Occupational and environmental exposure to bioaerosols from composts and potential health effects - A critical review of published data

Prepared by **The Composting Association** and
Health and Safety Laboratory
for the Health and Safety Executive 2003

RESEARCH REPORT 130

HSE
Health & Safety Executive

Occupational and environmental exposure to bioaerosols from composts and potential health effects - A critical review of published data

J R M Swan, A Kelsey and **B Crook**
Health and Safety Laboratory
Broad Lane
Sheffield
S3 7HQ

E J Gilbert
The Composting Association
Avon House
Tithe Barn Road
Wellingborough
Northamptonshire
NN8 1DH

The primary objective of this study was to critically review published literature related to studies of airborne micro-organisms or their constituent parts (bioaerosols) associated with organic waste composting facilities, and to establish whether there is a risk to worker health from the inhalation of these bioaerosols. The review aimed to identify the personnel at risk on compost sites, identify the circumstances which increased the risk and indicate suitable control measures to control the risk. A further consideration was that airborne dispersal of bioaerosols from compost facilities could affect neighbouring facilities or residents, leading to health concerns, and the review also looked at evidence of bioaerosol dissemination from sites, potential exposures and reported ill health.

Further objectives were to review computational modelling tools for estimating dispersion of bioaerosols from composting facilities and to recommend suitable models. Existing experimental data, previously derived from environmental sampling at composting sites by the Composting Association who collaborated on this project, were re-examined to provide comparison between experimental and modelled data.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

HSE BOOKS

First published 2003

ISBN 0 7176 2707 1

CONTENTS

EXECUTIVE SUMMARY

OBJECTIVES

The primary objective of this study was to critically review published literature related to studies of airborne micro-organisms or their constituent parts (bioaerosols) associated with organic waste composting facilities, and to establish whether there is a risk to worker health from the inhalation of these bioaerosols. The review aimed to identify the personnel at risk on compost sites, identify the circumstances which increased the risk and indicate suitable control measures to control the risk. A further consideration was that airborne dispersal of bioaerosols from compost facilities could affect neighbouring facilities or residents, leading to health concerns, and the review also looked at evidence of bioaerosol dissemination from sites, potential exposures and reported ill health.

Further objectives were to review computational modelling tools for estimating dispersion of bioaerosols from composting facilities and to recommend suitable models. Existing experimental data, previously derived from environmental sampling at composting sites by the Composting Association who collaborated on this project, were re-examined to provide comparison between experimental and modelled data.

MAIN FINDINGS

Detailed information was retrieved on levels of bioaerosols associated with composting, although many composting studies focussed on environmental emissions and the potential risk to sensitive receptors, e.g., persons susceptible to ill health in the nearby vicinity, rather than occupational exposure. There is limited information available on workers' personal exposure to bioaerosols associated with specific tasks in composting, and few studies have described controls used. Data that have been reported indicate that workers at compost sites are at risk of regular exposure to bioaerosols between 10 and 1,000 times greater in concentration than may be expected normally in ambient air. The allergenic fungus *Aspergillus fumigatus* is a significant component of compost bioaerosol.

In waste handling, as in other industries where workers may be exposed to large concentrations of organic dust, there is reported evidence mainly from studies in mainland Europe of raised levels of antibodies and inflammatory mediators associated with compost handling. Also as with other industries where workers are exposed to organic dust, there is the potential for progressive respiratory ill health with continued high exposure. As composting on a major scale is a relatively new and rapidly expanding industry and symptoms of chronic ill health may not yet have had time to develop, there may be justification in long term health monitoring of workers. Only two published case studies reported evidence of respiratory infection, such as allergic bronchopulmonary aspergillosis, one from USA and one from mainland Europe.

Concern has been raised by residents in the vicinity of composting sites that composting activities could increase levels of bioaerosols, such as airborne *Aspergillus fumigatus* spores. Most reports show numbers to have declined to 'background' within 200 m from a compost bioaerosol source, although some report levels above background at greater distance. Background or typical ambient bioaerosol levels may differ by orders of magnitude depending on location, weather and season, which hinders interpretation. Few published studies exist where the health of residents near composting sites has been investigated, but where such work has been done there is no evidence of ill health compared to controls. Enclosed and in-vessel

composting systems may increasingly be used in the UK, which may overall reduce dispersed emissions, but at present few UK sites use this method and little data currently exist.

Methods used in some previous studies to measure occupational exposure to bioaerosols released during composting may have underestimated workers' total exposure to allergenic or immunotoxic agents, or missed peaks of exposure related to specific work tasks. The use of longer term sampling methods may be relevant to address this potential discrepancy, while simpler sampling methods may make regular monitoring of sites more achievable. Recent developments in molecular biology or nucleic acid-based methods could be applied to the 'tracking' of compost bioaerosol emissions to increase understanding of the contribution they may make to the ambient bioaerosols in the vicinity.

Bioaerosol concentrations decline with distance from source due to atmospheric dispersion and dilution. Mathematical and computational models can be used to estimate this dispersion and to examine the effects that different atmospheric stability classes have on reduction of bioaerosol concentrations. Only limited published data are available to attempt to estimate bioaerosol emission rates from compost at different stages of the composting process. In this study, preliminary application of a computational model was made to evaluate published data and to compare the results from the model to experimental data previously derived by the authors at composting sites. Under certain atmospheric stability classes modelled, representing infrequently encountered worst case conditions, bioaerosol concentrations would not be reduced to the background value within 250 m. However, there is significant natural variability in both background concentrations and releases from composting.

RECOMMENDATIONS

Personal worker exposure data are required to identify the personnel at risk from exposure to bioaerosols on composting sites, to identify work tasks which increase risks and measure the effectiveness of controls. Long term monitoring at selected sites would establish a more complete picture of bioaerosol levels, especially at the periphery of sites. Molecular biology based techniques should be considered as a means of profiling bioaerosols dispersed from compost sites. The overall exposure associated with in-vessel systems requires further investigation. Longitudinal monitoring of worker exposure and respiratory health, including serological tests for biomarkers and investigation of exposure/response may have a role in detecting early onset of chronic respiratory disease.

Further work needs to be done to establish source terms for application in computational dispersion models. Data on emission rates and their natural variation need to be obtained. These could include laboratory tests to estimate the bioaerosol concentration and size distribution associated with mechanical handling of known quantities of compost material, and also estimate emission rate. If data on emission rates and their variation become available then further dispersion calculations should be performed. These should examine predicted concentrations in the context of differing atmospheric conditions and the likelihood of different exposure levels and durations.

While most published studies indicate that bioaerosols are reduced to background within the 250 m distance currently prescribed by the Environment Agency for risk assessment purposes, some experimental studies and dispersion modelling exercises suggest that bioaerosols sometimes may exceed concentrations chosen as background levels at distances greater than 250 m. There is no published evidence that exposure to bioaerosols disseminated from compost facilities cause respiratory ill health in residents or workers at nearby locations, or that slightly greater than background bioaerosol levels represent a significant excess risk. However, because

there is no agreed ‘safe’ value and range for background concentrations, and exposure measurement data and health-related dose-response data is limited, it is recommended that no change should be made to the 250 m ‘limit’ until further research is completed which can supplement knowledge where published evidence is absent.

A previous review, published almost ten years ago by a US group of experts, posed the question “Do bioaerosols associated with the operation of biosolids or solid waste composting facilities endanger the health and welfare of the general public and the environment?”. They concluded that “Composting facilities do not pose any unique endangerment to the health and welfare of the general public”. In the intervening years, although further studies have highlighted potential respiratory health concerns for workers on composting facilities, there is no published evidence to contradict their conclusions about the general public. However, there are concerns over respiratory health and these need to be evaluated and placed in the context of risks presented by other environmental hazards.

1 INTRODUCTION

Approximately 400 million tonnes of waste is produced in England and Wales every year. As a consequence of a European Directive (EU Landfill Directive) to reduce the amount of waste going to landfill, there is an obligation to reduce the quantities of biodegradable municipal solid waste (MSW) sent to landfill to 35% of 1995 levels by 2020 (Environment Agency web site www.environment-agency.gov.uk).

As part of waste management strategy, a hierarchy of preferences for waste management/ recycling have been established, in descending order, as follows:

- Waste reduction at source;
- Materials recovery;
- Composting;
- Incineration;
- Landfill.

Consequently, composting organic waste forms an increasingly important component of the waste management process in the UK. As a result, over recent years there has been an increase in the number of composting operations starting up, with several more at the planning stage.

The composting process can be defined as: the controlled biological decomposition and stabilisation of organic substrates, under conditions that are predominantly aerobic and that allow the development of thermophilic temperatures as a result of biologically produced heat. It results in a final product that has been sanitised and stabilised, is high in humic substances and can be beneficially applied to land, which is typically referred to as 'compost' (modified from Haug, 1993).

Farmers have practised composting for centuries, returning waste organic residues to the land in order to maintain soil fertility and organic matter. It is only relatively recently that modern society has begun to recognise the importance composting has to play in managing the ever increasing quantities of waste it produces. Composting is now employed as a treatment process for a wide range of organic substrates such as municipal solid wastes, sewage sludges, and agricultural and industrial by-products (Gilbert, *et al*., 2001). Actively composting materials, or finished composts, have been shown to degrade a wide range of organic pollutants, and are thus used in the bioremediation of contaminated soils (Semple, *et al*., 2001). This review of data will concentrate primarily on issues related to composting of organic ('green') waste, although some of the information in terms of exposure to bioaerosols may be relevant to other co-composted materials.

There are a number of ways in which composting can be carried out, ranging from small-scale composting of garden wastes by householders, through medium-scale composting by community groups and farmers, to large-scale composting at specially designed sites (centralised composting sites), although the range of technologies at the latter can vary considerably.

The most recently reported industry survey figures for the UK, for 1999, recorded 62 operators running 80 centralised composting sites, 65 on-farm compost sites and 52 community composting sites (Slater *et al,* 2001). With a year on year increase in numbers of sites of 25-30%, it was

anticipated that the number of sites would increase to 104 by 2000. Twenty seven sites were in the process of coming into operation, i.e., at various advanced stages of planning.

Centralised composting sites account for most (92% as determined from the 1999 survey) of the material composted in the UK. Approximately half of these sites are considered small, i.e., less than 7,000 tonnes throughput.

The size of the sector in terms of employee numbers is difficult to disaggregate, but few sites will employ more than 20 staff. Therefore, staff involved in composting are few compared to other areas of waste handling such as door to door refuse collection, but a large proportion of the workforce are likely to be 'hands on' actively involved in various stages of the waste composting process.

2 PURPOSE OF THE REVIEW

2.1 BACKGROUND

Despite the obvious benefits of organic waste composting, there are concerns that exposure to composting products could be detrimental to health. In particular, these concerns focus on the microbiological component of compost. Composting, as previously defined, is biological decomposition of organic material which necessarily leads to multiplication of micro-organisms within the composting substrate. It is the potential for these micro-organisms to become airborne as the compost is being handled (often referred to as bioaerosols) that leads to concern that exposure could be detrimental to respiratory health.

Some of the micro-organisms associated with compost production are recognised allergens. Examples include thermophilic actinomycetes and *Aspergillus fumigatus*. Thermophilic actinomycetes are a group of spore forming bacteria naturally present in vegetation and are fundamental to the production of compost because they break down celluloses and lignins. In actively composting material, a succession of micro-organisms grow with an increase in temperature until, at optimum conditions of around 55^0C, thermophilic actinomycetes flourish and as a consequence they are likely to be present in numbers in excess of 10 million spores per gram. *Aspergillus fumigatus* is a species of fungus again naturally present in vegetation and ubiquitous in the environment, but because it is a thermotolerant fungus it grows well at raised temperatures experienced during the composting process. Both thermophilic actinomycete species, such as *Saccharopolyspora faeni* and *Thermoactinomyces vulgaris*, and the fungus *Aspergillus fumigatus* have been implicated in occupation allergic lung diseases such as Farmers Lung Disease and mushroom workers lung disease, where gross exposure, typically greater than tens of millions of spores per m^3 of air, have triggered the immune response (Lacey and Crook, 1988). Repeated exposure to such allergens stimulates the immune system, causing a cascade of responses including release of histamines, constricting airways and reducing lung capacity resulting in chronic bronchitis, asthma or alveolitis. In addition, *Aspergillus fumigatus* is an opportunist pathogen (ACDP Hazard Group 2) and can cause lung infections (aspergillosis, aspergilloma). Individuals with severely compromised or suppressed immune systems, e.g., following chemotherapy, organ transplant or if suffering from immune deficiency diseases, are at particular risk (Latge, 1999).

There is a need for robust and reliable information on the potential microbiologically related health risks associated with waste composting, to ensure that adequate controls are in place to reduce occupational exposure and to address issues related to the proximity of sites to local residents. Those potentially at risk to a greater or lesser degree include:

- Workers closely associated with on site activity, e.g., drivers of front end loaders, windrow turning machines, shredders;
- Workers intermittently associated with on site activity, e.g., drivers of delivery vehicles, site maintenance workers, other visitors;
- Workers at premises in the vicinity of waste composting sites;
- Members of the public living in the vicinity of waste composting sites;
- Members of the public passing by the periphery of waste composting sites.

The above list is in order of what may be perceived to be the likely scale of exposure, i.e., workers handling compost are most likely to encounter peaks in gross exposure, but other factors need to be taken into account. For example, such workers are more likely to use engineering control (such as air conditioned cabs) or personal protective equipment including dust masks, but information on where and when they are used and their effectiveness may be limited. Residents in the vicinity of composting sites are likely to be exposed to considerably smaller bioaerosol concentrations because of the dilution effect of airborne dispersal with increasing distance from a bioaerosol source, but there is much debate over the distances needed to reduce bioaerosol numbers to background levels. If composting activity does result in an increased level of ambient bioaerosol in the vicinity, there is a need to know how much that increase is above background, for how long after composting activity the increased level is sustained, and whether this represents a significant effect on respiratory health.

A further aim of the study was to examine factors affecting dispersion of bioaerosol from composting facilities. Raw data was made available from a previous study undertaken by the Composting Association to measure bioaerosol concentrations at and near to composting sites. In this earlier work an attempt had been made to model decline in bioaerosol numbers with distance from source, but only using a simple logarithmic decline model (Gilbert, 2002). As part of the Review, an examination was made of the possible role of computational modelling to estimate the potential dispersion of bioaerosols from composting material to the immediate surroundings (i.e., on site) and to distant locations, such as beyond the site boundary. Results from application of the selected dispersion model were then compared to the bioaerosol data generated by the Composting Association and to other reported data.

The HSL study team included microbiologists with expertise in health based exposure studies and bioaerosol exposure measurement, and a computational modeller with experience in development of modelling tools for occupational risk assessment. All of the team have previous experience in undertaking impartial reviews of data on occupational health related issues. The involvement of the Composting Association in the review, as well as providing access to the raw data, provided an additional source of environmental microbiology expertise and access to literature, as well as knowledge of the composting industry.

2.2 MECHANISM OF DATA GATHERING

The aim of the data gathering exercise was as far as possible to follow the principles established for systematic review of literature, e.g., as used by the Cochrane Collaboration for researching health care interventions (www.cochrane.org). A series of search terms were determined by discussion and based on existing knowledge of the subject area. These were then used to interrogate online publications databases such as PubMed, as well as the databases available through the HSE Information Centre as follows:

Agricola
Agris
BIOSIS
CAB
Compendex
Conference papers Index
DHSS-Data
Enviroline
Environmental Bibliography
Excerpta Medica
Inside Conferences
Life Sciences
OSHROM - MEDLINE
Pollution Abstracts
Waste Info

Literature searches are constructed for HSL researchers such that strategies encompass all aspects of the question in hand; all concepts are covered and searches are executed across the major bibliographic files for each concept to ensure thorough coverage. Strategies are examined to cover all synonyms, spelling variations, language options, year ranges. Searches are executed across a range of authoritative commercial databases covering learned journals, technical papers, monographs, conference proceedings and grey literature (authoritative primary scientific report literature in the public domain, often produced "in-house" in government research laboratories, university departments or large commercial research organisations), as well as access to newspaper files, British and European legislative files, worldwide standards and business data. This was supplemented by access to waste disposal related literature available through the Composting Association data gathering and archiving facility. Reports of papers not in English were translated through the Translation Service available to HSL.

In addition, hand searches were done through reprint archives held at both collaborating establishments. A secondary search was undertaken by checking the references of key publications for relevant citations which may not have been retrieved by the initial search. A cut off date of 20 years back from the search year was used for the initial search, with earlier papers deemed to be particularly relevant retrieved from hand searches.

A summary of the content of each relevant paper was compiled as a means of categorising them, e.g., to identify those that presented original data as distinct from reviews, comments or general articles such as those in trade journals. Further distinction was made between exposure and health based studies and within health studies between those presenting case studies and population studies.

Over 500 initial 'hits' were evaluated for potential relevance, eliminating publications which fell outside the scope of the review on the basis of examination of title and abstract. Full versions of remaining papers were further evaluated and considered as relevant if there was evidence of scientific peer review and if the paper presented original material rather than reviewed data. Other factors, such as choice of methodology, controls used in health based studies, were taken into consideration in the evaluation and are described in the following Report of the information gathered.

2.3 REPORT STRUCTURE AND CONTENT

This Report has been structured to present the review data as follows:

- Basic information on composting practices.
- Background information; composting principles and the microbiology of composting.
- Bioaerosols associated with composting and the potential for human exposure.
- Potential health consequences of exposure to bioaerosols.
- Reported studies on exposure and respiratory health consequences
- Ambient bioaerosol levels and bioaerosols in other industries.

- Dispersion of bioaerosols from composting and application of computational models for measurement.

Key studies on occupational and environmental exposure and respiratory health cited in the report are summarised in a table in Appendix A, cross referring to their citation in the report and the content of the study.

Where possible, from the information gathered the aim was to identify the personnel at risk on composting sites, quantify that risk with regard to exposure and uptake, identify circumstances which increase the risk and indicate suitable measures to control the risk. A further aim was to identify gaps in current knowledge to assist in planning future investigative field work.

It is a further intention, upon completion of the Final Report, to submit it for assessment by an international expert in compost bioaerosols and health (Dr Patricia Millner, U.S. Department of Agriculture). Dr Millner chaired a committee of experts which previously completed a similar review and published a detailed report on the subject (Millner *et al*, 1994).

3 COMPOSTING PRACTICES

3.1 OVERVIEW

The activities carried out at a composting site, irrespective of its size, are aimed at amending or controlling feedstock structure, composition, temperature or oxygen content.

Most materials received at a composting facility require processing prior to composting. In practice, there are four main activities, namely: shredding, to reduce particle size and increase the surface area to volume ratio; mixing different feedstocks together to improve homogeneity and adjust the carbon to nitrogen (C : N) ratio and / or moisture content; adding water where particularly dry materials are received, and removing contaminants.

The degree of process control employed during the active composting phase varies depending upon the size and location of the site, the nature of the feedstocks and the intended end uses of the composted materials. In practice there are four principal approaches that can be adopted for composting wastes on a large-scale, described in the following subsections.

3.2 WINDROW SYSTEMS

Open-air turned windrows are the simplest system, and they are widely used to compost green wastes (sometimes called botanical residues or yard trimmings). Feedstocks are laid out in long piles called 'windrows', usually shaped as an elongated triangular prism, although the exact shape varies according to the material and equipment used. The term originates from the farming practice of piling hay in rows so that it will dry out in the wind.

These windrows are 'turned' to blend the composting mix, introduce fresh air, and release trapped heat, moisture and stale air. In practice, the technique often involves breaking up the windrows by lifting the composting materials into the air and allowing them to drop back down.

At smaller facilities, a tractor with a front-end loader or grab is often used to scoop up portions of the composting materials. Each bucket-load is carried to another area and emptied onto the ground, re-forming a new windrow. At larger sites, which process greater quantities of material, specialised windrow turning machines are often employed.

3.3 AERATED STATIC PILES

Some mechanised systems may dispense with turning, and either blow (positive aeration) or suck (negative aeration) air through the composting materials. These 'forced aeration' systems often rely on a perforated pipe running through the pile or a trough underneath the composting materials, which is attached to an air compressor. However, some operators may combine both approaches, using a forced aeration system with some element of physical turning.

The rate of aeration may be linked to oxygen concentration and / or temperature via a negative feedback system, or fans may be switched on and off for defined periods of time. The exhaust gases from negative pressure systems may be passed through a biofilter or scrubber before discharge to the environment, whereas in positive pressure systems the piles may be covered with

layers of mature compost to act as an *in situ* biofilter. These techniques have been widely employed in the USA to compost sewage sludges.

3.4 IN-VESSEL SYSTEMS

Unlike windrows and aerated static piles, in-vessel systems contain the composting feedstocks in vessels that are usually enclosed, which affords a much greater level of process and emission control. Wide ranges of systems are marketed, each with their own unique benefits and applicability to different feedstocks and situations. In broad terms there are six different types of in-vessel system, although many may be classified into more than one category:

- Containers – These are generally small-scale systems designed for decentralised use, especially food processing and catering wastes. Most systems operate as batch units, supplying air through perforations in the floor of the container.

- Tunnels - These tend to be larger and more sophisticated than containers, and have been adapted from the mushroom composting industry. They operate in similar ways to containers although some element of mechanical agitation may be employed. Both batch and continuous systems have been developed.

- Agitated bays - These consist of rows of rectangular beds separated by low walls on each side along which turning and shredding machines run. The machines mix the compost and deposit it further along the bay in a continuous flow; forced aeration may also be provided via flooring ducts.

- Rotating drums – These are large rotating cylinders (generally 3 – 4 metres in diameter, and anywhere up to 50 metres long) that are slightly inclined from the horizontal. Feedstocks are introduced in the top end and mixed and fragmented as they move towards the outlet. Water and nutrients may be added and forced aeration provided.

- Silos or tower systems - These are vertical units that operate on a continuous basis. Feedstocks are loaded into the top of the unit and are composted as they pass down through the unit. The resultant composts are harvested at the bottom of the vessel using augers.

- Enclosed halls - These compost material on the floor of the hall and are usually contained in one long bed. The whole composting process tends to occur in the same hall; large bucket wheels are used to turn and move the material through the system.

3.5 VERMICOMPOSTING

Vermicomposting is the process of using selected species of earthworms to help compost organic wastes, and stems from the established business of vermiculture (the breeding of earthworms, mainly for the fishing bait market). It is usually carried out in long troughs in which the temperature is kept below 35 ºC. With traditional composting, the compost piles are mixed and aerated mechanically, whilst with vermicomposting it is the earthworms that fragment, mix and help aerate the waste.

3.6 POST PROCESSING OF COMPOST

Following composting, most facilities grade the composts into different particle size fractions to create products for varying end uses, and to remove contaminants or partially composted fragments. This process is termed 'screening' and often involves the use of purpose-built machines, of which there are three common types, namely: oscillating or shaker screens, rotary trommel screens, and disc or star screens.

Screening compost is the most common method of adding value. Most of the compost sold as soil improvers in the UK is screened to a diameter of 10 mm or less, most mulches to a diameter between 11-25 mm, although different markets and intended uses require different particle sizes. Blending composts with other materials (such as coir and/or artificial plant nutrients) is often carried out to create high-value products for specialist uses in horticulture and turf management.

3.7 UK USE OF DIFFERENT COMPOSTING SYSTEMS

Data from the most recently reported Composting Association survey of the composting industry, in 1999 (Slater *et al*, 2001), showed that the large majority of sites used open air mechanically turned windrow systems. Out of 80 centralised composting sites, 65 used this method, which accounted for 88% of all material composted. Three used contained mechanically turned windrow systems and five used contained in-vessel systems. The latter therefore accounted for 4.5% of all material composted by centralised composting sites.

Of 65 on-farm sites, 55 used open air windrow systems, two used contained windrows and two in-vessel systems. Similarly, almost all 52 community compost sites used open air windrows.

Although these figures relate to 1999, they provide a general guide to the proportional use of the composting systems in existence and it is not expected that the proportions will have changed greatly in more recent years. Although in-vessel systems are considered to be the way forward, their use is still not yet widespread.

4 MICROBIOLOGY OF THE COMPOSTING PROCESS

4.1 SUMMARY OF THE COMPOSTING PROCESS

In very simple terms there are three key stages to the composting process (Table 1), although they are by no means mutually exclusive, and are dependent upon the feedstocks and processing conditions employed.

Table 1. Key stages of the composting process (source: Gilbert *et al,* 2001).

