark compost biofilter, the removal efficiency for organics decreased steadily when the temperature of the exhaust air increased. As the temperature increased from 40°C up to 55°C, the organics removal efficiency decreased from 95% down to 85%.

Therefore, it appears that there is some uncertainty when it comes to the impact of temperature on the performance of the biofilter, even when it is within the 'optimum' range quoted in the literature. In this study the temperature of the inlet air to the biofilters was measured and overall the range of temperature fits with the range quoted in the literature, with only one site slightly above the range at 42-43°C (Table 71). It is clear that even when the operating temperature is outside the range quoted in the literature, the performance of the biofilter was not adversely affected. The data collected in this study, is however, not sufficiently complete to confirm to what extent biofilter performance may decrease, as temperature increases further.

Table 71 Performance of biofilters outside the 'optimum' temperature range

Parameter	Removal efficiency (%)	
	Overall range for all biofilters	Sites > 40°C
A. fumigatus	-316 to 97	67 to 82
Total bacteria	-35 to 90	53 to 65
Gram negative bacteria	-116 to 92	-25 to -6
Odour	64 to 96	86 to 94
Hydrogen sulphide	21 to 100	100
Ammonia	24 to 100	41 to 90
Total VOC	-100 to 100	67 to 79

The range of moisture content quoted in the literature is between 20% and 70%, however there are some authors who have found that even within this range, there is a potential difference in the performance of a biofilters, particularly in terms of the removal of chemical compounds. Pinnette et al (1994) found that there was a loss of biological degradation of odorous compounds in their biofilter, when the moisture content went below 40%.

Ottengraf and Van den Oever (1983) reported that at moisture contents of between 50% and 70% the biofilter performed well. However, below this range they found that they had lower microbial activity and above this range they found that anaerobic zones developed. Ergas et al (1995) observed that in a full scale biofilter the performance improved when the moisture content was increased from 50% to 55%, through the addition of water. They found that there was a dramatic increase in the removal of VOCs and hydrogen sulphide.

In this study all the biofilter moisture contents were broadly within the range quoted in the literature, with the exception of UOL05 and UOL06, where the upper range was slightly exceeded. The study data therefore offers little evidence upon which to assess, how performance may vary from an odour removal perspective, under sub optimal conditions. It is however interesting to note that in spite of this, the removal performance of many of the biofilters was poor in terms of bioaerosols, which may imply that even when the moisture content is deemed to be within the optimal range, the removal of bioaerosols may not be significant. However, it may also be the case that moisture content is not the key performance indicator when it comes to bioaerosols and that the poor removals observed in some cases may be due to other biofilter design and operating parameters.

Although the literature contains references and suggestions as to the 'ideal' media pH for biofilters, there is very little actual data on the performance of biofilters and the media pH. Smet *et al* (1996) found that they got acidification of their biofilter and that this was associated with a decrease in removal efficiency. Yang and Allen (1994) found that hydrogen sulphide removal efficiency decreased markedly at a pH of less than 3.2, but that above this there appeared to be no relationship between removal efficiency and pH.

In this study, the pH of the media in the biofilters ranged from 6.6 to 8.1, with only UOL06 operating outside the range at a pH of 8.1, on one sampling occasion. The data obtained during this study indicated that there is no relationship between pH and any of the removal efficiencies obtained. This may be because the pH range of the biofilters is rather narrow, with the majority operating between pH 6 and 7 and also because media analysis was only carried out at three of the eight sites included in the study.

The literature relating to the nutrient content of the media is more limited, with some authors suggesting that nutrient availability is important for the maintenance of an active microbial population, but they don't have the data to suggest what the nutrient levels should be. Morgenroth et al (1996) found that hexane removal improved significantly when nitrate was added to the biofilter media, while Morales et al (1998) and Wu et al (2006)

reported that VOC removal increased after the injection of ammonia gas into the biofilter media.

Generally the concentrations of NH_4-N, NO_2-N and NO_3-N were lower for site UOL07 than either UOL05 or UOL06. Looking at the removal efficiencies (Table 70), it appears that the removal efficiencies for bioaerosols are generally lower than the other two sites; this is particularly true for *Aspergillus fumigatus* and total bacteria. The removals of hydrogen sulphide, odour and ammonia appear to be unaffected by the concentration of these three nutrients in the biofilter media.

6.3.2 Design and operating parameters

The data from this study would suggest that the odour emission concentration appears to be independent of the abatement system used. Whether the biofilter is open, or enclosed, appears to have no observable effect on odour emission concentrations, with the measured odour concentrations falling in the range 212 to 5,516 OU_E/m^3 (mean = 2,047 OU_E/m^3) for enclosed biofilters, and 985 to 4,927 OU_E/m^3 (mean = 2,372 OU_E/m^3) for open biofilters.

It is also apparent that the presence of an upstream scrubber had no direct impact on the odour emission concentration achieved by the biofilter at the study sites. The odour concentrations measured fell within the range of between 212 and 5,516 OU_E/m^3 (mean = 2,047 OU_E/m^3), for systems with an upstream scrubber and between 402 and 4,927 OU_E/m^3 (mean = 2,372 OU_E/m^3), for those systems without an upstream scrubber.

It should however be noted that without the application of scrubber technology at sites UOL02, UOL03 and UOL07, the elevated concentration of ammonia sulphide within the process air may have led to operational problems within the downstream biofilter that would have affected odour removal performance. The data therefore confirms that from an odour treatment perspective, scrubbers do serve a useful purpose in terms of conditioning the process air to remove potentially toxic constituents, prior to biofilter treatment.

The removal efficiencies for bioaerosols vary depending on the abatement system used, but based on the limited amount of data from this study, the type of system that favours the removal of one bioaerosol, may not necessarily be the one that achieves good removals of another bioaerosol. For *Aspergillus fumigatus,* the sites using a scrubber followed by an enclosed biofilter performed very poorly and most were found to have a higher outlet concentration than inlet. The sites with a scrubber and an open or enclosed biofilter, were extremely variable with removals ranging from only 0.3% up to 97%, and up to 29% respectively. Overall the most consistently good removals of *Aspergillus fumigatus* were observed for sites incorporating an open biofilter alone.

The best system for the removal of total bacteria appears to be those using a scrubber and enclosed biofilter; these consistently achieved over 84%. Slightly less effective, but still

reasonable, were those using either an open biofilter or enclosed biofilter alone, with removals of up to 52% and 72% respectively. Overall the sites that incorporate a scrubber and open biofilter were more variable and on occasion, were found to have a higher outlet concentration than the inlet.

The situation with the gram negative bacteria is more variable with the enclosed biofilter system at UOL01 being the only systems performing consistently well.

The removal efficiency of some bioaerosols varies depending upon the type of biofilter media being used (Table 70). The removal efficiency of *Aspergillus fumigatus* and gram negative bacteria were extremely variable for the woodchip biofilters, however they did appear to be generally good for the removal of total bacteria. The granular peat biofilters achieved good removals of total bacteria and gram negative bacteria, but in all samples were found to be net emitters of *Aspergillus fumigatus*. The woodchip/brash biofilters achieved good removals of total bacteria and gram negative bacteria, but the performance in terms of *Aspergillus fumigatus* removal was variable. The clay aggregate biofilter at UOL04 performed well for total bacteria and was a net emitter of gram negative bacteria. The performance of the clay aggregate biofilter for *Aspergillus fumigatus* removal could not be assessed, as no *Aspergillus fumigatus* was found in the inlet samples.

Tunee (2011) investigated the removal of a range of VOCs using two different biofilters containing different media (peat and woodchip) and found no difference in the removal of VOCs. In the present study this was also the case, with no apparent difference between the removal of VOCs achieved by the granular peat and woodchip biofilters sampled. Overall the emission concentration of odour is independent of the biofilter media type being used. The data also suggests that some volatile components of the outlet air may be released by the media and by the woodchip media in particular (e.g. Terpenes).

Ergas et al (1995) found that the removal of some individual VOC compounds increased as the inlet air flow to the biofilter increased, but that it reached a maximum between 0.7 and 1.7 $m^3/m^2/hr$. However, the increase in air flow rate was accompanied by a decrease in the empty bed residence time and therefore it is not possible to determine if the air flow rate, or the empty bed residence time is the important parameter.

Ottengraf & Konings (1991) reported that capture of microorganisms by impingement on the media surface was an important mechanism for the removal of bioaerosols by biofilters and that this mechanism was affected by the gas velocity, biofilter media particle size and the size of the bioaerosols. They also suggested that these parameters would also affect the emission of microorganisms from the wet bio-layer surrounding the biofilter media particles. Conversely Schlegelmilch *et al*. (2005) reported that air flow rate has a minor effect on the efficiency of removal of bioaerosols in a biofilter and Zilli *et al*. (2005) concluded that velocity has no effect on emissions.

The information presented by Ottengraf & Konings (1991) suggests that in order to optimise the removal of bioaerosols the gas velocity through the biofilter should be increased and the

particle size of the media should be reduced. However, this may lead to problems with clogging of the biofilter bed and together with the higher gas flow rates, would reduce residence times and therefore reduce odour removal. This has serious implications for the design and operation of biofilters for bioaerosol and odour removal since the optimum parameters for bioaerosol and odour removal may not be compatible. Therefore, it may not be possible to achieve optimal odour and bioaerosol removal in a single biofilter. It may be that a two stage biofilter or combined system needs to be considered in order to optimise the removal of bioaerosols and odour.

The data obtained in this study did not show a relationship between the removal of bioaerosols and the inlet air flow rate. For example it has been suggested that the higher the air flow, the greater the impingement of bioaerosols and the greater the removal efficiency. During this study the site with the lowest air flow rates was UOL06 (0.7 m^3/s), yet the bioaerosol removal rate was 47-71% for *Aspergillus fumigatus*, 49-72% for total bacteria and 83-92% for gram negative bacteria. On the other hand, the site with the highest air flow rates was UOL03 (29.1 m^3/s), and although the removal rates for total bacteria and gram negative bacteria were good (90% and 83-85% respectively), the biofilter appeared to emit a significantly higher concentration of *Aspergillus fumigatus* than those measured going in (increases of 128% and 236% were observed). This may support the observation by Ottengraf & Konings (1991) that the higher air flow rates may increase the emission of *Aspergillus fumigates* from the media.

The literature suggests that the mechanisms for the removal of chemical compounds within a biofilter rely on the adsorption of the compound from the gas phase into the biofilm and that this in turn relies on having a sufficiently long gas retention time within the media. Lui et al (2009) found that for total VOCs, the removal efficiency was higher at higher EBRTs. Yang and Allen (1994) found that at residence times of less than 23 seconds the transfer of hydrogen sulphide from the gas phase into the biofilm was reduced.

In comparison the removal mechanism for bioaerosols is primarily impaction onto the media and therefore higher residence times would not be expected to have the same positive impact on removal. The removal of bioaerosols may, in fact, be improved by increasing the air flow within the biofilter media, which in itself will decrease the residence time. Therefore it may be that the bioaerosol removal efficiency increases when the empty bed residence decreases. This further supports the idea that a two stage biofilter system may be a more viable alternative to trying to achieve odour and bioaerosol removal in a single biofilter. It would allow the design and operating parameters in each stage to be optimised to achieve optimum odour and bioaerosol removals.

The data provided by Sanchez-Monedero et al (2003) shows that for the full scale plants they monitored there was no apparent relationship between residence time and removal efficiency for either *Aspergillus fumigatus* or mesophilic bacteria. At residence times ranging from 29 seconds up to 97 seconds, they found removal efficiencies of more than 90% for *Aspergillus fumigatus.* For the mesophilic bacteria the picture was very confusing, with

removals of 90% at a residence time of 236 seconds and a removal of only 39% at a residence time of 37 seconds.

The data obtained during this study (Table 70) shows that the site with the lowest empty bed residence time was UOL04, at 41 seconds. The biofilter at this site routinely achieved good removals for *Aspergillus fumigatus*, total bacteria and gram negative bacteria. The same was true for UOL06 which had an empty bed residence time of 43 seconds, but achieved in excess of 48% removal for all bioaerosols. At the other end of the scale was UOL07, which had an empty bed residence time of 84 seconds and achieved removals of 0.5% for *Aspergillus fumigatus*. For total bacteria at UOL07, removal efficiencies ranged from an increase to a 10% reduction and for gram negative bacteria an increase to a 55% reduction. The worst performance in terms of *Aspergillus fumigatus* removal was seen at UOL02 and UOL03, which had empty bed residence time values of 78 seconds (UOL02), 68 seconds (UOL03 GW) and 65 seconds (UOL03 OGM) and were found to emit significantly higher concentrations of *Aspergillus fumigatus* than those going in (net increases of 316% and 236% respectively). Overall it appears that for bioaerosols there is no relationship between empty bed residence time and removal efficiency for the sites sampled during this study.

6.4 Review of the degree of aerobicity/anaerobicity in existing enclosed biowaste treatment facilities

The literature contains a number of references to the conditions that favour the development of anaerobic conditions during the treatment of biowaste and the impact that this may have on the emission of odorous compounds. However, there is no reference in the literature to the impact that the presence of anaerobic conditions will have on the emission of bioaerosols.

When sampling was undertaken at different biowaste treatment sites during this study, it was hoped that the information obtained would provide an insight into the degree of aerobicity/anaerobicity that exists in enclosed biowaste treatment facilities and the impact that this has on the concentrations and types of bioaerosol and odour emitted. Since it is not possible to determine directly the extent to which anaerobic conditions exist within a mass of material, two different approaches were used.

The first approach involved identifying the presence of anaerobic indicators within the air coming out of the composting vessels. The use of methane as a suitable indicator compound was dismissed because it was felt that it was unlikely to provide a conclusive picture of the presence or absence of anaerobic sites within the composting mass. This is because it will be oxidised to carbon dioxide very quickly and is unlikely to be detected in the air coming from the composting vessels.

A similar conclusion was reached with regard to utilising the majority of the VOCs detected in the process air as marker compounds. Although compounds were detected that indicated that anaerobic conditions are likely to be present across all the sites to some degree (i.e. hydrogen sulphide, dimethyl sulphide, dimethyl disulphide), no direct correlations were identified between these compounds and the odour concentration of the process air, as determined through olfactometry at the study sites.

A correlation was identified between total concentrations of odour relevant compounds in process air against odour concentration for 13 of the 14 sites visits (Figure 20). Visit one to UOL06 was excluded from the analysis as a potential outlier, since the odour concentration of process air measured during this visit was substantially higher than the remainder of the dataset. This appears to support the observation made earlier in this report that process odour from composting operations, is influenced by the interaction of a wide range of odorous compounds that act in combination.

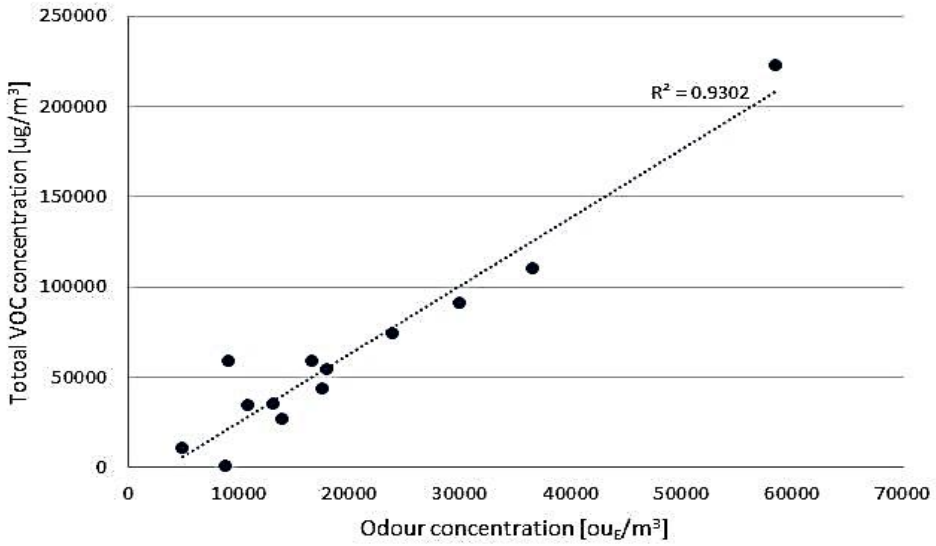

Figure 20 Odour concentration vs. concentration of odour relevant compounds

Further analysis also indicated a correlation between ethanol and odour concentration (Figure 21) in the exhaust air from the enclosed biowaste facilities sampled during this study. This is expected to some extent, since ethanol is a key by-product of biowaste composting process and an increase in ethanol concentration in the air extracted to the biofilter is indicative of the contribution of process related air.

