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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: WR0606
2. Project title: Exposure-response relationships for bioaerosol emissions from waste treatment processes
3. Contractor organisation(s): IOM Consulting Ltd
4. Total Defra project costs (agreed fixed price): £ 45750
5. Project: start date .... 01 March 2007

   end date .... 18 January 2008

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so.. **YES** ☒ **NO** ☐

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(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

***This research was commissioned and funded by Defra. The views expressed reflect the research findings and the author's interpretation. The inclusion of or reference to any particular policy in this report should not be taken to imply that it has, or will be, endorsed by Defra*.**

INTRODUCTION

This study was undertaken to provide DEFRA with an updated understanding of the exposure-response relationship between bioaerosol emissions from waste treatment processes and the potential impact on human health. The aims were to:

- Collect and critically review the literature on the sources of bioaerosols from waste treatment processes, identify the components of greatest relevance to human health and their potential effect and to identify those within the population who may be most sensitive to effects;
- Establish exposure-response relationships for key bioaerosol components and health endpoints.
- Place this information into a regulatory context including determining which bioaerosol components should be monitored to adequately assess the potential impact of waste treatment activities; and
- Identify the knowledge gaps and make recommendations for further research.

This study considered the effects of airborne organic dust, viable (culturable) and non-viable bacterial and/or fungal particles, endotoxin and beta (1→3) glucans. Endotoxins are present as a structural component in some bacteria that is released when the cell wall is damaged. Beta(1→3) glucans ((1→3)β-D-glucan) are polysaccarides that form part of the cell wall of certain fungi, particularly *Aspergillus* species.

BIOAEROSOL EXPOSURE

Elevated levels of workplace exposure to bioaerosols are found throughout the waste industry including waste collection, materials recovery, composting and the storage of waste material prior to incineration. There are insufficient data to determine the importance of waste management activities in contributing to overall community exposure to bioaerosols. Background levels of exposure to bioaerosols are hugely variable with time and location and there are significant nonwaste sources including agricultural activities and natural emissions. Raised levels of community exposure to bioaerosol may arise within 250 m downwind of a composting facility and under rare circumstances at distances of up to 0.5 km.

HEALTH EFFECTS

The findings of a large number of individual studies and reviews of the published literature indicate that workplace exposure to bioaerosols in the waste industry is associated with increased risks of developing upper and lower respiratory symptoms and chronic respiratory illness. There is more limited evidence of increased risks of gastrointestinal illness or fatigue. Exposure levels vary within individual sectors suggesting that there is potential to reduce exposures through good practice. Specific studies of residential exposure to bioaerosols arising from the domestic storage of organic waste have found no excess of respiratory symptoms (possibly because exposure levels are low) but evidence of an association with skin symptoms. There has been relatively little investigation of the effects of community exposure to bioaerosols arising from waste management processes. Some extremely limited data suggest that living in close proximity to a compost facility may be associated with an increased risk of respiratory symptoms and the development of long term respiratory illness as well as symptoms such as excessive tiredness. On consideration of all the available studies, it is apparent that there are no clear thresholds of effect for different bioaerosol components and some individuals may experience adverse effects at background levels of exposure, in the absence of any waste derived bioaerosols.

SUSCEPTIBLE SUBGROUPS OF THE POPULATION

There is clear evidence of wide variability in individual sensitivity to bioaerosol exposure and the genetic factors underlying some of this variability have been extensively examined in recent years. A relatively substantial proportion of individuals (perhaps >10% of the population) may be susceptible to developing respiratory symptoms at levels of bioaerosol exposure that are encountered in the general community, in the absence of any specific point sources of bioaerosols. A large proportion of these individuals are likely to be atopic (ie have a tendency towards the development of allergic disease). In addition, bioaerosol exposure, particularly endotoxin, may enhance the response of individuals with asthma to allergens or other airborne pollutants. A small proportion of individuals with asthma and also some cystic fibrosis patients have a greatly increased risk of developing hypersensitivity to specific mould species leading to serious respiratory illness at ambient levels of exposure. A small proportion of individuals have highly compromised immune systems and are at particular risk of invasive fungal infection.

USE OF EXPOSURE-RESPONSE INFORMATION FOR BIOAEROSOLS IN REGULATION

In principle the exposure-response information collated in this project could help inform the setting of guideline levels of exposure, emissions limits or stand off distances intended to control community exposure to bioaerosol to concentrations below those associated with adverse effects. If combined with the exposure information, the exposure-response information could be used to quantify benefits arising from improved regulation of bioaerosol emissions and in the comparison of different regulatory options (including the “do nothing” option).

Air quality guidelines provide a clear guide to acceptable exposure levels. There is a strong evidence base for the development of guidelines for endotoxin, a much weaker evidence base for organic dust, fungi, microbes or beta (1→3) glucan and insufficient evidence for bacteria. It would be difficult to demonstrate compliance through measurement or through the use of dispersion modelling. Similarly it will be difficult to establish and monitor compliance with emissions limits. Alternative approaches include using marker species to monitor the specific impact of waste on community bioaerosol exposure or the development of modified PM_{10} objectives for use in the vicinity of waste operations. Stand off distances would be easy to implement for new sites but not at existing sites. There is little information to support the development of appropriate stand off distances for different types and sizes of process. A code of best practice is an attractive regulatory option because best practice would anyway be required of operators as part of permitting and licensing conditions and would have to be implemented to comply with any air quality guidelines. It is easy to demonstrate compliance with best practice during site inspection, but less easy to demonstrate compliance between inspections or that community exposure is controlled to acceptable levels. A requirement for ISO14401 might reduce the inspection burden on regulatory officers.

KNOWLEDGE GAPS

It is not clear whether bioaerosol emissions from waste actually present a significant public health problem, although the information collected in this study could be used to make a more quantitative assessment of the potential scale of effects. There are insufficient data to set exposure guidelines for most components of bioaerosols other than endotoxin. In the absence of information about levels of endotoxin in ambient air, it is unclear whether such guidelines could be achieved.

Most studies of the health of waste workers have examined the immediate effects of exposure to bioaerosols and there is very little information about the long term health effects of bioaerosols in the waste industry. Experience from the agricultural and cotton industries suggests that long term workplace exposure to bioaerosols is associated with an increased risk of chronic respiratory illness.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
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   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

This research was commissioned and funded by Defra. The views expressed reflect the research findings and the author's interpretation. The inclusion of or reference to any particular policy in this report should not be taken to imply that it has, or will be, endorsed by Defra.