Stage	Key features	Stage characteristics	Approximate duration
High rate composting	Micro-organisms consume forms of carbon they can easily break down, e.g. sugars and starches.	High rate of biological activity characterised by high oxygen demand and of heat generation rates. Tendency for pH to initially drop below the optimum of 6 – 8, then rise above 8 as composting proceeds.	4 – 40 days depending upon system type.
Stabilisation	Micro-organisms consume forms of carbon they can break down fairly readily, e.g. cellulose.	Biological activity starts to decline. Oxygen demand gradually decreases. Declining heat generation. Tendency for pH to remain above 8.	20 – 60 days depending on system type.
Maturation (Curing)	Amount of available carbon is much reduced and microbial consumption slowed down. Re-colonisation by soil microbes.	Reduced biological activity. Medium to low oxygen demand. Little heat generation; temperature should be below 50 ° Oxidisation of ammonium to nitrate ions. Tendency for pH to fall towards neutral (7).	Variable duration depending upon test method used and intended end use.

The biochemistry and microbiology of composting remains poorly understood to date. Despite extensive research over the past twenty years into engineering aspects and the benefits of using composts, composting is still essentially considered a 'black box' process. This stems, in part, from the inherent complexity of the composting process, which is heterogeneous in nature and is directly influenced by factors such as feedstock composition and structure, temperature, pH, moisture, oxygen and ammonia concentrations (Miller, 1996). In many cases indirect methods, such as calorimetric analyses for example, have been used to measure microbial metabolic activity (Weppen, 2001).

Composting relies upon the inter-related activities of a diverse range of micro-organisms to convert organic waste substrates into a stabilised material ('compost'), which is high in humic substances ('humus') and contains useful plant nutrients. In most feedstocks, the principal source of carbon and energy is derived from lignocelluloses (Lynch, 1993). Cellulase activities in composting materials have been widely studied and correlated to decreases in cellulose content (Stutzenberger, *et al*., 1969). The degradation of recalcitrant lignins in composting systems has been less well characterised, although thermophilic microfungi, and to a lesser extent actinomycetes, are thought to play key roles (Tuomela, *et al*., 2000).

Humification (the process of forming humus) is complex and thought to involve a number of degradative and condensation reactions involving lignins, carbohydrates and nitrogenous compounds (Lynch, 1993; Tuomela, *et al*., 2000). Nuclear magnetic resonance spectroscopy, gas chromatography – mass spectrometry and Fourier transform infrared spectroscopy have all been used to track changes in feedstock composition and the formation of humic substances (for example González-Vila, *et al*., 1999).

The composting process can be split into three key stages based on changes in temperature (Miller, 1996):

- Phase 1, is characterised by an increase in temperature from ambient as a result of microbial metabolic activity and has been termed the 'high rate' composting phase. During this phase simple carbohydrates and proteins are readily degraded, firstly by mesophiles, which are then succeeded by thermotolerant and thermophilic species as the temperature rises above 45 °C.

- Phase 2, has been termed the 'stabilisation' phase and is characterised by the attainment of thermophilic temperatures (> 50 °C), which selects for thermophilic bacteria (Strom, 1985). However, this may be an over simplistic assumption, as the survival of isolates typically characterised as mesophiles has been suggested by Droffner *et al*. (1995). The thermophilic stage plays a key role in the thermal destruction of pathogenic micro-organisms, weed seeds and propagules, although antagonisms such as competition and the formation of secondary metabolites may be significant (Sidhu, *et al*., 2001).

The thermophilic composting phase has received the greatest attention to date, especially composts produced for the cultivation of mushrooms on a commercial scale (Kleyn and Wetzler, 1981). Thermophilic actinomycetes (Lacey, 1997), *Bacillus* species (Kleyn and Wetzler, 1981; Ghazifard, *et al*., 2001; Strom, 1985), *Thermus* species (Beffa, *et al*., 1996) have all be shown to dominate, whilst thermotolerant fungi from the genera *Aspergillus* and *Penicillium* have been widely reported (Millner, *et al*., 1977; Miller, 1996).

However, species diversity is thought to decrease at high temperatures (Strom, 1985; Ghazifard, *et al*., 2001), whilst Gram-positive bacteria have been shown to predominate (Ghazifard, *et al*., 2001; Dees and Ghiorse, 2001).

Phase 3, is the 'maturation' phase and is typically characterised by a reduction in temperature towards ambient as a result of decreases in metabolic activity following oxidation of readily biodegradable substrates. Mesophilic actinomycetes and fungi begin to predominate during this stage, and are though to be responsible for degrading and converting lignins, which occurs optimally at these lower temperatures (Tuomela, *et al*., 2000).

In recent years a number of approaches have been adopted to monitor the changes in microbial communities during the composting process. Dynamic changes have been tracked using carbon source utilisation and phospholipid fatty acid analyses (Herrmann and Shann, 1997; Hellmann, *et*

al., 1997; Carpenter-Boggs, *et al*., 1998). Advances in nucleic acid techniques are now beginning to shed light on the roles of microbial communities during the composting process (Blanc, *et al*., 1999). Many of these techniques have been applied in soil microbiological studies, where the phenomenon of non culturable but viable (NCBV) state is known to exist (Kondrój and van Elsas, 2001). Consequently genera previously not identified in composts using classical plate culture techniques are now being identified (see for example, Beffa, *et al*., 1996; Dees and Ghiorse, 2001). Blanc, *et al*. (1999) described the characterisation of Operational Taxonomic Units based on endonuclease restriction profiles of cloned 16S ribosomal DNA recombinants isolated from hot composts, and measured changes in population diversity in young and old composts. Similarly, Peters *et al*. (2000) demonstrated changes in microbial communities at different stages of the composting process using PCR amplification of small-subunit ribosomal RNA genes.

4.2 TEMPERATURE OF COMPOST

Monitoring the temperature of composting materials is important for two reasons. Firstly it is an indirect way of measuring the activity of micro-organisms within a windrow, thus it can indicate if there is a problem with the composting mix. Secondly, it enables an operator to assess whether the composting materials have been sanitised. Elevated temperatures are important during the composting process, as this helps destroy many pathogenic micro-organisms, weed seeds and weed propagules, thereby reducing the risk to human, animal and plant health. Déportes *et al* (1995) reviewed the literature available on the survival of pathogens in compost. They reported that at least one hour at 68^{o}C will kill most pathogens, for example *Salmonella* species require 15 to 20 minutes at 60^{o}C, *E. coli* and *Shigella* species require one hour at 55^{o}C. Other authors recommend that temperatures of 55 to 60^{o}C for at least three days will destroy most pathogens (Epstein and Epstein,1989; Finstein and Miller , 1985). Otten *et al* (1999) detected no *E. coli* or *Salmonella* species in compost from source separated kitchen and yard waste. Examples of selected pathogens and weed seeds and the holding temperatures required to destroy them are given in Table 4.1. Most of the human and animal pathogens listed should not be present in composted organic waste, unless sewage sludge, animal waste or food is being composted or contaminating the process.

Table 2. Elimination temperatures for selected human, animal and plant pathogens and weed seeds

Organism	Elimination temperature (°C)	Exposure time
Human pathogens[1]		
Vibrio cholerae (bacterium; causes cholera)	55	15 minutes
Shigella species (bacteria; cause dysentery)	55	60 minutes
Salmonella species (bacteria; cause food poisoning)	60	20 minutes
Clostridium tetani (bacterium; causes tetanus)	105	3 – 25 minutes
Ascaris lumbricoides (round worm)	55	60 minutes
Taenia saginata (tape worm)	55	Few minutes
Animal pathogens[1]		
Bacillus anthracis (Bacterium; causes anthrax)	100	10 minutes
Brucella abortus (Bacterium; causes brucellosis)	60	10 minutes
Swine fever (virus)	78	1 hour
Foot and mouth disease (virus)	56	30 minutes
Scrapie (prion)	100	Withstands 2 hours
Plant pathogens[2]		
Phytophthera cryptogea (fungus with resting spores)	64-70	2-3 weeks
Sclerotinia sclerotiorium (fungus with sclerotia; causes white mould)	64-70	2-3 weeks
Pseudomonas syringae pv. phaseolicola (bacterium; causes halo blight of bean)	35	4 days
Tobacco necrosis virus (TNV)	55	72-96 hours
Tobacco mosaic virus (TMV)	50-75	Survived 6 weeks
Weed seeds[3]		
Rosebay willowherb (*Chamaenerion angustifolium*)	45	3 days
Annual meadow grass (*Poa annua*)	45	3 days
Black nightshade (*Solanum nigrum)*	55	3 days
Common chickweed (*Stellaria media*)	45	3 days
Prickly sow-thistle (*Sonchus asper*)	45	3 days

1 CEN (1999) . 2 Compiled from Johansson *et al*, 1997 3 Adapted from Grundy et al, 1988.

To date, there have been few UK-specific recommendations about pathogen reduction temperatures and for how long they should be sustained. However, following the Foot and Mouth disease epizootic the Department for the Environment, Food and Rural Affairs (DEFRA) commissioned a risk assessment looking into the fate of animal pathogens in catering (food)

wastes. This led to proposals for temperature/time requirements for the composting of catering wastes, which are being drafted into legislation at the time of writing. The guidelines most often quoted were established by the United States Environmental Protection Agency for sewage sludge composting in its Part 503 regulations as a 'Process to Further Reduce Pathogens (PFRP)'. These state that temperatures in excess of 55^{o}C should be maintained for at least three days using in-vessel or aerated static pile composting systems. For windrow composting systems, the temperature must exceed 55^{o}C for at least 15 days, with a minimum of five turnings (to ensure that all of the materials have been exposed to the high temperatures at the centre of the windrow) during this period.

In addition the European Commission is also considering sanitisation aspects in its working document on the 'Biological Treatment of Biowaste'. At the time of writing it was suggested that windrows be subjected to either a temperature equal to or above 55 ºC for at least two weeks with a minimum of five turnings, or a temperature greater than or equal to 65 ºC for at least one week with a minimum of two turnings. The Commission also suggested a process validation test that would involve 'seeding' the composting materials with an indicator micro-organism to test the efficiency of the sanitisation phase.

.

5 BIOAEROSOL COMPONENTS AND HAZARD TO HUMAN HEALTH

This section deals generally with the potential hazards to health associated with bioaerosols, i.e., airborne micro-organisms and their components. It is placed into context by consideration of those micro-organisms likely to be present in compost. Subsequent sections deal with the risk of ill health from exposure to compost bioaerosols.

5.1 MICRO-ORGANISMS IN COMPOST

As described in the previous Section, the presence of bacteria and fungi in high concentrations are fundamental to the composting process. For example, Dees and Ghiorse (2001) reported total counts in the order of 10^{10} cells per gram of compost [dry weight] measured using epifluorescence microscopy, with thermophilic heterotrophic aerobes measured in the order of 10^{8} colony forming units (cfu)/g dry wt. Lacey (1997) reported actinomycetes in mushroom composts in the order of 10^{6} cfu/g dry wt; Strom (1985) and Millner *et al*. (1977) reported concentrations of *Aspergillus fumigatus* in excess of 10^{5} cfu/g dry wt in composting sewage sludge, whilst; Beffa *et al*.(1996) reported concentrations of thermophilic bacteria related to the genus *Thermus* in the range of 10^{7} to 10^{10} cells/g dry wt. A cfu is defined as the unit of one or more cells or spores which, when inoculated onto suitable growth medium, grows to form a single colony.

Whenever composting materials are moved around, for example during the shredding, turning and screening processes, these micro-organisms can be aerosolised, forming what is termed a bioaerosol. Actively managed, medium- to large scale composting harnesses the activity of indigenous micro-organisms commonly present in the soil that naturally decay, such as fallen leaves. Therefore, the microbial components of bioaerosols generated during the composting process contain many of the same micro-organisms that are commonly isolated from "normal" outdoor air. The main difference is that of scale. The handling of large quantities of compost potentially can lead to the release into the air of large quantities of the bacteria, fungi and actinomycetes and their components, found in compost, as a bioaerosol.

Exposure to the micro-organisms found in compost could potentially cause ill-health in the people exposed to them either by infection, allergy or an adverse response to toxins. The composting process generates heat, so any human pathogens present in the raw materials, such as coliform bacteria from faecal material which could give rise to gastro-intestinal infection, should be rapidly killed off during the composting process (see previous Section).

Some of the micro-organisms which increase in number during the composting process are toxic and/or allergenic. Even after the microbial cells have ceased metabolic activity and entered a 'resting', or non culturable but viable stage (NCBV), or for a period after cell death before proteinaceous components have degraded, there is still the potential for microbial cells to be toxic or allergenic.

There are two main routes of exposure to compost micro-organisms; ingestion of the micro-organisms or inhalation of bioaerosols created during the handling of compost. Good hygiene practices such as wearing of gloves and provision of hand washing facilities on composting sites should control risks from ingestion. However, control of bioaerosols generated by composting processes is more complex.

In order to understand the potential health hazards associated with exposure to compost bioaerosols, it is first important to examine in detail the microbial components of bioaerosols generated during the handling of compost.

5.2 FUNGI

During the handling of fresh green waste the micro-organisms present are predominantly the saprophytic "field" fungi such as *Cladosporium* spp., *Alternaria* spp, *Verticillium* that colonise plants during growth. As the composting process progresses, the numbers and types of associated contaminants change. Some fungal spores naturally present in low numbers may germinate and grow. These are referred to as "storage fungi" because they flourish in stored organic materials. They include *Aspergillus* , *Eurotium*, *Penicillium*, *Trichoderma*, *Absidia*, *Mucor* and *Rhizopus* species. These fungi can grow at lower water availability and predominate over the field fungi which are less well suited to multiplication in these conditions. The increased metabolic activity can lead to spontaneous heating of the compost. This can result in a succession of microbial growths so that, if enough water is available, temperatures of 65^{o}C can be reached, allowing the growth of thermophilic and thermotolerant fungi (Dutkiewicz, 1997; Lacey, 1980; Darke *et al*., 1976; Lacey and Crook, 1988).

Aspergillus fumigatus is particularly important in the composting process due to its capacity to degrade cellulose and hemicelluloses. Its optimum growth temperature is 37^{o}C and rapid growth can occur between 30 and 52^{o}C. Consequently it is likely to be present in significant numbers in compost, having increased from background numbers in the optimum growth conditions. However, its presence is also an important consideration from a human health viewpoint. It is an allergenic fungus and is an opportunistic pathogen which can cause aspergillosis in immunocompromised subjects (Vinken, 1984; Latge, 1999; Allmers *et al*, 2000).

Aspergillus fumigatus has a worldwide distribution and is essential in recycling carbon and nitrogen. One characteristic of its biological cycle is its capacity to generate large number s of spores, which results in the ubiquitous presence of between 1 and 100 spores in the air indoors and outdoors (Latge, 2001). Consequently, these spores are continuously inhaled by humans but rarely have an adverse effect as they are eliminated by the immune response. It has been estimated that all humans will inhale at least several hundred *Aspergillus fumigatus* spores per day (Goodley *et al*, 1994; Latge, 1999) without harm.

However, in rare instances they can cause infections (invasive aspergillosis) which is severe and usually fatal. Two case studies have been reported associated with composting (see section 10). The spores (conidia) of the fungus are small (2-3 µm in diameter) and can reach the alveoli of the lung. If they overcome the immune defence in the lung, they germinate to produce mycelia which invade the lung tissues. Until recently this was most likely to occur as aspergilloma, or ‘fungus ball’, an overgrowth of the fungus on the surface of pre-existing lung cavities such as caused by previous tuberculosis infection. However, because of the increased number of immunosuppressed and therefore susceptible patients, a fourfold increase in invasive aspergillosis was observed over the 12 years up to 1999 and the infection was estimated to occur in 10 to 25% of all leukaemia patients and 0.5 to 5% of patients after cytotoxic treatment of blood diseases or solid organ transplant (Latge, 1999). Presence of *Aspergillus fumigatus* in the air is therefore of particular concern in hospitals.

Aspergillus fumigatus can also produce mycotoxins (see section 5.6). Other *Aspergillus* species, and a wide range of other fungal species including those present in compost, are potentially

allergenic if inhaled in large numbers. Allergic response to *Aspergillus* species, and to fungal spores such as those of *Rhizopus, Cladosporium, Penicillium* and *Trichoderma* species, have been reported associated with workers exposed to microbially colonised materials.

5.3 BACTERIA

Bacteria can be divided into two main types; Gram-negative bacteria and Gram-positive bacteria. Gram-negative bacteria predominate in dusts of plant origin, bacteria such as *Pseudomonas spp., Klebsiella spp., Pantoea agglomerans, Rahnella spp.* and *Alcaligenes spp*. are commonly present (Dutkiewicz 1997). Gram-positive bacteria predominate in dusts of animal origin, but are also present in dusts of plant origin, bacteria such as *Corynebacteria, Bacillus spp,* and cocci such as *Staphylococcus spp., Micrococcus spp*., and *Streptococcus spp*. (Dutkiewicz 1997), and therefore potentially present in composts. Gram-negative bacteria found in dusts and more likely to be solely of animal origin include *Acinetobacter* and *Enterobacter* spp. Consequently, these species are unlikely to be present in composts except as chance contaminants in relatively small numbers. Other Gram negative bacteria of animal faecal origin, the coliform bacteria such as *Escherichia coli, Campylobacter* and *Salmonella* species, could be present in compost feedstock depending on its origin. Composts prepared from animal manures and sewage sludge obviously are most likely to contain coliforms, but organic waste may be contaminated by animal faeces.

The elevated temperatures achieved in composting should kill off coliform bacteria, although it should be recognised that inadequate compost turning could lead to temperature stratification and survival of coliforms in cooler layers. This is particularly of concern with highly pathogenic strains of *E. coli*, such as the verocytotoxic *E. coli* O157, which has been shown to survive for several days in soils (Maule, 2000; Ogden *et al*, 2001). Workers handling composts from animal manures need to take additional hygiene precautions, such as thorough hand washing, and public access to composting animal manures, such as on open farms, should be restricted. Other bacterial pathogens of animal origin include *Leptospira*, the causative agent of Weil's disease. This bacterium multiplies in the kidneys of infected rats and is spread in contaminated urine, causing infection in humans through entry via skin abrasions and mucus membranes. For this reason among others, vermin control on compost sites is important.

Bacteria, therefore, can be hazardous to health as pathogens, e.g., coliforms as described above, but the main route of infection is by ingestion. Respiratory infection caused by bacteria is unlikely to be a significant hazard in composting. However, bacteria present in airborne dust from composts could cause allergies and may be toxin producers (see endotoxin).

5.4 ACTINOMYCETES

In addition to the bacteria as described above, actinomycetes are also found in these environments. Actinomycetes are filamentous Gram-positive bacteria that are commonly found associated with soil and plant materials. Thermophilic actinomycetes, with a growth temperature range of 30 to 60^{o}C, thrive in wet compost that has begun the self heating process. Therefore they can be used as indicator organisms for self heating of organic material, and as indicator organisms for the presence of bioaerosols generated from compost (Dutkiewicz, 1997; Lacey, 1980; Lacey and Crook, 1988). The most common species present are *Saccharopolyspora (Faenia) rectivirgula, Saccharomonospora spp* including *S. viridis, Thermoactinomyces*

thalpophilus, Thermoactinomyces vulgaris and *Thermomonospora* spp. Mesophilic species such as *Streptomyces* are also commonly present in high numbers.

Thermophilic actinomycete species are recognised respiratory allergens. Actinomycetes produce thousands of very small spores (1-3μm diameter) which easily become airborne in large numbers when heavily colonised material is disturbed. Their small size means that they are potentially capable of penetrating deep into the human lung. They are primarily responsible for occupational allergic lung diseases such as Farmers Lung Disease and Mushroom Workers Lung Disease, which are forms of extrinsic allergic alveolitis (Hodgson and Flannigan, 2001).

5.5 ENDOTOXIN

Endotoxin is a macromolecule with a lipopolysaccharide core, which is found in the cell walls of all Gram-negative bacteria (Jacobs *et al.,* 1997). Gram-negative bacteria are present in the oral cavities and intestinal tracts of humans and animals; they also live on the surfaces of animals and plants. Consequently the general population is exposed to low levels of environmental endotoxin and it is found in house dust.

Inhalation of endotoxin in large quantity can cause short term illness, with flu-like symptoms, fever, myalgia, and malaise. This is often termed inhalation fever or organic dust toxic syndrome (ODTS). This acute clinical symptom response occurs between 6-12 hours after exposure and lasts about 4 hours. Chronic exposure to endotoxin has been linked to work related symptoms such as inflammation leading to chronic bronchitis, chronic obstructive pulmonary disease and reduced lung function (Jacobs *et al.*, 1997).

In occupational settings, intense exposure to endotoxin is usually a result of work which creates aerosols of organic dusts contaminated with Gram-negative bacteria, e.g., grain and cotton dust, dusts containing animal faeces, e.g., in swine confinement buildings and poultry houses, and sewage sludge. Environmental measurements of endotoxin are expressed in reported literature either as Endotoxin Units (EU) per m^3, a measurement based on biological activity, or as ng/m^3, a measure of chemical activity. The relationship between the two is that 10 EU is equivalent to 1 ng. In agriculture, such as grain handling, exposure up to 770,000 ng/m^3 has been measured (Swan, unpublished data, HSL), while in cotton mills exposure is up to 7,000 ng/m^3 (Simpson, 1999). Workers handling contaminated process waters in factories may be exposed to up to 27,000 ng/m^3 (Milton *et al*, 1995), in waste water treatment levels of up to 300 ng/m^3 have been measured (Liesivuori, 1994) and in biotechnology where the process organism is a Gram negative bacterium workers' exposure has been measured up to 160 ng/m^3 (Palchak, 1988). Endotoxin is also present in waste materials as a result of the presence of Gram negative bacteria and although its presence in the air during general waste handling was measured only at concentrations of up to 20 ng/m^3 (Heldal *et al*, 1997; Sigsgaard *et al*, 1994;1997), this value equates to a proposed health-based limit value for endotoxin (see section 10.6). The potential for endotoxin to be present as a significant component of the bioaerosol associated with composting processes has warranted its investigation.

5.6 MYCOTOXINS

Mycotoxins are non volatile low molecular weight toxic secondary metabolites produced by some species of fungi during their growth in organic materials. The most common route of exposure is by ingestion of fungally contaminated food. The toxins can cause acute or chronic disease in vertebrate animals with effects ranging from neurotoxicity to carcinogenicity and teratogenicity (Gravesen *et al* 1994). It has been hypothesised that mycotoxin exposure may contribute to occupational lung disease in workers exposed to organic dusts. *Aspergillus* spp. including *A. fumigatus* and *Penicillium* spp. produce mycotoxins and both are usually present in the dust generated during the handling of compost. However, their possible role in causing respiratory symptoms is not fully understood and the presence of mycotoxins in compost dust has not been widely studied. Fischer *et al* (1998b and 1999a) have investigated the presence of secondary metabolites associated with fungi, in particular *A. fumigatus* mycotoxins, in bioaerosols from composting facilities in Germany. Cultured isolates of *A. fumigatus* produced a range of mycotoxins. Extracts of total dust and bioaerosols from a composting hall contained two *A. fumigatus* mycotoxins, 2 tryptoquivaline (which has tremorgenic properties) and trypacidin. They did not find the most toxic mycotoxins produced by *A. fumigatus* (gliotoxin and verruculogen) in the bioaerosols. In the 1998 study of Fischer mycotoxins were not found in samples of airborne spores, organic dusts and bioaerosols from composting sites. The results indicated that fungal spore counts need to be above $10^7/m^3$ air to enable detection of fungal metabolites or toxins. Compost handling, like other industries such as grain and animal feed handling, could represent a theoretical hazard of mycotoxin exposure. Previous research has not shown a recognised occupational occupational health risk posed by these fungal metabolites in compost bioaerosols, but their toxigenic potential could justify further investigation.

5.7 GLUCANS

(1-3)β-D-glucan is a polyglucose compound in the cell walls of fungi, some bacteria and plants. It is a potent inflammatory agent that induces non-specific inflammatory reactions and may also be a respiratory immunomodulatory agent. (1-3)β-D-glucans may be involved in contributing to the inflammatory responses resulting in respiratory symptoms and adverse lung function effects in response to the inhalation of bioaerosols. Exposure to (1-3)β-D-glucans has been associated with an increased prevalence of atopy, decreases in FEV_1, and adverse respiratory health effects in the indoor and occupational environments, including waste handlers (Douwes *et al*, 2000; Thorn and Rylander, 1998; Fogelmark and Rylander, 1994). There is also evidence that (1-3)β-D-glucans may enhance pre-existing inflammation (Douwes *et al*, 2000). Because it is present as a component of fungi, it will be present in compost and potentially therefore airborne dust associated with compost. This has warranted some investigation into its potential effect on the health of compost workers.