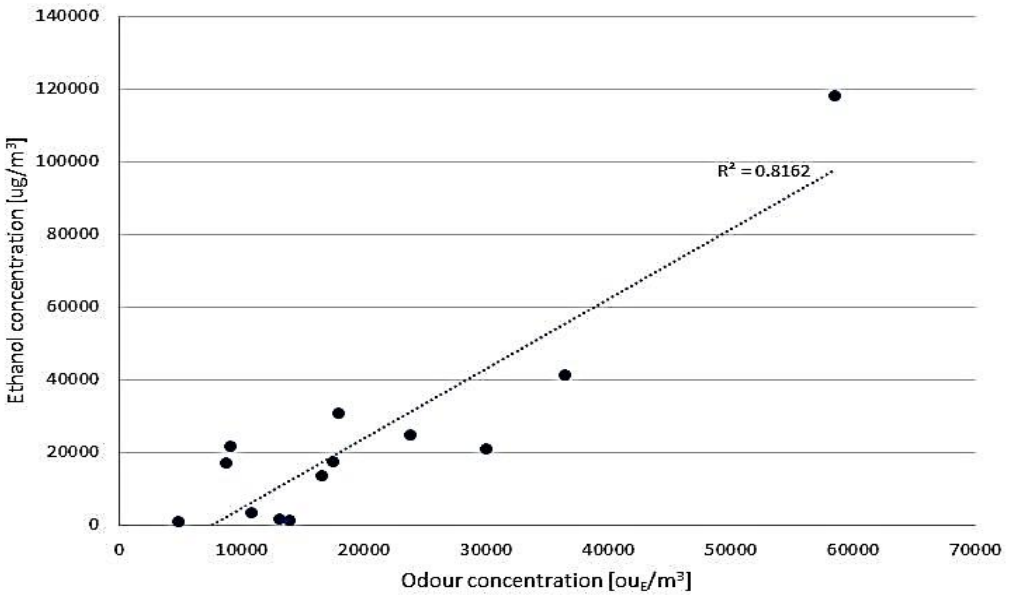

Figure 21 Correlation between odour concentration and ethanol

Notwithstanding these results, the overall conclusion of the research is that it has not been possible to identify a clear indicator for anaerobic/aerobic conditions within the dataset from the perspective of a single or combination of easy to measure VOCs. Further research incorporating a range of sites with suboptimal process conditions may lead to a different conclusion and this is therefore recommended as an area for further study.

The second approach involved the evaluation of some of the indirect indicators that may be used effectively to determine the presence of anaerobic sites within a compost mass of material. The preferred approach was to obtain data regarding the time/temperature profiles of the compost within the vessels, to determine how it deviates from the expected aerobic heating profile. The overall approach was to examine the time temperature profiles to determine the time taken to reach temperatures of 55-60°C. If this is taking place within one or two days, this would indicate that there are no issues with significant anaerobic activity within the composting material. If the time temperature profiles indicate that the time taken to reach 55-60°C is excessive, then more information would be requested on the moisture content and bulk density of the feed material, prior to it being loaded into the vessels.

Data provided by the majority of the sites and further discussions with the plant operators revealed that the moisture content and bulk density of the feed stocks are not routinely measured. Operating experience is used to determine the appropriate mix of material to achieve the correct bulk density and moisture content within the vessels. Most IVC operators reported that in the majority of cases, a failure to reach the ABPR required temperature within a 'reasonable' time period, is indicative of problems with the feedstock mix and will usually result in the material being removed from the vessel, remixed and returned to the vessel. Some operators also report that the air flow rate through the

material is also monitored and a reduction in flow will also indicate a problem with the material and again will prompt its removal, remix and reload.

During this study, none of the sites sampled reported any temperature or air flow issues with the material present at the time of sampling and as far as the authors are aware, none of the material loads had to be removed from the vessels. Examination of the time/temperature profiles indicated that at the majority of the sites, the material self-heated within a reasonable period and quickly achieved its ABPR temperature. The only exception was UOL07, where the time/temperature profile for the batch of waste in tunnel 16, during the second visit, suggested that the waste has failed to reach the ABPR threshold temperature. The air flow data supplied by the operator shows a high pressure on the ventilation system and that very little air was passing through the mass of material. The data showed that the fans were struggling to aerate the material and the fresh air fan was running at maximum. The operator had to override the control on the fresh air fan to avoid damaging the motor. This suggests that the bulk density of the material may have been too high and the operator was intending to remove the material from the tunnel and recombine it with additional coarse green waste. The presence of this overly dense and under-aerated material in the tunnel at the time of sampling on the 12th November indicates that anaerobic zones may have been present in the material. This may affect the emissions in the inlet to the abatement system, particularly with respect to odour compounds. In terms of the odour characteristics of the exhaust air on that day, there was a higher odour concentration of 12,345 OU_E/m^3, compared to 8,685 OU_E/m^3 on the 2nd October 2013. The results also show that there was higher ammonia concentration of 60 mg/m^3, compared to 3 mg/m^3 on the previous visit.

6.5 Review of candidates for Best Available Technologies (BAT) for odour and bioaerosol abatement at enclosed biowaste sites.

The core findings of this study and literature review indicate that biofiltration does represent a viable abatement system for odours and bioaerosols generated from biowaste facilities. The technology is capable of achieving an effective level of odour and bioaerosol removal during biowaste processing and is likely to be applicable to all varieties of biowaste processing operations currently in use in the UK. However, at some sites it appears that significant odour and bioaerosol removals may not be achievable using a single biofilter, due to the apparent mismatch in the 'optimum' design and operating parameters required.

It is evident that due to the large degree of variation in odour emissions that occur at biowaste facilities, specification of BAT for biofiltration, by process type, is not currently possible or relevant. This section of the report therefore focuses on providing an outline recommendation on design criteria for all biofilter installations, as gleaned from the literature, from previous experience, and also from the data generated by this study. It identifies the core issues and candidate technologies that should be considered in

determining the requirement for pre-treatment of odours. Recommendations regarding BAT for monitoring of biofiltration systems to maintain optimal operation, and identify or diagnose problems, are also provided.

6.5.1 Key operational and design considerations for biofiltration

The review of the literature previously presented in this report identifies a range of operating parameters and design considerations that have a critical influence on biofilter performance, which include factors such as, the media moisture content, inlet air temperature, media pH. The parameters of interest and suggested operational ranges drawn from this review, which are considered to represent indicative BAT, are presented in Table 72. These will be discussed in more detail in the following sections.

Table 72 Suggested operational criteria for biofilters treating biowaste emissions

Operating parameter	Typical value
Media type	A wide variety of materials are available which are suitable for construction of biofilters. Media should be selected with reference to the following criteria: • Biologically active, but reasonably stable • Organic matter content >60 % • Porous and friable with 75 – 90 % void volume • Resistant to water logging and compaction • Relatively low fines content to reduce gas head loss • Relatively free of residual odour.
Media height	1 to 1.5 m for peat and compost biofilters. Up to 3m for woodchip. >2m for inorganic and synthetic media
Surface loading	<500 $m^3/m^2/hr$
Volumetric loading	5 – 500 $m^3/m^3/hr$
Mean effective gas residence time	40 - 100 seconds
Inlet odour concentration	500 – 350,000 OU_E/m^3
Inlet ammonia concentration	<5 mg/m^3
Inlet hydrogen sulphide concentration	<10 mg/m^3
Inlet air temperature	15 – 30°C
Outlet air temperature	<50°C
Inlet air relative humidity	> 95% (Devinny et al (1999) >98% (VDI)
Media moisture content	60% - 75%
Media pH	6 to 8.5 Stability of pH is important. Variations should be avoided.
Air distribution	Air should be distributed uniformly through the media using a plenum chamber or distributed pipe work. Up-flow and down-flow systems can be considered.

It is important to note that these parameters have been primarily defined on the basis of studies relating to odour and VOC removal. Since the mechanisms of odour/VOC (adsorption, absorption, oxidation and subsequent biodegradation) and bioaerosol (impaction) removals are completely different, it is likely that some of the biofilter design and operating parameters that are important in odour and VOC removal are not so critical when it comes to bioaerosol removal. There is currently very limited empirical data available from which to define operational ranges for biofilters that are relevant to bioaerosols. Observations that can be drawn from existing literature and this research are noted in the explanatory text below. However, this is clearly an area that requires further investigation through targeted research

It is also important to note that the performance of biofilters is influenced by a complex interaction of these factors, and direct correlations and relationships between specific variables have not been established. The ranges provided, therefore, reflect recommended values based on the current state of knowledge. It should be borne in mind that it is possible that effective control of odours may be achieved outside these ranges and hence it is important to consider these issues in the context of the overall performance of the unit (e.g. determined through direct olfactometry testing). A refined understanding of how the performance of biofilters may vary within the defined ranges would require further research.

6.5.1.1 Media type

The key requirements for an effective media are a large surface area, high water retention capacity, low bulk density, high porosity, structural integrity and resistance to compaction and water logging. A variety of materials (both organic and inorganic/synthetic) can be considered for use as biofilter media, either in isolation, or applied in mixtures to provide a biofilter medium, which achieves the desired biological and physical properties. In general terms, organic materials offer advantages in terms of availability and cost and also their inherent nutrient and microbial content. On the other hand, inorganic or synthetic materials, can offer advantages in terms of low head losses, larger specific surface areas, and solid phase adsorption of contaminants. The inclusion of activated carbon in media mixes can also offer advantages in terms of providing buffer capacity for airborne pollutants, which can be useful for treating variable air flows. Currently, biofilters in the UK are generally constructed of organic materials, such as woodchip, peat and compost. Inorganic media, such as lava-rock is also becoming increasingly applied.

A comparison of the characteristics of common media types is presented in the Table 73. From a nutrient perspective, organic media offer advantages over synthetic media, in terms of nutrient provision (primarily N, P and K) to sustain microbial growth. Operational advantages of using natural organic materials include: the presence of complex microbial communities capable of degrading a wide variety of pollutants, relatively high water

retention capacity and availability of organic matter and nutrients to sustain microbial life. It should however be noted that organic media can also pose operational problems that should be taken into account during media selection, as well as during definition of monitoring and maintenance programs, including the replacement frequency of the media (e.g. degradation of media can lead to odour generation; some media types appear to be net emitters of bioaerosols).

In general terms, the nutrient levels in organic media are likely to be sufficient to maintain a healthy biomass without the need to add specific nutrients. However, depending upon the rate of irrigation and process load, nutrient levels can decrease over time and hence regular monitoring is recommended to identify any deficiencies that may occur and facilitate remedial action.

If inorganic or synthetic media are applied (e.g. lava rock, plastic rings, or ceramic carriers), the media must be seeded with appropriate amounts of nutrients (N, P and K) and micro-organisms. Nutrients can be supplied through the application of commercial fertilizer into the media, the addition of slow release granules, or the introduction of liquid fertilizers through the humidification or irrigation systems, and must be sustained to ensure adequate supply over time.

For conventional organic media, the optimal void volume is approximately 50%. Variations may be justified for other media material types or mixes, for example lava rock void volumes are typically between 35 and 40%. However, significant deviations from the 50% target should be justified at design stage and evaluated if necessary using a pilot plant.

Some materials such as seaweed and seashells have buffering capabilities, which can also be beneficial in terms of maintaining pH of the biofilter bed and countering the effects of particularly acid, or alkali gases.

Table 73 Properties of filter media and bulking agents (VDI, 2004)

Material designation	Properties	Strengths	Weaknesses	Notes
Bark mulch	pH: 6.5 to 7.5 Bulk density: 650 to 750 kg/m^3 Porosity: 0.4 to 0.55 Nutrient content in mg/kg DS: N (soluble) = 300 to 800 P = 300	High efficiency High indigenous microbial density Good water retention capacity Good buffer capacity	High bulk density Poor drainage High pressure drop	Variable particle size according to cut of bowl screen, addition of expanded clay or coniferous wood chips to improve performance, addition of N salts, if required
Fibrous peat	pH: 4.5 to 5.5 Bulk density: 100 kg/m^3 Porosity: 0.85 Nutrient content in mg/kg DS: N (soluble) = 100 P = 50	Low pressure drop Long service life	Low microbial density Poor in nutrient salts and nutrients Tends to agglomerate	Non-uniform moisture distribution, only suitable when combined with bulking agent (e.g. fir brushwood)
Coniferous wood chips	pH: approx. 6 Nutrient content in mg/kg DS: N (soluble) = 200 to 500 P = 50 ρ = 250 to 400 kg/m^3	Good drainage capabilities Long service life	Limited spectrum of microorganisms Reduced specific degradation efficiency Minor buffer effect	Excellently suited as additive and base layer for uniform gas flow distribution; especially suited to aerosol-laden or oversaturated waste gases
Fir bark chips	pH: 6 to 7 Nutrient content in mg/kg DS: N (soluble) = 200 to 500 P = 50 to 100 ρ = 250 to 400 kg/m^3	Structurally stable Good drainage capabilities	Poor degradation efficiency Low microbial density	Used in thick media beds >> 1.5 m; should be combined with an 0.4 m to 0.6 m top layer of wood chips; pine bark is unsuited
Screen overflow of yard waste composting	Nutrient content in mg/kg DS: N (soluble) = 300 to 800 P = 100 to 200 Particle sizes > 40 mm, > 80 mm >120 mm	Good drainage capabilities Reduced service life Structurally stable Low pressure drop	Poor specific degradation efficiency because of small inner surface area; Large void volume	Well suited for use in open surface filters; bed depth 1.0 m to 1.5 m

Material designation	Properties	Strengths	Weaknesses	Notes
Coconut fibre	pH: 4.5 Nutrient content in mg/kg DS: N (soluble) < 100 P < 50 ρ = 100 to 250 kg/m^3	Highly resistant to microbial decomposition No nutrient or nutrient salt source Poor water retention capacity	Low microbial density	Bulking agent only
Expanded clay	bulk density: 400 kg/m^3 porosity: approx. 0.6 to 0.7	Improves structure and water retention capacity Acid-resistant	Limited frost protection	Use as bulking agent in conjunction with bark compost
Biowaste compost	pH: 6.5 to 7.5 nutrient content in mg/kg DS: N (soluble) = 400 to 800 P = 200 to 400	High microbial density Large specific surface area	Sensitive to over-wetting Prone to crack formation	Very fine; only recommended in combination with additives
Heather	pH: 5.5 to 6.5 P = 50 to 100	Low pressure drop	Low specific degradation efficiency Poor water retention capacity l Low microbial density	Bulking agent
Perlites, Styropor compost and additives	pH: 6.5 to 7.5 Bulk density: 280 to 340 kg/m3 Porosity: 0.41	Durably homogeneous Structure Uniform flow distribution and low pressure Drop High microbial density Minor mineralization	Need to separate compost from polystyrene for disposal; if required, special disposal or reuse of the used filter media	Styropor beads to maintain a homogeneous structure of the bed media
Torn root wood	Fibre length: 40 mm to 200 mm	Improved inner surface as a result of the tearing process (fibres are teased apart) Good service life Low pressure drop	Small active surface area Non-uniform moisture distribution	Normally used in conjunction with a top layer to improve the residence time Minimum bed depth: 1.5 m; in addition, a top layer of bark mulch, approx. 0.2 cm thick, for pressure equalization and rain protection

6.5.1.2 Media depth and condition

Recommended depth is 1 to 1.5 m (compost). Up to 3m for wood chip; up to 5m for inorganic media.

A maximum packing height of 1.5m is recommended for organic media, such as peat and compost to prevent compaction. Increased packing heights may be viable for woodchip (through careful selection of fraction size), compost oversize and inorganic/synthetic materials such as lava rock and plastic rings. Media heights greater than 1.5m are also possible using multiple layer (cage) systems, or by providing structural support through incorporation of bulking agents. The height to which media can be place will depend upon the characteristics of the individual media types.

Media should be kept level and significant undulations should be avoided. Growth of mosses and vegetation should also be avoided (particularly vegetation with tap roots) and any weed growth removed by routine maintenance. Pesticides should not be applied to the biofilter to avoid adversely affecting the performance of the microbial biomass.

6.5.1.3 Moisture content

Recommended range: 60 to 75% by weight.

Maintenance of media moisture content can be achieved through a combination of the humidification of the incoming process air and irrigation. Irrigation can be applied to the surface of the biofilter, or through in-situ delivery systems distributed across the media. The use of such systems can be beneficial for up-flow biofilter designs, to ensure moisture is maintained in areas close to the inlet, where bed drying is most likely to be occurring.