INTRODUCTION

This study was undertaken to provide DEFRA with an updated understanding of the exposure-response relationship between bioaerosol emissions from waste treatment processes and the potential impact on human health.

There is an increasing public awareness and interest in the changing profile of waste management in the UK and a need to fully understand the real and perceived hazards and risks associated with different waste management options. Bioaerosols are complex mixtures and different components of the mix have variable potentials to cause illness in different individuals. For example, fungi and bacteria may cause illness directly through infection or indirectly as a result of fungal or bacterial toxins such as endotoxin or glucans. Alternatively complaints of ill-health may arise as a result of allergic reaction to specific bioaerosol components or as a result of exposure to malodours or chemical components of the aerosol mix.

The overall aims of the study were:

- To collect and critically review the literature on the sources of bioaerosols from waste treatment processes, identify the components of greatest relevance to human health and their potential effect, including consideration of sensitisation, allergy, infection and toxicity and sensitive receptors, such as asthma sufferers, the old, the very young, and immuno-suppressed individuals, that will be more at risk from opportunist pathogens (e.g. *Aspergillus fumigatus*) than the general public or workers close to the source;

- To establish exposure-response relationships for key bioaerosol components and health endpoints.

- To place this information into a regulatory context including determining which bioaerosol components should be monitored to adequately assess the potential impact of waste treatment activities; and

- To identify the knowledge gaps and make recommendations for further research.

Specific objectives were to:

- Review the methods used to measure bioaerosol exposure arising from waste management activities, particularly in the context of available epidemiological information;
- Determine the nature of bioaerosols emitted from different waste handling processes;
- Review background levels of exposure to bioaerosols and levels of workplace and community exposure arising from waste management activities;
- Determine the importance of waste management activities as an influence on population exposure to bioaerosols;
- Review the health effects associated with bioaerosol exposure;
- Describe the exposure-response information available from studies of bioaerosol exposure in the waste industry;
- Describe exposure-response information for bioaerosol from studies of bioaerosol exposure in other industries or in the general community;
- Determine a no effects level and/or lowest effects level, if possible, and determine which bioaerosol components have important potential impacts on health;
- Comment on the likely exposure-response relationships in potentially susceptible subgroups of the population; and
- Consider how the available exposure-response information could be used to inform the development of best practice guidelines and quality standards for waste management activities and in the evaluation of alternative strategies of biowaste management.

Information was sought from earlier reviews of the health effects of bioaerosols and a series of searches using PubMed (a free database of abstracts of the peer reviewed literature available from the internet). Searches were undertaken for studies about bioaerosols, exposures and health effects in workers in the waste industry, the effects of endotoxin exposure and more general information about community exposure to bioaerosols.

MAJOR COMPONENTS OF BIOAEROSOL

Dust

Concentrations of airborne particulate matter or dust are widely reported in studies of bioaerosols emitted by the waste industry. A range of metrics are used:

- Inhalable dust fraction: the size fraction of airborne particles that are able to penetrate the airways and may be deposited within the respiratory system;

- Respirable dust fraction: the size fraction of airborne particles that may be deposited in the gas-exchange region of the lung;
- PM_{10} (thoracic function): the size fraction of airborne particles that may be deposited in the lung; and
- $PM_{2.5}$ (high risk respirable): the size fraction of airborne particles that may be deposited in the gas-exchange region of the lung in those with compromised respiratory health.

Bacteria

Concentrations of bacteria in air can be described in terms of counts of viable (culturable) and non-viable bacterial particles. A number of studies specifically refer to actinobacteria, more commonly termed Actinomycetes. The actinomycetes are a group of Gram-positive bacteria that play an important role in decomposition of organic materials and produce external spores, similar to fungi.

Endotoxin

Endotoxins are present as a structural component in some bacteria that is released when the cell wall is damaged. Endotoxin is not a single uniform substance and includes lipopolysaccharides (LPS) or lipo-oligo-saccharides (LOS). The symptoms of many infections with pathogenic Gram-negative bacteria are due to endotoxin.

Peptidoglycan

Peptidoglycan, also known as murein, is a polymer consisting of sugars and amino acids that forms a homogeneous layer outside the plasma membrane of bacteria. It has not been widely used as a marker of bioaerosol exposure in the waste industry. Peptidoglycan and partial structures of petidoglycan are associated with symptoms typical of bacterial infections such as fever, inflammation, leukocytosis and lymphocyte stimulation.

Fungi

Fungi and moulds play a major role in the decomposition of organic waste. Fungi are generally present in ambient air in the form of spores. Spores degrade rapidly in air and both viable spores and the remains of spores that are no longer viable may be present in air.

Certain types of moulds produce toxic secondary metabolites that are termed mycotoxins that may play a role in the causation of adverse health effects. Exposures to mycotoxins have not been widely evaluated in the waste industry.

Beta(1→3) glucan

Beta (1→3) glucans ((1→3)β-D-glucan) are polysaccarides that form part of the cell wall of certain fungi, particularly *Aspergillus* species. Beta glucans also occur in some cereals such as barley, oats, rye and wheat. Beta (1→3) glucan is associated with effects on the immune system.

MEASUREMENT OF BIOAEROSOL EXPOSURE

Overview of available methods

Despite considerable research effort, a wide range of parameters are used to characterise bioaerosol exposure and there is considerable variability in the way that individual parameters are determined. There is also interlaboratory variability in the determination of individual parameters using single assays.

The most commonly reported parameters are dust, viable fungi, viable bacteria and endotoxin. The fungi and/or bacteria may be subdivided into mesophilic and thermophilic types and/or xerophilic types (species thriving at temperatures of 25-40 ^{o}C or over 45 ^{o}C or in very dry conditions, respectively). Some studies have also reported beta (1→3) glucan levels. Less commonly total fungi and/or bacteria counts including both viable and nonviable particles have been reported.