5.8 VOLATILE ORGANIC COMPOUNDS AND ODOURS

Volatile organic compounds (VOCs) are generated by many sources in the compost mixture including micro-organisms. Eitzer (1995) found that most VOCs were emitted during the early stages of processing. Emissions were concentrated at the tipping floors where waste arrives, at the shredder and at the initial active composting region. VOC concentrations, even 'worst case' samples collected right next to the compost were well below USA permissible workplace levels.

They also found great similarities between facilities operating under differing conditions, in sites ranging from aerated in-vessel systems to open windrows.

Fischer (1999b) screened 13 fungal species, frequently isolated from a composting facility, for their ability to generate microbial VOCs. Various hydrocarbons and terpenes were identified. However, although these VOCs were generated under laboratory conditions, they were not necessarily produced when the fungi were growing in the compost.

A wide variety of VOCs can also originate from plant material, and one study suggested that VOCs from petrol driven vehicles passing a site could have affected VOC levels (Wheeler, 2001). There is insufficient evidence available on exposure to microbial VOCs at composting sites to enable full assessment of potential health risks, although the limited data suggests they are not likely to be a major risk.

Although issues related to odours lie outside the remit of this Review, it is important to note their potential role in the perception of health problems associated with bioaerosols and composting activities. The chief cause of odours from composting is when anaerobic microbial activity takes place causing the release of mainly sulphurous compounds. This is an unwanted occurrence and can result in complaints from neighbours. Although the dispersion behaviour of odorous compounds is different from bioaerosols, there may be the assumption that a detectable odour from composting activities is synonymous with exposure to bioaerosols.

6 POTENTIAL ILL HEALTH EFFECTS AMONG COMPOST WORKERS

6.1 OVERVIEW

The effects of occupational exposure to organic dusts on respiratory health have been investigated, but the mechanisms through which these respiratory effects are caused are not yet fully understood.

Many of the micro-organisms found in dust generated during composting are known respiratory sensitisers. Fungi such as *Aspergillus* spp., *Penicillium* spp., *Cladosporium, Rhizopus* and *Alternaria* are well known allergens (Darke *et al.*, 1976; Dutkiewicz *et al.*, 1985; Dutkiewicz *et al.*, 1989; Lacey 1995) while Gram-negative bacteria may also be a source of endotoxin (Dutkiewicz, 1976).

Inhalation of organic dust can cause a range of immunological respiratory symptoms which can be divided into four types of respiratory reaction (Chan-Yeung *et al*., 1992; Lacey, 1990; Lacey and Crook, 1988; Rylander, 1994) as well as, very infrequently, infection. These are described below. Subsequent sections in this report will describe studies on the occurrence of these diseases in compost workers and others exposed to organic dusts.

6.2 ALLERGIC RHINITIS AND ASTHMA

When a patient is sensitised to airborne allergens, exposure to those allergens can trigger the immunoglobulin E (IgE) pathway of the immune system causing allergic rhinitis (inflammation of the nasal passageways) or allergic asthma (upper respiratory tract broncho-constriction). Rhinitis and asthma frequently coexist in the same patient and both diseases are increasing in prevalence in the general population. Organic dust rhinitis and asthma are not caused by a single allergen present in the dust; different allergens may be responsible in different patients (Crook, 1994; Lacey and Crook, 1988; Blainey *et al.*, 1989; Zuskin *et al.*, 1994). Workers handling compost are often exposed to higher levels of allergens than the general population and the species to which they are exposed may differ. Published studies of allergic rhinitis and asthma in compost workers are therefore described in later sections of this report.

6.3 CHRONIC BRONCHITIS AND CHRONIC OBSTRUCTIVE PULMONARY DISEASE (COPD).

Chronic bronchitis is an inflammation of the mucous membrane of the bronchial tubes characterised by chronic cough, hypersecretion of phlegm and/or sputum and dyspnea and/or airways obstruction. The role of airborne fungal spores is uncertain, but airborne bacterial endotoxins may be involved in these diseases (Clapp *et al.*, 1994; Olenchock *et al.*, 1990; Lacey and Crook, 1988). Clapp *et al.* (1994) found evidence of additional endotoxin independent mechanisms of lung inflammation.

6.4 EXTRINSIC ALLERGIC ALVEOLITIS OR GRANULOMATOUS PNEUMONITIS

Extrinsic allergic alveolitis or granulomatous pneumonitis is generally an occupationally-related disease. Extrinsic allergic alveolitis is a T lymphocyte CD8 predominantly, granulomatous, inflammatory reaction of the peripheral gas exchange tissue. Onset can be acute or insidious (Fink, 1973) . Repeated exposure to large concentrations of spores, in excess of 10^6 spores m^{-3} of air (and mostly 1-5μm in diameter) has been suggested as the cause of acute symptoms (Chan-Yeung *et al.,* 1992). However prolonged exposure to lower concentrations of spores may also cause chronic symptoms (Lacey and Dutkiewicz, 1994), although the evidence for this is limited. Acute symptoms occur 4 -6 hours after exposure to the dust. These are chills, fever, dry cough, malaise, increasing breathlessness and, eventually, permanent lung damage may occur (Darke *et al.,* 1976; Lacey and Crook, 1988; Weber *et al.,* 1993). The characteristic immunological feature is the occurrence of predominantly IgG antibodies against specific antigens in the organic dust. Farmer's lung disease is caused by inhalation of the fungal and actinomycete spores present in large numbers in contaminated organic dusts. The actinomycetes *Saccharopolyspora (Faenia) rectivirgula* and *Thermoactinomyces* spp. in particular have been implicated (Lacey, 1990; Hodgson and Flannigan, 2001). Mushroom workers' lung has been linked to the inhalation of actinomycete spores associated with the mushroom compost (Kleyn *et al* 1981; Crook *et al* 1996; Hodgson and Flannigan, 2001). The principles involved in the production of mushroom compost are comparable to organic waste composting, although some of the production practices may create a greater potential for intense exposure to spores.

6.5 TOXIC PNEUMONITIS/ ORGANIC DUST TOXIC SYNDROME

Toxic pneumonitis/ Organic dust toxic syndrome (ODTS) is an acute illness occurring during, or shortly after, high exposure to airborne dust. Influenza-type symptoms develop, with leucocytosis and fever. No prior sensitisation is needed, antibodies do not develop and respiratory symptoms may or may not occur. The aetiology is unknown, but this also may be caused by inhalation of mycotoxins or endotoxins present in organic dust (Lacey and Crook, 1988; Chan-Yeung *et al.,* 1992). Further evidence for the role of endotoxins in ODTS has been provided by human challenge studies. Challenge studies with pure endotoxin have shown that in normal healthy subjects an inhalation of over 30-300 μg endotoxin can cause a clinical response. (Rylander *et al* 1989, Rylander, 1997, Michel *et al* 1997). Inhalation of endotoxin can also result in decreases in lung function and inflammatory responses. A decrease in lung function is caused by inhalation of over 80 μg of endotoxin in healthy subjects and over 20 μg endotoxin in asthmatics (Michel *et al* 1989,1992,1997) this response is significant 30 minutes after endotoxin inhalation and lasts five hours or more. Inflammatory responses to an acute inhalation of LPS in healthy subjects has been reported to occur after inhalation of less than 0.5 μg. Endotoxins have strong adjuvant effects on the reactions to antigens and increase the production of antibodies, they can have a synergistic effect on the skin prick test response and may facilitate the development and persistence of hypersensitivity pneumonitis and allergic asthma via their inflammatogenic and adjuvant properties (Rylander, 1997; Michel *et. al*., 1991; Fogelmark and Rylander, 1994). The adjuvant effect could be very important in the context of occupational exposure to the mixed allergens and toxins in compost dust. The intense exposure to organic dust required to elicit ODTS response could occur at certain stages of compost handling which create aerosols, such as post compost screening.

7 REPORTED STUDIES OF BIOAEROSOLS GENERATED BY COMPOSTING ACTIVITIES AND POTENTIAL HUMAN EXPOSURE

7.1 BACKGROUND; EXPOSURE MEASUREMENT METHODS

It is important to associate exposure to a hazardous substance with health effects and to understand the relationship between Host-Agent-Environment or Source-Pathway-Receiver. In considering compost bioaerosols, the host/receiver is an on-site worker or off-site sensitive receptor, the agent/source is the bioaerosol, the environment is the workplace or surroundings and the pathway is the air. Representative measurements are therefore made of exposure to hazardous substances. However, for bioaerosols the exposure measurement methods are less rigorously defined than for some other occupational hazards such as many chemical agents. The issues influencing these methods are as follows:

- Collection of a viable agent. The most commonly used methods of measurement are based on culture of the microbial cells present in the bioaerosol and this means there is a requirement to collect a representative bioaerosol in a way that preserves the viable and culturable state of the organisms present. This is important for identification purposes, although it must also be recognised that culture-based sampling may underestimate total exposure because of unculturable (NCBV) organisms, those not capable of growing because of incompatibilities with the culture conditions, and intact but non-viable cells which could still be toxic or allergenic. It is estimated that less than 10% of all bioaerosols may be culturable (Amman et al, 1995; Blomquist, 1994). Methods other than culture exist for measuring bioaerosols, including direct microscopic counting of fluorescent labelled cells, or analysis of cell constituents (endotoxin, glucan), but these are less frequently used and many are still under development.

- Sampling method. Most occupationally related exposure studies use personal sampling methods, with samplers located in the worker's breathing zone. However, personal sampling methods for bioaerosol measurement are less readily available and less commonly used. The most common method used, and therefore in most of the following reported compost studies, is fixed point sampling taken at single locations judged to be representative of work activities on site. Most exposure studies use the Andersen impaction sampler. These deposit airborne particles directly onto agar plates at an air flow rate of 28.3 litres/min (1 cu. ft/min). This has the advantage of direct inoculation of the agar plate on which the biological agent grows, but they are susceptible to overloading and sampling periods are short, ranging from approximately 30 minutes for background samples to as short as one minute in highly contaminated environments (Crook, 1995a). While such sampling can be greatly influenced by fluctuations in airborne concentrations caused by periodic differences in activities, on the other hand they can be used to record short term bioaerosol generation events associated with specific activities close to compost handling on site, or longer term background sampling at peripheral locations. For short term sampling, it is particularly important to record the activities taking place at the time of sampling. Personal sampling methods, such as filtration samplers in workers' breathing zones, have been used less frequently but can be run for up to the full duration of a work shift, operating at a lower flow rate typically of 2 litres/min, and provide a more representative measurement of workers' daily exposure (Crook, 1995b). In the following review, the sampling methods used have been described to allow these factors to be taken into consideration in evaluating the data presented.

7.2 BIOAEROSOLS ASSOCIATED WITH ORGANIC WASTE SITES

Wheeler *et al* (2001) investigated microbial emissions and worker health at 3 composting sites in the UK. These included one open windrow site processing green waste, an open windrow site processing mixed green and source separated household organic waste, and an in-vessel system processing mixed green waste, source separated household organic waste and refuse derived fuel production fines. In the investigation a range of aerobiological samplers were used to monitor airborne viable micro-organism levels during the different composting processes on different days (filtration, Andersen and cyclone samplers), but all were used at fixed point locations. VOCs were sampled using Tenax tubes and dust by filtration. Odour measurement was carried out using Tedlar gas bags and sniffed at various dilutions to determine an olfactory threshold concentration. No personal monitoring was carried out. Handling of green waste compost in the open generated levels of airborne bacteria which exceeded 10^6 colony forming units (cfu; a measure of culturable microbial cells) /m^3 air sampled on occasions. Levels of Gram-negative bacteria, fungi and actinomycetes each at times exceeded 10^5 cfu/m^3 air sampled. The handling of mixed waste compost generated levels of airborne bacteria at times in excess of 10^5 cfu/m^3. Gram-negative bacteria sometimes exceeded 10^5 cfu/m^3, fungi 10^4 cfu/m^3 and actinomycetes 10^5 cfu/m^3 air sampled. Most measurements for total bacteria were in the range of 10^4 - 10^5 cfu/m^3. Levels of airborne bacteria were highest during shredding and turning, airborne fungi during screening and airborne actinomycetes during screening and shredding at the open sites. The in-vessel composting process generated the highest levels of airborne bacteria and Gram-negative bacteria which both exceeded 10^7 cfu/m^3 air. Fungi and actinomycetes both exceeded 10^4 cfu/m^3. Levels of airborne micro-organisms were highest during unloading of the vessel and at the biofilter at the in-vessel system processing mixed green waste, source separated household organic waste and refuse derived fuel production fines invessel site. The author found that comparisons of the different operations gave no clear view of the relative emissions from screening, shredding and turning. The highest emissions of bacteria tended to be associated with the shredding operations, turning and screening operations appeared to have similar range of bacterial emissions. Fungal emissions were slightly higher during turning and shredding operations.

Inhalable dust was generally low and reached 'normal' levels, i.e., indistinguishable from background, within 250m of the site. VOCs were also generally low and well below the safety guidelines.

No personal bioaerosol sampling was done, but a clothing survey was carried out in an attempt to gauge the potential hazards to the families of workers, who may launder overalls and other work clothing. A study to assess the contamination levels on overalls was undertaken at two sites. The workers were requested to wear, for one working day, a set of disposable overalls. However, no comment was made by the authors as to how the disposable overalls compared to their normal overalls in terms of potential for collecting and harbouring dust. Two patches from each overall were taken from the most heavily soiled part of the garments and from a less contaminated region these were then assessed for microbiological contamination. At the open windrow site processing mixed green and source separated household organic waste workers spend most of the time within the cabs of their vehicles and had limited exposure to the waste, they had quite low contamination of their clothing, 370,000 bacteria/m^2 material and 80,000 fungi. At the in-vessel site levels were much higher 80,000,000 bacteria/m^2 material and 67,000,000 fungi. The author recommended the provision of laundry facilities for work clothing as overalls with these levels of contamination can be a risk within the home. There is some evidence from studies on farmers that dust containing allergens can be carried into the home on contaminated clothing (Parvaneh *et al*, 2002).

Recommendations from this study included:

- Not siting a compost site closer than 250 m to a sensitive receptor unless effective mitigation techniques are employed;

- A requirement for further research on dose response relationships, risk to human health, and how this is affected by factors such as length of exposure, keeping the compost moist, dust suppression during open turning, screening and shredding and keeping the site surfaces and roads clean.

Lacey (1997) reported the preliminary results from a UK study of actinomycetes in green waste compost. During the shredding of fresh green waste, concentrations of airborne actinomycetes were less than 5 x 10^4 cfu/m^3, and levels averaged 10^6 cfu/m^3 close to the compost piles during turning. It was found that *Saccharomonospora* was the predominant taxon during shredding, *Streptomyces albus* and *Thermoactinomyces* were also present. During composting other taxa such as *Streptomyces* increased in numbers.

Haas *et al* (1999) measured airborne thermophilic actinomycetes in the vicinity of composting facilities over a one year period in Austria, using Andersen impaction samplers. Median values of actinomycetes close to an open composting plant were less than 100 cfu/m^3 with a maximum count of 1308 cfu/m^3.

Folmsbee and Strevett (1999) investigated levels of airborne micro-organisms at an outdoor composting centre in Oklahoma USA. Samples were collected by Andersen sampler, at 3 sites on the compost site and 2 background sites, one to three times weekly during June to October. The three test sites approx. 10 yds (9 m) from the compost windrows, representing the perimeter of the active area. Two background sites were several miles from the facility, one in open fields and one in a sheltered back yard. Sampling "was generally not performed when activity was visible at the compost site". Sampling was not associated with occupational activities and results reported were highly summarised. The on site samples sited near to and downwind of the main composting activity showed a tenfold increase in all the micro-organisms monitored in comparison with the other sites. The average, on site, concentration of total viable bacteria was 5,059 cfu/m^3, averages at the three sites ranging from 2,000 to 7,000 cfu/m^3, of which Gram-negative bacteria were 2,023 cfu/m^3. Fungi averaged 972 cfu/m^3 overall, with averages at the three sites ranging from 500 to 15,000 cfu/m^3. Thermophilic actinomycetes averaged 2,159 cfu/m^3 overall, with averages at the three sites ranging from 1,000 to 3,500 cfu/m^3. Overall, fungal levels were lower than those of bacteria. By comparison, the background values averaged approx. 1,500 and 2,000 cfu/m^3 bacteria, 600 and 700 cfu/m^3 fungi and 600 and 1,200 cfu/m^3 actinomycetes.

Hryhorczuk *et al* (1996; 2001) and Curtis et al (1999) measured bioaerosol emissions from a green waste composting facility in Chicago. Andersen samplers were used to measure viable fungal and bacterial levels (288 samples), samples were collected in the mornings at a location relevant to the piles that had most recently been disturbed, but at a time when no compost pile activity was taking place. These on site samples were taken 1 metre away from the compost piles. Filtration samples (45 samples) were used to monitor dust, Asp fl protein, endotoxin and beta glucans, one filtration sampler was used as a personal monitor. Spore counts were conducted using a Kramer-Collins spore sampler (38 samples). Concentrations of airborne bacteria, total fungal spores, endotoxin and beta glucans were significantly higher on-site than off site, i.e., beyond the boundary fence 75 metres away from the nearest piles. Levels of bacteria next to the compost piles reached 7.9 x 10^4 cfu/m^3 and averaged 11,879 on-site, compared to 3,204 off-site. Total fungal spores reached 26,067 spores/m^3 (average 13,451 spores/m^3 on site

8,772 spores/m^3 off site), levels of viable fungi reached 1.8 x10^4 cfu/m^3. Mean total viable fungi were higher off site than on site (average 3,068 on-site, 8,651 off-site). Endotoxin levels on site reached 6.06 ng/m^3 (60 EU/m^3) (average 1.94 ng/m^3 on site, 0.14 off site) and beta glucans reached 14.45 ng/m^3 (average 2.17 ng/m^3 on site, 0.24 off-site). The most predominant fungi were *Aspergillus* (45%) and *Penicillium* (21%); *Cladosporium* (8%) and *Alternaria* (5%) were also present. Activities on the compost facility significantly increased downwind concentrations of bacteria on and off-site. While bacterial concentrations averaged 19,044 cfu/m^3 next to the compost piles on-site, the average was down to 5,915 cfu/m^3 at the boundary fence. The highest concentrations of total particulates (1,805 ng/m^3), endotoxin (6.06 ng/m^3), and beta glucans (14.45 ng/m^3) were observed in the personal samplers worn by the workers or attached next to the worker in an open-cab front end loader. Asp fl protein on a personal sampler peaked at 22.17 ng/m^3 during turning activity. It was found that concentrations of total viable fungi and total fungal spores in the community adjacent to the composting facility were similar to outdoor fungal concentrations in other control communities. It was also found that the mean total viable fungi was higher off-site than on-site (8,651 vs 3,068 cfu/m^3), the area surrounding the facility being wooded with wetland areas. This provided a thorough study of levels of bioaerosols associated with composting sites, however, as most of the sampling was carried out at a time when no compost pile activity was taking place it does not cover potential "worst case" exposure levels for the workers. Personal filtration samples were collected although these were few in number and the personal exposure data for the workers was not reported in detail. Even though many samples were collected, the high variability of background measurements highlights the difficulty in interpreting bioaerosol exposure data.

7.3 BIOAEROSOLS ASSOCIATED WITH MUNICIPAL BIOWASTE SITES

Nielsen *et al* (1997) investigated micro-organisms and endotoxin in experimentally generated bioaerosols from composting source separated household waste. Although not providing information on worker exposure, this study gave useful data to define the source of bioaerosol from compost. The compost used in the study comprised 86% biowaste, 10% straw, 4% paper. Samples of 1, 5 and 9 week old compost were collected and used to generate bioaerosols. The micro-organisms in the compost were predominantly bacteria and actinomycete spores (total of 10^9-10^{11} cells/g). There was a significant increase in numbers between week 0 and week 9, and numbers increased steadily over the 11 week period. The fungal concentrations were low, yet *Aspergillus fumigatus* was the predominant viable fungal species. Fungi increased significantly at the end of the composting period but numbers were still just above the detection level (200 cfu/g) in most samples. Endotoxin levels varied, with a significant increase between the minimum measured (2.5 μg/g) at week 5 and the maximum (110 μg/g) at weeks 9-11. Actinomycete spores in particular were capable of being made airborne and the authors concluded that thermophilic actinomycetes were the predominant source for airborne micro-organisms.

Lavoie and Alie (1997) investigated bioaerosols at two household waste sorting and composting plants in Canada, both sites comprising a reception area and a fermentation building. Site A had fermentation cylinders and indoor windrows, while site B had indoor windrows and outdoor curing. Bioaerosol sampling was carried out using Andersen samplers. At both sites peak levels of airborne micro-organisms occurred in the reception and fermentation areas and this was regardless of season. At site A total bacteria reached 10^5 cfu/m^3, of which 10^2 cfu/m^3 were Gram-negative bacteria. Actinomycetes reached 10^3 cfu/m^3 and fungi 10^4 cfu/m^3, with peak concentrations of *A. fumigatus* also measured at 10^4 cfu/m^3 air sampled. At site B total bacteria reached 10^4 cfu/m^3 total bacteria, of which 10^2 cfu/m^3 were Gram-negative bacteria.

Actinomycetes and fungi both peaked at 10^4 cfu/m^3 , with peak concentrations of *A. fumigatus* at 10^3 cfu/m^3 air sampled. Levels of bacteria were over 10^4 cfu/m^3 at several of the indoor sampling areas. In several areas total fungal concentrations were significantly higher than in the outdoor air, and the *A. fumigatus* levels measured in all workstations at both sites were significantly higher than in the outdoor air nearby. Bioaerosol concentrations in air 100 m downwind from the sites were not affected by operations.

Tovalen *et al* (1998) reported a thorough investigation of bioaerosols from composting source separated biowastes in Finland. The compost was processed outdoors. Andersen samplers were used to collect samples 20m from the windrows and 4m from a composting drum. Filtration samplers for dust and endotoxin were positioned statically round the site as well as in the vehicle cabs and as personal samplers in the breathing zone of the workers, though for relatively short sampling periods of 0.5 to 1.5 hours. Concentrations of airborne microbes and endotoxin were highest during crushing of fresh waste and turning of compost. Both bacterial and fungal levels ranged between 10^3-10^5 cfu/m^3, levels were higher in the summer when the compost was dry. The predominant fungi were *Aspergillus* spp and *Penicillium spp*. Concentrations of actinomycetes were lower than fungi during all stages of the composting process, 0-3,000 cfu/m^3, compared to background concentrations less than 120 cfu/m^3. They reported that these results probably underestimate the true levels due to overloading of the Andersen samplers. Endotoxin levels were high at 0.8 - 344.5 ng/m^3 (about 80 - 3,445 EU/m^3) outside and 0 - 152 ng/m^3 (about 0 - 1,520 EU/m^3) inside vehicle cabs.

Different methods of crushing the fresh waste were investigated with a view to reducing worker exposure to bioaerosols, as a result of which a gentle method of simultaneously crushing and turning was adopted. They also tested drum composting which resulted in a lower worker bioaerosol exposure but the results were not reported in detail.

The numbers of faecal streptococci, faecal coliform and *Clostridia* at different stages of the composting process were also investigated (Tovalen *et al* 1998). Levels were highest in fresh biowaste, 10^4-10^6 cfu/g, and, in well managed compost, decreased over the first 4 weeks to 150 cfu/g. In poorly managed compost the numbers increased over 6 weeks. In mature compost numbers of faecal streptococci were 100 to 300 cfu/g, faecal coliform 600 to 3,800 cfu/g and *Clostridia* were 4,000 to 5,000. Pathogenic bacteria such as *Escherichia coli, Salmonella typhimurium* and *Klebsiella* were found in the 2-4 week old compost. Psychrotrophic bacteria predominating at 2 months were overtaken by mesophilic bacteria at 3 months. Thermophilic bacteria numbers were high all the time and were most abundant in the fresh compost. As a result of these potential levels of exposure, they authors advised cleaning out the cabins of the machines at least twice a week, and the wearing of respirators.

Marchand *et al* (1995) undertook sampling at a municipal solid waste recycling and composting plant in Quebec, Canada using Andersen samplers. In at least one sample from each workstation, the air concentrations of total bacteria exceeded 10^4 cfu/m^3 (maximum 5.3 x 10^5 cfu/m^3). The concentrations of Gram-negative bacteria were above 1,000 cfu/m^3 in the air from six out of nine workstations (maximum 7,900 cfu/m^3) although the compost method used appeared to kill Gram-negative bacteria. The indoor concentrations of fungi were higher than outdoor concentrations in most areas (maximum 7,200 cfu/m^3). Although this was a detailed study, no personal monitoring of workers' exposure was done.