In order to maintain optimal moisture content within this range, humidification of the incoming air to >98% moisture by weight, is strongly recommended to minimise the drying effect of air passing through the bed. It is however important to note that the heat generated by biological activity in biofiltration may increase the temperature of the bed medium, above that of the inlet gas. As a result, maintenance of moisture content using humidification of the inlet air is unlikely to be sufficient in isolation.

Over-wetting of the media should be avoided, since too much moisture can lead to leaching of nutrients and microbes from the media and also inhibit the transfer of oxygen into the biofilm, leading to the formation of anaerobic zones within the bed.

The rate of irrigation can be determined on the basis of the water field capacity of the media mix applied, taking into account the effect of any humidification of the inlet airstream and anticipated variations in inlet temperature. Details of this method are provided in Table 75. Regular monitoring of the moisture content of the bed should be conducted to ensure optimal moisture levels are maintained. In the case of open biofilters during wet periods,

modification to humidification and irrigation rates may be necessary to prevent over-wetting.

6.5.1.4 pH

Recommended range: 6-8.5 for organic media.

The optimal pH to maximise the diversity of microbial populations is around pH 7. However, a viable microbial population can be maintained at a lower and higher pH range within the stated range, which enables the use of a wider range of materials for construction of biofilters as illustrated in Table 72. Variations in pH should however be avoided, since rapid changes in pH have an adverse influence on the population diversity. Regular monitoring of pH should therefore be conducted and corrective actions taken where significant variations (e.g. greater than 10% of the typical value) are noted.

6.6.1.5 Temperature

Recommended range for inlet air temperature: 15 to 30 °C.

The temperature of biofiltration is mainly influenced by the temperature of the inlet air stream, although exothermic biological reactions in the bed will also have an influence to some degree. The optimal temperature for various species range widely, but most biofiltration applications operate at temperatures in the mesophilic range (20 to 45°C).

The potential for deviations in temperature (e.g. due to changing processing conditions, climatic effects and process downtime) should be assessed during the design stage. Provision should then be put in place to prevent significant variations over time. For hot airstreams, this may involve mixing with cooling air (e.g. from the waste processing buildings), or cooling of the air through the use of a scrubber or humidification system. Conversely, where low temperatures are expected (e.g. during winter periods), consideration should be given to the requirement for duct insulation / trace heating.

It is important to ensure the temperature of the air entering biofilters is maintained during plant shutdown periods and outside operational hours.

6.5.1.6 Residence time

Recommended range: 40 to 100s (indicative).

A sufficient residence time is necessary to allow the transfer and degradation of pollutants to occur, which makes it a critical design and operating parameter. Review of the literature indicates that the recommended range for residence time based on ERBT values is between 15 and 60 seconds, which compares to the range identified at the study sites of between 41 and 84 seconds.

Bearing in mind that the lower values are based on pilot scale filters, the minimum residence time recommended for a full scale biofilter for odour control purposes is 40 seconds, with higher values preferred for odour treatment purposes. Lower residence times should be justified through direct and sustained testing.

The literature suggests that bioaerosol removal does not appear to be related to the residence time and that within the range 30 to 100 seconds the removal remains in excess of 90%. However, the data from this study showed that over an EBRT range of 41-84 seconds, the removal of bioaerosols was extremely variable with examples of net increases of up to 315% and removals of close to 100%. Overall the data from this study strongly suggests that there is no relationship between the EBRT and the removal efficiencies achieved. This is clearly an area that requires further research.

6.5.1.7 Surface loading

Recommended range is 50 to 500 $m^3/m^2/hr$.

Achieving a suitable surface loading rate for good odour and bioaerosol removal in biofilters appears to be a balancing act on the basis of this research, since the mechanisms for the removal of odour and bioaerosols differ significantly. Effective odour removal clearly relies upon achieving a sufficiently long residence time, which implies a lower surface loading is required. Conversely, the literature indicates that minimisation of bioaerosol emissions from the media appears to be linked to the application of higher surface loading rates.

The data obtained in this study did not however, show a clear relationship between the removal of bioaerosols and the inlet air flow rate or the surface loading rate, as suggested in the literature. The biofilter with the lowest air flow rates achieved consistently good bioaerosol removal and the performance of the biofilter with the highest air flow rates was variable. In fact evidence was found that indicated higher air flow rates produce a net increase in *Aspergillus fumigatus.*

It is not therefore possible to offer firm recommendations on the surface loading rate that reflects the best solution for both parameters at this time. The range identified above is considered reasonable for odour. However, further research is required to clarify to what extent it promotes effective bioaerosol control.

It is possible that biofilters may need to be designed using different operational flow parameters for odour and bioaerosols, which would imply that two stage systems may reflect the best approach. However, this also requires further investigation.

6.5.2 Enclosed or open biofilters

There is no evidence to suggest enclosed biofilters offer any clear advantages over open biofilters from an odour removal performance perspective. The evidence collected during

this study indicates that both types of system are capable of achieving comparable abatement levels and residual odours concentrations, providing adequate control of the key operating parameters outlined in Table 72 can be demonstrated and achieved.

For bioaerosols, it appears that open biofilters performed significantly better than enclosed biofilters, with respect to their removal efficiency for *Aspergillus fumigates,* whilst enclosed biofilters produced the highest removals for total bacteria. This observation does however require further investigation, before firm conclusions can be drawn.

It is important to note that open/enclosed biofilters can pose different challenges in terms of maintenance and monitoring of key operational parameters. For example:

- Open biofilters are subject to potential adverse effects from heavy rainfall, surface drying, or ambient temperature variations.
- Enclosed biofilters are more difficult to maintain within an effective temperature range during summer conditions.
- Enclosed biofilters pose challenges in terms of monitoring media conditions, moisture content and flow distribution. Monitoring can also be inhibited because of the health and safety implications of working within a confined space.
- Open biofilters are less easy to monitor from a performance perspective.

These factors should therefore be considered carefully and adequate provision made during design.

The main advantage of enclosure is that it offers the option to enhance atmospheric dispersion and dilution of residual odours released from the biofilter, to minimise offsite odour exposure levels. Enclosed biofilters should therefore be considered in circumstances where there is a risk that biofilter emissions may adversely impact on sensitive receptors close to the site, such as residential properties, or as part of a broader odour or bioaerosol mitigation strategy to reduce the offsite exposure levels, in keeping with planning or licencing requirements.

Stack height requirements for closed biofilters should be assessed on a case by case basis. For odour, heights are generally determined using dispersion modelling to reduce offsite odour exposure concentrations to below the indicative impact criteria published in Environment Agency Odour Guidance [EA, 2011]. The indicative criteria are presented in the form of indicative maximum offsite odour exposure concentration expressed as a 98th percentile of hourly average concentrations over a typical meteorological year (e.g. the indicative odour impact criterion for waste sites is typically 1.5 OU_E/m^3). A similar approach could also be applied for bioaerosols to overcome the current reliance upon ambient sampling, which is unlikely to adequately assess the influence of changing meteorological conditions on bioaerosol dispersal.

6.5.3 Pre-treatment

There is little evidence from the data collected during this study to indicate that the application of pre-scrubbers to biofilters serving biowaste odours has any significant effect on filter performance in terms of overall odour removal, or the odour emission concentrations that are achieved at the end of the process.

In terms of bioaerosols, the literature suggests that the addition of a scrubber (water or acid) can improve the removal of bioaerosols (Aarnink et al., 2005; Zhao et al., 2011). Seedorf and Hartung (2002) found that for bacteria and fungi the inclusion of a scrubber improved the removal efficiencies obtained from 74% up to 96% for bacteria and from 41% up to 85% for fungi. The data from this study shows that the performance of scrubbers is extremely variable and there is little evidence to suggest that the addition of a scrubber to either an open or enclosed biofilter system improves the overall performance.

The primary purpose of applying scrubbers in the composting sector is currently to enable control of substances that are potentially toxic or result in changes to the pH of the media over time. Scrubbers can also be used to reduce dust levels, to prevent particulate attrition of the media, as a means to humidify incoming air; and to assist in controlling the temperature of incoming process air.

The main chemical component that poses a risk to biofilters at biowaste sites is ammonia, due to the potential for development of unfavourable pH conditions that reduce microbial diversity. VDI3177 (2004) recommends that the concentration of such compounds should be maintained below 5 mg/m^3, unless buffer capacity is available within the selected biofilter media. Hydrogen sulphide can also pose operational challenges for biofilters due to potential for acidification of the bed. Operational limits for composting processes for this gas generally range between 5 and 10 mg/m^3.

However, given the wide variety of process types and configurations that are applied in the UK for biowaste treatment, and the increasing trend of using biofiltration to treat both process air from ancillary waste treatment activities such as effluent treatment and drying, it is recommended that the requirement for scrubbing and their subsequent design is determined on a site-by-site basis at design stage. This should consider factors such as the process gas temperature, anticipated particulate load, the chemical composition of the airstream (which should include but not be limited to ammonia and hydrogen sulphide) and requirements for moisture control.

Key operational characteristics of for scrubber operation are outlined in Table 74 and a benchmarking of process emissions to inform design is strongly recommended.

Table 74: Performance and operational criteria for scrubbers for ammonia removal

Application	Candidate technique	Key operational parameters	Monitoring requirements
Ammonia removal	Acid scrubbing	pH 3 to 6 airflow 50 – 500,00 m^3/hr Removal effectiveness: 90 to 99% >10 mg/m^3 of particulates	Continuous pH monitoring of liquors. Flow monitoring of scrubbing liquors linked to pH control Regular assessment of solids build up

6.5.4 Monitoring and maintenance of biofilter operation

There are a number of parameters which can be used to monitor the ongoing performance and operation of biofilters following their installation. These can be split into three main areas:

- Performance/environmental parameters, which are used to assess whether the biofilter is achieving effective removal of airstream contaminants (i.e. odour) and establishing compliance to environmental protection objectives.
- Diagnostic monitoring, that can be used to assist in identify underlying reasons for poor performance and facilitate remediation.
- Operational parameters, which can be used to identify whether the biofilter is operating as designed and to ascertain the reason for any performance issues. These parameters will assist in identifying areas in which maintenance may be required.

In terms of the operational and maintenance parameters, the properties and characteristics of the biofilter media, such as the degree of compaction, water retention capabilities, ability to host microbial population and porosity are the main factors which influence the effective performance of a biofilter (Devinny, 1999). As such, parameters which will enable these characteristics to be assessed and controlled (e.g. airflow, media moisture content), should be monitored on a frequent basis.

Table 75 outlines some of the key parameters which could be used for routine monitoring and control of biofilters at composting facilities. A number of these parameters can be directly measured by site operators, although it is anticipated that external testing will also be required periodically to undertake more technical complex testing (e.g. bioaerosols and odour) using accredited methodology. In all cases trending of results is important to allow observation of changes over time, which could indicate that maintenance is required.

Where general limit/ranges values are provided or defined in a permit, the results of tests should be compared to these values. Where values are not specified (e.g. airflow, moisture content and pH of media), it is recommended that the operator should define suitable measurement limits/ranges that they can audit against. Where possible, these should be defined in consultation with the installer of the biofilter and should be fit for purpose.

Where a reduction in biofilter performance is identified, or when measurement results fall outside these limits, further investigation should be conducted to identify any issues and return the biofilter to its normal operating condition. Operators should also ensure the accurate operation of any continuous monitors, for example by checking that pressure lines are clear of dirt or water.

Facilities which operate a pre-scrubber, in addition to a biofilter, should utilise the same routine monitoring to assess the performance of both the scrubber and biofilter, to ensure that the combined system operates effectively.

Table 75 Biofilter monitoring

Monitoring type	Parameter	Suggested frequency	Purpose, approach and assessment criteria
Performance/environmental	Odour (Outlet or inlet)	Periodic	Samples of the biofilter off-gas are collected and analysed in accordance with the requirements of the British Standard for olfactometry (BSEN13725) to provide an assessment of the overall performance of the system in terms relevant to human perception. For regulatory purposes, sampling and analysis should be conducted by a suitable UKAS / MCERTS accredited test house. The odour concentration should be measured at the outlet of the biofilter to assess compliance to relevant licence standards. Triplicate samples are recommended. Simultaneous measurement of the inlet air stream is beneficial to provide an understanding of load and evaluate removal effectiveness where relevant. *Assessment criteria:* Design/BAT standards and/or Licence conditions.
Environmental	Odour quality / Hedonic tone (relative unpleasantness / pleasantness)	Periodic	Odour quality analysis can be conducted by the operator or using trained laboratory panels The technique provides information to assess whether odours released from the biofilters falls within the expected range (musty, media related smell) and to identify potential breakthrough of process on a subjective level. Analysis should be conducted where possible using a standardised set of odour descriptors. Hedonic Tone Analysis is a sensory odour analysis technique that enables the relative unpleasantness or pleasantness of odours to be determined. This technique provides more objective data that can assist in assessing the performance of the biofilter and identifying an appropriate odour exposure standard for the purposes of assessing odour impact as defined in the Environment Agency Guidance Note H4. Analysis is conducted in a specialist laboratory in accordance with VDI 3882:1997, Part 2 Determination of Hedonic Tone, typically at the same time as olfactometry analysis. Assessment criteria: Industrial/site specific benchmarks and benchmarks defined in guidance.
Environmental	Bioaerosol (Outlet only)	Periodic (defined in licence)	The concentration of bioaerosols emitted from the biofilter can be measured at source using the methods outlined within the Environment Agency document TGN M2 (enclosed biofilters) or in the future release of the Environment Agency document TGN M9 (open biofilters). For regulatory purposes, sampling should be conducted by a suitable UKAS/MCERTS accredited test house. The bioaerosol concentration should be measured at the outlet of the biofilter to assess

Monitoring type	Parameter	Suggested frequency	Purpose, approach and assessment criteria
			compliance to the relevant licence standards. Where the licence conditions specify limit concentrations at local receptors, atmospheric dispersion modelling can be used to assess the likely bioaerosol exposure levels in the area surrounding the site. Assessment criteria: Design/BAT standards and/or Licence conditions.
Performance/Environmental	Ammonia / hydrogen sulphide or other pertinent VOCs (e.g. DMS/DMDS) (Inlet & Outlet)	Weekly	Routine testing can be conducted using indicative colorimetric tubes. Regulatory testing should be conducted using the relevant method drawn from M2 using a UKAS/MCERTS accredited test house. Measurements should be conducted at the inlet and outlet of the biofilter to determine whether the biofilter is effectively removing these components from the process airstream. *Assessment criteria:* Design/BAT standards and/or Licence conditions.
Diagnostic	Molecular analysis	As required.	Testing is conducted by drawing a sample of the odour into a bag or onto a suitable sorbent material, which is then analysed using gas chromatography/mass spectroscopy. The results can be used as a useful diagnostic tool to investigate the cause of elevated odour emissions levels determined by olfactometry and develop suitable remediation strategies. *Assessment criteria:*
Diagnostic	Media health	As required.	Testing should be undertaken on subsamples of media from across the bed with subsequent analysis for one or more of the following: - Moisture content. - Electrical conductivity. - N, P and K levels. - Nitrate content - Sulphate content. *Assessment criteria:* Comparison to typical levels by media type and gained through experience. Results should be trended over time.
Diagnostic	Particle size distribution	As required	Testing is conducted on subsamples of media extracted from across the bed. The results are used to assess media condition. As biofilter media ages, degradation occurs and media particle size becomes smaller which leads to compaction of the biofilter bed. This can reduce the airflow through the bed. Periodic monitoring of the particle size distribution of the biofilter media can provide an early indicator that the media needs to be replaced. *Assessment criteria:* Dependent upon choice of media.