A wide range of instruments have been used to capture bioaerosols on filter, in fluid or onto gel. One of the issues with the collection of viable microorganisms is the preservation of their viability during the actual sampling process (eg minimising collision with the sampler) and subsequent to collection. These considerations have driven the development of a wide range of collection devices with very variable collection efficiencies. Side by side comparisons of sampling devices have demonstrated considerable variability in performance, particularly in respect of viable microorganisms that are destroyed to greater or lesser degrees by different sampling devices and protocols. Generally studies of viable organisms have used gel or fluid media to reduce the loss of viability of organisms within the sampler although studies of personal exposure have collected samples on filter using IOM heads or other personal sampling devices. Samples collected on filter must be quickly transferred into a fluid once sampling is complete. The most commonly used samplers for static sampling are the Andersen impactor which collects onto a gel and liquid filled impingers (particularly the All Glass Impinger – AGI30). The Andersen impactor may be used with one, two or six separate sampling plates each representing a different size fraction. Samples for endotoxin analysis can be collected as dust on filter or using a liquid impinger. Samplers for beta (1→3) glucan are typically collected onto filter. Because of the difficulties in preserving organism viability during sampling, sample times for bioaerosol measurement tend to be very short from a few minutes to an hour and half whereas bioaerosol concentrations can vary dramatically in the space of a few hours. The EA (2004) highlight the importance of acquiring large number of samples over an extended period, in order to gain a representative picture of bioaerosol concentrations.

Conditions during the transport and storage of samples can have a profound effect on apparent bioaerosol concentrations. Samples for microbial analysis should be kept cool and analysed within a defined time period to ensure viability is preserved. The Composting Association have recommended storage of samples at a temperature of less than 4^{o}C and the initiation of laboratory processing within 12 hours. Microbial growth under damp conditions or desiccation and disintegration under dry conditions could also give rise to an erroneously high measurement of endotoxin, although poor sample storage can also lead to a loss of activity. Samples for endotoxin analysis can be frozen for periods of months before analysis, but as endotoxin is also destroyed by repeated freeze-thaw cycles, it is important to ensure that samples are only frozen and defrosted once.

The analysis for viable organisms involves culturing the sample in a suitable medium and at an appropriate temperature to support the growth of the organisms of interest – either bacteria or fungi and at temperatures appropriate to mesophilic and thermophilic species. The concentrations of micro-organisms in different studies are not necessarily comparable as the exact fraction of bioaerosol considered may not be equivalent. The analysis is then performed by counting the number of colonies that develop. Counts of total viable and nonviable organisms are made microscopically using fluorescence staining to aid identification. There are uncertainties in the counting of both viable and nonviable organisms that arise from the random distribution of organisms within samples and the random selection of fields of view for enumeration.

A number of recent studies have explored alternative approaches to the characterisation of airborne microbial samples. These include the use of gas chromatography – mass spectroscopy (GC-MS) for the identification of characteristic compounds associated with specific groups or specific species of microbe eg 3-hydroxy fatty acids (markers of endotoxin), ergosterol (marker of fungal biomass), and muramic acid (marker of peptidoglycan/bacterial biomass). GC-MS can also be used to identify characteristic compounds emitted by specific microbial species. A number of investigators have investigated the use of quantitative polymerase chain reaction (PCR) to determine the presence and quantity of specific target DNA sequences that can be linked to individual fungal or bacterial species. A few studies have used flow cytometry to analyse bioaerosol samples. None of these alternative assessment methods have been used in epidemiological investigations of the health effects of bioaerosol exposure in the waste industry and they are of limited relevance to the consideration of exposure-response relationships based on existing studies.

Endotoxin is most commonly measured using a chromogenic Limulus amebocyte lysate (LAL) assay based on blood derived from the horseshoe crab. There are several commercial suppliers of kits for the analysis and IOM has found that there is considerable variation in the reliability and sensitivity of kits originating from different suppliers. Two different approaches have been used with the LAL assay. The reaction can either be allowed to progress for a fixed time period and the concentration of endotoxin assessed from the colour intensity at the end of that period (endpoint assay) or the concentration can be assessed from the rate of change of colour during the reaction (kinetic assay). There is not a consistent correlation in the results obtained using the two methods. A smaller number of studies have used GC-MS to determine the LPS content of samples. LPS levels reported using GC-MS are not directly comparable with endotoxin levels determined in the LAL assay.

Several assays have been developed for the measurement of beta (1→3) glucan, in medicine because of its clinical importance in the detection and quantification of fungal infections:

- Glucan-specific LAL assay;
- Inhibition Enzyme-Linked ImmunoSorbent Assay (ELISA); and
- Sandwich ELISA.

The intercomparability of these methods in the assessment of exposures in the waste industry is uncertain.

Towards method standardisation

The Environment Agency (2004) recommends that bioaerosols are collected by active impaction onto agar using Andersen or split samplers or liquid impingers followed by analysis for viable micro-organisms based on cultivation of the sample and colony counting or counting of total micro-organisms using optical microscopy and staining. A draft EA report indicates that in the future samples may be collected onto filter and analysis is likely to focus on thermophilic actinomycetes and Aspergillus fumigatus. The Composting Association (1999) has recommended the use of the Andersen sampler to collect bioaerosols and sampling at a minimum of three locations: upwind of the site, downwind of the site, and adjacent to the nearest sensitive receptor (occupied building). They recommend the collection of relevant weather data and stipulates that sampling should not be performed at temperatures less the $5^{o}C$ or during precipitation.

A CEN (European Committee for Standardization) working group on the "Measurement of bioaerosols in ambient air and emissions"(CEN/TC 264/WG 28) has recently been formed but this group is still at the stage of investigating current practice in different member states and no draft protocols have been proposed for wider adoption.

The American Society for Testing and Materials (ASTM) method E884-82 recommends use of a multistage impactor (eg Andersen sampler) and all-glass liquid impingers with sampling times of 30 minutes and up to 1.5 hours, respectively. It is recommended that sampling is undertaken at least one site 300 m upwind and one site 100 m downwind of the site (three replicates upwind and five downwind).

In addition to standardisation of measurement methods there is a need for a harmonised approach to sampling strategy.

Biomarkers of exposure

There are no widely used biomarkers of exposure to bioaerosol. Specific IgG antibodies to moulds and actinomycetes do not appear to be an effective measure of exposure in waste workers in comparison to unexposed controls. Various studies have assessed inflammatory markers in nasal lavage and sputum, but these markers are not specific to bioaerosol exposure.