7.4 BIOAEROSOLS ASSOCIATED WITH IN-VESSEL COMPOSTING

Danneberg *et al* (1997) examined microbial and endotoxin emissions in the neighbourhood of a Herhof box-system composting plant. Measurements of micro-organisms and endotoxins were taken using filtration samplers. Concentrations measured at a distance of 150m downwind of the composting facility were used to calculate the emission rate. Next to a rotating sieve, i.e., at the point of emission, airborne bacteria were measured at 76,000 cfu/m^3, compared to 2,800 cfu/m^3 150 m downwind. At 75 m upwind, the value measured was 433 cfu/m^3 and at a control location 311 cfu/m^3. Airborne *Aspergillus fumigatus* next to the sieve measured 2,000 cfu/m^3, 150m downwind were 200 cfu/m^3 and 75 m upwind none were detected. At the control location 78 cfu/m^3 *Aspergillus fumigatus* were measured. Airborne endotoxin next to the sieve measured 200 EU/m^3 (= 20 ng/m^3), and a value of 2 EU/m^3 both 150m downwind and 75 m upwind. Less than 1 EU/m^3 was detected at the control location. Exhaust air emitted from the biofilter contained 33 cfu/m^3 bacteria, 600 cfu/m^3 *Aspergillus fumigatus* and < 1 EU/m^3 endotoxin.

Maricou *et al* (1998) investigated airborne concentrations of micro-organisms at a large indoor composting plant in Belgium where vegetable and garden waste was being co-composted with paper waste comprising mainly disposable nappies. Monitoring was carried out for a year using impaction samplers. The data in this paper was highly summarised, but provided a general overview. Counts of total bacteria, fungi and yeasts were approximately 10 to 100 times higher inside the composting halls compared to ambient levels outside, with the highest values reached during summer. Concentrations of airborne faecal coliforms, chosen as indicator organisms for this waste feedstock, were within the range of 1 - 10,000 cfu/m^3 , levels increased by a factor of 10 to 1,000 when fresh stock was delivered to the compost hall. Airborne micro-organisms increased by 1 to 4 orders of magnitude at the onset of mechanical activities, and decreased to their original levels within two to five hours after mechanical operations ceased. The authors recommend the wearing of respiratory protection inside the halls and following of basic hygienic rules such as hand washing and removal of working clothes before lunch, the consumption of foodstuffs containing *Lactobacilli* (as protective factors against gastro-intestinal infection) and showering after the working day.

Haas *et al* (1999) measured airborne thermophilic actinomycetes in the vicinity of an enclosed (Herhof type) composting facility over a one year period in Austria, using Andersen impaction samplers. Median values of actinomycetes close to the plant were 213 and 549 cfu/m^3, with a maximum count of 4356 cfu/m^3.

Schilling et. al (1999) compared an enclosed composting plant with biofilters with a partly open plant. Air samples were collected using fixed point filtration samplers. They found that at the enclosed composting plant levels of thermophilic fungal spores 50m downwind ranged from 20 to 500 cfu/m^3, with *Aspergillus fumigatus* ranging from 100 to 400 cfu/m^3. By comparison, at the partly open site 5m downwind thermophilic fungal spores ranged from none detected to 10,000 cfu/m^3, with *Aspergillus fumigatus* in the same range, and even at 100m downwind thermophilic fungal spores ranged from none detected to 6,000 cfu/m^3, with *Aspergillus fumigatus* ranging from none detected to 7,000 cfu/m^3.

Heida *et al* (1995) investigated bioaerosols in an indoor green waste composting facility. The facility is housed in a large hall with ventilation shafts supplying fresh air and keeping the temperature between 30 - 40 ^{o}/c and relative humidity between 70 - 130%. The composting process is designed to operate automatically but workers are still present for surveillance, maintenance and repair. Micro-organisms were collected using an Andersen impaction sampler. VOCs were collected using Tenax absorbent tubes. Total bacteria counts were more than 28,000

cfu/m^3, Gram-negative bacteria were up to 9,100 cfu/m^3 and included the genera *Pseudomonas, Acinetobacter, Shigella* and *Yersinia*. Total fungal counts were less than 9,000 cfu/m^3 and included *Aspergillus* (60%), *Penicillum* (20%), *Mucor* and *Rhizopus*. A slimy substance on the facility walls was found to be *Pseudomonas spp*., a Gram-negative bacterial species that produce endotoxins. Concentrations of VOCs were low, only limonene was elevated, all were well below the current Dutch provisional threshold values. Workers at the site had reported respiratory distress and upper airway infection but this was not investigated further. Although a detailed study, no personal monitoring was carried out, also it would have been useful to know if the automation reduced worker exposure. The authors concluded that this operation may have significant health hazards for the workers and recommended the wearing of disposable protective suits and caps as well as high efficiency filter respirators and that thorough hand washing should be carried out each time a worker leaves the premises.

7.5 BIOAEROSOLS ASSOCIATED WITH MUSHROOM COMPOST

During the commercial production of mushroom compost, the highest levels of airborne micro-organisms are associated with handling of the compost, such as when the mushroom spawn is being mixed with the compost, or when disposing of spent compost after mushroom growth has been completed. The predominant micro-organisms are thermophilic actinomycetes. Aerobiological studies at mushroom farms have shown that during the mixing of compost with spawn thermophilic actinomycetes may be present in the air in enclosed facilities at concentrations of 10^7 to 10^9 cfu/m^3 , with fungal concentrations from 10^3 to 10^5 cfu/m^3 (Crook and Lacey, 1991; van den Bogart *et al*, 1993). During the emptying of trays of spent compost, actinomycete concentrations were measured at 10^4 cfu/m^3 and fungi at 10^5 cfu/m^3 using Andersen impaction samplers (Crook and Lacey, 1991). In an earlier study (Kleyn *et al*, 1981) total spore counts were made by microscopic examination, estimating the airborne spore levels to be in the region of 10^5 /m^3, with actinomycetes predominating. These authors also estimated that a worker dumping spent compost could inhale 6 x 10^7 micro-organisms during the 2.5 hours taken to complete the task. Air samples taken out of doors in a mushroom compost preparation area revealed considerably smaller bioaerosol concentrations (Crook and Lacey, 1991). Between windrows of Phase 1 composting material numbers ranged from 10^3 to 10^5 cfu/m^3, compared to 10^2 to 10^3 cfu/m^3 upwind of the site, showing the influence of the proximity of the composting material on the airspora.

7.6 BIOAEROSOLS ASSOCIATED WITH SEWAGE COMPOST

Millner *et al* (1980) reported levels of 1.5 x 10^4 cfu/m^3 thermophilic actinomycetes downwind of the turning of compost windrows containing a mixture of wood chips and sewage sludge. Actinomycetes identified included *Nocardia, Saccharopolyspora, Saccharomonospora* spp. and *Streptomycete* spp.

High airborne endotoxin levels were measured at an indoor municipal sewage sludge composting plant in Colorado (Darragh *et al* 1997). No culturable bacterial or fungal measurements were made. Ventilation at the facility was designed to give six changes air/hour. Fixed point filtration and cascade impactor samplers were used, no personal monitoring was carried out. Endotoxin levels ranged from 28.9 to 5930.6 ng/m^3 (about 289 - 59,306 EU/m^3) which is 30 times greater than the threshold at which ODTS is thought likely to occur (Rylander, 1997). The maximum

total dust level measured was 173.8 mg/m^3 measured during screening and sweeping operations , the mean dust levels on days with no sweeping and screening ranged from 1.18 to 1.73 .mg/m^3. Gases were also measured and found to be low. Dust was generated by traffic, mixing the sludge, and screening operations at the composting facilities. The dust was composed of large cellulose materials and small sewage particles. A very large percentage of the aerosol was of a sufficiently small particle size to allow penetration into the lungs to the gas exchange region, where it can potentially cause the most damage. The study included no personal exposure data.

Kothary *et al* (1984) investigated levels of *A. fumigatus* in air and in compost at an outdoor sewage sludge composting site, using an impaction air sampler. Up to one million colony forming units per gram of compost were detected. *A. fumigatus* comprised 59 to 98 % of the thermotolerant fungal population in the air. Levels reached 4000 cfu/m^3 1m downwind from the compost piles, decreasing to 1000 cfu/m^3 50 m downwind.

7.7 REDUCING THE LEVEL OF EXPOSURE TO BIOAEROSOLS FROM COMPOSTING

It may be possible to reduce emissions of bioaerosols, and therefore workers exposure, by changing work practices. Fischer *et al* (1998a) investigated the effect of turning frequency on levels of *Aspergillus fumigatus* during windrow composting of garden and kitchen waste. An impaction sampler was used to collect samples at head height 2 m, 5 m and 10 m downwind from the turning machine. *A. fumigatus* levels in the centre of windrows were reduced after two weeks of composting from >10^3 cfu/g dry weight compost (gdw) down to 10^2 cfu/gdw. Surface *A. fumigatus* counts remained high in less frequently turned windrows. Airborne concentrations of *A. fumigatus* were highest (6 x 10^5 cfu/m^3) while compost was being turned after eight weeks, but release of fungal spores was always 1 to 2 orders of magnitude lower if the compost had been turned daily or weekly during that time. The more frequently the windrow was turned (daily or weekly) the faster the temperature increased to a level which can eliminate *A. fumigatus*. They concluded that health risks for personnel working at composting sites could be lowered by frequently turning the windrows and thus reducing the levels of *A. fumigatus* on the surface of the compost. Investigation of concentrations 10 m downwind of turning process showed numbers already two to three orders of magnitude lower. Outside the perimeter of the site *A. fumigatus* levels were normally not higher than in control samples. Personal occupational exposure levels of workers was not investigated. From an occupational exposure point of view the benefits of decreasing the *A. fumigatus* levels in the environment would have to be balanced against the extra exposure of the workers turning the compost more frequently.

Epstein *et al*. (2001) reported a thorough investigation of an enclosed biosolids composting facility. Personal monitoring was carried out using an impaction sampler and personal exposure to respirable dust was measured. *A. fumigatus* levels were monitored using an Andersen sampler. Air monitoring was conducted during feedstock mixing, pile construction, pile covering, pile tear down, and screening. Exposure levels were <50 - 7.06 mg/m^3 for dust, <0.5 - 640 ng/m^3 (5 - 6,40 EU/m^3) endotoxin and 74 - 6,241 cfu/m^3 *A. fumigatus*. The dustiest processes with highest endotoxin levels were pile construction and breakdown. The workers were observed predominantly to work and move about the site in enclosed cabs with filters. Personal dust exposures reached 1.41 mg/m^3 during mixing of the compost. *A. fumigatus* levels were highest during feedstock mixing. When dust control measures were introduced, such as increasing the moisture content of the feed mix, altering air flow into the compost to reduce drying prior to screening, suppressing dust in the composting area floor using a water spray, and placing a dust

hood and baghouse dust collection system over the screen, concentrations of dust, endotoxin and *A. fumigatus* were reduced by around 90 %. Putting in place water misting devices over the screen conveyors was also recommended. The authors concluded that workers at enclosed biosolids composting sites may be subject to frequent exposure to high levels of dust, endotoxin, and *A. fumigatus* for shorter periods of time. They suggested several design and operational measures that can reduce worker exposure. These included moisture control of the stock and composting; isolation of the screening operation from the composting operations; dust control and collection systems in dry climates; sweepers and water vehicles to control dust in roadways; air filters in cabins of mobile equipment; adequate ventilation in buildings; personal hygiene equipment.

Breum, *et al*., (1997) used a dustiness drum to look at airborne micro-organisms and endotoxin of stored waste and showed that materials stored with free access to air gave significantly higher concentrations of airborne micro-organisms and endotoxin than those stored with low access. Concentrations of bioaerosols were correlated to the weight loss of water in storage.

8 AMBIENT BIOAEROSOL LEVELS, BIOAEROSOLS FROM OTHER INDUSTRIES AND DISPERSAL FROM COMPOST SITES

8.1 "NORMAL" LEVELS OF MICRO-ORGANISMS IN SOILS

The case studies described above show the levels of bioaerosols to which workers handling compost, and the people in the vicinity, may be exposed. However, to place these data in context, it is important to recognise that bioaerosols are constantly present in the ambient atmosphere as a consequence of dust from soil and the natural breakdown of vegetation. In addition other human activities, such as various agricultural practices, will create bioaerosols.

Soil is a major source of micro-organisms and one of the most complex of natural communities. It is generally accepted that only a small percentage, possibly as few as 1%, of the micro-organisms present in soil are culturable, and there may be as many as 4,000 species per gram of soil (Ogram and Feng, 1997). The numbers present will depend on the type of soil, organic loading, temperature and moisture content etc. However, as a general guide, bacterial density in soils, sludges and sediments can be considered to be in the range of 10^8 to 10^{10} per gram (Holben, 1997). As a consequence, any dusts made airborne by the disturbance of soil will support large numbers of micro-organisms.

8.2 BACKGROUND LEVELS OF BIOAEROSOLS IN AMBIENT AIR

In the absence of any significant bioaerosol sources, natural atmospheric conditions in a typical suburban area were reported to give rise to 0 - 7.2 x 10^3 (mean 273) cfu/m^3 mesophilic fungi, 0 - 193 (mean 2.1) cfu/m^3 thermophilic fungi, 0 - 71 (mean 1) cfu/m^3 *A. fumigatus*, 42 - 1.6 x 10^3 (mean 79) cfu/m^3 bacteria. The highest concentrations occurred during summer and autumn (Jones and Cookson, 1983). Crook and Lacey (1988) reported concentrations of viable airborne micro-organisms outdoors to be: 500 cfu/m^3 total bacteria, 10 cfu/m^3 Gram-negative bacteria, 1,200 cfu/m^3 total mesophilic fungi, 300 cfu/m^3 thermophilic fungi and 60 cfu/m^3 thermophilic bacteria and actinomycetes. Ambient levels of viable airborne bacteria in an agricultural area were reported by Bovallius *et al*. (1978), 2 - 3.4 x 10^3 (mean 99) cfu/m^3, and in a city 100 - 4.0 x 10^3 cfu/m^3 (mean 850).

Bioaerosol levels inside non-industrial buildings, including offices and homes, are generally considered to reflect outdoor levels except at a lower level, in the absence of a bioaerosol source such as contaminated air conditioning or damp problems. A large study of airborne fungi inside and outside buildings in USA was reported (Shelton *et al*, 2002). Over 12,000 air samples were taken using Andersen samplers from 1,717 building located across USA, including over 9,000 indoor air samples and 2,000 outdoor samples. Overall, the median indoor fungal concentrations were 6 to 7 times lower than the median outdoor samples. The overall mean concentrations of fungi measured in the study were 930 cfu/m^3 outdoors compared to 300 cfu/m^3 indoors. The 75th percentile values were 1,200 cfu/m^3 outdoors and 240 cfu/m^3 indoors, with maximum values recorded of >8,200 cfu/m^3 outdoors and >10,000 cfu/m^3 indoors. Predominant fungal species both inside and out were *Cladosporium*, *Penicillium* and *Aspergillus*, being isolated in 86%, 80% and 62% respectively of all samples indoors. Outdoors, the frequency of isolation was 92% for *Cladosporium*, 77% for *Penicillium* and 49% for *Aspergillus*. When detected outdoors, *Aspergillus* was found at median concentration of approx. 20 cfu/m^3 with a 95% CI range of 12 to 170 cfu/m^3. Concentrations of airborne *Aspergillus fumigatus* are summarised in Table 3.

Table 3. Concentrations of *Aspergillus fumigatus* inside and outside buildings in USA (from Shelton *et al*, 2002)

Treatment of data	Outdoors			Indoors		
	Mean	**Median**	**95th percentile**	**Mean**	**Median**	**95th percentile**
Far West USA region	69	18	140	22	12	65
Northeast USA region	54	12	300	23	12	59
Midwest USA region	74	18	380	96	12	650
Northwest USA region	28	12	130	24	12	71
Southeast USA region	32	18	110	20	12	53
Southwest USA region	43	12	150	16	12	44
Autumn	48	18	150	37	12	71
Spring	38	12	130	39	12	47
Summer	73	12	320	49	12	130
Winter	43	12	190	22	12	75

In summary, across the whole of USA typical concentrations of outdoor airborne *Aspergillus fumigatus* range from 38 cfu/m^3 in Spring to 73 cfu/m^3 in Summer, with maximum exposure typically in excess of 130 cfu/m^3 in Spring and 320 cfu/m^3 in Summer. Regionally, typical concentrations may range from 28 cfu/m^3 to 74 cfu/m^3, with maxima ranging from 110 cfu/m^3 to 380 cfu/m^3.

Hunter and Lea (1994), reported a survey of 24 randomly selected homes in the West of England, where airborne fungi were measured using Andersen samplers in living rooms and bedrooms. Counts of total airborne culturable fungi ranged from 28 - >35,000 cfu/m^3, with an overall geometric mean of 1096 cfu/m^3. Similar counts were found in living rooms and bedrooms, with a seasonal variation from a monthly geometric mean of <1000 cfu/m^3 from November to April, steadily rising to peak at 4000 cfu/m^3 in October. They found location had little influence - a geometric mean of 1047 cfu/m^3 in inner city areas, 1023 cfu/m^3 in suburbs, 1202 cfu/m^3 in rural town/village areas and 1174 cfu/m^3 near the coast. They concluded that a normal range (95 percentile) gave a maximum value of 7450 cfu/m^3 in living rooms and 4900 cfu/m^3 in bedrooms. By comparison with the study in USA by Shelton, the overall mean and maximum values of fungal levels indoors were approximately three times greater. This may have been influenced by national differences, but more likely that in the US study the majority of the indoor environments studied were offices (46%) with only 4% of the total being residences. Both however provide valuable baseline data for typical ambient levels of fungi and fungal components.

Mullins (2001) summarised data from spore trapping studies that have been performed regularly in and around Cardiff for more than 40 years. The method of collection is a spore trap, for which the method of measurement is direct microscopy, so the numbers may overestimate culturable numbers, and the fungus *Cladosporium* is used as one of the main indicator organisms;

Aspergillus was not reported, but as a point of comparison Shelton *et al* (2002) found *Cladosporium* numbers to be ten times greater than *Aspergillus* spp. Numbers of airborne *Cladosporium* spores in central Cardiff range from less than 100 spores/m^3 in winter months to a peak of 3500 to 4000 spores/m^3 in July and August. By comparison, at a sampling site in a mixed deciduous woodland, during summer months airborne *Cladosporium* levels were 30 % greater than in the city centre site. While airborne *Cladosporium* spores tend to peak in summer, *Aspergillus fumigatus* spores peak in number in mid-late autumn (see also Hunter and Lea, 1994). Mullens *et al* (1984) measured outdoor culturable *Aspergillus fumigatus* numbers in Cardiff and compared them with numbers from St Louis in USA. Average concentrations recorded were 13.5 cfu/m^3 in St Louis and 11.3 cfu/m^3 in Cardiff, with a similar range in both cities from <20 cfu/m^3 in March to September to a peak of 50 - 60 cfu/m^3 occurring in October in St Louis and November in Cardiff. In a previous report, Mullins *et al* (1976) also recorded peaks in *Aspergillus fumigatus* during autumn/winter, citing plant debris in the form of compost heaps and stacks of hay and straw baled with a high moisture content in which self-heating occurs as being potential sources for producing large numbers of spores which may be liberated into the air causing high but localised counts if disturbed. This may not be the case now, with changes in agricultural practices, but the authors also cited the widespread distribution of decaying leaves following leaf fall as representing a potential source of smaller concentrations of spores but over a much larger area. They stated that the availability of decaying plant debris with high water content fulfils the growth requirements of *Aspergillus fumigatus* and is the probable explanation of its winter seasonality.

Airborne fungal spores were monitored weekly for two years in France (Chaumont *et al,* 1990). Numbers differed greatly between the two years, with up to 2,999 cfu/m^3 in the first year and 9,841 cfu/m^3 in the second year. The pattern of predominant fungi was similar to UK studies, with *Cladosporium* most abundant in summer and *Aspergillus* in autumn. Likewise, a study in the Netherlands showed that peaks in overall fungal numbers occurred from May to September, but that *Aspergillus* and *Penicillium* species prevailed in autumn and winter (Beaumont *et al*, 1985).

Kock *et al* (1998) sampled at seven sites in metropolitan and rural areas in Austria, counting airborne bacteria and fungi at two weekly intervals over one year. Bacterial and fungal counts in a village area dominated by agriculture exceeded the corresponding counts in a suburban residential area fourfold (327 cfu/m^3 air of bacteria) and twofold (185 cfu/m^3 air of yeasts and moulds) respectively. They found that the proportion of *Aspergillus fumigatus* in the fungal counts was highest in the village area with 23%, compared to 10% in open land.

As part of an investigation into a composting facility, Hyhorczuk *et al* (1996, 2001) took 55 background samples at four locations in fields and wooded areas several hundred metres from the compost facility. Mean fungal concentrations were relatively high, at 8,651 cfu/m^3 (median 3,200 cfu/m^3), mean bacteria were 3,204 cfu/m^3 (median 2,080 cfu/m^3), Gram negative bacteria were 1,664 cfu/m^3 (median 1171 cfu/m^3) and actinomycetes 94 cfu/m^3 (median 0 cfu/m^3). The high median values compared to means for airborne fungi suggests data were skewed by some particularly high values, and the range of values reported was up to 94,000 cfu/m^3. This highlights the potential for occasional very high bioaerosol counts even in the absence of obvious bioaerosol sources. In another US study (Folmsbee and Strevett, 1999), background sites located some miles from composting facilities averaged lower counts of around 600 to 700 cfu/m^3 fungi and 1,500 to 2,000 cfu/m^3 bacteria.

Because of its potential role as an opportunist pathogen, there is concern about elevated levels of *Aspergillus fumigatus* in the vicinity of hospitals, where immunocompromised patients may be at

increased risk of infection. Consequently, monitoring for airborne *Aspergillus fumigatus* has been done at hospitals in a limited number of studies. Streifel *et al* (1983) measured airborne *Aspergillus fumigatus* concentrations in the vicinity of demolition work being done at a hospital in USA. They found that the outdoor concentrations of *Aspergillus fumigatus* increased by an average of almost one hundred fold at one location and one thousand fold at another site. In another study at a hospital site in central London during building work, Goodley *et al* (1994) monitored airborne *Aspergillus* species for one year. *Aspergillus fumigatus* predominated, but they found little seasonal difference in numbers and little difference between numbrs indoor and out. Nasal swabs were taken from patients, and though six percent were positive for *Aspergillus fumigatus*, no patient became infected. Leenders *et al* (1999) found that an increase in numbers of patients with invasive Aspergillosis could not be explained by an increase in the number of *Aspergillus* conidia in the outside air. They found that the outside air contained 0-9 cfu/m^3 with *A.fumigatus* numbers relatively constant, decreasing only from January to April. Rainer *et al* (2001) reported the monitoring of hospital air in a special care unit over a one year period. Among 98 fungal species isolated was *Aspergillus fumigatus*. Airborne concentrations ranged from 124 to 485 cfu/m^3, but neither the degree of fungal air contamination nor the species composition inside the special care unit differed from those found in a corridor outside the unit. Table 4 summarises the above and data from other studies.

Table 4. Fungal and bacterial concentrations in ambient air

Location	**Airborne fungi (cfu/m^3)**	**Airborne bacteria (cfu/m^3)**	**Reference**
UK suburban	273 (0-7200)	79 (42-1600)	Jones & Cookson, 1983
UK urban/industrial	1,200	500	Crook & Lacey, 1988
UK in homes	1096 (28-35,000)		Hunter & Lea, 1994
Outdoor ambient, Paris	92 (3-675)		Mouilleseaux *et al* 1994
France	2,999- 9841 max.		Chaumont *et al*, 1990
Netherlands	941		Verhoeff *et al*, 1992
Netheralnds	0 - 15,643		Beaumont *et al*, 1985
Austria rural	185	327	Kock *et al* 1998
Scandinavia rural		99 (2 - 3,400)	Bovallius *et al* 1978
Scandinavia urban		850 (100 - 4,000)	Bovallius *et al* 1978
Finland	750		Nevalainen *et al*, 1994
US urban	930 (0 - >8,200)		Shelton *et al*, 2002
US rural	600	2,000	Folmsbee & Strevett, 1999
US urban	700	1,500	Folmsbee & Strevett, 1999
US rural	8,651 (80-94,000)	3,204 (160-17,600)	Hryhorczuk *et al*, 1996

8.3 BIOAEROSOLS GENERATED BY OTHER INDUSTRIES

A wide range of industries may give rise to exposure of workers to bioaerosols, either through workplace activities purposefully involving the handling of micro-organisms, e.g., biotechnology, or through incidental exposure while working with contaminated materials. Both factory- based and agricultural activities have been investigated, mostly with respect to potential respiratory sensitisation or irritation in exposed workers. Reviews of bioaerosol exposure levels in various

industries are given by Crook (1995), Eduard (1997) and Crook and Swan (2001), summarised in Tables 5 and 6.