Monitoring type	Parameter	Suggested frequency	Purpose, approach and assessment criteria
Operational	Biofilter condition	Visual inspection Weekly	Testing is conducted by visual inspection to assess: • Absence of vegetation, moss and fungus: The media should be in good condition and clear of vegetation (tap roots) which could allow channelling of contaminated air or lead to increased resistance to airflow in areas of the biofilter. A photographic record of the biofilter bed can be used to determine how the bed changes over time. • Media depth: The media depth should be checked regularly to identify whether compaction and decomposition of the media is occurring. The media depth can be assessed using vertical rulers located in the biofilter bed. • Surface condition: Identification of any channelling, gaps or shrinkage of the biofilter bed. • Irrigation: Inspection of the uniformity of irrigation if a sprinkler system is used. If there are areas which are too dry or excessively wet, the homogeneity of airflow and treatment effectiveness of the biofilter can be impaired.
Operational	Static pressure	Continuous (using inline monitor) or weekly (manual test)	Inline monitors (e.g. manometer) in the inlet ducts (or inlet and outlet ducts for enclosed systems) or periodic manual testing to provide an assessment of system pressure drop over time. This information can be used to identify issues such as media compaction, excessive biofilm clogging the media, excessive moisture restricting airflow, and air flow short circuiting. *Assessment criteria:* System design standards.
Operational	Volumetric airflow	At commissioning and annual thereafter (unless significant variation is expected)	Measurement of the volumetric airflow data can provide an indication of whether there is any flow loss across the biofilter (e.g. leakage) or whether the biofilter bed may be blocked (i.e. a reduction in airflow). Trends in the data should be monitored as these can provide an early warning of these issues. The data can also be compared to design data to assess whether the biofilter is overloaded. Biofilters can cope with familiar fluctuations in airflow which have been accounted for at the design stage and are related to the process (e.g. differing numbers of composting tunnels in use). Operators should ensure that they have an understanding of these fluctuations and their effects on the biofilter as the operational characteristics of the bed can be altered and in turn can reduce treatment capacity. For example, water evaporation rates can be changed by an increase or decrease in airflow and the biofilter may require an adjustment in irrigation. Adequate airflow should be maintained at all times to prevent the potential development of

Monitoring type	Parameter	Suggested frequency	Purpose, approach and assessment criteria
			anaerobic conditions within the biofilter bed and to ensure that the microbial population is sustained. *Assessment criteria:* Design / indicative BAT standards
Operational	Process air temperature	Daily (or continuous where variations are expected).	Airstream temperature is monitored upstream of the biofilter by periodic manual measurement or where variations are expected, using a continuous inline monitor. Results should be trended to identify temporal variations and seasonal effects. *Assessment criteria:* Design / indicative BAT standards.
Operational	Media temperature	Daily	Media temperature is monitored by insertion of a thermocouple into the media (open systems) or monitoring in the outlet stack of enclosed systems. Results should be trended to identify temporal variations and seasonal effects. *Assessment criteria:* Design / indicative BAT standards.
Operational	Surface airflow distribution (open biofilter only)	Annual or after media replacement / regrading	Homogeneity of airflow distribution can be assessed by using a flow hood to measure the efflux velocity at a pre-determined number of points across the bed based on the method outlined in VDI 4257 Part 1. The results of the velocity profile are used to evaluate airflow homogeneity. Where variations are noted, investigation should be undertaken to identify and resolve the underlying cause. A smoke test provides a simple visual assessment of the airflow across the entire biofilter bed and should indicate homogenous airflow distribution across the biofilter.
Operational	Media and leachate pH	Weekly (site operator)	The pH of the media has a key role in microbial activity and hence the effectiveness of the biofilter at removing contaminants from the process airstream. The pH of the media should be monitored at different depths and locations across the biofilter bed. Trends in the data should be monitored to provide early indication of any potential issues. Investigation should be undertaken if significant variation from the normal pH of the bed is observed. Assessment of the leachate pH provides information on the condition of the media near the bottom of the biofilter bed and should be assessed in combination with the media pH.

Monitoring type	Parameter	Suggested frequency	Purpose, approach and assessment criteria
Operational	Media moisture content	Weekly	The moisture content of the media should be measured at different depths and locations across the biofilter. This is particularly important for up-flow biofilters where drying may occur at the bottom of the bed where irrigation is difficult. The range of acceptable moisture content for an individual biofilter can be determined via laboratory experiment to determine the field capacity of the media material at design stage. The field capacity can be determined by saturating a sample of media, allowing it to drain and then determining the weight loss on drying at 100^{o}C. Regular monitoring of the media moisture content can then be conducted by conducting simple laboratory dry solids analysis on sub samples of the media. Trends in moisture content should be monitored alongside other operational factors to enable the operator to understand when additional/less irrigation may be required. Where viable, moisture content sensors should be linked to irrigation systems so that the biofilter bed can be automatically maintained at the correct moisture content.

6.6. Review of achievable odour and bioaerosol concentrations for biofilter technology

The information presented in this section includes an evaluation of the potential emission concentrations for odour and bioaerosols for the BAT candidate technologies outlined in the previous section. It should be stated that these emission concentrations represent the performance that could be anticipated as a result of the application of these techniques with the broad design and operational ranges outlined previously. They should not be interpreted as limit values, but rather the level that may be expected to be achieved over an extended period of time, in a well maintained and operated installation or process, using those techniques.

6.6.1 Odour

Review of the data obtained during this project from biofilters that were operating in broad compliance with the principals of indicative BAT outlined in Section 6.6, indicates that odour emission concentrations in the range 200 to 5,500 OU_E/m^3, with a mean of 2,209 OU_E/m^3 (table 76). These results are also consistent with data obtained from privately funded studies and research and can, in the authors' view, be considered to represent a reasonable indication of the achievable performance of biofilters serving biowaste processes.

Table 76: Indicative performance and emission characteristics of biofilters treating biowaste odour (based on consolidated study data)

Target parameter	Inlet concentration [ou_E/m^3] Min – max (mean)	Outlet Concentration [ou_E/m^3] Min – max (mean)	Removal (%) Min – max (mean)
Odour	4856 -145311 (28543)	212 – 5516 (2209)	64-98 (88)

The relatively large range of emission concentrations illustrates the complexity of factors that can influence odour generation from biofilters, which include: variations in treatment capacity of specific odorous volatile organics in the process air, in the rate of in-situ biogenic generation of odorous volatiles, and the contribution of odorous volatiles indigenous to the biofilter media.

For the purposes of assessing what is achievable from biofilters, an upper limit in the order of 5,000 OU_E/m^3 is therefore suggested. This value can be used for design and regulatory purposes to enable selection of abatement systems that respond to existing odour related exposure standards, through the application of dispersion modelling. In assessing compliance to this limit, it is important to recognise the uncertainties of the BSEN13725 in terms of analytical uncertainty.

It is important to note that the percentage removal of odour for a given system is limited by the concentration of air entering the system and the concentration of odour generated

within the bed, due to these processes. As a result, percentage removal of odour exhibits substantial variation from site to site, as a result of varying inlet load, and caution should therefore be applied in using this parameter as a benchmark for biofilter performance.

In terms of specific volatile compounds, the removal effectiveness and emission concentration also appears to vary as a result of these factors. This results in a relatively large range of performance across the biofilter studies from the perspective of removal and emission of compound groups, and individual odorous components, detected above their odour threshold. An illustration of the performance of biofilters from this regard is provided in Table 77, which is drawn directly from the data obtained in this study.

Table 77: Indicative performance of biofilters by compound group (based on consolidated study dataset)

Target parameter	Inlet concentration [ug/m^3] Min – max (mean)	Outlet Concentration [ug/m^3] Min – max (mean)	Removal (%) Min – max (mean)
Aromatic hydrocarbons	91-10275 (3433)	57 – 5066 (1776)	34-96 (57)
Cyclic Hydrocarbons	74-7415 (2306)	0 – 4292 (1395)	14-100 (53)
Aliphatic Hydrocarbons	28-24776 (6754)	19 – 9587 (3011)	-136 – 97 (48)
Alcohols	141-164242 (30565)	0 – 13957 (2130)	62-100 (95)
Esters	0-10063 (2983)	0 – 2235 (233)	61-100 (96)
Ketones	412-34473 (13853)	0 – 11387 (1514)	39-100 (90)
Aldehydes	129-3672 (1476)	0 – 647 (186)	-6 – 100 (74)
Chlorinated compounds	23-3284 (910)	0 – 2988 (565)	-1481 – 100 (-93)
Organic S-compounds	220-2986 (1591)	0 – 2721 (800)	8 – 85 (50)
Furans	40-2104 (809)	0 – 1471 (337)	13-100 (70)
Ethers	0-356 (138)	0 – 494 (77)	-859-100 (-23)
Terpenes	524-50178 (12852)	79 – 8960 (3174)	25-99 (70)
Organic N compounds	72-921 (291)	0 – 56 (9)	-100 – 100 (29)
Organic acids	26-16882 (2164)	0 – 700 (71)	-100 – 100 (77)

In terms of odorous compounds above odour threshold, the data indicates that emissions from biofilters can be expected to contain a variety of chemical components which include aldehydes, ketones, reduced sulphur compounds, terpenes and organic acids (Table 78). The emission concentrations of these odour relevant compounds typically range from micro grams to milligram levels. It is important to note that other odorous components are also likely to be present in the airstream at levels below odour threshold that may contribute to the odour released.

Table 78: Odorous compounds identified in biofilter outlet air

Compound group	Compound	Outlet concentration [ug/m^3]	Removal [%] Min – max (mean)

		Min – max (mean)	
Inorganic	Ammonia	<LLOD – 1.5 (<LLOD)	24-100 (74)
	Hydrogen sulphide	<LLOD – 7.5 (<0.5)	23-100 (87)
Aromatic hydrocarbons	Styrene	94-212 (149)	50-100 (69)
	Toluene	3692-3692 (3692)	25-25(25)
	Decahydronaphtalene	9-341 (159)	-100 – -100 (-100)
	Propylbenzene	33-149 (60)	-100 – 100 (27)
	1-methylethylbenzene	49-50 (50	-3 – 100 (56)
	1-ethyl-3-methylbenzene	183 – 317 (268)	-100 – 100 (25)
	1-ethyl-4-methylbenzene	62 – 105 (89)	45 – 100 (68)
Alcohols	Ethanol	44-8148 (2766)	73-100 (97)
	1-propanol	1945-1945 (1945)	94-100 (100)
	2-methyl-1-propanol	65-204(116)	-100 – 100 (73)
	3-methyl-1-butanol	113 – 113 (113)	91 – 100 (99)
	Phenol	24 – 97 (57)	-20 – 100 (40)
Ketones	2,3-butanedione	69 – 69 (69)	95 – 100 (99)
	2-butanone	722-4306 (1957)	72 – 100 (95)
	2-pentanone	322-322 (322)	77 – 100 (97)
	2-heptanone	306 – 306 (306)	66 – 100 (97)
Aldehydes	Acetaldehyde	9 -288 (99)	-100 – 100 (81)
	Heptanal	7 – 49 (28)	22 – 100 (81)
	Nonanal	9 – 191 (85)	-100 – 100 (53)
	Decanal	16 – 98 (52)	-100 – 100 (47)
Sulphur	Dimethylsulfide	157 – 1245 (571)	-100 – 100 (70)
	Dimethyldisulfide	24 – 1235 (395)	-50 – 100 (48)
Terpenes	Alpha-pinene	192 – 1758 (637)	26 – 100 (72)
	Beta-pinene	57 – 453 (236)	-100 – 100 (83)
	Limonene	169 – 5105 (2065)	37 – 100 (79)
Organic acid	Acetic acid	18 – 321 (140)	-100 – 100 (56)

There is some evidence to suggest from literature and the results of this study that dimethyl sulphide and dimethyl disulphide may contribute significantly to the odours generated from biofilters treating biowaste process air. This is likely to be due to the insoluble nature of these gases, which means that they are more difficult to treat. No direct correlation between the concentration of these substances and odour unit values has however been identified. This is likely to be due to complex interactions between individual odorous components from a sensory perspective, which may be additive, reductive and synergistic, and which cannot be defined using molecular analysis techniques.

On the basis of the data obtained during this study, it is apparent that ammonia is not a particularly relevant component of biofilter emissions from an odour perspective for effectively operating biofilters, due to its relatively high odour threshold. Hydrogen sulphide is also not identified as a key contributor, although this substance is likely to represent a useful indicator parameter for sub-standard biofilter performance.

6.6.2 Bioaerosols

Review of the data obtained during this project from biofilters that were operating in broad compliance with the principals of indicative BAT outlined in Section 6.6 indicates that the emission concentrations and the removal efficiencies for bioaerosols are extremely variable (Table 79). The maximum emission concentrations observed during this study were 10^4 cfu/m^3 for *Aspergillus fumigatus*, 10^5 cfu/m^3 for total bacteria and 10^4 cfu/m^3 for gram negative bacteria.

Kummer and Theil (2008) found *Aspergillus fumigatus* emission concentrations from biofilters to be between 10^2 cfu/m^3 and 10^3 cfu/m^3. Frederickson et al (2013) found that the concentrations in the exhaust air from the biofilters they sampled were 10^4 cfu/m^3 for bacteria, 10^2 cfu/m^3 for gram negative bacteria and 10^3 cfu/m^3 for fungi. The data obtained by Sanchez-Monedero et al (2004), during their full scale monitoring of biofilters at composting facilities, showed that for *Aspergillus fumigates,* the emission concentrations ranged from 10^2 up to 10^3 cfu/m^3 and for mesophilic bacteria, it was generally an order of magnitude higher at 10^3 to 10^4 cfu/m^4.

Table 79 Bioaerosol performance and emission characteristics of biofilters treating biowaste exhaust air

Bioaerosol	Inlet concentration [cfu/m^3] Min – max (mean)	Outlet Concentration [cfu/m^3] Min – max (mean)	Removal (%) Min – max (mean)
Aspergillus fumigates	9 – 25,780 (3290)	0 – 1337 (650)	-57 – 100 (41)
Total bacteria	7101 – 111,644 (25,095)	515 – 61,541 (11,103)	-37 – 95 (58)
Gram negative bacteria	746 – 33685 (8509)	144 – 35,911 (4762)	-66 – 93 (49)

Overall the data presented in the literature for the emission concentrations for bioaerosols are generally lower than those found during this study. The data from Sanchez-Monedero (2013) should be treated with some caution due to the sampling method used, since it is likely that the concentrations quoted are low due to the potential 'dilution' of the sample with ambient air during sampling. Kummer and Theil (2008) provide no information regarding their sampling methodology, which just leaves Frederickson et al (2013). The method used during their study of full scale biofilters was similar to that used during this study and therefore the data is comparable to that obtained in this study.

Therefore using the data obtained from this study, together with the data from Frederickson et al (2013), it is anticipated that for biofilters operating in broad compliance with the principals of indicative BAT (as outlined in Section 6.6), the upper limit of bioaerosol

emission concentrations that can be expected would be up to 10^4 cfu/m^3 for *Aspergillus fumigatus*, 10^5 cfu/m^3 for total bacteria and 10^4 cfu/m^3 for gram negative bacteria.

The concentrations suggested are much higher than the current Environment Agency guidance for bioaerosols at open windrow compost sites, which recommend maximum concentrations at the nearest sensitive receptor. It is not clear how the concentrations measured at the biofilter outlet will impact on sensitive receptors, as this will be very site specific. However, the data measured at the biofilter outlet could be used as a source term in dispersion modelling.

7.0 Summary and conclusions

This research was undertaken in order to address a number of key knowledge gaps and to answer some key questions presented in Section 1 of this report. In order to do this and to attempt to recommend a Best Available Techniques (BAT) for bioaerosol and odour abatement, it was necessary to carry out an evaluation of the emission of odour and bioaerosols at a range of biowaste sites.

The abatement systems at a total of eight sites were sampled over a period of approximately 1 year. Analysis was undertaken for odour, hydrogen sulphide, ammonia, VOCs and the bioaerosols, *Aspergillus fumigatus*, total bacteria and gram negative bacteria. The sites were chosen to ensure that as large a range of different abatement system arrangements and process parameters as possible were captured. The key variables that were considered were whether the biofilter was open or enclosed, whether the abatement system includes a scrubber or not, the type of biofilter media being used, the biowaste type, and the treatment process being used.

It is important to note that all of the biofilters sampled as part of this study were observed to be in good condition. The media condition and particle size were good and there was no visual evidence of drying, or significant weed growth. More detailed analysis of the biofilter media in the open biofilters showed that the pH, moisture content and electrical conductivity were within the intermediate to optimal range to support a healthy microbial population. The nutrient analysis of the biofilter media showed slight deficiencies at two sites, which may suggest some potential for inhibition in growth of microbes at these sites.

Therefore the conclusions that are presented in the following sections are drawn from sampling carried out on abatement systems and biofilters in particular that can be considered to be well designed, operated and maintained. The results of this study do not allow conclusions to be drawn regarding the performance of abatement systems that are badly designed and operated and poorly maintained. Further sampling would need to be undertaken to determine the impact on the emission of odour and bioaerosols and removals that can be achieved by such systems.

From the site design and operating information obtained and the results of the sampling and analysis that was undertaken, a number of general conclusions have been drawn and are presented below. There were also a large number of more specific observations that arose during this project and these are presented within the report. During the project a number of remaining knowledge gaps were identified. These are presented in the final section of the report.