Measurement of bioaerosol exposure in published epidemiological studies

Uncertainty in bioaerosol measurement is a major issue affecting the interpretation of exposure-response information. The comparability of measurements of individual measures of bioaerosol exposure made by different groups is likely to be limited. The use of slightly different exposure metrics by different groups further limits interstudy comparison. It is unclear how well published data in epidemiological studies represent actual levels of exposure.

BACKGROUND LEVELS OF BIOAEROSOL EXPOSURE

Background levels of exposure to bioaerosol are hugely variable with time and location.

Fungal concentrations in outdoor air vary by location and season. Both UK data and the results of studies elsewhere suggest that concentrations in urban air are typically less than 1000 $cfum^{-3}$ but may be considerably higher, particularly during the autumn (Swan *et al*, 2003). Extensive measurements made by DSTL (Defence Science & Technology Laboratory) during the 1990s demonstrated that concentrations of individual microbial species varied from below detection limit levels to thousands of organisms/m^3 on different days (unpublished data supplied to IOM by the EA). Concentrations also varied during the course of individual days. For example, measurements of Aspergillus/penicillium made in Birmingham Botanic Gardens during the course of one day ranged from 439 to 16176 spores/m^3 rising to 21231 spores/m^3 early the next day and then falling to 472 spores/m^3 by that evening. There is less information available about concentrations of bacteria. Allowing for uncertainties in the measurement data and the small quantity of data available, it seems probable that typical bacterial concentrations in urban air are less than 1000 $cfum^{-3}$ (Swan *et al*, 2003).

Most studies of bioaerosol exposure in rural areas have focussed on occupational exposure associated with intensive livestock rearing and there has also been some interest in the impacts of sewage sludge spreading. There is very little information about typical concentrations of bacteria or fungi in rural areas.

Both external air quality and building dampness play an important role in governing exposure to airborne moulds in indoor environments with reported concentrations in indoor air ranging from <100 to 20000 $cfum^{-3}$ (Horner *et al*, 2004; Lee *et al*, 2006; Chao *et al*, 2002; MacIntosh *et al*, 2006; Shelton *et al*, 2002; Gorny & Dutkiewicz, 2002). Concentrations of bacteria in indoor environments are typically about 100 $cfum^{-3}$ but may be considerably higher in some environments (Tsai and Macher, 2005; Bouillard *et al*, 2005 Gorny & Dutkiewicz, 2002; Krajewski *et al* , 2001b, Lee *et al* , 2006).

Typical endotoxin levels in outdoor urban air are less than 1 EUm^{-3}, but slightly higher concentrations may arise in some rural locations where agricultural activities emit endotoxin (Madsen, 2006). Indoor concentrations of endotoxin are heavily influenced by environmental tobacco smoke (Sebastian *et al*, 2006).

Background concentrations of bacteria and fungi measured in studies of the impacts of waste management processes tend to be higher than those typically found in indoor air or outdoor air in urban areas but are comparable to levels reported in some buildings with damp problems. Background concentrations of endotoxin reported in studies of waste management processes are about 2 EUm^{-3}, comparable with those found in urban air.

BIOAEROSOL EMISSIONS FROM WASTE HANDLING PROCESSES

The limited data available suggest the nature of bioaerosol emissions from stored waste in the home and its subsequent collection varies depending on the waste composition and its storage conditions. The potential for exposure to bioaerosols and biologically-active liquid leachate is anticipated to increase given the emphasis being placed on alternative and more sustainable waste management practices (e.g. composting, recycling) in homes across the UK and elsewhere. There is potential to minimize exposure, however, through good practice.

Bioaerosol emissions during composting are greatest during active handling of the waste including initial shredding and subsequent turning operations and are likely to have the greatest impact on local bioaerosol concentrations where these operations are conducted out of doors. A number of studies have investigated the changes in the microbial population in waste during the composting process which is likely to be a major influence on emissions. During the early stages bacteria dominate and there is an initial increase in bacterial counts as temperature increases and mesophilic species are replaced by thermophilic species. Provided sufficient heat is generated during the composting process, the number and diversity of bacteria is reduced as temperature increases and any human pathogens should be destroyed. Fungal species dominate during cooling and stabilisation of the compost. Emissions of volatile organic compounds (VOCs; and odour arising from VOCs) are influenced by the microbial population present in composting waste.

There is very little information about bioaerosol emissions from landfill or other waste handling operations, although data are available about workplace exposures in these other waste sectors that provide some indication of the variability in emissions rates and exposure control between sites.

Several measures have been suggested to reduce the build up of bioaerosols, VOCs and any biologically-active liquid during the storage of household waste prior to collection, including timely waste preparation and good storage container hygiene within the household.

A number of measures have been suggested to reduce emissions from commercial composting operations including appropriate control of moisture content and airflow during composting, using water mist to dampen dust over screen conveyers, providing adequate ventilation in buildings and using in-vessel systems. Biofiltration may be an effective method for reducing odour nuisance and may also reduce microbial counts.

Several studies have demonstrated the importance of heat in the reduction of the bacterial content of wastes, particularly in faecal waste from animals. These studies have also demonstrated, however, that incomplete sterilisation or subsequent recontamination by leachate may lead to bacteria recolonising the waste during maturation and cooling of the compost. Current practices may be insufficient to completely remove pathogenic species from the end product and therefore, potentially from emissions.

BIOAEROSOL EXPOSURES ASSOCIATED WITH WASTE HANDLING PROCESSES

Waste collection

The exposure of waste collection workers to bioaerosols has been investigated in a number of studies that have reported widely varying results (Heldal *et al* 2003a; Krajewski *et al*, 2002; Thorn 2001; Wouters *et al*, 2002; Bunger *et al*, 2000). Reported mean or median concentrations of viable fungi vary from 30 to 10000 $cfum^{-3}$, mean/median concentrations of bacteria range from 1700 to 80000 $cfum^{-3}$, mean/median dust concentrations range from 0.4 to 8 mgm^{-3}, mean/median endotoxin concentrations from 13 to about 370 EUm^{-3} and mean/median beta (1→3) glucan concentrations range from about 10 to more than 1000 ngm^{-3}. There are clear differences in the pattern of exposure in different studies with the highest levels of exposure to dust, fungi, endotoxin or beta (1→3) glucan arising in separate studies. The results of a Canadian study suggested that levels of fungal exposure were greater where green waste was collected on a fortnightly rather than weekly basis (Lavoie *et al*, 2006).