Table 5. Airborne bacteria and fungi cfu/m^3 and endotoxin (ng/m^3) in various workplaces - agriculture (from Crook, 1995, Eduard, 1997 and Crook and Swan, 2001)

Work activity	Bacteria	Fungi	Endotoxin (where measured)	Predominant organisms
Grain stores on farms	10^5	10^4	10^3	Fungi including *Aspergillus*
Handling mouldy hay, grain on farms	10^8	10^8		*Aspergillus fumigatus*, actinomycetes
Grain harvesting	10^7 - 10^8	10^5 - 10^7		Fungi including *Aspergillus*, Gram positive bacteria
Animal feed mills	-	10^3	10^1 -10^2	Fungi including *Aspergillus*
Cattle sheds	10^3 - 10^5	10^4 - 10^5	10^3 - 10^4	Fungi including *Aspergillus*
Horse stables	10^5	10^3 - 10^4	10^1 - 10^3	Fungi including *Aspergillus*
Pig houses	10^4 - 10^6	10^4 - 10^5	10^2 -10^4	Gram positive and negative bacteria
Poultry houses	10^5	10^3	10^2	Fungi including *Aspergillus*
Handling mushroom compost	10^7	10^5		Actinomycetes
Picking mushrooms	10^3	10^5		Fungi (*Trichoderma*)
Wood bark composting	10^4 - 10^5	10^6 - 10^7		Fungi (*Paecilomyces*)

Table 6. Airborne bacteria and fungi cfu/m^3 and endotoxin (ng/m^3) in various workplaces - food processing and industry (from Crook, 1995, Eduard, 1997 and Crook and Swan, 2001)

Work activity	Bacteria	Fungi	Endotoxin (where measured)	Predominant organisms
Handling domestic waste (doorstep collection)	10^3 - 10^4	10^4 - 10^5	0-20	Gram negative bacteria, *Aspergillus*, *Penicillium*
Domestic waste transfer station	10^5	10^6		Gram negative bacteria, *Aspergillus*, *Penicillium*
Domestic waste incineration	10^7	10^7		Gram negative bacteria, *Aspergillus*, *Penicillium*
Domestic waste materials recycling	10^5	10^5	10^3	Gram negative bacteria, *Aspergillus*, *Penicillium*
Domestic waste landfill sites	10^6	10^5		Gram negative bacteria, *Aspergillus*, *Penicillium*
Citrus warehouse	-	10^5		Fungi (*Penicillium*)
Sugar beet factory	10^5	10^3		Gram negative bacteria
Potato processing	10^5	-	10^2	Gram negative bacteria
Tea factory	10^2	10^3		*Aspergillus*
Textile mills	10^5	10^5	10^1 -10^3	Gram negative bacteria
Paper mills	10^4 - 10^6	10^2	0-20	Gram negative bacteria
Fibreboard and chipboard factories	-	10^4	10^1 -10^2	*Aspergillus fumigatus*, *Penicillium*
Humidifiers in factories	10^5	-		Gram negative bacteria
Metalworking in engineering works	10^6	-	10^2	Gram negative bacteria
Industrial process water	10^3	-	10^4	Gram negative bacteria
Fermenters in biotechnology	10^2 - 10^4		10^2	Process organism (Gram negative bacteria)

Detailed figures specifically related to the incidence of allergic respiratory disease caused by bioaerosols are not available. Some information can be derived from the Labour Force Surveys of self-reported work related illness in the UK and other ill health reporting schemes. In the most recently reported data from 1999 (Jones *et al*, 2001), 1.3 million people were estimated as being affected by a work related illness during the twelve month reference period, which is 4.6% of employed individuals. Of these, 'breathing and lung problems' accounted for 53,000 cases or 0.18% of employed individuals. The incidence was much greater than the average in occupations related to agriculture, where 14,000 cases were estimated (3.5% of those employed in the industry) and it can be assumed that exposure to organic dust will play a significant part in these health problems. Working population numbers and ill health cases attributable to waste disposal

were too few to give recordable numbers in the survey. Data from the 1995 survey (Jones *et al*, 1998) gave more details on respiratory disease. At that time, nearly 10% of individuals with work-related illness reported lower respiratory disease, which was an estimated 202,000 people. Of these, 151,000 were estimated to suffer from work related asthma, 83,000 from chronic bronchitis. Fumes and dusts were reported to be the cause in 89% of cases. The SWORD (Surveillance of Work-related and Occupational Respiratory Disease) surveillance scheme has run for more than 10 years, providing a picture of the incidence of occupational respiratory disease in the UK through new reported cases to the scheme (Meyer *et al*, 2001). All new cases of respiratory disease reported have totalled around 1000 per year, of which occupational asthma has accounted for between 204 and 312 cases per year, or 22% to 29% of all cases, over the last eight years. Most commonly identified sensitizing agents are isocyanates, but flour and grain and other organic dusts account for more than 10% of cases.

8.4 DISPERSION OF BIOAEROSOLS FROM COMPOSTING SITES

Bioaerosols are formed during the composting process whenever materials are agitated mechanically. However, concentrations have been shown to decrease to background after site activities cease, suggesting that windblown aerosolisation is insignificant (Millner, *et al*., 1980; Passman, 1983). As bioaerosol masses are typically small (hence they have small settling velocities), they can be carried long distances by the wind and thermal currents (McCartney, 1990). The pattern of dispersal of bioaerosols around a composting site depends upon a number of factors, including the emission rate (the number of micro-organisms liberated per unit time), prevailing atmospheric conditions (wind speed and direction, solar incidence, temperature gradients and relative humidity (Lighthart and Mohr, 1987; Lighthart, 1997) and local topography which will determine the air flow around the site (Heisler and Dewalle, 1988). The emission rate will depend on the process carried out, the type of machinery used, the moisture content of the compost, the microbial content of the material processed, and whether or not the process is enclosed or carried out in the open air.

Concerns have been expressed by residents in the vicinity of composting facilities and workers at other sites on the periphery of compost facilities, citing potential adverse health effects resulting from inhalation of bioaerosols from the site (Millner, *et al*., 1994; Browne, *et al*., 2001). A number of studies have aimed to assess the potential impact of composting facilities on bioaerosol levels in the vicinity. However, it is recognised that monitoring bioaerosols in an outdoor environment is beset with practical difficulties which limit the ability to predict with accuracy their dispersal (Lacey, *et al*., 1996). Consequently, there have been few detailed studies reported in the scientific literature that relate specifically to composting. By contrast, there are numerous reports on the dispersal of pollen and spores, especially those that are of agronomic importance (see, for example, McCartney, 1994), which are thought to decrease in concentration away from the source term following either the power law or exponential models (Fitt, *et al*., 1987).

In an attempt to assess potential adverse impacts, Millner *et al*. (1994) conducted a comprehensive review of published data. The authors considered a number of different studies where downwind bioaerosol concentrations had been measured, and concluded: “the data have indicated that at distances of 250 – 500 feet [76 – 152 m] from the compost facility perimeters the airborne concentrations of *A. fumigatus* were at or below background concentrations.”

More recently, 200 metres was the distance by which concentrations of *Aspergillus fumigatus* and total mesophilic bacteria were found to reach background concentrations in a UK study (Gilbert and Ward, 1999; Gilbert *et al*., 2002). This was used as the basis for the recommendation that

routine sampling at a composting facility should be carried out if a 'sensitive receptor' lies within 200 m of the site boundary (Gilbert and Ward, 1999).

The Environment Agency, the waste regulator in England and Wales, established a position in 2001 against "permitting any new composting process (or modification to an existing process) where the boundary of the facility is within 250 metres of a workplace or the boundary of a dwelling, unless the application is accompanied by a site-specific risk assessment, based on clear, independent scientific evidence which shows that the bioaerosol levels are and can be maintained at appropriate levels at the dwelling or workplace". The basis for this statement was work carried out by Wheeler *et al*. (2001) who monitored bioaerosol dispersal from three composting facilities in England. Samples were collected downwind at the facilities using filters held in personal dust samplers designed for use in occupational exposure assessments. The data were modelled using the United States Environment Protection Agency SCREEN3 model, and estimates of the distances to assumed reference concentrations of 1000 cfu/m^3 for total bacteria, 1000 cfu/m^3 for total fungi, and 300 cfu/m^3 for gram-negative bacteria were made. Despite modelling positive slopes (increases in concentrations with distance from source) on a number of instances (which were ascribed to additional emissions and probably also reflected the small sample sizes), the authors concluded that concentrations generally reached the reference levels within 250 m of the source. Wheeler *et al*. (2001) did, however, observe that many of the bioaerosols formed aggregates large enough to exhibit non-gaseous behaviour. It was suggested therefore that concentrations would decline with distance at a greater rate than a Gaussian dispersal model would predict. This distance of 250 metres provides an additional 'safety factor' over the 200 metres suggested by Gilbert and Ward (1999) recommendation which in turn is greater than the distances suggested by Millner *et al* (1994). Further studies, described below, have examined the concentrations of bioaerosols found at distance from composting activities.

Syzdek and Haines (1995) monitored *Aspergillus fumigatus* spores in the vicinity of the Islip (USA) composting facility. Exposure of a study community 540m from the facility was compared with a control community 10,000m from the facility. A Burkard-Hirst volumetric spore trap was used, which collect spores and pollens for microscopic examination (a method commonly used in measuring pollen levels for hay fever studies). The sampler was operated continuously from 21 August to 30 November 1992. The *Aspergillus fumigatus* spores were then differentiated from the other spores in the samples by microscopic examination and counted. *Aspergillus fumigatus* were detectable at all sites, but concentrations were much greater at the compost facility, averaging 552 spores/m^3 compared to 44 spores/m^3 at the control site. At the study community site, average concentrations were 151 spores/m^3. Valuable information was derived from continuous sampling of this nature using spore trapping, although it was recognised that the method is labour intensive and there are difficulties in differentiating the *A. fumigatus* spores from other almost identical common spores such as *Penicillium* spores by eye. Immunofluorescent labelling or molecular based testing could overcome these problems. Another way of analysing the continuous sampling data was to examine the frequency with which concentrations of airborne spores exceeded certain arbitrary values. The researchers recognised that bioaerosol concentrations fluctuate greatly, but as a point of reference at the compost site spore counts exceeded 100 spores/m^3 for 39% of samples and were >500 spores/m^3 for 17% of samples. By comparison, at the study community site spore counts were >100 spores/m^3 for 22% of all samples and >500 spores/m^3 for 7% of samples, and at the control community site spore counts were >100 spores/m^3 for less than 14% of all samples and >500 spores/m^3 for 2% of samples.

Millner *et al*.(1980) and Lighthart and Mohr (1987) both suggested that wind turbulence played a key role in the dispersal of airborne micro-organisms. Millner *et al*. monitored concentrations of

A. fumigatus at a sewage sludge composting facility and applied a Pasquill dispersion model to the data. It predicted that background concentrations of *A. fumigatus* would be attained between 500 – 600 metres from the source under unstable (turbulent) conditions, with distances in excess of 1 km under stable conditions. Lighthart and Mohr used a simulated virus (whose properties were derived from two actual viruses) and applied a Gaussian model. Their data suggested that turbulence dramatically affected downwind concentrations, with dilutions of 10^{-4} suggested within 30 m downwind from the source.

Similar decreases in concentrations of bioaerosols at composting facilities have been measured directly. Lacey and Williamson (1995) observed a reduction of airborne fungi and bacteria to concentrations less than 10 % of those measured within 1 m of a turned pile of compost. Beffa *et al*.(1998) noted a 100 – 1000 decrease in concentrations of *A. fumigatus* 10 m from a turning machine; at 500 m down wind, concentrations of between 0 – 20 cfu m^{-3} were measured.

Passman (1983) monitored concentrations of *A. fumigatus* at new composting facilities in Maine, USA. They concluded that ambient background airborne spore concentrations (<50 cfu/m^3) did not change during the first year of operation, nor did they differ from concentrations recovered before the composting facility was constructed. Samples taken 150 m downwind were not above background concentrations, whilst at one site concentrations were at background levels at 90 m downwind. Transient high concentrations of *A. fumigatus* were observed, up to 10,000 cfu/m^3 associated with wood chip manipulation activities, but seasonal differences were less obvious. Aerospora concentrations always returned to background levels within 1 hr after the monitored activities ceased. They observed that meteorological conditions which tended to reduce dust concentrations also decreased *A. fumigatus* aerospora yields. The conclusions from the results of the study were that residents in the vicinity of the composting operations were not exposed to increased concentrations of airborne *A. fumigatus* spores.

Reinthaler *et al*. (1998/99) measured concentrations of airborne micro-organisms at a number of waste handling and treatment facilities in Austria. At one composting site concentrations of bacteria were greater at 700 m than at 500 and 600 m, which was attributed to vehicle movements. Increased counts in residential areas adjoining the facility were ascribed to neighbouring farms. However, based on the data collected, the authors concluded that significantly lower counts were measured at distances greater than 200 m from the source. Haas *et al* (1999) measured airborne thermophilic actinomycetes in the area surrounding composting facilities over a one year period in Austria, using Andersen impaction samplers. Actinomycetes in an area at some distance from composting plants were isolated infrequently, at a maximum value of 494 cfu/m^3 near to an agricultural area.

Kothary *et al* (1984) detected up to 4000 cfu/m^3 *A. fumigatus* 1m downwind from the compost piles, the numbers decreasing to 1000 cfu/m^3 by 50 m downwind. Levels at a residential area 250 m away were less than 50 cfu/m^3 and peaked during the screening of the compost. Levels at control sites away from potential bioaerosol sources ranged from 0 - 2 cfu/m^3.

Schilling et. al (1999) measured bioaerosols downwind from an enclosed composting plant with biofilters with a partly open plant. At the enclosed composting plant levels of thermophilic fungal spores 50m downwind ranged from 20 to 500 cfu/m^3, with *Aspergillus fumigatus* ranging from 100 to 400 cfu/m^3. By 200m, thermophilic fungal spores ranged from none detected to 200 cfu/m^3 and *Aspergillus fumigatus* from none detected to 20 cfu/m^3. Background values away from the bioaerosol source ranged from none detected to 30 cfu/m^3 and none detected to 20 cfu/m^3 respectively. By comparison, at the partly open site 5m downwind thermophilic fungal spores ranged from none detected to 10,000 cfu/m^3, with *Aspergillus fumigatus* in the same range.

At 100m downwind thermophilic fungal spores ranged from none detected to 6,000 cfu/m^3, with *Aspergillus fumigatus* ranging from none detected to 7,000 cfu/m^3. By 200m downwind both thermophilic fungal spores and *Aspergillus fumigatus* ranged from none detected to 20,000 cfu/m^3, i.e., an increased range compared to 100m. By 500m the range of values had dropped to none detected to 600 cfu/m^3 for thermophilic fungi and none detected to 500 cfu/m^3 for *Aspergillus fumigatus*. This was still however about ten times above background, which ranged from none detected to 70 cfu/m^3 and none detected to 50 cfu/m^3 for thermophilic fungal spores and *Aspergillus fumigatus* respectively.

Kock *et al* (1998), studying metropolitan and rural areas in Austria, counted airborne bacteria and fungi in a village area dominated by agriculture and found that in the vicinity of a composting facility located in the same residential area, micro-organism counts exceeded those of the neighbouring "unaffected" area by 29% in the case of bacteria and by 54% in the case of yeasts and moulds. However, at an industrial and business site with heavy traffic, the counts were twice that of the area affected by the composting facility (146 cfu/m^3 for bacteria and 168 cfu/m^3 for yeasts and moulds).

Recer *et al* (2001), as part of a major environmental and health study at a composting site at Islip, USA, compared on site measurements with background sites well away from the compost site and in a residential neighbourhood about 500 m downwind of the site. Bioaerosol levels on the site were about 20 times greater than background and airborne *Aspergillus fumigatus* concentrations tended to be two- to four fold higher than background. The authors concluded that emissions from the composting site increased bioaerosol levels at the residential site.

Danneberg *et al* (1997) collected bioaerosol samples adjacent to a biofilter and trommel screen and at a single downwind sampling point at 150 m at a composting facility in Germany. They used the data to predict dispersal using a German TA Luft model, and concluded that typical background concentrations would be reached at 500 m.

There are a number of reasons why the use of mathematical models provide uncertain results when used to predict bioaerosol dispersal. Most have been developed to simulate atmospheric transport of particles over medium to long ranges (for example, estimating the release of particles from smoke stacks), with little information available on short range (< 1 km) dispersal. Determining the emission rate (source term) is complex, made more so because it is often moving and intermittent, and few attempts have been made to measure it directly. Most attempts at modelling compost bioaerosol dispersion are based on estimates of emission concentrations (Danneberg, *et al*., 1997; Millner, *et al*., 1980). Additionally, buoyancy effects caused by the release of hot air into the cooler atmosphere have not yet been accounted for within any reported models. Added to this are the effects of the high degree of variability of naturally occurring background concentrations (Jones and Cookson, 1983) and the effects of traffic movements and neighbouring bioaerosol sources, such as agricultural activities.

9 POTENTIAL USE OF COMPUTATIONAL MODELLING TO ESTIMATE BIOAEROSOL DISPERSION FROM COMPOSTING

9.1 INTRODUCTION

In several studies, as described previously in this Report, exposure measurements have been made on site at composting facilities, and in most of these some attempt has been made to measure bioaerosols dispersed away from the composting source. Whilst providing valuable data, the ranges in concentrations reported also highlights the variables involved which can influence bioaerosol release and dispersal. These relate not only to site activities, but also to factors such as site topography and meteorological conditions and this combination of factors can be unique to each site. One potential way to provide a more empirical method of assessing dispersion of composting bioaerosols would be to support bioaerosol measurement data with computational dispersion models to account for individual site conditions. This has been done in a limited number of studies which will be discussed, together with a review of the factors which need to be modelled, and preliminary application of a selected dispersion model.

9.2 REVIEW OF PREVIOUS USES OF MODELLING

There are few papers that specifically address the modelling of dispersion of bioaerosols from composting. There are a greater number of papers about modelling of bioaerosol dispersion in general. This review concentrates on modelling of dispersion of bioaerosols from composting, though papers on other aspects of bioaerosol dispersion may also be addressed. In some instances, modelling has been used to estimate bioaerosol emission rates based on measurements of bioaerosols made at distance from source. These emission rates have then been used in calculations to examine dispersion under conditions for which no measurements have been undertaken**.**

Millner *et al* (1980) describe concentration measurements and dispersion modelling of *Aspergillus fumigatus*, released from composting sewage sludge when disturbed due to turning. Emission rates were estimated using a Gaussian dispersion model (Pasquill, 1961) by fitting 31 individual concentration measurements, taken at distances from 10 - 620m. The calculated emission rates varied from 2.3×10^4 to 6.7×10^{10} *Aspergillus fumigatus* particles per second. It was assumed that the *Aspergillus fumigatus* spores were sufficiently small that a Gaussian dispersion model was appropriate and deposition was not modelled. Also it was assumed that for the times and distances considered viability of *Aspergillus fumigatus* spores was not an issue. Based on the calculated emission rates, and 'some judgement', an effective emission rate of 4.6×10^6 *Aspergillus fumigatus* particles per second was then used in calculations examining the effect of different atmospheric conditions on dispersion. These calculations found that under unstable atmospheric conditions background concentrations were approached 0.5 to 0.6km downwind of the source. The fact that there were variations in emission rates between compost piles containing similar concentrations of *Aspergillus fumigatus* was mentioned to explain at least some of the range of calculated emission rates.

Danneberg *et al* (1997) made concentration measurements and used these to estimate emission rates by modelling dispersion. Concentrations were measured downwind of a composting plant at points on four lines, 45^o apart, originating at the plant. Three samples were taken at each point. The emission rate of *Aspergillus fumigatus* was calculated using the mean of the concentrations

measured at 150m downwind. The emission rate was then estimated using two models, one a regulatory dispersion model from the German Technical Instructions on Air Quality Control, TA Luft, (1986), the other an expression developed to examine NOx emissions from tall chimneys. Since emissions from compost are not from a large height the result from the original tall chimney expression was doubled. There is no obvious reason for this modification and no justification was given for the modification or for its size. The models were found to give similar *Aspergillus fumigatus* emission rates to those calculated by Millner *et al* (1980). Dispersion calculations using the estimated emission rate indicated that concentrations were less than 500 cfu/m^3 at 500m, this concentration was assumed to be equivalent to background concentration.

Deportes *et al* (1997) modelled the exposure to plant dust, rather than bioaerosols, from open windrow composting. They collected a series of samples of compost over 11 months of compost production. These were sieved. The average mass fraction below 32µm for all the samples was then used as a conservative estimate of the mass fraction of material below 5µm. Based on the amount of material handled a day, and the duration of turning, an emission rate, assuming all the material below 32µm was released, was calculated. This was then used as the source term in dispersion calculations. A limited comparison with experimental measurements was performed.

Dowd *et al* (2000) modelled dispersion from biosolid placement, rather than composting. Their approach to estimation of emission rates was also to use downwind concentration measurements in a dispersion model to estimate emission rates. They extended their dispersion predictions to different types of bioaerosol by the using relative concentrations in the biosolid to predict emission rates of bioaerosols for which no sampling had been performed. This of course assumes that the relative release rates for different bioaerosol materials are similar.

Wheeler (2001) presented the results of measurements and dispersion modelling of bioaerosols, inhalable dust, VOCs, odour and noise around composting sites. Difficulty in establishing an emission rate for bioaerosols is identified as a problem as the emission source is not contained or well specified. The approach adopted was to attempt to fit data from multiple points using a simple Gaussian screening model, SCREEN3 (USEPA, 1995), by varying emission rate and effective release height. It proved impossible to achieve a fit between data and model. The concentration data used was measured using filter samplers. These sampled for a constant period, removing the problems of differing sample time, or overloaded samplers, seen with Andersen samplers. The filter samplers still often showed low concentrations near to the release position, demonstrating that the low values obtained using Andersen samplers were probably not purely the result of sampling duration. Two reasons are suggested for the problems fitting a model to the data; these are the particle size distribution of released material and bioaerosol viability.

Wheeler used three different types of sampler. From comparisons of measurements and knowledge of the characteristics of the different samplers he concluded that a significant fraction of the bioaerosol particles were formed from clumps of micro-organisms, rather than individual micro-organisms or spores. Simple Gaussian models assume an emission that can be treated as gaseous. They would therefore underpredict the rate of reduction in concentration when enhanced by deposition. This would result in overprediction of bioaerosol concentrations.

Generally, the hazard associated with a micro-organism is related to its viability and therefore ability to grow and cause disease. Exposure to the atmosphere when aerosolised will reduce viability because of the effects of dehydration and exposure to UV light. Failure to model this effect will reduce the rate at which viable concentrations decay with distance. For simplicity, however, in modelling compost bioaerosols an assumption can be made of no significant viability losses, because the predominant microbial species are fungal spores and actinomycete spores.

The dense spore cell wall means that they are more capable of withstanding aerosolisation stress than are vegetative cells such as Gram negative bacteria. If the emission rate has been obtained by fitting a model to downwind measurements then any loss of viability in the sample will affect the predicted emission rate. Ignoring loss of viability will then affect both the emission rate and dispersion calculations, the overall effects will be harder to predict.

At present data are not available on particle size distributions or micro-organism viability of bioaerosols from composting. Wheeler makes a recommendation that such data should be collected to improve, or indeed make possible, predictions of emission rates and hence bioaerosol dispersion from composting processes.

9.3 FACTORS AFFECTING THE APPLICATION OF MODELLING TO COMPOST BIOAEROSOLS AND CHOICE OF MODEL

At present open air turned windrow composting is the most common approach used in the UK and it is the possible bioaerosol releases from that process that are considered further. Enclosed composting facilities can also be used. In these processes the emissions of bioaerosols to the atmosphere can be controlled by the use of filters. However, the bioaerosol concentrations found within enclosed composting facilities can exceed those found with open composting, even at the point where turning occurs. There are therefore issues regarding exposure levels of workers and members of the public using different composting processes. Concentrations and releases from enclosed composting processes are not addressed further here.

To model bioaerosol dispersion from composting the processes leading to release of bioaerosols need to be identified and appropriate representations developed. Possible influences that can modify the dispersion must also be identified. Finally data, both to specify the problem and check results, needs to be available. Possible influences on the dispersion and approaches to representing these influences are discussed below.

9.3.1 Open composting

An open composting site will consist of a number of windrows; elongated piles of material being composted. Each windrow will be at a different stage in the composting process. The types and quantities of micro-organisms present and the bioaerosol formed when they are disturbed will vary during the composting process. There will also be variation between windrows at similar stages in the composting process.