Emission of odour and bioaerosols from enclosed biowaste treatment facilities:

- The concentration of bioaerosols and odour in the process air varied from site to site and sometimes between visits to the same site. The data shows that there was no relationship between the type of waste being treated, or the treatment system being used and the concentration of bioaerosols or odour emitted. It would appear that it is a function of a complex interaction between specific process operating conditions and waste characteristics at the time of sampling.
- Overall the concentration of bacteria (total and gram negative) in the process air was significantly higher than the concentration of *Aspergillus fumigatus* regardless of the treatment system being used and the type of waste being treated. There was no relationship, either positive or negative, between the concentrations of *Aspergillus fumigatus*, total bacteria or gram negative bacteria.
- The concentration of hydrogen sulphide and ammonia in the process air was generally low, but this study group may not be representative.
- A more in depth analysis showed that process air comprised a complex mixture of odorous components with the dominant compound groups being aliphatic hydrocarbons, alcohols, ketones and terpenes. No correlations were identified between waste type, process type and the dominant chemical compound groups.
- The compounds detected in the process air above their odour threshold value varied from site to site. The compounds detected with the highest concentration/odour threshold value ratios included selected sulphur compounds, aldehydes, ketones, esters and amines.
- From the data obtained during this study, it was not possible to identify a clear indicator for anaerobic/aerobic conditions from the perspective of a single, or combination of, easy to measure VOCs. Further research incorporating a range of sites with suboptimal process conditions may lead to a different conclusion and this is therefore recommended as an area for further study.

Emission of odour and bioaerosols from the abatement systems

- The concentration of bioaerosols emitted from the abatement systems varied from site to site and also between visits to the same site. The data showed that the impact of the type of abatement system on the concentration of bioaerosols emitted was inconclusive. More bioaerosol data will be required to be able to determine whether open or enclosed biofilters achieve lower bioaerosol concentrations and whether the inclusion of an upstream scrubber leads to a lower bioaerosol emission concentration.
- For all three bioaerosol types, no relationship was found between the inlet and outlet concentrations. It would appear that for the sites sampled, the concentration of

bioaerosols being emitted from the abatement system, regardless of what system is employed, is independent of the concentration entering.

- The biofilters sampled were capable of maintaining a relatively stable odour emission concentration and this was independent of the variation in the process load, as indicated by the inlet measurement.
- The data showed that odour emission concentrations from open and enclosed biofilter systems were comparable; indicating that enclosure of the biofilter had little impact on the concentration of odour emitted. The same is true for scrubbers as the data indicated that the presence of an upstream scrubber had little influence on the emission concentration of odour.
- There were no apparent correlations between biofilter empty bed residence time or media type, and outlet odour concentration.
- More detailed analysis showed that the odour from biofilters comprised a mixture of odorous components, which include aromatic hydrocarbons, alcohols, ketones, aldehydes, reduced sulphur compounds, terpenes and organic acids. Dimethyl sulphide and dimethyl disulphide were found to yield the highest concentration/odour threshold value ratios for five of the eight sites sampled.
- Hydrogen sulphide concentration does not appear to be a significant component of biofilter off-gas.
- The emission concentration of ammonia showed variation between sampling visits and sample sites. Overall there did not appear to be any correlation between biofilter media type, the abatement system design and the ammonia emission concentration. From this data, ammonia is unlikely to contribute significantly to the odours released from the biofilters from a sensory perspective, due to its relatively high odour threshold.
- A number of individual VOCs were identified in the outlet air that did not occur in the corresponding inlet sample, particularly prevalent with the aromatic hydrocarbon, terpene and reduced sulphur compound groups. The sulphur compounds may have been produced as a result of partial oxidation of other sulphur compounds, or areas of anaerobic activity within the biofilter, which lead to the generation of sulphides. The Terpene compounds are likely to originate from the biofilter media.

Bioaerosol and odour removal efficiency

- Based on the data from this study, the performance of the abatement systems in terms of bioaerosol reduction efficiency was extremely variable from site to site and between visits to the same site. Overall the same abatement system did not appear to be able to simultaneously achieve significant removals of *Aspergillus fumigatus*, total bacteria and gram negative bacteria.

- It was not possible to determine the impact of an upstream scrubber on the overall performance of the abatement systems. This is due to the fact that the study did not have similar sites (in terms of biofilter media, empty bed residence time etc.), with and without a scrubber. However, it is possible from that data obtained during this study to evaluate the performance of the scrubber alone. All the upstream scrubbers sampled were capable of achieving reductions in the concentration of bioaerosols and were particularly effective against *Aspergillus fumigatus*. However, they appear to be less effective against bacteria and total bacteria in particular. The performance of the two stage acid and alkali scrubber system appeared to be more effective than the acid scrubber alone, regardless of the bioaerosol type.
- The performance of the scrubbers in terms of odour removal was extremely variable from one site to another and overall the operation of a scrubber appeared to have limited or no effect on the odour concentration in the air stream. The ammonia removal efficiency across the scrubbers was also extremely variable and ranged from an increase of 70%, to a reduction of 98%. The addition of a scrubber does not appear to have any impact on the removal efficiency of VOCs by the biofilters, and at most sites the concentration of a number of VOCs appears to increase through the scrubber.
- The scrubber removal efficiency for *Aspergillus fumigatus*, total bacteria and odour appears to be independent of the concentration in the inlet. In contrast for gram negative bacteria, the performance may be influenced by the inlet concentration.
- The odour removal efficiency across the biofilters sampled in this study showed some variation between sampling visits. Overall the data suggested that odour removal efficiency is not always a good indicator of biofilter performance and should be evaluated in combination with other biofilter performance indicators, such as odour emission concentration.
- Taking the data for the biofilters on their own, it appeared that open biofilters performed significantly better than enclosed biofilters with respect to their removal efficiency for *Aspergillus fumigatus*. In contrast for total bacteria, enclosed biofilters produced the highest removals. It is not clear from this data set whether open or enclosed biofilters are better for the removal of gram negative bacteria.
- The ammonia removal efficiency across the biofilters ranged from 24% up to 100%. Overall there appears to be no difference in performance between the ammonia removal efficiency of enclosed and open biofilters.
- The *Aspergillus fumigatus* removal efficiency of the biofilters appeared to be related to the inlet concentration, with poor removals at low inlet concentrations. The data suggested that biofilters may be consistently emitting *Aspergillus fumigatus* and that this can only be observed when the inlet concentration is low. It may also mean that when using a biofilter alone, or in conjunction with an upstream scrubber, it will not be possible to completely eliminate *Aspergillus fumigatus* from the air stream. Although

not conclusive, the suggestion that biofilters are a constant source of *Aspergillus fumigatus* may advocate the use of downstream scrubbers to negate the net emission of *Aspergillus fumigatus* by the biofilter, and improve the overall performance of the abatement system.

- The impact of biofilter media type varied between the different types of bioaerosols. The granular peat biofilters were extremely poor at reducing the concentration of *Aspergillus fumigatus.* However, in contrast they produced reasonable reductions in gram negative bacteria and significant reductions in total bacteria. Looking at the performance of woodchip, clay and brash biofilters, there appeared to be little difference in the performance for both *Aspergillus fumigatus* and total bacteria. The performance of woodchip biofilters for gram negative bacteria is extremely variable and the data shows very poor removals for the brash and clay biofilters.
- In contrast to the bioaerosols, the type and characteristics of the abatement system appears to have little impact on the odour removal efficiency. Biofilters with each of the media types sampled (e.g. woodchip, peat, brash and clay aggregate) all achieved odour removal efficiencies in excess of 90%. Biofilters with a granular peat media appeared to achieve the lowest ammonia removal efficiencies and the performance of the brash and woodchip biofilters was also generally good.
- Key design and operating parameters such as air flow rate, surface loading rate, empty bed residence time, media nutrient and moisture contents and pH appear to have no impact in the removal efficiency of bioaerosols.
- The data indicates that almost all of the biofilters sampled during this study were effective at reducing the concentration of hydrogen sulphide to below the limit of detection of the analysis technique. It also shows that the characteristics of the abatement system do not appear to influence the removal efficiency.
- The ammonia removal efficiency shows variation between visits and does not appear to correlate to inlet concentration. The characteristics of the abatement system do not appear to influence the ammonia removal efficiencies of the biofilters.
- The removal efficiency of VOCs exhibits significant variation from site to site. A number of compound group concentrations were reduced by up to 100%, however the individual removal efficiencies of specific VOCs varied considerably, indicating that some components are easier to remove than others. The removal efficiency will depend upon the solubility of each compound and its amenity for absorption into and oxidation within the biofilm of the biofilter media.

8.0 Knowledge gaps and future research

This study has generated some valuable data and provided a significant contribution to the knowledge surrounding the gaseous emissions from enclosed biowaste sites and the performance of abatement systems. However it has also highlighted some knowledge gaps and areas for further research and these are presented in this section.

1. Overall there continues to be a lack of good quality data regarding the concentration of bioaerosols in the air emitted from enclosed biowaste processes and biofilters. This makes it extremely difficult to evaluate the performance of abatement systems and in particular, biofilters for the control of bioaerosols. The data that does exist is extremely variable due to the different sampling techniques that have been used, particularly for biofilter outlets. More sampling needs to be undertaken using robust, standardised sampling procedures in order to provide a more comprehensive data set.
2. Information obtained during site visits revealed that all the sites in this study were operating well, with no apparent issues with process parameters, such as air flows, temperature profiles, moisture contents etc. As a result this study was not able to provide an insight into the effect of anaerobicity on the emission of odour or bioaerosols. Therefore more data is needed to investigate the impact of anaerobicity on odour and bioaerosol emissions and more specifically, whether there are any relationships between specific VOCs / VOCs groups and odour, which may serve as markers for anaerobicity / abnormal conditions.
3. This study has provided data on the performance of biofilters and scrubbers when used to treat air from a range of biowaste treatment process under 'normal' operation. More research is needed to investigate the performance of these systems in terms of their ability to treat the air emitted from biowaste process that are operating under 'abnormal' conditions. This will help to define the operational limits for application of biofilter and scrubber technology to composting processes.
4. A detailed analysis of the volatile organic compounds contained in the air emitted from the biowaste treatment processes was carried out. This data revealed an apparent correlation between the concentration of ethanol and total volatile organic compounds. More data needs to be gathered in order to investigate this relationship in compost process air for 'normal' operating processes.
5. Further research is required to evaluate the performance of biofilters with different media types (e.g. lava rock, organic media and activated carbon), or with combinations of different media, or media mixes, in terms of odour and bioaerosol emissions and removal.
6. The literature contains apparently contradictory information regarding the impact of biofilter design and operating parameters on odour and bioaerosol emissions and removal. The data provided in this study did not provide a clear picture of the impact of

parameters such as media moisture content, biofilter temperature, absorptivity, process air temperature and media porosity. Further research is needed to investigate the criticality of these parameters, in order to refine operational ranges, and firmly define boundary conditions between normal and abnormal biofilter operation.

7. The data obtained during this study, together with data available in the literature, suggests that the mechanisms involved in the removal of odours and bioaerosols are different. If this is in fact the case, then it may imply that significant removals of odour and bioaerosols cannot be achieved simultaneously, in a single biofilter system. Further research is needed to determine if a single biofilter can be optimised for the removal of bioaerosols and odour. Additional research should be carried out on the feasibility of using a two stage biofilter system, with each stage optimised for the removal of odour or bioaerosols.
8. The performance of biofilters in terms of bioaerosol and in particular *Aspergillus fumigatus* removal showed that biofilters may be net emitters. The impact of this is that at low inlet concentrations, the removal efficiency is relatively low. Further research is needed to investigate the potential for net emission of bioaerosols from biofilters, both in terms of the overall concentration and also the individual species. This research should also evaluate the potential for applying scrubbing post biofiltration to remove bioaerosols.
9. This report identified that there is a lack of information regarding the range of biowaste treatment options being used throughout the UK and also the abatement systems that are being employed. Therefore it would be beneficial to liaise with the biowaste treatment industry and attempts to compile a database regarding the current biowaste treatment options being used in the UK together with the abatement system currently being employed.
10. This research highlighted a great deal of variability in the performance of scrubbers for both odour and bioaerosol removal. This may have been due to the limited number of sites included in this study which employed scrubbers and biofilters. Therefore further work should be carried out to look specifically at the performance of scrubbers and also to determine whether for bioaerosols the scrubber liquor represents a significant source of bioaerosols and therefore adversely affects their performance. This may lead to the development of clear guidelines for the operation and maintenance of scrubbers for odour and bioaerosol removal. The research should encompass a range of different scrubber arrangements in terms of the liquid and the packing used and could also investigate the potential for the use of a downstream scrubber post-biofilter for effective bioaerosol removal.
11. The literature appears to be divided over the subject of ammonia toxicity within biofilters. Some authors have suggested that elevated ammonia loading rates can have a significant impact on the performance of a biofilter at composting sites due to the

occurrence of ammonia toxicity leading to microbial inhibition, causing a reduction in the capacity of the biofilter to adsorb and decompose ammonia. However others have observed no ammonia toxicity effects even at relatively high ammonia concentrations, suggesting that even high initial levels of ammonia in exhaust gases may be removed effectively using biofiltration. The results from this study showed that ammonia removal was extremely variable and that the removal efficiency was not related to the inlet concentration. As a result further work is needed to establish whether biofilters are capable of achieving ammonia removal at elevated concentrations and whether ammonia toxicity is a factor affecting performance of biofilters. Work should also be carried out to determine the biological response to elevated ammonia concentrations to establish whether the microbial population within the media adapts to elevated ammonia concentrations or whether a specialised population is already in-situ.

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Appendix 1 Bioaerosol Results

Rep 1-3 indicate where replicate analysis was undertaken in the laboratory on each sample.

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL01 on the 9th April 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)	Removal efficiency (%)
Inlet Sample 1	1622	-
Inlet Sample 2	498	-
Inlet Sample 3	262	-
Outlet Sample 1	834	49
Outlet Sample 2	350	30
Outlet Sample 3	831	-217

Sample	Total bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Inlet Sample 1	13855	-
Inlet Sample 2	14630	-
Inlet Sample 3	14393	-
Outlet Sample 1	6795	51
Outlet Sample 2	8344	43
Outlet Sample 3	9376	35

Sample	Gram negative bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Inlet Sample 1	9868	-
Inlet Sample 2	11891	-
Inlet Sample 3	8112	-
Outlet Sample 1	4530	54
Outlet Sample 2	4259	64
Outlet Sample 3	6528	20

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL01 on the 12th June 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	6283	6842	6423	6516	291	-
Inlet Sample 2	2893	2342	2618	2618	276	-
Inlet Sample 3	0	1498	1635	1044	907	-
Outlet Sample 1	156	311	156	208	90	97
Outlet Sample 2	2577	2425	3032	2678	316	-2
Outlet Sample 3	613	1993	766	1124	756	-8

Sample	Total bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	53197	55152	54175	54175	977	-
Inlet Sample 2	27694	29623	27280	28199	1250	-
Inlet Sample 3	47814	46860	47541	47405	491	-
Outlet Sample 1	9497	10120	9341	9653	412	82
Outlet Sample 2	31833	32742	33045	32540	631	-15
Outlet Sample 3	4905	4139	4598	4547	386	90

Sample	Gram negative bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	13265	14242	15219	14242	977	-
Inlet Sample 2	27281	28934	26867	27694	1094	-
Inlet Sample 3	7084	6675	7628	7129	478	-
Outlet Sample 1	4515	5138	6383	5345	951	63
Outlet Sample 2	14552	15765	17432	15916	1446	43
Outlet Sample 3	153	153	307	204	89	97

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL02 (OGM1) on the 23rd October 2012

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)	Removal efficiency (%)
Scrubber Inlet Sample 1	582	-
Scrubber Inlet Sample 2	208	-
Scrubber Inlet Sample 3	406	-
Scrubber Outlet Sample 1	123	79
Scrubber Outlet Sample 2	304	-46
Scrubber Outlet Sample 3	123	70
Biofilter Outlet Sample 1	1000	-72
Biofilter Outlet Sample 2	443	-113
Biofilter Outlet Sample 3	355	13

Sample	Total bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Scrubber Inlet Sample 1	11014	-
Scrubber Inlet Sample 2	10120	-
Scrubber Inlet Sample 3	8219	-
Scrubber Outlet Sample 1	1716	84
Scrubber Outlet Sample 2	7711	24
Scrubber Outlet Sample 3	6446	22
Biofilter Outlet Sample 1	588	95
Biofilter Outlet Sample 2	719	93
Biofilter Outlet Sample 3	237	97