Waste transfer stations

There is little published information about bioaerosol exposure at waste transfer stations. Particularly high concentrations of total fungi and bacteria (10^6 cfum^{-3}) were reported in the dumping pit at one waste-transfer plant (Van Tongeren *et al*, 1997).

Composting

There has been considerable interest in bioaerosol emissions and exposure associated with composting. Reported mean/median workplace exposure concentrations are hugely variable (eg Van Tongeren *et al*, 1997; Krajewski *et al*, 2002; Douwes *et al*, 2000). For dust, they range from about 0.5-5 mgm^{-3}, for bacteria from about 5 x10^3 to 10^7 cfum^{-3} and for fungi from about 20 to 10^7 cfum^{-3}. Reported mean/median endotoxin concentrations range from less than 100 to over 700 EUm^{-3} and mean/median beta (1→3) glucan concentrations range from about 0.5-5 ugm^{-3}.

Several groups have investigated community exposure to bioaerosols emitted from composting. Concentrations of >10^5 cfum^{-3} of thermophilic actinomycetes, moulds, and total bacteria have been reported 200 m from a large composting site, dropping to near background concentrations within 300 m (Swan *et al*, 2003; Herr *et al*, 2003, Hryhorczuk *et al*, 2001). The results of several other studies also suggest that microbial counts generally drop to background levels within 300 m although raised microbial concentrations may occasionally arise at distances of up to about 0.5 km from composting operations (Syzdek and Haynes, 1995; Kothary *et al* 1984; Schilling *et al*, 1999). In an investigation of odour nuisance, compost-derived and microbial volatile organic compounds (MVOC) were found at distances of up to 800m from the composting facilities.

The Environment Agency for England and Wales has sponsored several studies of bioaerosol emissions from composting and municipal solid waste activities. In a study of three sites, Wheeler *et al* (2001) found that all operations released bioaerosols but emissions were very variable due to the batchwise nature of the composting process. On some days minimal concentrations were measured within the site or within 5 or 10 m of the site boundary whereas on other days concentrations of viable bacteria exceeded 7 x10^5 cfum^{-3} at one site and 4 x10^5 cfum^{-3} at the other two sites. Concentrations of bioaerosols were shown to decline with distance from the site and concentrations measured at distances of 100 – 150 m were mostly close to zero. Concentrations of viable bacteria measured 80 m from the site were generally less than 100 cfum^{-3} and the levels at 150 m were less than 5 cfum^{-3}.

Materials recovery facilities

There have been relatively few studies of bioaerosol exposure at materials recovery facilities (MRFs). Reported median/mean dust concentrations for MRFs are between about 2 and 8 mgm^{-3} and are associated with endotoxin levels of about 50 – 600 EUngm^{-3} (Gladding *et al*, 2003; Van Tongeran *et al*, 1997; Krejewski *et al*, 2002 and Kirviranta *et al*, 1999). In other studies that have examined microbial exposures, mean total viable bacterial counts have ranged from less than 10^3 to more than 10^6 cfum^{-3} and mean fungal counts have ranged from about 10^3 to about 10^6 cfum^{-3}. Waste sorting is associated with particularly high exposures in some plants with reported exposures to moulds that exceed 10^5 cfum^{-3} and exposures to bacteria exceeded 10^4 cfum^{-3}. Concentrations of beta (1→3) glucan of about 15 ngm^{-3} were reported in a single study (Gladding *et al*, 2003).

Other waste treatment processes

There has been little investigation of bioaerosol exposure arising at waste incineration plants but the limited available data suggest that exposure concentrations associated with waste storage may be extremely high in some plants. Tolvanen and Hänninen (2005) reported mean concentrations of 3.3 mgm^{-3} for dust, 24500 and 2670 cfum^{-3} for mesophilic and thermophilic bacteria, 118225 and 5235 cfum^{-3} for mesophilic and thermophilic fungi and 39500 EUm^{-3} for endotoxin. The results of two studies of the production of refuse-derived fuel (RDF) indicate variability in levels of bioaerosol exposure in different plants. Mahar *et al* (1999, 2002) reported mean personal exposure concentrations of 0.50 mgm^{-3} for total dust, 29.0 EU m^{-3} (2.9 ngm^{-3}) for endotoxin, and 6.8 x 10^5 total organisms m^{-3} (viable and nonviable) compared with total concentration of microbes (viable and nonviable) of approximately 4.8 x 10^6 particles m^{-3} reported for another plant.

There is little information about bioaerosol exposure in relation to landfill operations. Reported mean exposure concentrations for landfill workers for dust range up to 1.5 mgm^{-3}, concentrations of fungi range from <100 cfu m^{-3} to more than 2.6x10^5 spores/m^3, concentrations of thermophilic bacteria range from <10^3 to 21x10^3 organisms/m^3 and concentrations of total bacteria of up to 8.2 x10^5/m^3 have been reported (Swan *et al*, 2004). Reported workplace exposures to endotoxin are variable from <70 EUm^{-3} at one site (Swan *et al*, 2004) to 4000 EUm^{-3} (Krajewski *et al*, 2002). Concentrations of bioaerosols reported on landfill sites downwind of active operations are generally lower than the personal exposure concentrations reported for workers. Bioaerosol concentrations measured downwind of active operations are not consistently higher than those measured upwind.

Factors influencing bioaerosol exposure

Elevated levels of workplace exposure to bioaerosol are found widely throughout the waste industry including waste collection, materials recovery, composting and the storage of waste material prior to incineration. Exposure levels in most sectors tend to be higher during the summer but are not clearly linked with waste composition. There is limited evidence that prolonged waste storage may lead to increased exposure concentrations and more substantive evidence that increased activity levels are associated with increased bioaerosol exposures. Exposure levels vary within individual sectors suggesting that there is potential to reduce exposures through good practice.

Community exposure to bioaerosol emitted from waste management

There are insufficient data to determine the importance of waste management activities in contributing to overall community exposure to bioaerosol. Raised levels of community exposure to bioaerosol may arise within 250 m downwind of a composting facility and under rare circumstances at distances of up to 0.5 km. In a UK study, elevated concentrations arose intermittently at 100 m from the site boundary but on other occasions, on-site concentrations and concentrations close to the site boundary were close to zero (Wheeler *et al*, 2001).