As part of the composting process the material being composted is turned. This is necessary to aerate the composting material, rebuilding the structure of the material. The rebuilt structure allows passive air exchange to occur, ensuring that the composting process remains aerobic. The disturbance caused by the turning process also releases bioaerosols. When composting is performed in the open the turning of composting material will introduce bioaerosols directly into the environment.

Measurements of bioaerosols in the vicinity of composting indicate that it is the turning process that releases large quantities of bioaerosols and that releases are low unless turning is actually in progress. Other possible sources exist, build up of dust on hard surfaces can lead to bioaerosols

being emitted by vehicle movements on site. However, the build up of dust can be managed to remove this potential source. It is therefore the release of bioaerosols during turning that is considered in defining a source term.

The turning process may be performed by dedicated windrow turning machines, or more typically in the UK by the use of a front end loader. Typical dimensions for a windrow formed using a front end loader are 1.8 - 3.6m high and 3-6m wide at the base (NRAES, 1992). Bucketfuls of the composting material are lifted by a front end loader then dropped back onto the windrow from above, releasing bioaerosols. A typical bucket size would be $3.5m^3$, with a release height of 5m (Millner *et al*, 1980). Turning a windrow, working along its length takes a number of hours. Sources and emissions, representing the releases due to this process, must be described to calculate the bioaerosol dispersion.

9.3.2 Choice of model

Modelling was performed by HSL using ADMS (CERC, 1999), a state of the art dispersion modelling tool - developed by a number of sponsors, including HSE. The results from such a tool are more relevant away from the immediate vicinity of the release. Where the flow and release are complex in the area of the source then these will not be resolved. A more sophisticated modelling approach, for example, computational fluid dynamics, would be able to improve resolution of some aspects of the flow close to the release but would still have problems resolving the actual release process. Such an approach might be considered to attempt to improve the modelling of worker exposure. However, during turning operations the position of workers with respect to the releases will vary and workers will also be exposed to bioaerosols while performing other operations on the site. Personal monitoring would therefore probably provide a more suitable method for examining worker exposure.

ADMS was used in part because the model of the boundary layer is based on more recent research than that found in other dispersion models. In addition it includes models to examine wake effects, fluctuations and deposition. Of these only wake effects are examined in the present work but the others are also considerations when examining bioaerosol dispersion. Calculation of fluctuations will allow the probability of exposure to higher concentrations over time periods of less than an hour to be considered. Deposition modelling can be used to examine the significance of particle size distribution on predicted concentrations.

9.3.3 Bioaerosol dispersion

To model dispersion of bioaerosols from composting a source and emission rate must be specified. The processes contributing to dispersion must be considered and models of the necessary components identified. These are initial calculations to examine possible influences on bioaerosol dispersion during composting and to identify areas where further information is needed. The influence of different effects can be considered by looking at the variation in downwind concentrations. If a particular site was under consideration then actual meteorological data would be used. Sensitive receptors would be identified and the results of bioaerosol dispersion calculations, based on the meteorological data, used to examine the potential effects of composting.

While it is worth considering the possible influences on the dispersion of bioaerosols and the effects that these could have on concentrations it should be noted that there are a number of uncertainties associated with bioaerosol dispersion from composting. The first is the considerable uncertainty in the emission rates of bioaerosols. This is due both to the difficulties of taking measurements and natural variability in the bioaerosols released from windrows during turning. The bioaerosols emitted from a windrow during turning will vary in both quantity and type during the composting process. The difficulties in performing measurements mean that only limited data are available and that these data will not cover the full range of possible emissions. There are also uncertainties associated with interpretation of results from dispersion calculations. Acute or chronic effects may occur and there are variations in individual sensitivity. Background concentrations can also vary by orders of magnitude.

9.3.4 Description of source

Release of bioaerosols due to turning of windrows using a front end loader occurs as a series of discrete releases. Dropping the composting material from the bucket of the front end loader, over the windrow, releases the bioaerosols. The position of these releases moves along the length of a windrow during the turning process and takes place over a number of hours. There is no initial momentum to the source though the initial temperature of the material could lead to buoyancy effects, as described later. The release of bioaerosols, due to turning during composting, could be described by a series of sources and emissions: representing the discrete releases from a bucket and their movement along a windrow. With the possible exception of buoyancy effects the source and emissions will not affect the atmospheric flow. The total effect of turning a windrow could then be found by summing the results of a calculation of the time varying dispersion of the release from a single bucket. The effect of this calculation could then be summed, at positions in space and time representing the turning of a windrow, to give the total effect due to turning a windrow.

In the calculations presented here a steady state release rate from a single point was used, representing an average release rate for the turned windrow. A more detailed representation would have required information on the rates of turning windrows that was not available. Close to the source this approach will underestimate peak exposures. Further away the peak concentrations due to the discrete release will be reduced by dispersion. Any peaks due to the discrete nature of the release would be most significant close to the source where the local flow field is complex and not resolved. The use of a single release point will increase peak concentrations downstream due to the reduced area over which the releases are predicted to spread. The actual release point will move along the windrow increasing the area over which releases are spread. Using calculations based on dispersion from a single point would therefore be conservative for the predicted concentrations downstream of a windrow.

The actual release occurs from the bucket of a front end loader above the windrow. A release height representing this can be used, a height of 5m is suggested in Millner *et al* (1980). A front end loader bucket mouth area of $2.8m^2$ is assumed, this area is used for the source area. Use of a dedicated windrow turning machine would probably lead to lower narrower windrows and lower release heights with the turning process in fact becoming continuous. The effect of the release height can easily be examined by performing calculations for a range of release heights.

A possible alternative representation of the source would be an area, or volume, with uniform concentration. Since turning causes the release of bioaerosols and that occurs from a single point

it was decided not to use this source representation. However, if bunds, or shelter belts, were used to enclose a composting site then build-up of bioaerosols within the bunds and the release characteristics might make it an appropriate representation of the source for off site dispersion calculations.

9.3.5 Temperature effects

During the composting process temperatures can reach as high as 70-80^{o}C inside windrows (Fischer *et al*, 1998). Typical operating temperatures to optimise the rate of biodegradation are between 45 and 55^{o}C with an initial period above 55^{o}C to sanitise material (Stentiford, 1996). The surface temperature will remain much closer to ambient. The increased temperature within a windrow is due to the activity of micro-organisms within the windrow, however, the rate at which heat is generated is slow and it is the rate of dissipation of that heat that causes the temperature increase.

There are two possible ways that the heat generated in a windrow could affect the dispersion of bioaerosols released by turning. The first of these is that air trapped in the composting material, and at the temperature of that material, is released as a bucket is tipped. The second is that warm material, forming the surface of a windrow after turning, may heat air with which it is in contact causing a rising flow.

A front end loader with a 3.5m^3 bucket, assuming a bucket load dropped every minute (NRAES, 1992), can be considered as an energy flow rate equivalent to the amount required to heat a volume of air equal to the size of the bucket from ambient to the temperature of the windrow material. For a windrow at 55^{o}C with ambient air at 15^{o}C this gives a heat flow rate of 2.5kW, increasing the tipping rate to 5 buckets a minute (Millner *et al*, 1980), gives 12.5kW (details summarised in Appendix B).

The material tipped from a bucket forming a new surface to a windrow can also warm air. The material will have been heated by the activity of micro-organisms and its temperature will fall as the air is heated. Assuming surface temperatures of 55^{o}C and 35^{o}C gives heat flow rates of 8kW and 4kW respectively (Appendix B).

Both of the above heat sources will overestimate the heat available as they assume that all the available heat is transferred to the releases. The effect of these temperature inputs on dispersion can be evaluated using equivalent source areas and the stated temperatures.

9.3.6 Bioaerosol emission rate

Reported estimates of the emission rates of bioaerosols during turning of compost (Millner *et al*, 1980, Danneberg *et al*, 1997) have been made by fitting dispersion models to individual downwind measurements to determine an emission rate. A range of over six orders of magnitude in the emission rate was calculated by Millner *et al* (1980), judgement was then used to specify an effective emission rate.

Wheeler (2001) attempted to fit a dispersion model to a number of downwind measurements simultaneously, by varying emission rate and effective source height, but failed to obtain a

reasonable fit. Wheeler suggests that the lack of fit is due to not modelling bioaerosol viability and particle size distribution, as these were not accounted for in the model used. He suggests that data be collected to examine bioaerosol viability and particle size distribution. These issues are discussed later .

Estimation of emission rates from downwind measurements preferably requires multiple measurements, an approach used by Millner *et al* (1980). Even this only represents emissions from a windrow at a particular stage of the composting process. An improved representation, including bioaerosol variability and particle size distribution, might improve the estimate, but this has to be balanced against cost and practicality, as it would take considerable effort to make such estimates, given the practical difficulties in outdoor bioaerosol measurements. Some of the potential problems are discussed later in the context of measurements made by the Composting Association.

An alternative approach would be to estimate the bioaerosol load that could be generated by compost and use this to estimate an emission rate. This is a similar approach to that used to examine dispersion of plant dust from composting described in Deportes *et al* (1997). Breum *et al* (1997) measured dustiness of compostable waste, including micro-organism concentrations, to examine possible exposure of waste collection workers to bioaerosols. The measurements used a rotating drum to generate dust from the compostable waste. Sampling was performed to measure the total quantity of dust released and bioaerosol concentrations. Work described in Nielsen *et al* (1997) applies the technique to material in the process of being composted, but information linking bioaerosols measured to mass of composting material are not presented. This offers a possible approach to measuring bioaerosols from compost without the difficulties found trying to take measurements in the vicinity of windrows and the requirement of multiple readings to make a single estimate of source strength.

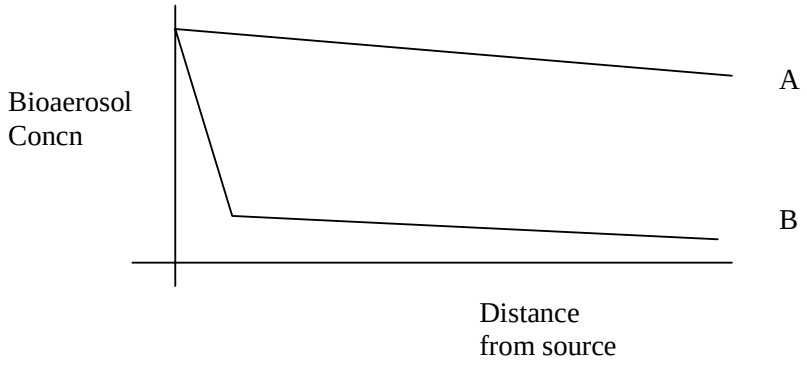
9.3.7 Bioaerosol viability

The issue of bioaerosol viability during dispersion and its effects on concentration was raised by Wheeler (2001). The viability of micro-organisms in the atmosphere has been studied experimentally (Ganio *et al*, 1995), and dispersion modelling studies have been performed, (Lighthart and Mohr, 1987). However, the bioaerosol viability of micro-organisms released by compost turning has not been studied. While micro-organisms released from composting will be affected by issues of viability this may not be significant when considering the consequences. If spores are released, for example from *Aspergillus fumigatus*, their viability is unlikely to be affected over the times and distances considered in this work. Even when viability is an issue, many of the problems relating to bioaerosols are due to allergic reaction or toxicity and these do not depend on the viability of the micro-organisms in the bioaerosol. For the present work viability effects will not be considered. This will lead to predictions of higher downwind concentrations and is therefore a conservative assumption.

9.3.8 Size distribution

Mullins (2001) provides an overview of the factors affecting micro-organisms in the outdoor air. The density of most spores approximates to 1.0, and in still air the rate of fall of an airborne spore is given by Stoke's Law, which is that the rate is proportional to the square of the radius.

Consequently, a small spore of 4 μm diameter has a rate of fall of 0.05 cm /sec (3 cm /min). This is consistent with earlier experimental data where the time taken for *Aspergillus fumigatus* spores in mouldy hay to settle was estimated to be 1 cm in 34 sec. (Lacey and Dutkiewicz, 1976). Consequently, settling out will not be a significant factor for single spores or cells. However, Wheeler (2001) identified the fact that the bioaerosols released during composting include a range of particle sizes, due to clumping, although the size distribution was not measured in their study. Particle size can affect concentrations as larger particles are preferentially deposited due to higher settling velocities. Ignoring particle sizes, by assuming all particles are small, will lead to prediction of higher concentrations, since deposition will be reduced. This therefore is also a conservative approach. Assuming that particles are small enough to follow the flow will also be conservative as some deposition would in fact occur; acting to reduce the concentration. Effects of particle size distribution are not modelled in the current study.



The above is a theoretical representation of the potential effect losses due to particle deposition would have. Assumptions based on emissions from compost, but not taking account of particle deposition, would lead to a predicted dispersion similar to slope A, whereas if significant particle deposition did occur, the immediate effect would be to reduce airborne concentration as in the steep slope of B, followed by a much lower level of dispersed bioaerosol as in the later part of slope B.

Some previous studies at composting sites have provided size distribution data where size selective bioaerosol samplers have been used, e.g., multi stage Andersen impaction samplers. For example, Reinthaler *et al* (1997) in different compost handling areas found 8 – 15% of bioaerosols deposited on stage one of Andersen samplers, which equate to particle sizes greater than 7 μm, 8 – 13% deposited in the 4.7 – 7 μm range, 9 – 16% in the 3.4 – 4.7 μm range. Therefore, 56 – 73% of particles were deposited on stages equating to particles less than 3.4 μm. Cox (1995) calculated the terminal velocity of bioaerosol particles falling under still air conditions, which for bioaerosols of 3.4 μm was 0.04 cm/sec, i.e., likely to be buoyant. However for larger bioaerosol particles, or those attached to clumps of material, terminal velocity increases greatly with velocity for a 20 μm equal to 1.28 cm/sec, 30 μm is 2.9 cm/sec, 50 μm is 8 cm/sec and 100 μm is 32 cm/sec. The papers by Reinthaler and others do not state how close to the composting material the samplers were positioned, so although there are size distribution data presented, there is no way to predict whether the bioaerosol measured has already been affected by particle drop out.

9.3.9 Effect of windrows on flow

The presence of windrows will affect the atmospheric flow. There will not be sufficient windrows for the boundary layer to become fully developed in their presence and in any case the information we seek would make this an inappropriate assumption. Thus the roughness length used to describe the boundary layer should therefore reflect the surroundings of the composting site, rather than the area of windrows. Individual windrows could affect the flow and dispersion due to separation and recirculation effects. Since the windrows form elongated, parallel piles the effects they have could also vary with the wind direction relative to the windrows. The exact geometry and spacing of windrows might also affect the dispersion of bioaerosol. However, as a first approximation a simple representation of windrows as a single block will be used to examine this effect. The individual influence of windrows on the local flow field contribute to difficulties calculating the dispersion in the immediate vicinity of the turning process. Based on the dimensions of windrows at one of the sites studied by the Composting Association, a block 18m x 44m, centred on the release point, was used to represent windrows in the present calculations and examine their effect on bioaerosol dispersion.

9.3.10 Atmospheric stability

Wind speed and atmospheric conditions will also affect dispersion from the composting process. Pasquill and Smith (1983) defined atmospheric conditions for dispersion modelling as stability classes ranging from A to G where A is extremely unstable (turbulent with high winds), through D as neutral to F and G moderate to highly stable. Since stable atmospheric conditions at low wind speeds will lead to the highest concentrations at a point downstream due to reduced mixing, only D2, D5 and F2 conditions (stability classes) will be considered in the current application. D2 and D5 represent neutral atmospheric conditions, with relatively low 2 and 5m/s wind speeds at a height of 10m, while F2 represents stable atmospheric conditions with a wind speed of 2m/s at a height of 10m. Application of these stability classes simplifies the model for preliminary calculations, but give 'worst case' scenarios in the model. It should be recognized, however, that these stable conditions are most likely to occur at night or during winter mornings and evenings, reducing the frequency with which they are likely to occur during turning activity. Farmer (1984) compared the frequency with which different stability classes occurred at a UK location. Class A occurred 0.2 to 0.7% of the time; B 3.5 – 7.0%; C 12 – 18%; D during the day 25 – 33%; D at night 21 – 36%; E 7.1 – 21%; F 4.2 – 7.2% and G 0.2 – 7.3%. Unlike many industrial processes the release of bioaerosols from composting does not occur 24 hours a day, only when turning is in progress. Also turning will typically only be performed during the day.

9.4 APPLICATION OF A COMPUTATIONAL MODEL TO BIOAEROSOL DISPERSION FROM COMPOSTS

9.4.1 Application of a model to different theoretical scenarios

Examples of emission rates obtained by fitting Gaussian dispersion models to single concentration measurements are limited and indicate a wide range of possible values, as shown by Millner *et al* (1980) and Gilbert *et al* (2002). In the current investigation using the ADMS computational model, attempting to fit multiple measurements simultaneously resulted in no fit at

all, and estimates of possible emission rates calculated from compost samples are not available. Rather than using a particular emission rate, an assumed unit release rate of colony forming units (cfu) per second, i.e. 1cfu/m^3, was used, specifically to examine the variation in concentrations as a proportion of that unit value under different assumptions. It is assumed that the type and emission rate of micro-organisms did not affect the flow. Therefore the calculated variation in concentrations could be taken to be representative of any released bioaerosol. Previous estimates of emission rate can then be used to demonstrate predicted concentrations due to dispersion. Since there were no suitable data available on bioaerosol viability and particle size distribution, no attempt was made to examine their influence on predicted concentrations (see above).

The range of dispersion calculations performed are shown in Table 7. In the first calculations the effects on dispersion of different atmospheric stability classes and bioaerosol release heights were examined. Possible effects due to compost temperature were then examined. Two front end loader work rates were considered, one bucket tipped per minute and five buckets tipped per minute. Three different compost surface temperatures were considered. Finally, an initial examination of the possible effects of windrows, represented by a single block, 18m x 44m, at two orientations to the wind, were examined. All the calculations were performed for unit emission rate, that is 1 cfu/s and for an unspecified bioaerosol. Concentrations were output at a height of 1.7m above the ground. Neither bioaerosol viability nor particle size disitribution and deposition were modelled.

Table 7. Dispersion calculations

			Atmospheric stability			Release height
			D2	D5	F2	5m
Release height	0m		✓	✓	✓	
	2m		✓	✓	✓	
	5m		✓	✓	✓	
Temperature effects	Bucket	1/minute	✓	✓	✓	✓
		5/minute	✓	✓	✓	✓
	Surface	15°C	✓	✓	✓	✓
		35°C	✓	✓	✓	✓
		55°C	✓	✓	✓	✓
Windrows	18m x 44m x 3m		✓	✓	✓	✓
	44m x 18m x 3m		✓	✓	✓	✓

The effect of different **release heights** and **atmospheric stability classes**, without any **temperature effects**, are considered first. Any variation in concentration due to **release height** was small, only modifying concentrations within 150m of the release point.

Atmospheric stability has a much larger effect on downstream concentrations, found from running the model to be as summarised below:

- Predicted concentrations for F2, stable conditions, were 5 times higher than concentrations for D5, neutral conditions, at 200m and 6 times higher at 500m.

- Under D5, neutral conditions, an order of magnitude decrease in concentration occurred from 40m to 160m and a further order of magnitude reduction by 800m.

- For F2, stable conditions, the first order of magnitude decrease occurred between 40 and 280m and there was almost an additional order of magnitude reduction by 1km.

To illustrate the above variations with an emission rate of *Aspergillus fumigatus* bioaerosol from turned compost of 4.6×10^6 cfu/s (Millner *et al*, 1980), the median background concentration of 8 cfu/m^3, found in the Composting Association data (Gilbert *et al*, 2002), would not be reached within 1km either for D5 or F2 conditions. For D5 conditions the predicted concentration was within 1 order of magnitude of this median background concentration at 500m, while for F2 conditions this concentration had not been reached at 1km. Both the emission rate and background concentration represent choices from observed ranges that cover orders of magnitude. In particular note the observed range of background concentration reviewed in the previous section.

Two effects due to the **compost temperature** were considered. The first was the release of hot air from a front end loader bucket when compost was tipped. The second was the warming of air due to the compost surface temperature after turning. In summary:

- Under D5 conditions there was very little effect on predicted concentrations for any of the temperature effects.

- Including temperature effects always reduced the predicted concentrations under F2 conditions. At the highest heating level concentrations were initially reduced to below those for D5 conditions, due to buoyancy effects. However, that represents the largest possible amount of heat transfer of a windrow initially at 55^{o}C and as such represents an upper bound on the size of the possible effect.

Representation of the windrows, as a single structure, with a release point at the centre, did modify concentration levels. At distances up to 100m concentrations were increased, beyond that point they were decreased. Neither change was large, causing a difference of less than 10% at 200m and reducing thereafter.

The most significant influences on predicted concentrations were those due to atmospheric conditions. With one exception the results presented only discuss changes in magnitude due to the different possible influences. Where values are quoted the emission rate was from one study while the background concentration was the median of those observed in measurements made by the Composting Association. The results indicate a possibility, though not the probability of

occurrence, and the observed range of background concentrations should be remembered. Neither reduction in bioaerosol viability or deposition due to the presence of larger particles were modelled. Both of these effects would reduce concentrations more rapidly than calculated here, making the reductions with distance quoted conservative.

9.5 COMPOSTING ASSOCIATION EXPERIMENTAL DATA

The initial intention in this project was to model bioaerosol data collected by the Composting Association, to examine use of dispersion models on bioaerosols from composting. However, no direct measurements of bioaerosol emission rate were available from these, or any other, data, but estimates have been made by extrapolation. Those estimates of release rate that do exist show a wide range of possible emission rates, with little indication of the likelihood of their occurrence. Release rates, based on the Composting Association data, could have been estimated, though variability in the data would have made this difficult. Hence the previous section examined different effects on dispersion in the context of a unit release rate, rather than attempting to reproduce observations. There are considerable difficulties involved in making any bioaerosol measurements, which is widely recognised. These relate (see also section 7.1) to the balance that needs to be achieved between practicality of the bioaerosol sampling method and the representative nature of the sample collected. These practical difficulties are increased when trying to take measurements in the vicinity of compost while it is being turned. The difficulties are related both to the sampling itself, for example, the potential to overload the sampler because of the high bioaerosol release rate close to turned compost, and the variation of bioaerosol release in space and time. The measurements made in the Composting Association data showed considerable variations in concentration at individual points, but this was no different from what may be expected in other studies. The results also showed that the variation in bioaerosol concentration with distance was not always represented by a simple decay. These observations are discussed below.

The observed variability at measurement points will be, at least in part, due to actual concentration fluctuations. Andersen samplers were used to make the bioaerosol concentration measurements. These can become overloaded if used in regions of high concentration. To avoid this problem, different sampling durations were used to give samples on which individual colonies could be counted. Close to the source, sample durations of 10 seconds were used, while further away the sample durations were increased to 30 minutes. The variation in sample duration is more than one order of magnitude. This compromises direct comparison between the samples, but is an inherent limitation of this sampling method which is recognized. However, this sampling method is the one of choice in the majority of bioaerosol exposure studies. Shorter duration sampling is more likely to show more variability in concentrations, reflecting actual concentration fluctuations. Longer duration readings will tend to average out concentration variations. The actual process of turning the compost, using a front end loader, is discrete. There will therefore not be a continuous release of material. Again this is likely to have more effect on readings close to the source, due both to the reduced sample duration and dispersion of material with increasing distance downstream. Finally, a potential source of variation which is inherent in any air sampling is that the sampler may not always lie within the plume. Close to the source it may be hard to judge the expected path from the release point over the sample duration. Further away plume meandering will occur due to variation of the wind direction about the mean.

The decay in concentrations may not be monotonic with downwind distance because the samples are not always taken at the same position within the plume. At the sites at which measurements

were performed the composting material was formed into windrows. The turned material is released from above windrows, hence any bioaerosol is effectively released above the height of a windrow. The plume can therefore travel some distance before contacting the ground. Any buoyancy effects, due to the temperature of the composting material, could allow further rise from the release position, increasing the distance travelled before the plume contacts the ground. Close to the release position the sampling may therefore take place below the plume of released bioaerosol. This would lead to the measurement of lower concentrations close to the release point than further downwind, where the plume is in contact with the ground. Separated flows, downwind and between windrows, and associated recirculation may also affect local concentrations. A measurement taken in a region of separated flow may show a zero reading if no released material enters that recirculation, or, a prolonged low reading if material enters the separation zone, mixes, and then clears only slowly. Measurements were taken consecutively, but between sets of readings the source position and wind direction could vary. For each set of measurements the samplers were positioned downwind of the source position. The topography between source and receptor, particularly the number and positions of windrows, will therefore vary between readings. The individual measurements may therefore not be part of the same concentration curve.