Sample	Gram negative bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Scrubber Inlet Sample 1	5386	-
Scrubber Inlet Sample 2	2734	-
Scrubber Inlet Sample 3	2993	-
Scrubber Outlet Sample 1	368	93
Scrubber Outlet Sample 2	3218	-18
Scrubber Outlet Sample 3	-	-
Biofilter Outlet Sample 1	235	96
Biofilter Outlet Sample 2	387	86
Biofilter Outlet Sample 3	118	96

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL03 (GW1) on the 24th October 2012

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)	Removal efficiency (%)
Scrubber Inlet Sample 1	1403	-
Scrubber Inlet Sample 2	2119	-
Scrubber Inlet Sample 3	459	-
Scrubber Outlet Sample 1	499	64.4
Scrubber Outlet Sample 2	513	75.8
Scrubber Outlet Sample 3	104	77.3
Biofilter Outlet Sample 1	511	63.6
Biofilter Outlet Sample 2	1326	37.4
Biofilter Outlet Sample 3	335	27.0

Sample	Total bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Scrubber Inlet Sample 1	14009	-
Scrubber Inlet Sample 2	7514	-
Scrubber Inlet Sample 3	9837	-
Scrubber Outlet Sample 1	10815	22.8
Scrubber Outlet Sample 2	15590	-107.5
Scrubber Outlet Sample 3	13950	-41.8
Biofilter Outlet Sample 1	1405	90.0
Biofilter Outlet Sample 2	899	88.0
Biofilter Outlet Sample 3	1633	83.4

Sample	Gram negative bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Scrubber Inlet Sample 1	3880	-
Scrubber Inlet Sample 2	4480	-
Scrubber Inlet Sample 3	2345	-
Scrubber Outlet Sample 1	887	77.1
Scrubber Outlet Sample 2	3128	30.2
Scrubber Outlet Sample 3	3971	-69.3
Biofilter Outlet Sample 1	298	92.3
Biofilter Outlet Sample 2	171	96.2
Biofilter Outlet Sample 3	503	78.6

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL03 (OGM1) on the 25th October 2012

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)	Removal efficiency (%)
Scrubber Inlet	1233	-
Scrubber Outlet	212	82.8
Biofilter Outlet	713	42.2

Sample	Total bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Scrubber Inlet	7101	-
Scrubber Outlet	9539	-34.3
Biofilter Outlet	926	87

Sample	Gram negative bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Scrubber Inlet	2564	-
Scrubber Outlet	1590	38
Biofilter Outlet	244	90.5

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL04 on the 11th July 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Scrubber Inlet Sample 1	0	0	0	0	0	-
Scrubber Inlet Sample 2	0	0	0	0	0	-
Scrubber Inlet Sample 3	100	0	0	3	58	-
Scrubber Outlet Sample 1	0	0	0	0	0	-
Scrubber Outlet Sample 2	100	0	0	33	58	-
Scrubber Outlet Sample 3	0	0	0	0	0	100
Biofilter Outlet Sample 1	100	0	0	33	58	-
Biofilter Outlet Sample 2	0	0	0	0	0	-
Biofilter Outlet Sample 3	0	0	0	0	0	100

Sample	Total bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Scrubber Inlet Sample 1	22673	24353	30457	25828	4096	-
Scrubber Inlet Sample 2	-	-	-	-	-	-
Scrubber Inlet Sample 3	-	-	-	-	-	-
Scrubber Outlet Sample 1	10811	10318	9459	10196	684	61
Scrubber Outlet Sample 2	15570	8828	17978	14125	4743	-
Scrubber Outlet Sample 3	8174	9217	10435	9275	1132	-
Biofilter Outlet Sample 1	1511	1259	2015	1595	385	94
Biofilter Outlet Sample 2	1386	2045	852	1428	598	-
Biofilter Outlet Sample 3	1022	851	1192	1022	171	-

Sample	Gram negative bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Scrubber Inlet Sample 1	200	400	100	233	153	-
Scrubber Inlet Sample 2	900	300	2500	1233	1137	-
Scrubber Inlet Sample 3	-	-	770	770	-	-
Scrubber Outlet Sample 1	0	200	0	67	116	71
Scrubber Outlet Sample 2	200	300	200	233	58	81
Scrubber Outlet Sample 3	500	200	400	367	153	52
Biofilter Outlet Sample 1	500	400	400	433	58	-86
Biofilter Outlet Sample 2	0	0	0	0.0	0	100
Biofilter Outlet Sample 3	0	0	0.0	0.0	0	100

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL05 on the 23rd July 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	1467	2483	2145	2032	517	-
Inlet Sample 2	3430	3326	3846	3534	275	-
Inlet Sample 3	2977	3859	4851	3896	938	-
Outlet Sample 1	0	0	0	0	0	100
Outlet Sample 2	0	267	0	89	154	98
Outlet Sample 3	1067	3467	1333	1956	1315	50

Sample	Total bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	22573	21332	22912	22272	832	-
Inlet Sample 2	24948	24740	26092	25260	728	-
Inlet Sample 3	28115	28997	26351	27821	1347	-
Outlet Sample 1	4800	6133	5867	5600	706	75
Outlet Sample 2	5867	10400	5067	7111	2876	72
Outlet Sample 3	13867	15733	13333	14311	1260	49

Sample	Gram negative bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	2483	3725	2370	2859	752	-
Inlet Sample 2	5094	4366	4262	4574	453	-
Inlet Sample 3	4851	4300	4961	4704	354	-
Outlet Sample 1	4000	1600	2667	2756	1203	4
Outlet Sample 2	6133	6400	3733	5422	1469	-19
Outlet Sample 3	7467	8800	6133	7467	1333	-59

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL05 on the 8th October 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	1647	2471	1812	1977	436	-
Inlet Sample 2	3571	1857	1857	2429	990	-
Inlet Sample 3	1238	1376	1513	1376	138	-
Outlet Sample 1	1600	1200	0	933	833	53
Outlet Sample 2	0	0	533	178	308	93
Outlet Sample 3	800	533	533	622	154	55

Sample	Total bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	14662	15321	17133	15706	1280	-
Inlet Sample 2	16429	16000	12714	15048	2032	-
Inlet Sample 3	12792	14443	13205	13480	859	-
Outlet Sample 1	8800	7200	6400	7467	1222	53
Outlet Sample 2	4000	6400	7467	5956	1776	60
Outlet Sample 3	7733	6933	7497	7378	407	45

Sample	Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	2965	2471	1968	2471	494	-
Inlet Sample 2	1571	3571	4143	3095	1350	-
Inlet Sample 3	2614	3026	3164	2934	286	-
Outlet Sample 1	2400	2800	1600	2267	611	8
Outlet Sample 2	2933	4000	3467	3467	533	-12
Outlet Sample 3	2933	4000	3200	3378	555	-15

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL06 on the 6th August 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	2585	3579	2386	2850	639	-
Inlet Sample 2	945	2836	3025	2268	1150	-
Inlet Sample 3	3346	2231	2974	2850	568	-
Outlet Sample 1	2400	800	2400	1867	924	35
Outlet Sample 2	0	1067	2133	1067	1067	53
Outlet Sample 3	267	267	267	267	0	91

Sample	Total bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	6362	8549	5964	6958	1392	-
Inlet Sample 2	5860	8318	9263	7814	1756	-
Inlet Sample 3	12639	13383	12082	12701	653	-
Outlet Sample 1	800	800	1600	1067	462	85
Outlet Sample 2	2133	3467	4267	3289	1078	58
Outlet Sample 3	2667	3200	4267	3378	815	73

Sample	Gram negative bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	3777	4970	4374	4374	596	-
Inlet Sample 2	5293	6049	4726	5356	664	-
Inlet Sample 3	10967	10223	11338	10843	568	-
Outlet Sample 1	0	0	0	0	0	100
Outlet Sample 2	267	1600	1067	978	671	82
Outlet Sample 3	2400	1333	2667	2133	706	80

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL06 on the 19th September 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	3212	3212	3426	3283	124	-
Inlet Sample 2	3038	2532	3038	2869	292	-
Inlet Sample 3	2676	2190	3406	2758	612	-
Outlet Sample 1	1333	1067	1067	1156	154	65
Outlet Sample 2	1600	533	800	978	555	66
Outlet Sample 3	800	533	267	533	267	81

Sample	Total bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	8779	11135	7281	9065	1943	-
Inlet Sample 2	8101	11392	12405	10633	2250	-
Inlet Sample 3	8516	6326	8516	7786	1264	-
Outlet Sample 1	4000	3467	4533	4000	533	56
Outlet Sample 2	2667	2400	2933	2667	267	75
Outlet Sample 3	3200	4000	2667	3289	671	58

Sample	Gram negative bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	4497	4711	5782	4996	688	-
Inlet Sample 2	6076	7848	9114	7679	1526	-
Inlet Sample 3	4623	5353	4380	4785	507	-
Outlet Sample 1	1067	133	133	1244	154	75
Outlet Sample 2	800	0	0	267	462	97
Outlet Sample 3	800	533	267	533	267	89

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL06 on the 15th October 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	2317	2896	2510	2574	295	-
Inlet Sample 2	1727	1413	1256	1465	240	-
Inlet Sample 3	1858	1084	929	1290	498	-
Outlet Sample 1	533	1333	800	889	407	66
Outlet Sample 2	267	1067	1067	1067	0	27
Outlet Sample 3	533	1067	1067	622	407	52

Sample	Total bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	10618	9460	11776	10618	1158	-
Inlet Sample 2	6122	6593	7378	6698	635	-
Inlet Sample 3	6811	6037	4334	5728	1267	-
Outlet Sample 1	3200	4533	4000	3911	671	63
Outlet Sample 2	2933	3200	4267	3467	706	48
Outlet Sample 3	3467	4800	2933	3733	962	35

Sample	Gram negative bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet Sample 1	5985	5405	4247	5212	885	-
Inlet Sample 2	3611	3768	3297	3558	240	-
Inlet Sample 3	4489	4180	3870	4180	310	-
Outlet Sample 1	533	267	267	356	154	93
Outlet Sample 2	800	1333	1600	1244	407	65
Outlet Sample 3	0	800	267	356	407	92

Bioaerosol concentrations in the biofilter inlet samples with and without the scrubber operating and in the biofilter outlet samples at UOL07 on the 2nd October 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet scrubber off 1	627	627	627	627	0	-
Inlet scrubber off 2	601	901	601	701	173	-
Inlet scrubber off 3	326	652	652	543	188	-
Inlet scrubber on 1	0	0	0	0	0	-
Inlet scrubber on 2	0	0	0	0	0	-
Inlet scrubber on 3	0	0	0	0	0	-
Outlet 1	0	0	0	0	0	-
Outlet 2	0	0	0	0	0	-
Outlet 3	0	0	0	0	0	-

Sample	Total bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet scrubber off 1	18182	14107	16301	16196	2040	-
Inlet scrubber off 2	13514	14414	15616	14515	1055	-
Inlet scrubber off 3	19218	19867	20521	19870	652	-
Inlet scrubber on 1	17963	19303	17694	18320	862	-
Inlet scrubber on 2	17136	17371	16197	16901	621	-
Inlet scrubber on 3	12857	15306	15306	14490	1414	-
Outlet 1	14133	14400	16267	14933	1162	18.5
Outlet 2	11733	14667	16533	14311	2420	15.3
Outlet 3	14667	13867	16267	14933	1222	-3.1

Sample	Gram negative bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet scrubber off 1	10972	7837	6270	8360	2394	-
Inlet scrubber off 2	6306	7508	8408	7407	1055	-
Inlet scrubber off 3	8469	7166	6840	7492	862	-
Inlet scrubber on 1	8847	11260	17963	12690	4723	-
Inlet scrubber on 2	10563	12207	12441	11737	1023	-
Inlet scrubber on 3	10000	7551	11837	9796	2150	-
Outlet 1	5600	4800	4800	5067	462	60.1
Outlet 2	4267	5867	5600	5244	857	55.3
Outlet 3	5867	4267	4800	4978	815	49.2

Bioaerosol concentrations in the biofilter inlet samples with and without the scrubber operating and in the biofilter outlet samples at UOL07 on the 12th November 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet scrubber off 1	11.2	5.8	11.6	9.5	3.2	-
Inlet scrubber off 2	13.4	7.4	14.9	11.9	3.9	-
Inlet scrubber off 3	4.3	5.8	10.1	6.7	3.0	-
Inlet scrubber on 1	2.8	2.8	4.2	3.3	0.8	-
Inlet scrubber on 2	5.6	7.0	16.9	9.8	6.1	-
Inlet scrubber on 3	0.0	4.1	2.7	2.3	2.1	-
Outlet 1	2.7	8.0	8.0	6.2	3.1	-90.9
Outlet 2	21.3	5.3	5.3	10.7	9.2	-8.1
Outlet 3	0.0	0.0	0.0	0.0	0.0	100.0

Sample	Total bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet scrubber off 1	52325.6	71220.9	42151.2	55232.6	14751.3	-
Inlet scrubber off 2	TNTC	48214.3	36011.9	42113.1	8628.4	-
Inlet scrubber off 3	43478.3	33333.3	53043.5	38405.8	7173.5	-
Inlet scrubber on 1	43854.7	55865.9	34217.9	44646.2	10845.7	-
Inlet scrubber on 2	44662.9	42977.5	50000.0	46488.8	4965.6	-
Inlet scrubber on 3	38356.2	54520.5	TNTC	46438.4	11429.9	-
Outlet 1	69333.3	89066.7	66133.3	74844.4	12420.3	-67.6
Outlet 2	36533.3	61066.7	57866.7	51822.2	13336.9	-11.5
Outlet 3	68266.7	52266.7	53333.3	57955.6	8945.6	-24.8

Sample	Gram negative bacteria Concentration (cfu/m^3)					Removal efficiency (%)
	Rep 1	Rep 2	Rep 3	Mean	S.D	
Inlet scrubber off 1	29215	29651	25872	28246	2068	-
Inlet scrubber off 2	35417	50893	31101	39137	10407	-
Inlet scrubber off 3	37681	35507	27826	33672	5178	-
Inlet scrubber on 1	27933	22207	42040	30726	10207	-
Inlet scrubber on 2	18680	28511	10534	19242	9002	-
Inlet scrubber on 3	16438	20685	22740	19954	3214	-
Outlet 1	29867	31733	26133	29244	2851	-4.8
Outlet 2	55733	47733	28000	43822	14274	-127.7
Outlet 3	41600	34667	27733	34667	6933	-73.7

Bioaerosol concentrations in the biofilter inlet and outlet samples at UOL08 on the 20th February 2013

Sample	*Aspergillus fumigatus* Concentration (cfu/m^3)	Removal efficiency (%)
Biofilter Inlet 1 & 2 Mean Sample 1	18473	-
Biofilter Inlet 1 & 2 Mean Sample 2	31267	-
Biofilter Inlet 1 & 2 Mean Sample 2	27601	-
Biofilter Combined Outlet Sample 1	0	100
Biofilter Combined Outlet Sample 2	2890	91
Biofilter Combined Outlet Sample 3	0	100

Sample	Total bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Biofilter Inlet 1 & 2 Mean Sample 1	83751	-
Biofilter Inlet 1 & 2 Mean Sample 2	115528	-
Biofilter Inlet 1 & 2 Mean Sample 2	135654	-
Biofilter Combined Outlet Sample 1	18847	78
Biofilter Combined Outlet Sample 2	46965	59
Biofilter Combined Outlet Sample 3	11557	92

Sample	Gram negative bacteria Concentration (cfu/m^3)	Removal efficiency (%)
Biofilter Inlet 1 & 2 Mean Sample 1	11642	-
Biofilter Inlet 1 & 2 Mean Sample 2	15965	-
Biofilter Inlet 1 & 2 Mean Sample 2	23152	-
Biofilter Combined Outlet Sample 1	4712	60
Biofilter Combined Outlet Sample 2	0	100
Biofilter Combined Outlet Sample 3	1542	93

Appendix 2 Concentration of bioaerosols emitted from the sites arranged according to process type and waste type