HEALTH EFFECTS

Overview

The findings of a large number of individual studies and reviews of the published literature indicate that workplace exposure to bioaerosols in the waste industry is associated with increased risks of developing upper and lower respiratory symptoms and chronic respiratory illness. There is more limited evidence of increased risks of gastrointestinal illness or fatigue. Specific studies of residential exposure to bioaerosols arising from the domestic storage of organic waste have found no excess of respiratory symptoms (possibly because exposure levels are low) but evidence of an association with skin symptoms. There has been relatively little investigation of the effects of community exposure to bioaerosol arising from waste processes. Some extremely limited data suggest that living in close proximity to a compost facility may be associated with an increased risk of respiratory symptoms and the development of long term respiratory illness as well as symptoms such as excessive tiredness.

Fungi

The results of published studies suggest that exposure to fungi in the waste industry is associated with increased risks of developing respiratory illness, irritation of the eyes, nose and throat, impaired lung function and allergic symptoms (Bunger *et al*, 2000; Heldel *et al*, 2003 ab; Heldal & Eduard, 2004). Community exposure to elevated concentrations of fungi arising from waste management processes may also be associated with increased risks of respiratory illness (Herr *et al*, 2003). Some individuals are particularly susceptible to airborne fungi with cases of hypersensitivity reactions and the rare development of fungal infections such as aspergillosis in exposed workers. It is not clear whether these conditions have arisen in members of the general community as a result of waste handling operations. It has been speculated that high concentrations of thermo-tolerant/thermophilic actinomycetes (bacteria) and filamentous fungi at composting plants gave rise to a different spectrum of effects from those observed with other organic dusts.

There is limited evidence that the adverse effects of fungal exposure may extend beyond the respiratory system, although it is difficult to know whether fungi have been the causal agent in giving rise to reported effects or merely a marker for some other unmeasured component of bioaerosol. Reported effects include nausea and diarrhoea (Ivens *et al*, 1997, 1999).

Several studies have demonstrated an association between beta (1→3) glucan exposure and adverse respiratory and gastrointestinal effects and/or excessive fatigue in waste workers. Other studies, however, have failed to demonstrate significant relationships or have lacked the power to demonstrate a specific role for beta (1→3) glucan in the development of reported effects.

Bacteria, endotoxin and peptidoglycan

The role of airborne bacteria in contributing to the respiratory symptoms observed in waste workers is less clearly established than that of fungi. One study found that “rod-shaped” bacteria were associated with nose irritation and unusual tiredness and other studies have reported increased rates of infectious illness in waste workers.

The role of endotoxin has been extensively examined and results of a number of studies suggest an association between exposure to endotoxin and the development of respiratory illness, particularly in waste collection workers and compost workers (eg Gladding *et al*, 2003; Douwes *et al*, 2000; Thorn *et al*, 1998; Bunger *et al*, 2007; Wouters *et al*, 2002). The importance of the results of a small number of studies that failed to find a significant link between endotoxin and respiratory health is uncertain. It is possible that the absence of effect was due to poor exposure characterisation, the possibility that effects attributed to endotoxin in other studies were in fact due to confounding by some other unmeasured bioaerosol component that co-varied with endotoxin or was simply a chance finding. There is limited evidence linking endotoxin exposure to increased risks of gastrointestinal illness, but it is unclear whether observed effects were specifically due to endotoxin.

Peptidoglycan may be associated with airways inflammation but its effect has not been extensively investigated in waste workers.

Odour

Communities living near some waste management processes may experience severe odour nuisance at pollutant concentrations that are far smaller than those associated with toxic effects. Although one study of a composting facility found no association between irritative airway complaints and residential odour annoyance, other studies of odour arising from other processes (eg intensive livestock rearing) have found evidence of increased self-reported symptoms such as headache, nausea and fatigue. The results of experimental studies suggest that perception may play an important role in the development of symptoms.

EXPOSURE-RESPONSE INFORMATION

Studies of the waste industry

Organic dust: Limited data suggest that eye and nasal irritation may arise at dust levels of 0.2 mgm^{-3} (Heldal & Eduard, 2004; Kennedy *et al*, 2004) and respiratory symptoms such as chest tightness and wheeze may arise at about 1-2 mgm^{-3}(Douwes *et al*, 2000).

Bacteria: Bacterial exposures have not been widely measured in epidemiological studies of the waste industry. Adverse effects on respiratory health and more general health (excessive tiredness) have been reported at concentrations exceeding 10^6 total bacteria/m^3 or 10^5 $cfum^{-3}$ (Heldal & Eduard, 2004).

Endotoxin: Endotoxin is a widely used measure of bioaerosol exposure. The results of most studies suggest that concentrations exceeding 50 EU m^{-3} are associated with an increased risk of respiratory symptoms (Gladding *et al*, 2003; Douwes *et al*, 2000; Thorn *et al*, 1998; Bunger *et al*, 2007; Wouters *et al*, 2002). Other studies have, however, failed to detect adverse effects at exposure levels of 200-300 EU m^{-3} (Douwes *et al*, 2000). There are also limited data that are suggestive of increased risks of nasal irritation, cough, unusual tiredness and diarrhoea at exposure levels <10 EUm^{-3}(Mahar *et al*, 1999; Heldel *et al*, 2003 a and b; Heldal & Eduard, 2004).

Fungi: Adverse effects on respiratory health have been generally reported at concentrations greater than 10^4 $cfum^{-3}$ (Bunger *et al*, 2000) with limited data suggesting that gastrointestinal effects may arise at concentrations of less than 10^5 $cfum^{-3}$ (Ivens *et al*, 1999). Mild inflammation of the upper airways has been observed in workers exposed to concentrations of 10^3 to 10^6 total spores/m^3 as assessed by microscopy and gastrointestinal symptoms have been observed at spore concentrations of 10^5 spores/m^3 (Heldal *et al*, 2003a).

Beta (1→3) glucan: The results of several studies suggest that respiratory symptoms and airways inflammation are more prevalent in workers exposed to concentrations exceeding 25 ngm^{-3} than at lower levels of exposure (Wouters *et al*, 2002; Heldal *et al*, 2003a and b; Gladding *et al*, 2003).