Comparisons between measurements are difficult because of differences in sampling positions and duration. Measurements were always made downwind of the source position. However, this meant that the transport path varied, for example, the numbers and positions of windrows traversed differed between readings. The duration of readings had to be varied to avoid overloading samplers. When comparing measurements it is therefore difficult to be sure whether differences are due to concentration fluctuations, the location of the sampler within the plume, or its proximity to the plume when not actually in the plume.

The measurements, consistent with many other bioaerosol measurement studies, therefore represent snapshots. Fitting curves allows estimates of the source concentrations and the distance until concentrations fall to background levels to be obtained. But the observed ranges of background concentration and implied emission rates show that any such measurements are possible values within a range. Such data is nevertheless useful for monitoring. Also as the quantity of data available increases a better understanding of the concentration ranges and their distribution will be obtained and strategies should be considered to obtain bioaerosol release measurements from composting sites with either more frequent individual measurements over a given time frame to examine short term fluctuations or by continuous sampling over that time frame to obtain an overall picture.

10 REPORTS OF ILL HEALTH ASSOCIATED WITH EXPOSURE TO COMPOST BIOAEROSOLS

Examination of the publications retrieved as part of this Review has revealed that few reported studies have combined both health data and exposure data, therefore little can be concluded about dose response. Reported studies of ill health related to composting activity are summarised in Tables 8 to 10 and discussed in more detail in this Section.

Table 8. Summary of ill health in Compost Workers; population studies

Method	No. of workers	Symptoms	Exposure levels	Reference
Pre and post shift nasal lavages	14 + 10 controls	Acute and (sub-) chronic non immune or type III allergic inflammation in upper airways	Dust 0.4 to 3.1 mg/m^3 endotoxin 50-1000 EU/m^3, >10^5 fungi and bacteria	Douwes *et al* 1997, 2000
Questionnaire	28 exposed workers	A non significant association between working with compost and diarrhoea	Not reported	Ivens *et al* 1997
Immunological markers of exposure and medical examination	58 + 53 biowaste workers + 40 controls	Significantly morerespiratory symptoms and diseases. 1 case ODTS. Significantly raised antibody levels to specific fungi and actinomycetes.		Bünger *et al* 2000
Questionnaire	2303 waste workers + 1430 municipal workers control	diarrhoea associated with fungal exposure and endotoxin. Nausea associated with endotoxin	>10^7 fungi, > 6 x 10^7 bacteria, >500 EU/m^3	Ivens *et al* 1997 &1999
questionnaire	8 compost workers, 60 other waste workers and 119 water workers control	gastrointestinal symptoms	0.62 mg/m^3 dust , 5 x 10^4 bacteria, 0.8 ng/m^3	Sigsgaard *et al* 1997

Table 9. Summary of ill health in Compost Workers; case studies

Method	No. of workers	Symptoms	Exposure levels	Reference
medical examination	Single case study	ODTS/hypersensitivity pneuumonitis	7.7 x 10^8 bacteria, 4.7 x 10^8 fungi, 149 mg/m^3 dust 16,300 EU/m^3	Weber *et al*, 1993
medical examination	Single case study; non-occupational exposure	Hypersensitivity pneumonitis Precipitating antibodies to Thermoactinomyces vulgaris. Positive skin prick to *A.fumigatus*	Not reported	Brown *et al*, 1995
medical examination	Single case study	hypersensitivity pneumonitis Precipitating antibodies *A.fumigatus*	Not reported	Vicknen and Roels 1984
Medical and immunlogical examination	Single case study	Allergic bronchopulmonary aspergillosis and hypersensitivity pneumonitis with antibodies to *A.fumigatus*	Not reported	Allmers *et al*, 2000
medical examination	Single case study	ODTS and microgranulomatous aspergillosis	Not reported	Conrad 1992

Table 10. Summary of ill health investigations in residents near to composting facilities

Method	No. in study	Symptoms	Exposure levels	Reference
Symptom diary	63 residents near to site and 82 controls	No evidence of association between *A.fumigatus* and any increases in respiratory irritant symptoms	Average of 100 *A.fumigatus* spores /m^3 measured	Browne *et al*, 2001
Questionnaire, health symptoms and clinical evaluation	100 living close to site and 75 controls	No demonstration of significant health hazard, no significant differences in symptoms between exposed and control groups.	Particulate levels >0.01 mg/m^3 bioaerosol levels not measured	Cobb *et al*, 1995.

10.1 SENSITISATION

Bünger *et al* (2000) carried out a cross sectional study, in Germany, to look at work related health complaints and immunological markers of exposure to bioaerosols among biowaste collectors and compost workers. A total of 58 compost workers (mean duration of employment 3 years), 53 biowaste collectors (mean duration of employment 1.5 years) and 40 controls took part. The control population consisted of 16 compost workers and 24 biowaste collectors who were examined before taking up the occupation or within the first 3 weeks of employment . The workers were interviewed and examined by physicians. The levels of specific IgG antibodies to fungi and bacteria were measured as immunological markers of exposure to bioaerosols. At the composting plants non-compostable materials were removed by manual sorting, the biowaste was mixed with shredded garden waste and piled in rows, the finished compost was sieved.

The levels of specific IgG antibodies to *A. fumigatus, A. nidulans, A. niger, A. versicolor, Penicillium* spp. *Saccharopoylyspora hirsuta, Saccharopolyspora rectivirgula, Saccharomonospora viridis* and *Streptomyces thermovulgaris* were measured.

The compost workers were found to have significantly more symptoms and diseases of the airways and skin than the control subjects. These included tracheobronchitis, mucous membrane irritation, sinusitis, eczema, dermatomycosis, pyoderma, nausea and ear inflammation. One compost worker complained of typical ODTS symptoms. Severe cases of infection or EAA or asthma were not found. Twenty compost workers had one or several increased antibody concentrations compared with only three biowaste collectors and one control. Significantly higher antibody titres to *A. fumigatus* were measured in workers at the composting plants. Compost workers also had higher titres to the other fungal antigens compared to biowaste collectors and control subjects. Significantly increased antibody titres were also obtained for *Saccharopolyspora rectivirgula* and *Streptomyces thermovulgaris*. The concentrations for *Saccharopolyspora hirsuta* were also increased. There was a significant association between diagnosed diseases and increased IgG antibodies in the compost workers. There was also significant association between the duration of employment of the compost workers and the increased IgG titres, suggesting progressive development of IgG antibody responses with duration of exposure.

The workers involved in this study had been in the industry for a relatively short length of time (three years). The report concluded that longitudinal studies into the long-term health effects of exposure to compost bioaerosols are needed to investigate whether workers who develop IgG against the allergens to which they are occupationally exposed go on to develop more severe occupationally related symptoms. As to whether a longitudinal study of this nature is now underway is not reported.

Weber *et al.* (1993) described the case of a male who developed fever, myalgia and dyspnea 12 hr after shovelling composted wood chips and leaves. He was found to have elevated levels of precipitating antibodies to *Aspergillus flavus* and *Aspergillus niger.* Samples of bioaerosol and gases were collected using filtration samplers, All Glass Impingers, a five stage cascade impactor and gas samples were collected in Tedlar bags. *Aspergillus* and *Penicillium* were the predominant fungi. During experimental recreation of the exposure levels of airborne bacteria reached 7.7×10^8 cfu/m^3, fungi reached 4.7×10^8 cfu/m^3, dust 149 mg/m^3 and endotoxin 16,300 EU/m^3. Gasses were similar to background.

Browne *et al* (1995) reported a case study of a man who developed hypersensitivity pneumonitis after working on the compost in his garden. Symptoms included respiratory difficulty about two hours after commencing work, fatigue, a non-productive cough, fever, chills, and pain in the joints. The patient made a full recovery within a few days, but the symptoms reoccurred on two subsequent occasions. The patient was found to have

precipitating antibodies to *Thermoactinomyces vulgaris* and positive skin prick test to *Aspergillus.* The patient also had precipitating antibodies against an extract made from his compost pile. The patient had spent some considerable time gardening with the compost, working long hours every weekend. However, no information was reported on his possible exposure levels.

Vicknen and Roels (1984) report a case of hypersensitivity pneumonitis due to *A.fumigatus* in compost. A previously healthy 20 year old man presented with a three-day history of dyspnoea, dry cough and fever two months after starting work in a vegetable compost plant. A chest x-ray showed shadowing. Three weeks later, six hours after a social visit from his workmates in work clothes, the symptoms reoccurred. IgG antibodies against *A.fumigatus* were strongly positive. *A.fumigatus* was grown from sputum specimens.

10.2 UPPER AIRWAY INFLAMMATION

Douwes *et al* (1997, 2000) carried out a small study on 14 Dutch compost workers and 10 controls (University staff and students). For the duration of the study, nasal lavage was performed before and after the work shift on Mondays and Fridays. Mean personal dust and endotoxin exposures ranged from 0.4 - 3.1 mg/m^3 and 50-100EU/m^3 respectively, glucans ranged from 0.36 - 4.85 $\mu g/m^3$. Fungi levels were indicated to be over 10^6 cfu/m^3, total bacteria 10^9 cfu/m^3, Gram-negative bacteria 10^4 cfu/m^3. There was a cross shift increase in total cells and inflammatory mediator levels in the workers and a decrease in the controls. Total cells and inflammatory mediator levels in the workers were elevated pre shift on Mondays compared to controls, and were more elevated at higher than lower endotoxin exposures. Occupational exposure in the compost workers was found to causes acute and (sub-) chronic non-immune or type III allergic inflammation in the upper airways. The authors suggested that this was induced by non-allergic pro-inflammatory agents such as endotoxins and β (1-3) glucans, and that these findings should be confirmed in a larger study.

10.3 CYTOTOXIC EFFECT OF COMPOST

Non-immunological factors, such as cytotoxic effects, can also cause inflammatory responses. Cytotoxic responses have been linked to work related ill health in workers exposed to organic dusts. Roepstorff and Sigsgaard (1997a) used a cytotoxic assay to test a range of organic dusts and found that the most aggressive dusts tested were those with a high microbial content. Compost dust (5 week old organic household waste compost) and grain dust exerted an effect at very low concentrations after two hours incubation with monkey kidney cells and human lung carcinoma cells. The dusts tested, in order of decreasing cytotoxic effect, were compost, grain, swine and cotton. Further tests confirmed that the greatest cytotoxic potential occurred when the microbial activity was at its height in the composting process. However, pure endotoxin did not show any cytotoxic activity in the assay (Roepstorff and Sigsgaard,1997 b). Further investigations are required to find out which microbially associated components are responsible for the cytotoxic potential.

10.4 GENERAL ILL HEALTH

The outcome of a large study on the health of a population living near to a grass and leaf composting plant at Islip, New York was reported (Browne *et al* 2001). Sixty three people living near the site and 82 controls were asked to keep a symptom diary. Individual personal exposure data was not collected, but bioaerosols were measured at fixed sites. Daily

maximum *A. fumigatus* counts ranged from 30 -19,000 spores/m^3. Average counts were 50 spores/m^3 at the control neighbourhood, 100 spores/m^3 in the study neighbourhood and 500 spores/m^3 at the composting facility. Elevated spore counts (counts exceeding 300 spores/m^3) occurred in 15 % of the counts in the study neighbourhood, in nearly 20 % of the counts at the composting facility and in less than 5% of the counts at the control sites. When the study neighbourhood was downwind of the composting facility spore counts averaged four times the average background level. There was no evidence of *A. fumigatus* being associated with increases in respiratory or irritant symptoms, but there was an association with ragweed pollen (a common inhalant allergen), ozone, temperature, and time since the start of the study. Within the size limitation of the study, it was concluded that any major increase in allergy and asthma symptom prevalence in people living near the site were too small to detect, even though residents were exposed to elevated concentrations of *A. fumigatus* as a result of operations at the compost facility. The authors also noted that they took fixed point samples out of doors in the study neighbourhood, and that spore counts could differ significantly indoors, where people spend more of their time. Other studies have noted that indoor bioaerosol concentrations may be between 2% and 20% of those outdoors (Flannigan *et al*, 1991). In summary, the results from the study were:

- Concentrations of airborne *A. fumigatus* spores were greater in the study neighbourhood than in a control neighbourhood, but less than at the composting facility.

- Daily allergic and irritant symptom incidence averaged 21.4% among study area participants and 16.5% among reference area participants.

- Asthma related symptom incidence averaged 7.8% among study area participants and 5.0% among reference area participants.

- There was no positive association between respiratory symptoms and daily mean *A. fumigatus* concentrations, nor was there any association between respiratory symptoms and days with high counts.

- Symptom incidence was associated with ragweed pollen and ozone concentration.

Recer *et al* (2001), reported on the same study. Although their report concentrated on environmental data rather than health, in their conclusions they discuss the implications from the raised levels of *A. fumigatus* found by them in a residential area 500m from the compost facility. They observed that the degree of increased risk of allergic, inflammatory or irritant respiratory effects could not be readily estimated due to the lack of dose response data, but they speculated that the implications for severely immunocompromised individuals, such as bone marrow transplant patients, should mean that in the siting of facilities in heavily developed areas the usage of those areas, e.g., hospitals, should be considered.

Cobb *et al* (1995) investigated health complaints, from local residents, associated with commercial processing of mushroom compost. They administered a health symptoms questionnaire to people living close to the compost site and to a comparison group further away. They also surveyed local doctors for their clinical impressions. They could not demonstrate a significant health hazard. A comparison group, with no exposure to compost, had similar symptoms to those living within 3,000 feet of the site.

Marth *et al* (1997) examined the occupational health of 137 employees at different waste handling facilities, including 2 composting facilities and 3 waste sorting plants. Average length of employment for compost and waste handling was 83.6 months ranging from 1 - 466 months A medical examination, questionnaire and IgE measurements were carried out. No statistically significant increase of allergic diseases was found. There were no differences in lung function between workers and a control group. However, workers complained of hoarseness (38%), cough (35%), respiratory infections (23%), diarrhoea (18%), joint and

muscle disorders (13%) and conjunctivitis (12%), the prevalence of these complaints is not compared with a control population making the information hard to interpret. The report did not record the length of employment of the compost workers or whether data was collected in the study about previous working in waste handling or other jobs associated with organic dusts. The control population worked in the office of a food processing plant at a chicken farm, which would not necessarily exclude them from exposure to bioaerosols.

A later report from this study by Marth *et al* (1999) found that, while workers at manual waste sorting facilities showed evidence of increased levels of total IgE, lung function for the compost workers was within the normal range and that total IgE concentration did not differ within 3 years.

In the study by Wheeler (2001), occupational health monitoring was done on 11 workers. These included skin checks, respiratory function tests, spirometry, blood counts, kidney and liver function assessment and urine analysis, and a health survey questionnaire. The workers at the outdoor sites had no problems that might be associated with exposure to microbial emissions from the compost. However, the workers at the in vessel site had adverse reactions to particular operations. For example, where they had to work within the composting vessel and were potentially exposed very high levels of airborne dust and micro-organisms, symptoms were characteristic of ODTS, these workers also reported gastrointestinal symptoms, dust from waste causing itchy arms and eyes and steam from green waste causing dry throats and cough. It is noteworthy that workers were also concerned about the potential for needle stick injuries and cuts from needles and glass in the waste.

10.5 INFECTION

10.5.1 Aspergillosis

Under extreme circumstances, such as immunosuppression, *A. fumigatus*, an opportunistic pathogen, can cause infection.

Allmers *et al* (2000) investigated the case of a garbage collector with allergic bronchopulmonary aspergillosis. The garbage collector was involved in emptying biological waste, although details of the nature of this waste were not provided and exposure levels were not measured. In 1992 he complained of dyspnoea, fever, and flu-like symptoms during work. A chest x-ray showed streaky shadows. The IgE and IgG antibodies were strongly positive for *A. fumigatu*s. Total IgE was elevated. Bronchial challenge testing with commercially available *A. fumigatus* extract resulted in an immediate-type asthmatic reaction. Two years later he was still symptomatic and antibodies persisted at lower levels. The patient was diagnosed with allergic bronchopulmonary Aspergillosis including asthmatic responses as well as hypersensitivity pneumonitis due to exposure to mouldy household waste.

Conrad *et al* (1992) report on the case of a patient who developed microgranulomatous aspergillosis after shovelling mouldy wood chips. The patient described ODTS symptoms 6 hours after finishing work. Sputum cultures grew *A. fumigatu*s. The patient died 17 days after the work activity.

10.5.2 Gastric infections

Ivens *et al* (1997) carried out a telephone questionnaire survey of 28 composting employees working at 7 plants covering household and garden waste. 11% reported nausea and 11% reported diarrhoea, and there was a non-significant association between working with

compost and diarrhoea. Among waste collectors the groups with highest exposure to total fungi or total micro-organisms reported fewer symptoms compared to the lower exposed groups. No positive trend was found, although there was an association between fungal exposure and diarrhoea (Ivens *et al*, 1997). No non-occupationally exposed control population was reported in this study.

Ivens *et al* (1999) and Breum *et al* (1997) reported on an extensive investigation into the relationship between the gastrointestinal problems and bioaerosol exposure among waste collectors. Workers collecting garden waste and green waste were included in the study. A questionnaire was sent out to 2303 male waste collectors, and 1430 male municipal workers in mainly outdoor jobs (Ivens *et al*, 1999). A job exposure matrix for waste collectors was constructed using exposure data from a very extensive personal sampling programme (Breum *et al*, 1997). An exposure-response relationship was found between nausea and endotoxin exposure and between diarrhoea and exposure to both endotoxins and viable fungi. Viable fungal spores reached levels greater than 10^7 cfu/m^3, total fungal spores (viable and non-viable) reached levels greater than 2 x 10^7 cells/m^3 and endotoxin levels reached more than 500 EU/m^3. Bacteria levels were also very high, with total (viable and non-viable) micro-organisms exceeding 6 x 10^7 cells/m^3.

Sigsgaard *et al* (1997) investigated the health of eight compost workers. None had any skin problems and only one tested positive to a skin prick test against 10 common inhalant allergens. Mean total dust, total micro-organisms and endotoxin were 0.62 mg/m^3, 5.44 x 10^4 cfu/m^3 and 0.8 ng/m^3 respectively. Gastrointestinal symptoms, and ever having experienced vomiting or diarrhoea in relation to work, were significantly more common in composting industry than in controls.

10.6 OCCUPATIONAL EXPOSURE LIMITS FOR BIOAEROSOL COMPONENTS

Occupational Exposure Limits (OELs) for airborne hazardous substances are set at a level at which, based on current scientific knowledge, there is no indication of risk to the health of workers who breathe it in day after day. At present, no country has OELs for airborne micro-organisms or their associated toxins. The American Conference of Governmental Industrial Hygienists (ACGIH) Bioaerosols Committee summarises the reasons for this as being:

- Limitations in sampling methods for all biological components (as described in previous Sections).
- Insufficient data on exposure-response relationships between bioaerosols and allergic, irritant or toxic responses.
- The wide variation in individual susceptibility to biological agents (ACGIH, 1999).

Equally, a single OEL for bioaerosol exposure could not be set, because of differing allergenicity of different biological agents, and thus an OEL would need to be set for each individual micro-organism based on dose-response, together with a method for measuring exposure.

Although numerical standards are favoured by some, there are limitations, especially if it leads to risk management strategies which attempt to control exposure only to just below the limit value rather than adopting the ‘as far as is reasonably practicable’ approach.

Some attempts have been made to introduce health based occupational and environmental exposure limits. In the Netherlands, the exposure standards setting committee DECOS is progressing towards setting an occupational exposure standard for endotoxin (Gram negative bacterial toxin). Although it initially recommended a health based occupational exposure limit for airborne endotoxin of 50 EU/m^3 (4.5 ng/m^3) based on personal inhalable dust exposure measured as an eight hour time weighted average, DECOS has agreed upon a limit of 200 EU/ m^3 which is progressing toward a statutory value (D. Heederik, Utrecht University, pers. comm.).

Several researchers have suggested limits and health based thresholds for airborne micro-organisms or their components. Some are related to indoor air quality, i.e, exposure in office based environments. However, the scientific basis is not clear for some suggested limits. Published proposals are summarised in Table 11.

Table 11. Summary of suggested exposure limits for workplace and ambient bioaerosol exposure

Suggested Value	Bacteria cfu/m^3	Gram negative bacteria cfu/m^3	Fungi cfu/m^3	Actinomycetes cfu/m^3	Total micro-organisms	Reference
Threshold values	1,000	1,000				Rylander *et al* 1980, 1983
Suggested OELS in Scandinavia		1,000	10^5			Rylander *et al* 1994
Threshold values			5,000			Peterson & Vikstrom 1984
OEL		1,000			5,000-10,000	Makros 1992
OEL		2×10^4		2×10^4	1×10^4	Dutkiewitz & Jablonski 1989
Health based - number which can cause sensitisation				10^8		Malmberg 1991
Increased risk of EAA and ODTS					$> 10^6$	Lacey *et al* 1990
Threshold values		1,000				Lacey *et al* 1992
Suggested OEL (biotechnology)		300				Palchak 1990
Suggested OEL 8 hr average	5-10,000	1,000				Sigsgaard 1990
Health based OEL*		2×10^4	5×10^4	2×10^4	1×10^5	Dutkiewitz 1997
Number of spores necessary for development of acute symptoms					10^8	Miller 1992
Recommended maximum for residences, schools and offices	<4500			<10 in winter	<500 in winter <2500 in summer	Finnish Ministry of Social Affaires and Health 1997
Provisional Dutch guideline for indoor air in the work environment	10,000					Dutch Occupational Health Association NWA 1989.
Suggested OEL in Scandinavia		Toxic pneumonitis 10^5 Respiratory inflam. 10^2	Toxic pneumon. 10^7 Respiratory inflamm.10^5			Rylander 1994

*OEL Health based when continuous exposure to micro-organisms concentrations above 10^5 cfu/m^3 occurs work-related respiratory disorders in workers are very common

11 DISCUSSION AND CONCLUSIONS

11.1 OCCUPATIONAL BIOAEROSOL EXPOSURE

This Review has identified several well conducted and thorough studies documenting the levels of viable micro-organisms in bioaerosols associated with composting. This Report has aimed to summarise the microbiological basis of composting and the reasons why bioaerosols are generated from composting activities, to provide data from previous reported studies on the concentrations of bioaerosols and the types of micro-organisms and their toxins components associated with composting facilities.

The inter-site and inter-study variation makes it difficult to predict "typical" emissions of bioaerosols from composting operations, but a range of expected values can be determined. However, most studies have used fixed point bioaerosol measurement devices, and there is very little information available on personal exposure levels of workers carrying out the composting process.

An overall pattern emerges, that workers on composting facilities are potentially exposed to considerably higher concentrations of bacteria, including Gram-negative bacteria, actinomycetes, fungi and their associated toxins than are likely to be present in background air away from bioaerosol sources, and that the microbial components of compost bioaerosols have a known potential to cause respiratory ill health.

Levels of airborne micro-organisms generated during the handling of compost can vary greatly from site to site depending on the scale and type of operation. Different sampling methods, different siting of samplers and other method variations e.g. whether sampling took place during compost pile activity or not, make it difficult to compare results directly from study to study. Even at one particular site concentrations can vary greatly from hour to hour by more than 10 fold (Neef *et al* 1999). Different composting activities have a dramatic effect on the levels of microbial emissions, as can weather conditions, wind speed and direction (Hoffman *et al* 1999). The moisture content of the compost also affects the bioaerosol levels (Wheeler, 2001). As a result, different studies have reported widely differing levels (See table 4.1). It is not possible in many instances to deduce from the data presented in the published studies how the different types of composting activity, containment and automation might have affected the levels of bioaerosol generated.

Reported concentrations of bioaerosols generated from composting activities and measured at fixed point locations may not reflect accurately the concentrations to which the workers are exposed. For much of the work done on site, workers may be using tractors or front end loaders and therefore are protected by vehicle cabs which may also be air conditioned. Assuming that this is the case, and doors and windows are kept closed in the close proximity of actively handled compost, the workers' exposure will be considerably less than the bioaerosol levels outside the vehicle cab. Previous work by HSL (Thorpe *et al*, 1997) examined the protection afforded by vehicle cabs such as tractors and combine harvesters in agriculture and demonstrated that potential exposure could be reduced by several orders of magnitude. However, leakage of air around poorly fitted or badly maintained cab filters compromises the protection, and opening a door or window even for a short period in the vicinity of a bioaerosol source negates the protective effect within a very short period of time. For work activities outside of vehicles and in the vicinity of composting material, suitable respiratory protection would significantly reduce potential exposure. Few studies provided any detail about the use of respiratory protective equipment.