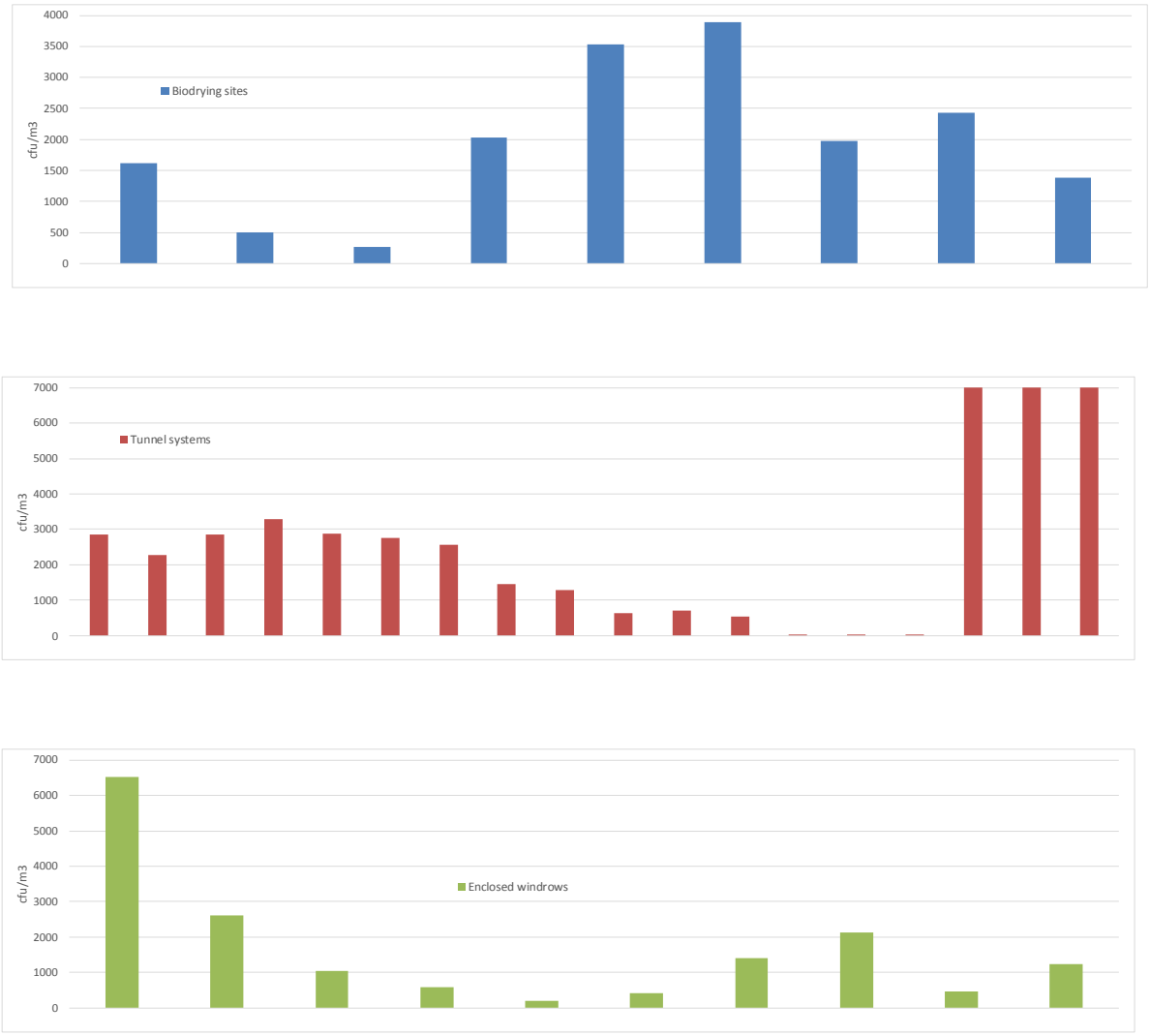

Figure 22 Concentration of Aspergillus fumigatus in the exhaust air from the sites arranged according to process type.

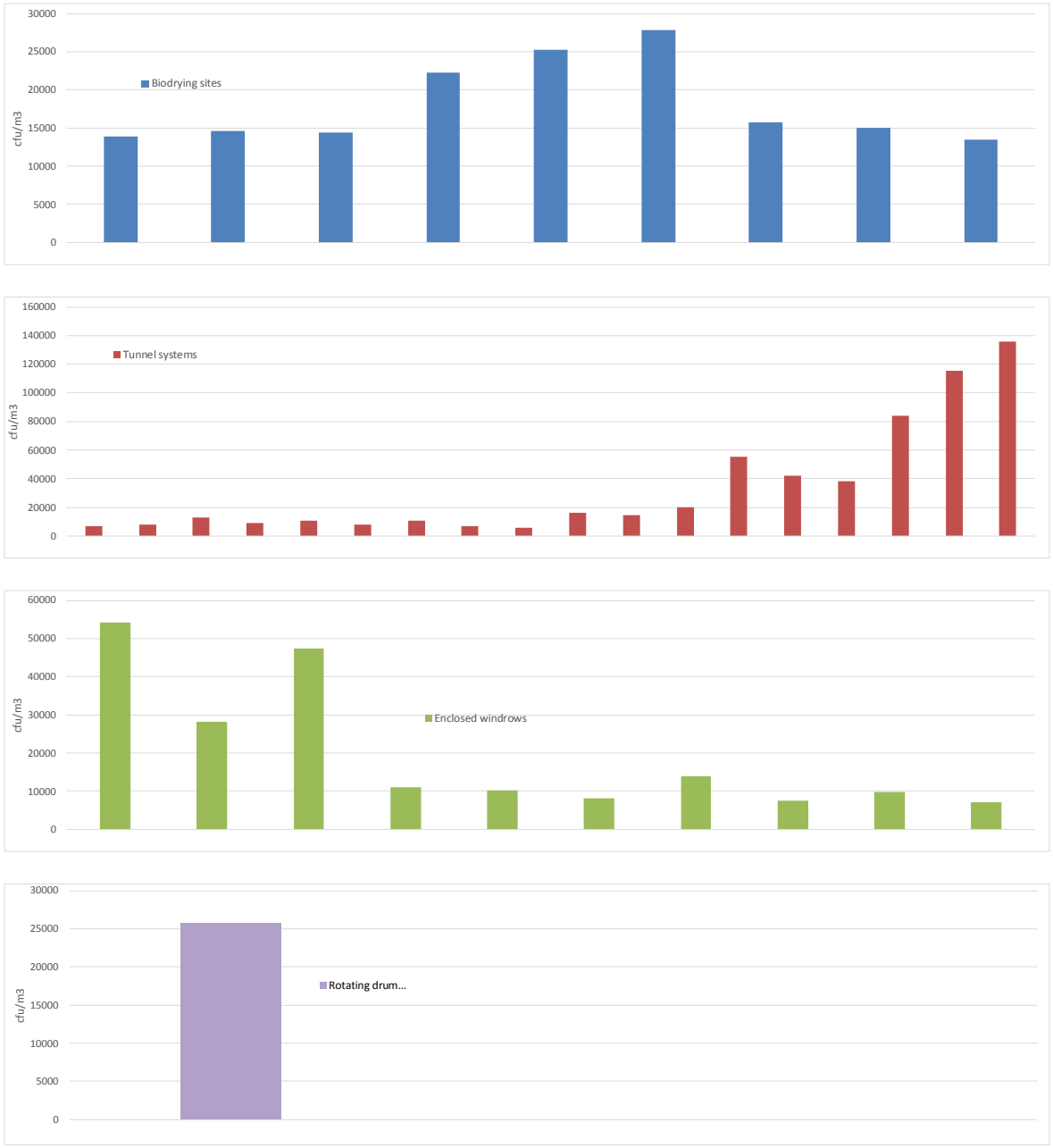

Figure 23 Concentration of total bacteria in the exhaust air from the sites arranged according to process type

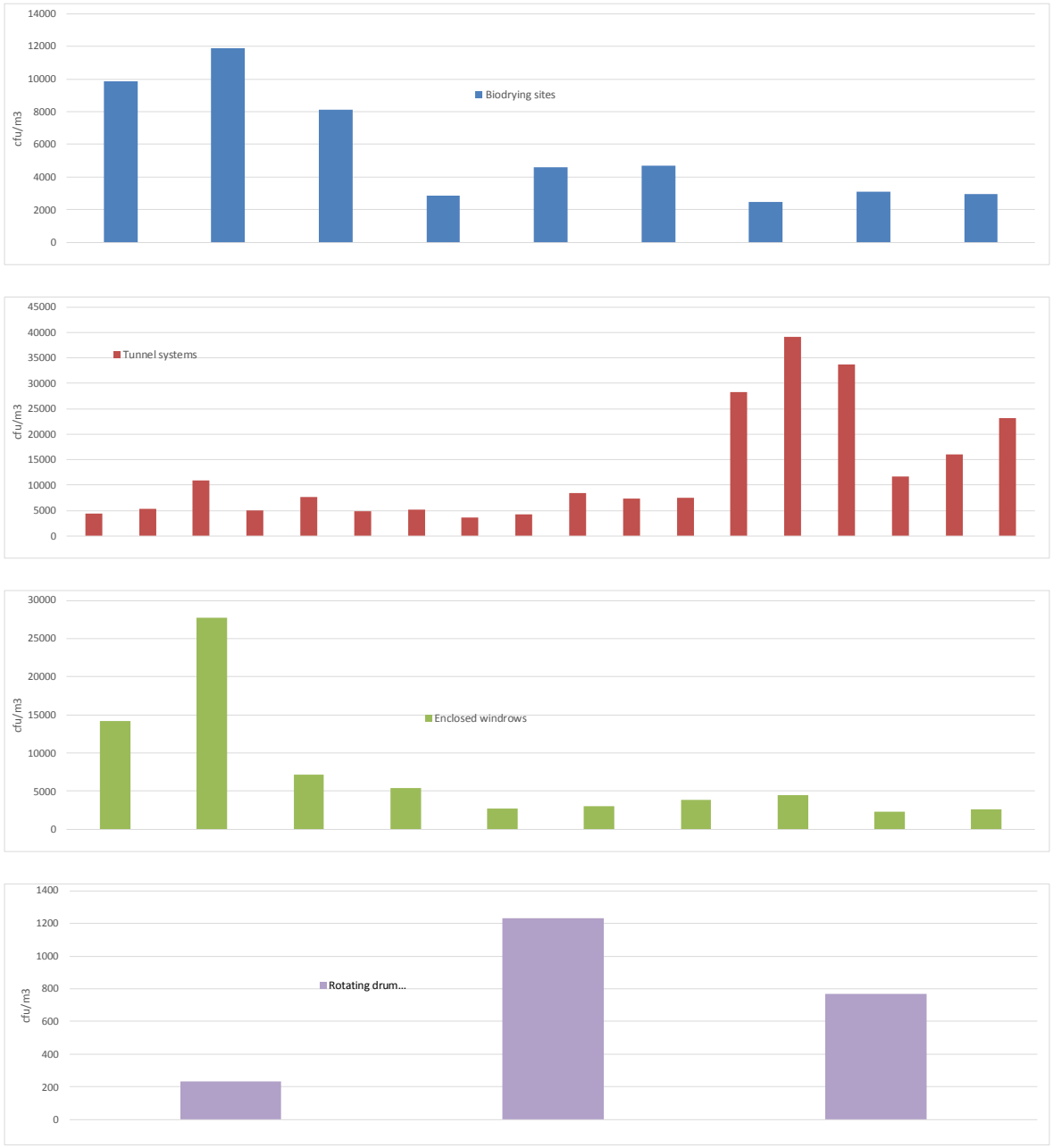

Figure 24 Concentration of gram negative bacteria in the exhaust air from the sites arranged according to process type

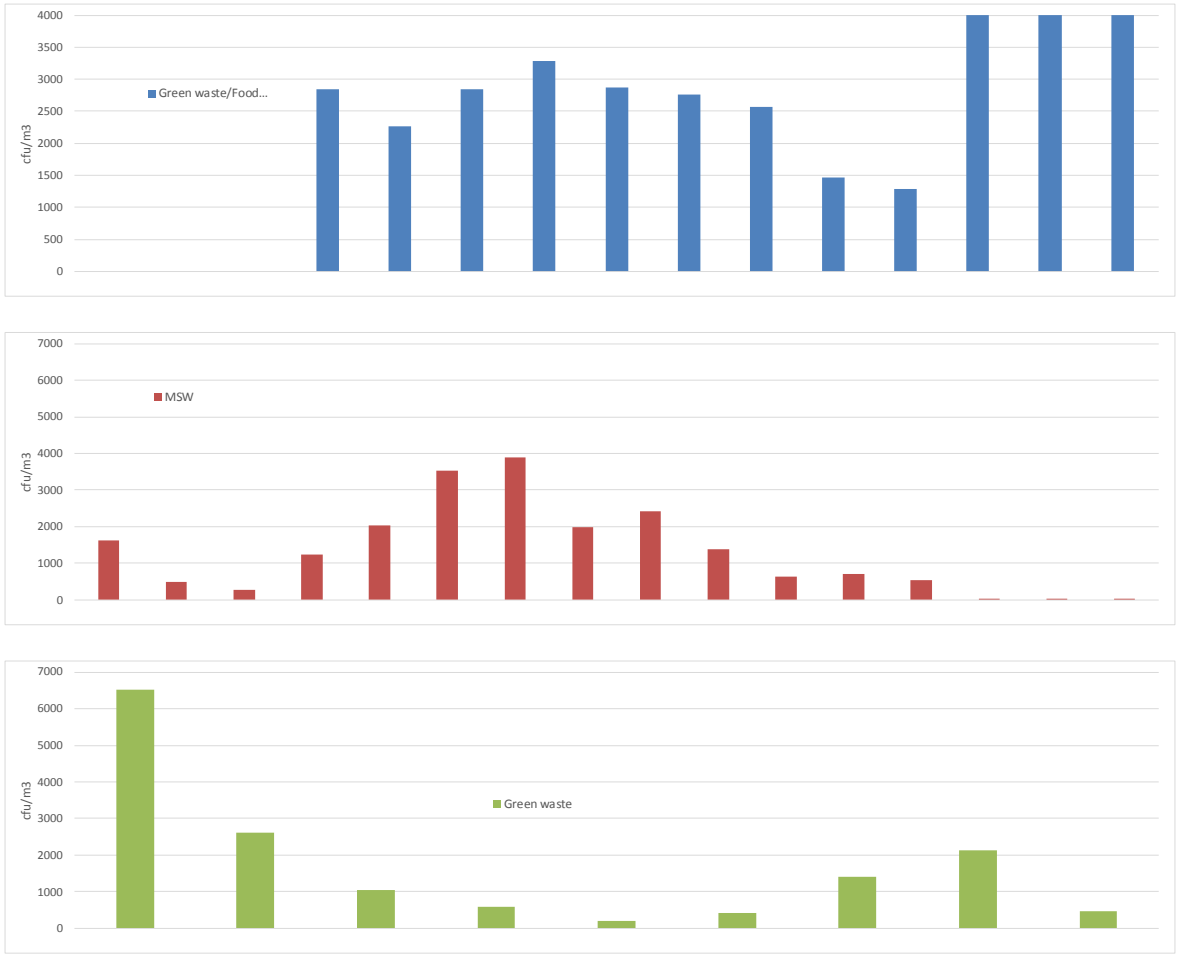

Figure 25 Concentration of Aspergillus fumigatus in the exhaust air from the sites arranged according to waste type