Studies in other work environments

Organic dust: Prolonged workplace exposure to organic dusts in the cotton, agricultural and timber industries is associated with chronic respiratory illness. Respiratory symptoms may arise following prolonged exposure to concentrations as low as 0.2 mgm^{-3} (Simpson *et al*, 1998). Serious irreversible conditions are normally associated with exposure concentrations exceeding 1.2 mgm^{-3}.

Bacteria: There are no exposure-response data relevant to bacterial exposures in the waste industry. Exposure to Actinomycetes species in agriculture has been linked to hypersensitivity pneumonitis and a small proportion of waste workers may similarly be at risk. Hypersensitivity is associated with different species in different places and environments, depending on the bacteria present. Exposure levels in the general community are unlikely to give rise to hypersensitivity.

Endotoxin: A number of studies have demonstrated exposure-response relationships in exposed workers. In a cross sectional study across 9 industries, the prevalence of symptoms ranged from 3% at 1 ngm^{-3}, 10% at 10 ngm^{-3}, 18% at 100 ngm^{-3} to 25% at 1000 ngm^{-3} (Simpson *et al*, 1998).

*Fung*i: Few of the many studies of mould-exposed workers have quantified airborne concentrations. An increased risk of respiratory symptoms has been reported in some studies at exposure concentrations of about 10^6 $cfum^{-3}$ (eg Eduard *et al,* 1993) whereas other studies have reported effects at less than 10^4 $cfum^{-3}$ (eg Dahlqvist *et al*,

1992) More severe respiratory symptoms including hypersensitivity pneumonitis have been reported at concentrations of 10^6-10^9 cfum^{-3} (Nordic Expert Group, 2006).

Beta (1→3) glucan: There is limited evidence of effects at concentrations less than 10 ngm^{-3} but there is no evidence of effects below 1 ngm^{-3} (Rylander, 1999). Although, exposure-response relationships have been reported, it is unclear that beta (*1→3*) glucan was the causal agent for effects.

Community exposure

Organic dust, bacteria and endotoxin: Community levels of exposure to endotoxin and organic dust are very low and no exposure-response information has been published. Herr *et al* (2004b) presented limited data suggesting exposure to microbial concentrations exceeding 10^5 cfum^{-3} in the vicinity of a composting facility was associated with increased risks of respiratory and gastrointestinal symptoms, headache and fatigue.

Fungi: Studies of the general population have demonstrated that a large proportion of individuals are sensitised to one or more common moulds and that mould sensitisation is associated with increased risks of asthma and allergic rhinitis. There is no clear relationship between respiratory symptoms and mould concentrations in air, but this may partly reflect inadequacies in the assessment of exposure. The results of a study in children with asthma suggest that it is possible that exposure levels as low as 350 cfum^{-3} in indoor air, may be sufficient to cause mild adverse effects on respiratory health. Adverse effects have been more commonly reported at concentrations exceeding 10^3 cfum^{-3} (Nordic Expert Group, 2006). A small increased risk of fatal asthma attacks has been reported at spore concentrations exceeding 10^3/m^3 in outdoor air (Targonski *et al*, 1995).

Experimental studies

Studies in human volunteers confirm the potential importance of endotoxin and airborne fungi in giving rise to adverse health effects but are less informative about the effects of beta (1→3) glucan. Fungi including some of the Aspergillus moulds have been observed to give rise to adverse effects in the absence of an allergic response. Experimental findings with endotoxin are consistent with the results of workplace studies that suggest a substantially greater prevalence of adverse effects at exposures exceeding 50 EUm^{-3} than at lower concentrations.

The results of animal experiments confirm that bioaerosols provoke an inflammatory response in the airways at relatively low levels of exposures and the role of endotoxin in enhancing the allergic response to other bioaerosol components.

No effects and lowest observed effects levels

Table 1 summarises the exposure-response information reviewed in this report.

Table 1: Summary exposure-response information for bioaerosols

Bioaerosol component	**Health endpoint**	**Exposure-response information**	**Study population**
Organic dust	Irritation of eyes and nose Chest tightness and wheeze Chronic respiratory illness	Symptoms reported at 200 ugm^{-3} Reported at 1 -2 mgm^{-3}, prevalence increases with concentration May arise at concentrations >0.3 mgm^{-3} but normally associated with concentrations >1.2 mgm^{-3}.	Waste workers Various industries Cotton workers
Fungi	Respiratory symptoms, nausea, headache etc	Symptoms reported at >10^4 cfu m^{-3} and between 10^3-10^6 spores m^{-3} Increased symptoms associated with concentrations of 2000 cfum^{-3} in indoor air or 1000 spores m^{-3} in outdoor air Mild adverse respiratory effects may arise at concentrations ≥ 350 cfum^{-3} in household air	Waste workers General community Children
Total microbes	Respiratory symptoms, nausea, headache etc	Symptoms reported at 10^3 cfum^{-3}, very limited evidence of increase in symptom prevalence with increasing exposure	General community near compost operations
Endotoxin	Respiratory symptoms, fatigue	Greater prevalence of symptoms at concentrations >50 EU m^{-3}, but indications of nasal irritation reported in one study of waste workers at 4.5 EUm^{-3}, clear evidence that risks increase with	Workers in various industries

		increasing exposure	
Beta(1→3) Glucan	Respiratory symptoms, nausea, headache etc	Limited evidence of adverse effects at concentrations 1<0 ngm^{-3}, no adverse effects at 1 ngm^{-3}	Studies of indoor air quality

On consideration of all the available studies, it is apparent that there are no clear thresholds of effect for different bioaerosol components and some individuals may experience adverse effects at background levels of exposure, in the absence of any waste derived bioaerosol. This may partly reflect the susceptibility of some individuals in the population to adverse effects (below), the importance of sensitisation in governing some health effects and the potential for infection. It is also worth noting that the concept of a no effects level comes from chemical toxicology and arises from the conduction of animal experiments with a limited gene pool and a limited number of animals. Virtually all the health information for bioaerosols arises from studies in human populations with a range of susceptibility to effects.

SUSCEPTIBLE SUBGROUPS OF THE POPULATION

There is clear evidence of wide variability in individual sensitivity to bioaerosol exposure and the genetic factors underlying some of this variability have been extensively examined in recent years. For example, marked individual differences in response to inhaled endotoxin partly reflect differences in the genetic coding for endotoxin receptors on cell walls.

A relatively substantial proportion of individuals (perhaps >10% of the population) may be susceptible to developing respiratory symptoms at levels of bioaerosol exposure (microbial counts of 10^2-10^4 $cfum^{-3}$) that are encountered in the general community, in the absence of any specific point sources of bioaerosol. A large proportion of these individuals are likely to be atopic (i.e. have a tendency towards the development of allergic disease). In addition, bioaerosol exposure, particularly endotoxin, may enhance the response of individuals with asthma to allergens or other airborne pollutants.

A small proportion of individuals with asthma and also some cystic fibrosis patients have a greatly increased risk of developing hypersensitivity to specific mould species leading to serious respiratory illness at ambient levels of exposure. A small proportion of individuals have highly compromised immune systems and are at particular risk of invasive fungal infection leading to a risk of developing serious illness at concentrations of airborne fungi of less than 10^3 $cfum^{-3}$. These individuals include transplant and cancer patients.

The limited exposure-response information available for bioaerosols is based on studies where the study population has included a range of sensitivity including people with asthma, atopy, specific sensitisation to bioaerosol components and an increased reactivity towards endotoxin. It is unlikely that most study populations will have included particularly sensitive individuals including those with severe immunosuppression. It is not clear whether thresholds will exist for adverse effects arising in the most sensitive individuals.

There is no clear evidence that children or the elderly are particularly susceptible to the effects of bioaerosol exposure. There is very limited evidence that women may have an increased susceptibility to effects during pregnancy and lactation and high levels of exposure to endotoxin may be damaging to the unborn child. This limited evidence, however, is based on animal experiments and therefore may not be directly comparable to human exposure.

USE OF EXPOSURE-RESPONSE INFORMATION FOR BIOAEROSOLS IN REGULATION

In principle the exposure-response information collated in this project could inform the setting of guideline levels of exposure, emissions limits or stand off distances intended to control community exposure to bioaerosols to concentrations below those associated with adverse effects. It could also be used to assess the effectiveness of good practice guidance where it is possible to establish the levels of community exposure arising from its implementation. If combined with the exposure information, the exposure-response information could be used to quantify benefits arising from improved regulation of bioaerosol emissions and in the comparison of different regulatory options (including the "do nothing" option).

Air quality guidelines provide an unambiguous guide to acceptable levels of community exposure. There is a strong evidence base for the development of guidelines for endotoxin, a much weaker evidence base for organic dust, fungi, microbes or beta (1→3) glucan and insufficient evidence for bacteria. There would be major difficulties in demonstrating compliance with guidelines through measurement because of the variability in background bioaerosol concentrations, the likelihood that background concentrations will exceed the guideline values and the difficulty in attributing bioaerosols to waste rather than other sources. The diffuse and poorly defined nature of bioaerosol emissions from many waste sites means that it will be difficult to demonstrate compliance using dispersion modelling. Similarly it will be difficult to establish and monitor compliance with emissions limits.

Alternative approaches to developing air quality guidelines include identifying marker species that could be used to monitor the specific impact of waste as opposed to other sources on community bioaerosol exposure. Another approach would be to develop modified PM_{10} objectives for use in the vicinity of waste operations. Any air quality guidelines that are developed are unlikely to provide complete protection for the most vulnerable members of the population, including the immunocompromised, who may become ill at background levels of bioaerosol exposure. It would be appropriate, however, to develop guidelines to protect most asthmatics who constitute a sizeable minority of the population.

Stand off distances would be easy to implement for new sites but not at existing sites. There are likely to be community concerns where housing is already present within what would be the stand off zone for any existing site. There is little information to support the development of appropriate stand off distances for different types and sizes of process. The use of stand off zones may make it difficult to open new sites and may stifle other developments around existing sites regardless of the real level of risk to health.

Best practice guidelines are an attractive regulatory option because they would anyway be required of operators as part of permitting and licensing conditions and would have to be implemented to achieve any air quality guidelines. It is easy to demonstrate compliance with best practice during site inspection, but less easy to demonstrate compliance between inspections. A requirement for ISO14401 might reduce the inspection burden on regulatory agencies and also drive operators towards continuous improvement. The major drawback of relying solely on best practice is that it may be difficult to demonstrate that current best practice is adequate to control community exposures to bioaerosols to acceptably low levels.

This report has focussed on the control of community exposure to bioaerosols but prevention of odour and dust nuisance is also likely to be key to convincing communities that the health risks associated with emissions from waste sites are adequately controlled. It is also important that workplace exposure to bioaerosols is properly controlled in order to prevent the development of serious respiratory illness following long term exposure in workers employed in recycling and composting.

KNOWLEDGE GAPS

There are some substantial knowledge gaps in relation to the potential health impact of bioaerosol emissions from waste management activities. It is not clear whether bioaerosol emissions from waste do present a significant public health problem, although the information collected in this study could be used to make a more quantitative assessment of the potential scale of effects. There are insufficient data to set exposure guidelines for most components of bioaerosol other than endotoxin. There is, however, almost no information about levels of endotoxin in ambient air and it may be desirable to undertake a measurement campaign for endotoxin in order to assess its potential value as a marker of exposure that could be used to support regulation. Although the adverse effects of exposure to $PM_{10}/PM_{2.5}$ in ambient air are well established, the relative harmfulness of bioaerosol versus urban PM is unclear as is the potential role of bioaerosol in giving rise to the effects observed with PM. It would be potentially possible to make a preliminary assessment of the relative harmfulness of bioaerosol versus urban PM through comparison of the exposure-response relationships found in workplace studies for organic dust with those found for low toxicity mineral dusts and assessment of the relative toxicity of low toxicity mineral dusts and urban PM from the results of published experimental studies and epidemiological investigations in communities exposed to PM from different sources.

Most studies of the health of waste workers have examined the immediate effects of exposure to bioaerosols and there is very little information about the long term health effects of bioaerosols in the waste industry. Experience from the agricultural and cotton industries suggests that long term exposure to bioaerosols is associated with an increased risk of chronic respiratory illness. There is a need to investigate the effects of long term exposure in the waste industry, both to better understand the potential risks of workplace exposure and also to inform risk assessment for the wider community.

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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