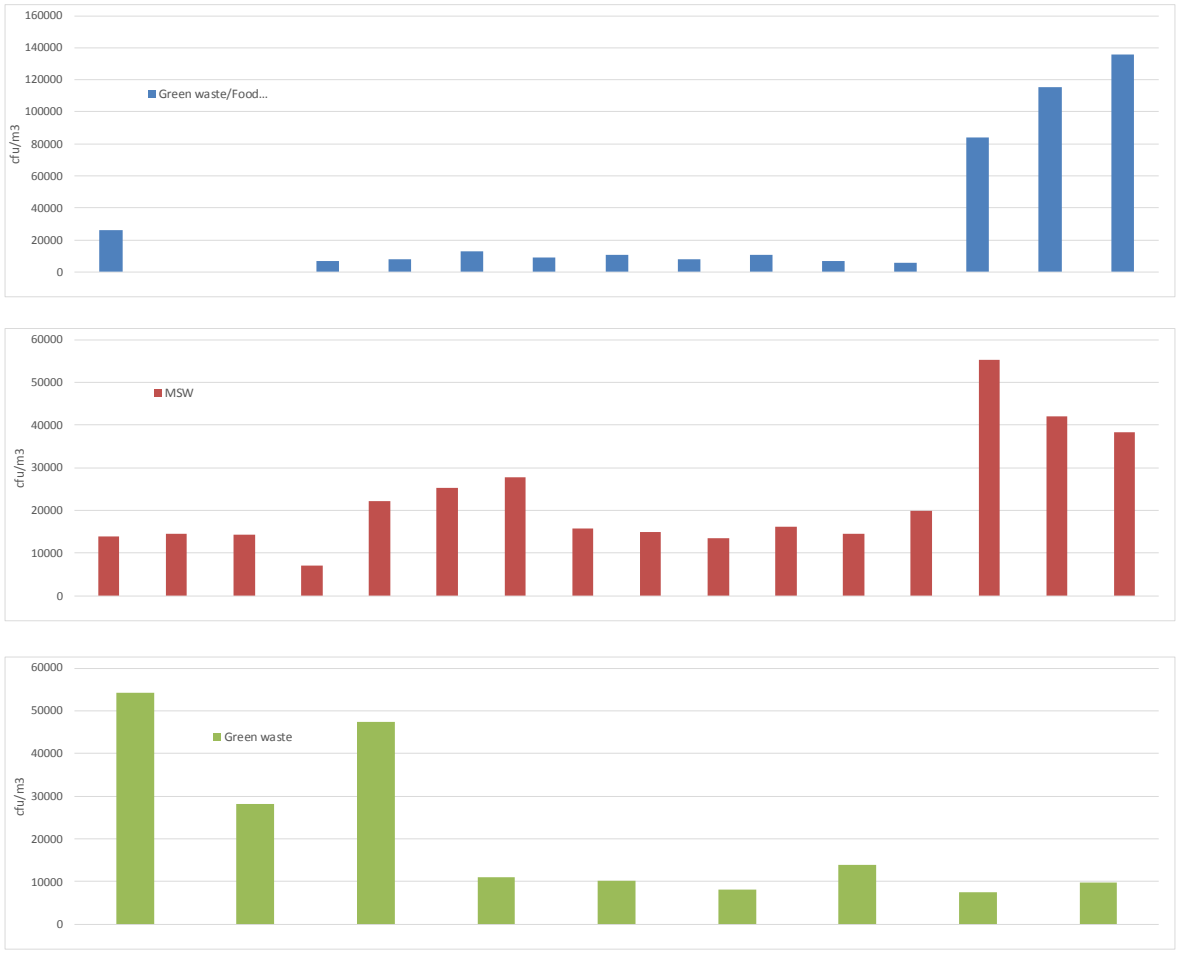

Figure 26 Concentration of total bacteria in the exhaust air from the sites arranged according to waste type

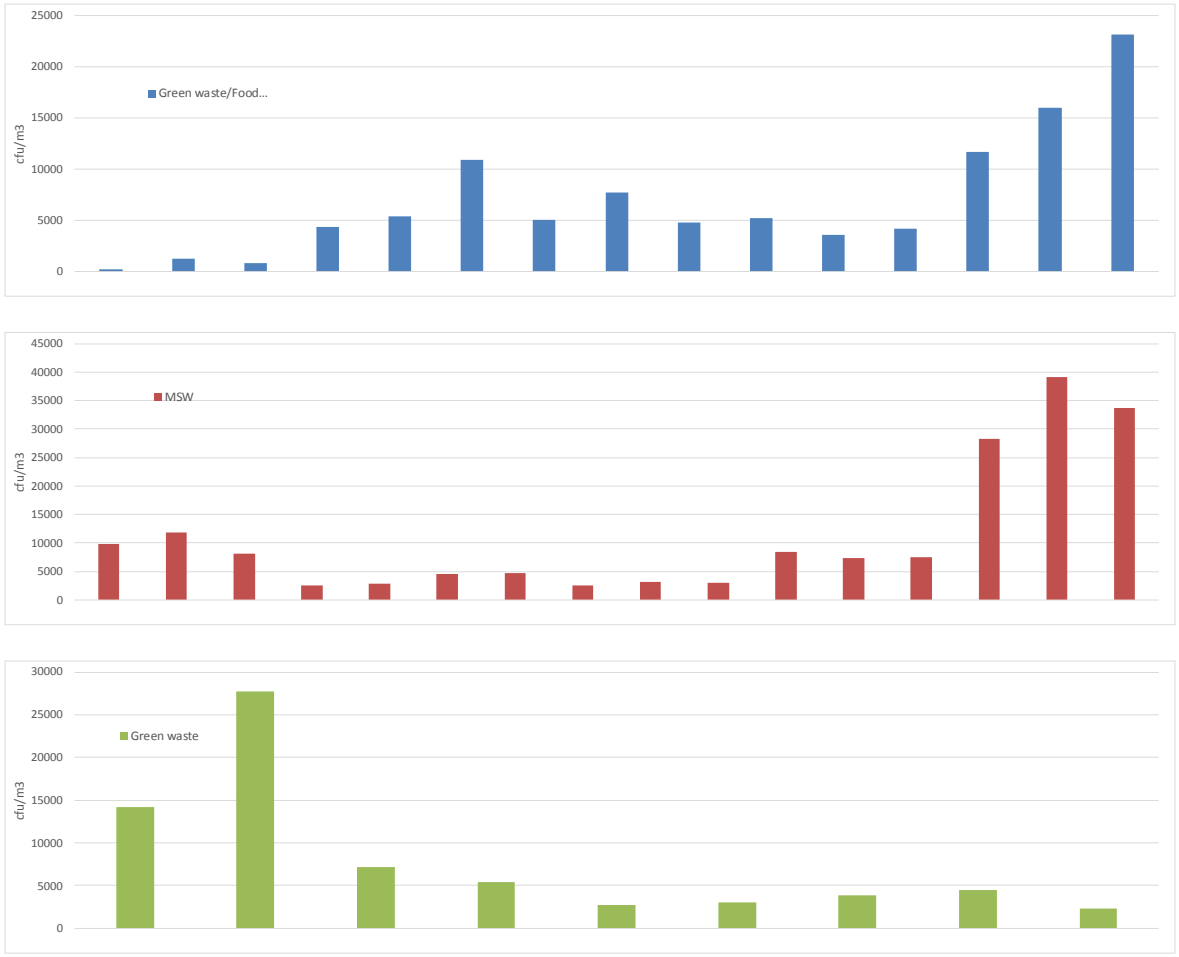

Figure 27 Concentration of gram negative bacteria in the exhaust air from the sites arranged according to waste type

Appendix 3 Odour, Hydrogen sulphide and Ammonia results

Odour concentrations in the biofilter inlet and outlet samples at UOL01 on the 9th April 2013

Sample Position	Measured concentration			% removal		
	Odour [ou_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	11149	9.8	6.5	-	-	-
Inlet 2	11577	-	-	-	-	-
Inlet 3	9749	-	-	-	-	-
Inlet mean	10796	9.8	6.5	-	-	-
Outlet 1	448	<LLOD	0.88	-	-	-
Outlet 2	337	-	-	-	-	-
Outlet 3	430	-	-	-	-	-
Outlet mean	402	<LLOD	0.88	96	100	86

Odour concentrations in the biofilter inlet and outlet samples at UOL01 on the 12th June 2013

Sample Position	Measured concentration			% removal		
	Odour [ou_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	34284	5.1	0.91	-	-	-
Inlet 2	39956	8.8	2.7	-	-	-
Inlet 3	35315	23.0	4.6	-	-	-
Inlet mean	36437	12.3	2.7	-	-	-
Outlet 1	4854	<LLOD	<LLOD	86	100	100
Outlet 2	2617	<LLOD	<LLOD	93	100	100
Outlet 3	2350	<LLOD	<LLOD	93	100	100
Outlet mean	3102	<LLOD	<LLOD	91	100	100

Odour concentrations in the biofilter inlet and outlet samples at UOL02 on the 23rd October 2012

Sample Position	Measured concentration			% removal		
	Odour [ou_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	38247	<LLOD	67	-	-	-
Inlet 2	102106	-	-	-	-	-
Inlet 3	51059	-	-	-	-	-
Inlet mean	58422	<LLOD	67	-	-	-
Intermed 1	40346	<LLOD	3.6	-5	-	95
Intermed 2	19681	-	-	81	-	-
Intermed 3	32675	-	-	36	-	-
Intermed mean	29604	<LLOD	3.6	37	-	95
Outlet 1	7222	<LLOD	1.5	82	-	58
Outlet 2	3894	-	-	80	-	-
Outlet 3	5968	-	-	82	-	-
Outlet mean	5516	<LLOD	1.5	81	-	58

Odour concentrations in the biofilter inlet and outlet samples at UOL03 on the 24th October 2012

Sample Position	Measured concentration			% removal		
	Odour [ou_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	16137	<LLOD	4.5			
Inlet 2	13098	-	-			
Inlet 3	12684	-	-			
Inlet mean	13892	<LLOD	4.5			
Intermed 1	15481	<LLOD	1.7	4%	-	62%
Intermed 2	13019	-	-	1%		
Intermed 3	8212	-	-	35%		
Intermed mean	11829	<LLOD	1.7	13%	-	62%
Outlet 1	861	<LLOD	0.86	94%		49%
Outlet 2	912	-	-	93%		
Outlet 3	1290	-	-	84%		
Outlet mean	1004	<LLOD	0.86	91%	-	49%

Odour concentrations in the biofilter inlet and outlet samples at UOL03 on the 25th October 2012

Sample Position	Measured concentration			% removal		
	Odour [ou_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	16949	<LLOD	60	-	-	-
Inlet 2	26091	-	-	-	-	-
Inlet 3	26724	-	-	-	-	-
Inlet mean	22778	<LLOD	60	-	-	-
Intermed 1	32819	<LLOD	<LLOD	-94%	-	98
Intermed 2	23599	-	-	10%	-	-
Intermed 3	29498	-	-	-10%	-	-
Intermed mean	28375	<LLOD	<LLOD	-31%	-	98
Outlet 1	2611	<LLOD	0.74	92%	-	24
Outlet 2	1728	-	-	93%	-	-
Outlet 3	1255	-	-	96%	-	-
Outlet mean	1782	<LLOD	0.74	93%	-	24

Odour concentrations in the biofilter inlet and outlet samples at UOL04 on the 11th July 2013

Sample Position	Measured concentration			% removal		
	Odour [ou_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	9683	<LLOD	2	-	-	-
Inlet 2	9333	-	-	-	-	-
Inlet 3	8176	-	-	-	-	-
Inlet mean	9040	<LLOD	2	-	-	-
Intermed 1	11683	<LLOD	3.4	-21%	-	-70%
Intermed 2	10835	-	-	-16%	-	-
Intermed 3	10440	-	-	-28%	-	-
Intermed mean	10974	<LLOD	3.4	-21%	-	-70%
Outlet 1	225	<LLOD	<LLOD	98%	-	88%
Outlet 2	259			98%	-	-
Outlet 3	163			98%	-	-
Outlet mean	212	<LLOD	<LLOD	98%	-	88%

Odour concentrations in the biofilter inlet and outlet samples at UOL05 on the 23rd July 2013

Sample Position	Measured concentration			% removal		
	Odour [ou_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	39359	0.9	14.4	-	-	-
Inlet 2	21919	0.3	6.8	-	-	-
Inlet 3	30999	1.8	10.0	-	-	-
Inlet mean	29950	1.0	10.4	-	-	-
Outlet 1	1933	<LLOD	2.0	95	100	86
Outlet 2	2048	<LLOD	0.5	91	100	92
Outlet 3	1367	<LLOD	0.9	96	100	91
Outlet mean	1756	<LLOD	1.1	94	100	90

Odour concentrations in the biofilter inlet and outlet samples at UOL05 on the 8th October 2013

Sample Position	Measured concentration			% removal		
	Odour [ou_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	23892	<LLOD	0.73	-	-	-
Inlet 2	12656	<LLOD	0.67	-	-	-
Inlet 3	15053	<LLOD	0.73	-	-	-
Inlet mean	16573	<LLOD	0.7			
Outlet 1	2580	<LLOD	0.5	89	-	36%
Outlet 2	2580	<LLOD	0.5	80	-	31%
Outlet 3	1722	<LLOD	0.3	89	-	54%
Outlet mean	2255	<LLOD	0.4	86	-	41%

Odour concentrations in the biofilter inlet and outlet samples at UOL06 on the 14th August 2013

Sample Position	Measured concentration			% removal		
	Odour [OU_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	160512	<LLOD	1.0	-	-	-
Inlet 2	153978	<LLOD	0.7	-	-	-
Inlet 3	124146	<LLOD	0.7	-	-	-
Inlet mean	145311	<LLOD	0.8	-	-	-
Outlet 1	4841	<LLOD	<LLOD	97	-	100
Outlet 2	5699	<LLOD	<LLOD	96	-	100
Outlet 3	4334	<LLOD	<LLOD	97	-	100
Outlet mean	4927	<LLOD	<LLOD	97	-	100

Odour concentrations in the biofilter inlet and outlet samples at UOL06 on the 19th September 2013

Sample Position	Measured concentration			% removal		
	Odour [OU_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	17494	< LLOD	7.1	-	-	-
Inlet 2	7448	< LLOD	11.0	-	-	-
Inlet 3	17085	< LLOD	7.1	-	-	-
Inlet mean	13057	< LLOD	8.4	-	-	-
Outlet 1	5009	< LLOD	0.61	71	-	91
Outlet 2	4296	< LLOD	0.54	42	-	95
Outlet 3	3899	< LLOD	0.41	77	-	94
Outlet mean	4378	< LLOD	0.52	64	-	94

Odour concentrations in the biofilter inlet and outlet samples at UOL06 on the 15th October 2013

Sample Position	Measured concentration			% removal		
	Odour [ou_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	5052	<LLOD	3.7	-	-	-
Inlet 2	7440	<LLOD	2.5	-	-	-
Inlet 3	3046	<LLOD	2.5	-	-	-
Inlet mean	4856	<LLOD	2.9	-	-	-
Outlet 1	868	<LLOD	0.2	80	-	95
Outlet 2	1031	<LLOD	0.5	84	-	81
Outlet 3	1452	<LLOD	0.4	43	-	83
Outlet mean	1299	<LLOD	0.4	69	-	86

Odour concentrations in the biofilter inlet and outlet samples at UOL07 on the 2nd October 2013

Sample Position	Measured concentration			% removal		
	Odour [OU_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet scrubber off 1	13033	0.3	3.8	-	-	-
Inlet scrubber off 2	7732	0.1	2.5	-	-	-
Inlet scrubber off 3	6502	<LLOD	2.8	-	-	-
Inlet scrubber off mean	8685	0.2	3.0	-	-	-
Inlet scrubber on 1	7298	0.4	0.1	-	-	-
Inlet scrubber on 2	16421	<LLOD	0.1	-	-	-
Inlet scrubber on 3	10345	0.4	0.5	-	-	-
Inlet scrubber on mean	10743	0.3	0.3	-	-	-
Outlet 1	1367	<LLOD	<0.1	81	100	100
Outlet 2	1024	<LLOD	<0.1	94	100	100
Outlet 3	683	<LLOD	<0.1	93	100	100
Outlet mean	985	<LLOD	<0.1	89	100	100

Odour concentrations in the biofilter inlet and outlet samples at UOL07 on the 12th November 2013

Sample Position	Measured concentration			% removal		
	Odour [OU_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet scrubber off 1	10789	0.3	65.0	-		
Inlet scrubber off 2	14401	0.6	60.0	-		
Inlet scrubber off 3	12110	0.3	56.0	-		
Inlet scrubber off mean	12345	0.4	60.2	-		
Inlet scrubber on 1	18660	0.7	8.3	-		
Inlet scrubber on 2	16624	1.0	5.4	-		
Inlet scrubber on 3	18660	0.6	6.1	-		
Inlet scrubber on mean	17955	0.8	6.6	-		
Outlet 1	1085	<LLOD	<LLOD	94	100	100
Outlet 2	1024	<LLOD	<LLOD	94	100	100
Outlet 3	912	<LLOD	<LLOD	95	100	100
Outlet mean	1004	<LLOD	<LLOD	94	100	100

Odour concentrations in the biofilter inlet and outlet samples at UOL08 on the 20th February 2013

Sample Position	Measured concentration			% removal		
	Odour [OU_E/m^3]	H_2S [mg/m^3]	NH_3 [mg/m^3]	Odour	H_2S	NH_3
Inlet 1	11666	0.75	<LLOD	-	-	-
Inlet 2	16894	-	-	-	-	-
Inlet 3	26975	-	-	-	-	-
Inlet mean	17453	0.75	<LLOD	-	-	-
Outlet 1	2062	<LLOD	<LLOD	85	100	-
Outlet 2	2483	-	-	88	-	-
Outlet 3	2402	-	-	90	-	-
Outlet mean	2308	<LLOD	<LLOD	88	100	-

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