A better evaluation of compost workers' exposure would be achieved during on site measurement studies by providing more detail about the work tasks undertaken, coupled with

personal exposure monitoring of individual workers and occupational hygiene-based work-task analysis to assess the length of time typically spend undertaken a certain task, together with details of control measures used. The state of the compost feed on arrival, activities such as hand sorting of the compost feed, direct contact the compost, enclosure of the process and the moisture content of the compost, can all affect the risks to workers.

In the absence of suitable controls or protection, workers at composting sites are potentially chronically exposed to high levels of fungi, bacteria including Gram-negative bacteria, actinomycetes and endotoxins. Levels of all the components of the bioaerosols were well in excess of "normal" outdoor levels at all sites. Bacteria levels were regularly greater than 10^4 cfu/m^3 (ranging from 10^2 - 10^8), including Gram negative bacteria which were also regularly recorded to be greater than 10^4 cfu/m^3 (ranging from 10^2 - 10^6). Fungal levels were generally lower than bacteria but still regularly exceeded 10^4 cfu/m^3 (ranging from 10^2 - 10^5), of which *A. fumigatus* was regularly found to be greater than 10^2 cfu/m^3 (ranging from 10^1 - 10^3). Actinomycetes regularly exceeded 10^3 cfu/m^3 (ranging from 10^1 - 10^4). Levels of endotoxin varied, but were regularly above the health based limits proposed by the Dutch and were extremely high in bioaerosols generated from one study conducted with the handling of sewage sludge compost. Little information was available on the levels of mycotoxins associated with compost handling, and in studies where attempts were made to measure them they were often below the level of detection. However, the health consequences of mycotoxin exposure remains an unknown factor in various workplaces where organic dust exposure occurs and there could be a potential problem as a result of occasional high acute exposure. Limited data was available on fungal beta-glucans, and VOC levels were generally reported to very low were measured.

Workers are at greatest risk of exposure to bioaerosols during the movement of the compost. The highest levels of the airborne micro-organisms at both outdoor and indoor sites were measured during shredding, turning, and screening of the compost. The highest levels associated with in the vessel composting were during the unloading and cleaning of the vessels. All workers directly involved in the composting process are at risk of high acute exposure and medium to low long-term chronic exposures to bioaerosols. Evidence from the reported studies showed that concentrations of airborne micro-organisms often significantly exceeded background levels at short distance from composting activities and others working on site may also be at risk of medium to low long-term exposure. For example, staff in offices and weigh-bridges may be exposed to bioaerosols, and though it is likely that they would be afforded protection by being inside a building there are no data available on their exposure.

The predominant fungi measured at most composting sites are *Penicillium spp.* and *Aspergillus spp.* (Hryhorczuk *et al* 2001; Tovalen *et al* 1998; Crook *et al* 1988; Heida *et al* 1995). Both genera are naturally present in the atmosphere, but are in greater numbers near to actively turned compost.

In most studies of micro-organisms associated with composting, only the viable micro-organisms present have been measured. However, it is important to take into consideration that allergic and immunotoxic health effects associated with inhalation of organic dusts can be caused by intact non-viable as well as viable micro-organisms. The studies reported here therefore underestimated the exposure to total (viable and nonviable) airborne micro-organisms. Microscopic counting has shown that plate counts of culturable micro-organisms can underestimate the numbers of workplace airborne micro-organisms by 10 - 20% (Blomquist, 1994). For example, Marchand *et al* (1995) found that the composting method they monitored appeared to kill the Gram-negative bacteria. Their maximum counts of viable Gram-negative bacteria were well over 10^3 cfu/m^3 and if levels had been measured to include the dead Gram-negative bacteria these would have potentially been much higher. Some microscopic counting methods, such as spore traps used extensively for pollen studies,

provide a further potentially valuable source of data as they are designed to operate continuously over several days. These methods were used in a major study in USA (Syzdek and Haines, 1995) and allow fluctuations in numbers to be recorded, as well as correlation between bioaerosol concentrations and activities. However, obtaining total counts including non-viable bacteria and fungi usually involves counting them directly by eye using a microscope. This is labour intensive and the presence of dust particles can obscure the sample. The application of newly available molecular based fluorescent stains and species specific fluorescent labels could however be applied to provide a simpler and more robust method of measurement.

It is very important that the composting process is properly managed. Levels of faecal coliforms, faecal streptococci and other potential pathogens in municipal waste have been shown to be greatly increased in badly managed compost (Tovalen 1998). In well managed compost, pathogens are killed off rapidly (Déportes *et al* 1995). Other management practices may reduce exposure to bioaerosols. Control measures that have been suggested in published papers include:

- Ensuring source compost feed is in good condition;
- Keeping the compost damp with a clean water source;
- Keeping hard surfaces and roads damp and cleaning them regularly;
- Local dust extraction;
- Good ventilation;
- Use of vehicles with air-conditioning and keeping doors and windows shut;
- Regular cleaning out of vehicles;
- Use of personal protective equipment including respiratory protection, overalls, gloves and eye protection;
- Good hygiene including washing hands on leaving the area, changing work clothes before eating or going home;
- Limiting potentially high exposure activities e.g. hand sorting;
- Operating and overseeing activities likely to generate significant bioaerosols from a distance.

A further method suggested for reducing emissions from compost sites was more regular turning of windrows, which was shown to reduce growth of *Aspergillus fumigatus*. However, from an occupational exposure viewpoint, the overall operation has to be considered, as the beneficial effect of reduced growth of Aspergillus fumigatus may be counterbalanced by more frequent exposure to lower levels. The use of some types of enclosed or in-vessel systems has great potential benefit in reducing bioaerosol emissions during the most active phase of composting. However, worker involvement is still required in handling feedstock prior to the in-vessel system, and when handling raw compost at the maturation stage, including size screening and turning to aerate during maturation. These activities will still create bioaerosols, and a full evaluation of all activities is required. Using a combination of personal exposure measurement related to work task, it would be possible to generate a risk assessment 'pick list', whereby an employer could select the tasks done by an employee and estimate the time taken and from that the potential exposure as a guide to implementing appropriate control measures.

11.2 BIOAEROSOL DISPERSION FROM COMPOSTING FACILITIES, POTENTIAL EXPOSURE AT REMOTE SITES AND THE POTENTIAL USE OF MODELLING TO PREDICT DISPERSION

There is no doubt that workers on composting facilities are at risk of exposure via the respiratory route to large concentrations of potentially allergenic and immunotoxic micro-organisms. Consequently, controls can be considered and implemented to manage their exposure. One of the most frequently asked questions regarding bioaerosol releases from composting facilities, however, is the potential health hazard to people in the vicinity of the sites. This may include passers-by and visitors to sites, workers at neighbouring premises or residents in the vicinity. The fundamental questions in this respect are:

- Does the presence of a composting facility nearby significantly increase overall bioaerosol concentrations, or specific microbiological components of the bioaerosol, above background values?

- If so, how far away from the focus of activity on site does that significantly increased bioaerosol occur?

- Is there a potential health consequence of bioaerosol exposure at levels greater than background concentrations and, if so, is there a threshold above which those health consequences are significantly increased?

Attempts to answer those questions from the current information available in reported studies are confounded by the wide variations in measured concentrations of bioaerosols generated from composting activities, for the reasons described above. Similarly, 'background values' of bioaerosol differ greatly according to location as described in earlier Sections, e.g., urban vs. rural, season and short term meteorological conditions.

In the majority of studies reported, where measurements have been made at the periphery of compost sites, it is the conclusion of the study authors that bioaerosol concentrations generally returned to background levels (as defined by the study authors) by between 100 and 500 m from the site, with the majority reaching background levels within 250 m from the compost. However, for any of these studies it can be argued that measurements provide only a 'snapshot' and with inherent fluctuations in numbers as described above. A more robust method may be to use dispersion modelling techniques to attempt to create more empirical values for compost bioaerosol dispersion. Consequently, as part of the Review, available dispersion modelling tools were evaluated, and ADMS, the method chosen as being most appropriate in our experience, was used to examine the range of physical effects that would influence bioaerosol dispersion and to attempt to determine the rate of decline in numbers of bioaerosols released from a compost site and at what distance numbers would fall to 'background' levels.

Of the effects examined, the different atmospheric stabilities made the most difference to predicted concentrations. As would be expected, the highest concentrations were predicted under F2 conditions without any temperature effects. However, these were also the conditions in which the inclusion of temperature effects caused greatest reduction in concentrations. When considering these results, the amount of time such atmospheric conditions prevail needs to be taken into account and therefore the significance of their overall contribution to exposure. The results of the dispersion calculations, based on a unit release, show a reduction in concentration of approximately two orders of magnitude over 1km. Under stable conditions the distance is slightly more than 1km, for neutral conditions 800m and for unstable conditions the distance would again be less. Using the emission rate for *Aspergillus fumigatus* suggested in Millner *et al* (1980) the median background level of 8

cfu/m^3 in Gilbert *et al* (2002) is not reached by 1km under either D5 or F2 conditions. However, this emission rate is based on a range of predicted emission rates that vary by more than an order of magnitude. Reducing the estimated emission rate by an order of magnitude would move the distance to background from 800m to approximately 500m under D5 conditions Some of the variation in the predicted emission rates is due to uncertainty in the measurements. However, some is due to actual variations in the emission rates, windrows with similar *Aspergillus fumigatus* concentrations in the compost had predicted emission rates that differed by an order of magnitude.

Dispersion modelling can be used to examine the effects of different influences on bioaerosol concentrations. The most significant effects calculated here were due to atmospheric conditions and windrow temperature. However, at present the uncertainty in emission rate, due to a combination of measurement uncertainty and natural variation, is several orders of magnitude, while the predicted decay in concentration over 1km is approximately two orders of magnitude. The background concentrations of bioaerosols may also vary over orders of magnitude. More data on emission rates and their uncertainties, measured and natural, need to be collected to produce ranges of emission rates coupled with probabilities of their occurrence. This information would then allow dispersion calculations to be performed to produce ranges of concentrations and their likelihood. A simpler approach might be to estimate maximum possible emissions and use these as conservative figures. This would probably lead to the prediction of very long distances to background levels. An improved understanding of the possible variation in emissions would also provide a better basis to determine exposure if acute and chronic effects were considered important.

All the reviewed attempts to estimate emission rates were based on the use of multiple downwind readings. This will always give problems with the number of measurements required to make a single emission estimate. In addition the inability of Wheeler (2001) to estimate a suitable source term, based on measurements, raises questions about the suitability of this approach. Alternative approaches to estimating bioaerosol emissions, such as agitation of compost samples under controlled conditions (similar to those used by Nielsen *et al*, 1997 to determine bioaerosol release from biowaste), should be examined to allow a reasonable number of estimates of emission rate and their variabilities to be determined. HSL has used such methods effectively in other applications to establish the 'dustiness' of material, using a European standard method designed as part of a collaborative project and described in HSE guidance (HSE, 1996). The emitted bioaerosol particle size distribution could also be examined in these measurements.

At present, while modelling can be used to examine the effect of different conditions, uncertainty in emission rates is so large as to make quantitative predictions difficult. In addition, particle size effects and bioaerosol viability were not modelled, as suitable data was not available. Including particle size effects would reduce concentrations due to deposition. Obviously modelling viability would reduce concentrations of viable bioaerosol, though total load may also be significant and its concentration may also need to be calculated.

A further potential value from application of molecular based microbiological detection methods, as mentioned above, is that methods now exist, such as denaturing gradient gel electrophoresis (DGGE), whereby a DNA profile can be derived of the microbial population from an environmental sample (ref). Using such methods, a 'fingerprint' of a compost bioaerosol from a particular site could be compared with samples taken at various distances from the source to determine whether any bioaerosol remains dominated by the compost source or is influenced by airborne micro-organisms from other sources.

11.3 POTENTIAL ILL HEALTH ASSOCIATED WITH COMPOST BIOAEROSOLS

Despite the bioaerosol concentrations measured on site at compost facilities, as discussed above, there was no documented evidence of a significant excess of serious chronic work related disease, such as asthma and extrinsic allergic alveolitis (hypersensitivity pneumonitis) in compost workers compared to workers in other industries. This may be because controls already in place limit exposure. However, several of the studies show "early" responses to microbial exposure, such as raised levels of IgG and inflammatory mediators in the workers (Bunger *et al*, 2000; Douwes and Heederik, 1997). Several also reported a link between gastrointestinal symptoms and working with compost (Ivens *et al*, 1999, Sigsgaard *et al*, 1997). More information is required on whether compost workers who have developed raised levels of IgG and inflammatory mediators go on to develop work related diseases/ill health.

Although large scale composting has been used for several years as a means of waste management, the potential increase in numbers of sites in the UK as a consequence of changes in waste handling strategy means that there is an increased worker population in this sector, and it is important that the opportunity is taken to protect the health of those workers at this early stage. In addition to consideration being given to exposure control measures needed, it would be appropriate to consider respiratory health screening and biological monitoring in the form of baseline immunoassay against representative biological components of compost, as well as measurement of serological biomarkers of early response to immunotoxic agents. Few of the reports from health based studies have given details of the duration of employment of the workers or prior history of employment, but this is an important factor to be considered in the potential for development of respiratory disease associated with organic dust exposure. Although there is no reported evidence in the composting industry, other industries experience a 'healthy worker effect', i.e., those who recognise that their work is potentially affecting their health leave for other jobs if they are in a position to do so. As the waste composting industry expands in the UK, it would be of value to determine the length of employment in the industry and whether staff movement is the result of a typical mobile workforce or due to health concerns.

As with studies in other industries where workers are exposed to biological material, there is insufficient information available on the dose-response relationships between microbial exposure and development of ill-health. Differing susceptibility of exposed individuals is a further confounding factor, with underlying atopy increasing the risk of becoming sensitised to allergens in the workplace even at relatively smaller exposure levels. As the micro-organisms associated with compost are common environmental contaminants to which the general population are exposed in low levels during their normal daily activities, it is important that control populations are well defined. For example, worker control populations must be chosen to exclude those who may be involved in handling microbiologically contaminated material. For studies on the health of residents near composting sites, where controls comprise residents away from sites it is important to record the other potential bioaerosol sources in the vicinity, e.g., agricultural premises, or large areas of vegetation such as woodland. It must be noted that in many of these studies, only viable micro-organisms were counted. Non-viable micro-organisms can also cause allergic reactions and this further complicates estimation of dose-response. Eduard (1997), studying workers' exposure to fungi contaminants of wood being handled in sawmills, estimated that IgG antibodies can be detected in response to 10^5 viable spores and 10^4 non-viable spores. The results from the airborne micro-organism surveys reported here show that the workers involved in composting are potentially regularly exposed to more than 10^5 viable spores.

High levels of airborne endotoxin were recorded at some sites (Tovalen *et al* 1998; Darragh *et al* 1997; Ivens *et al* 1999). Darragh *et al* (1997) recorded levels up to 59,306 EU/m^3. Some were several times greater than the levels shown to cause acute ill health responses and with

the potential to contribute to the development of chronic diseases (Rylander 1997). Ill health associated with similar bioaerosols of organic nature have been documented e.g. in farmers and cotton workers, where occupational exposure levels are similar. There is evidence in these industries of long-term exposure leading to chronic ill health. At present, there are no occupational exposure limits for endotoxin, but a proposed Dutch health based occupational exposure limit for airborne endotoxin of 200 EU/m^3 (20 ng/m^3) may be the first limit to be set by any country. A further consideration is that microbial emissions from composting sites are a complex mixture of biological material and dust and there is the potential for adjuvant effects when inhaling this mixture of toxins, irritants and allergens.

Containing compost handling activities in buildings, or using in-vessel composting systems, is likely to decrease emissions to the surrounding ambient air, but may potentially intensify exposure for compost workers. High concentrations of bioaerosol have been measured in enclosed facilities, e.g., Lavoie and Alie (1997). Although the in-vessel stage of waste composting reduces to a minimum bioaerosol generation, workers may be greatly exposed at the emptying and subsequent handling stage. Parallels exist with mushroom compost preparation, where tunnel composting systems are prevalent, and workers emptying and cleaning out tunnels have reported allergic respiratory symptoms (van den Bogart *et al*, 1993). There are very little data published on exposure of workers and dissemination of bioaerosols from in-vessel composting methods, and as this is perceived to be the future direction of large scale organic waste composting, it is recommended that further study should be done in this area.

People working directly with compost are at risk of exposure to significantly higher levels of bioaerosols than are neighbours to compost sites, but there is, as yet, limited evidence that this is generally causing greater ill health than unexposed controls. On this basis, those some distance away from composting activity, and who receive a much lower exposure, are unlikely to suffer ill health effects. There is no documented evidence that people living in the vicinity of composting facilities show significant excess of respiratory symptoms compared to controls living away from compost bioaerosols. However, few studies of this nature have been conducted.

Most reported studies have found that people living more than 250 m from composting sites are exposed to microbial emissions that are similar to 'background', i.e., are not significantly higher than can occur naturally. However, there are some recordings of high levels. In one study, increased concentrations were detected 500m away from a composting site, with concentrations of thermophilic actinomycetes reaching 10^6 cfu/m^3 200m away (Neef *et al* 1999). The predominance of *Aspergillus fumigatus* in bioaerosol emissions from compost may pose an increased risk of infection to immunocompromised persons, and individual case studies have been reported of allergic bronchopulmonary aspergillosis and invasive aspergillosis associated with the handling of biological waste and composted wood chips respectively (Allmers *et al*, 2000; Conrad *et al*, 1992) while allergic diseases such as hypersensitivity pneumonitis have been diagnosed in individual cases associated with compost handling both occupationally (Vinken and Roels, 1984; Weber *et al*, 1993) and recreationally (Brown *et al*, 1995). Consequently, persons known to have impaired immunity may be at increased risk of infection if exposed to A fumigatus in compost bioaerosols. However, to place this in context**,** a similar risk would occur with exposure to other organic dusts containing *Aspergillus fumigatus*, such as from other agricultural activities (grain harvesting and handling, also demolition of buildings).

12 SUMMARY AND RECOMMENDATIONS FOR FURTHER STUDY

1. During this Review, detailed information was retrieved on levels of airborne viable micro-organisms and their components (bioaerosols) associated with composting. The majority of published composting studies focus on environmental emissions of micro-organisms and the potential risk to sensitive receptors, rather than occupational exposure.

2. Because most published studies use fixed point samplers which provides an overall picture of bioaerosol concentrations, rather than samplers located in the workers' breathing zone which take into account worker activity, there is limited information available on personal worker exposure to bioaerosols associated with composting processes. Few studies give details of exposure related to workers' tasks associated with composting, or of the controls such as respiratory protection worn.

3. Within the limitations of the above, it is estimated from previous published studies that workers at compost sites are at risk of regular exposure to airborne micro-organisms and their associated toxins at levels ranging from 10 times to 1,000 times greater than may be expected normally to be present in ambient air.

4. Most published exposure measurement studies to date have focussed on open windrow composting. However, the future of large scale composting is likely to include greater use of enclosed facilities and especially in-vessel systems. Limited data are available on bioaerosol emissions from in-vessel systems, taking into consideration that certain material handling processes before and after the in-vessel phase will still generate bioaerosols.

5. **It is recommended that subsequent exposure measurement studies on composting facilities should include personal exposure measurement, coupled with work task analysis, to establish task-related exposure assessment. This should include investigation of the use of in-vessel systems, including all the associated pre- and post- in-vessel tasks, and for all compost sites include ad-hoc activities such as equipment maintenance and cleaning. More detail of workplace controls used, such as engineering controls or personal protection, should be recorded.**

6. There is little published evidence of serious/chronic disease in compost workers, although there is evidence of early ill health responses to bioaerosol exposure in compost workers, e.g., raised antibody levels and inflammatory mediators, and evidence of progressive allergic respiratory disease exists in industries such as other waste handling, agriculture and cotton mills, where similar exposure to bioaerosols may exist. Composting on a major scale is a relatively new and rapidly expanding industry in the UK. Chronic ill health may not yet have had time to develop.

7. Only few published studies exist where the health of residents near to composting facilities has been investigated, but where this has been done there is no evidence of significant ill health compared to unexposed controls.

8. **It is recommended that respiratory health screening and biological monitoring (immunoassay against representative biological components of compost, as well as measurement of serological biomarkers of early response to immunotoxic agents) should be implemented at existing and especially at new compost sites to establish baseline data of workers respiratory health and immune status and to allow a longitudinal assessment to be made of worker response to bioaerosol exposure. This is most likely to be the responsibility of the employer. Similar long term health**

monitoring of workers at neighbouring sites, or of residents near to new composting facilities may be appropriate, although the logistics and responsibilities for doing so is less clear. In either case, it would be most useful to link such health monitoring with exposure assessment.

9. The main health risks associated with composting are allergenicity and toxicity. Although in most published studies only culturable micro-organisms are measured, non-culturable micro-organisms can also trigger allergic or immunotoxic response. Therefore, counts of both non-culturable and culturable micro-organisms are important. Studies that include only viable organisms risk underestimating the toxic and allergenic potential of the bioaerosols.

10. Molecular based detection methods can be used to estimate total microbial exposure levels. In addition, recent developments in molecular methods allow a DNA profile or 'fingerprint' to be made of microbial populations, which could be used to track bioaerosol dispersion from a source.

11. **It is recommended that molecular based detection techniques should be applied to the measurement of compost bioaerosols, both to establish the full picture of occupational exposure to allergenic and immunotoxic bioaerosols and as a means of profiling bioaerosols dispersed from compost sites.**

12. As a consequence of the type of exposure measurement methods used and the funding available for such measurement, most measurements are made over a relatively short period and results in published studies reflect the potential wide variation in bioaerosol concentrations from short term sampling. Continuous sampling methods were used in one reported study, providing valuable data especially with respect to dispersal off site.

13. **It is recommended that, if resources allow, continuous monitoring may be appropriate at selected composting sites to establish a more complete picture of bioaerosol levels, especially at the periphery of sites.**

14. There is very little data on exposure to mycotoxins, fungal beta glucans or volatile organic chemicals associated with compost handling. However, there is no compelling evidence to suggest a major health hazard and this is considered to be of lower priority.

15. Computational models have been used in only a limited number of published studies to examine dispersion of compost bioaerosols, although further information on bioaerosol dispersion is also available from other studies. Balancing the advantages and limitations of various models, the dispersion model ADMS has good potential for application to compost site studies.

16. Application of the ADMS model to dispersion of bioaerosols from composting allowed the effects of atmospheric stability and temperature effects on dispersion to be examined. One of the major difficulties in applying the dispersion model was the lack of available data on source terms, i.e., the concentration of bioaerosol released from compost material. Some data on source terms has been estimated by extrapolation, indicating a wide range of possible values. Direct measurements have not yet been made. There is significant natural variability in emission rates, these need to be quantified to allow the effects on dispersion to be examined.

17. **It is recommended that further work be performed to establish source terms for use in dispersion models. One possible approach would be to use a laboratory method, such as the 'dustiness drum', to estimate bioaerosol concentration and size distribution associated with mechanical handling of known quantities of compost**

material at different stages of composting. The measured bioaerosol concentrations would give an indication of the possible range of release concentrations.

18. Off-site dispersion of bioaerosols can be modelled to obtain downwind concentration data. Due to the complexity of the release and flows in the near vicinity of composting material and equipment it would be difficult to model on-site dispersion. However, it is probably more relevant to examine on-site exposure by personal sampling.

19. Most published studies where bioaerosols generated from composting activities have been measured at locations remote from the source have found that bioaerosol concentrations have been reduced to 'background' levels within 200 m of the source. The experimental data derived by the Composting Association supported these findings. However, in subsequent work, Wheeler *et al* (2001) suggested that this should be extended to 250 m, and on this basis the Environment Agency produced interim guidance to confirm this as a limit, inside of which a case-by-case risk assessment of premises should be performed.

20. Using dispersion modelling based on the limited data available, it was found that under certain circumstances-such as stable atmospheric conditions, bioaerosol concentrations would not be reduced to the chosen background value within 250 m. It must be recognised that background values differ by orders of magnitude and the background value chosen was probably conservative. However, on this basis it is unsafe to recommend any change to the prescribed 250 m limit in the absence of absolute data that bioaerosols would be reduced to background levels, or any absolute data on dose-response relationship between compost bioaerosol exposure and respiratory ill health that can indicate a 'safe' level of exposure.

21. The 250 m limit addresses only off-site issues with regard to potential exposure and ill health, and does not give any assistance to employers in terms of risk management for potentially exposed workers. A rigid 250 m limit could be taken in any case by some to imply 251 m = acceptable, whereas in reality there is a gradation of risk with distance from source. An alternative approach to a fixed 250 m limit, therefore, would be to consider a zonation method, from high potential exposure, e.g., within 50 m of actively handled compost (turning, screening), to medium exposure zones outside of this area to low exposure zones at the periphery of a site, with different actions required in terms of personnel exclusion and protective interventions. Such a zonation method could be validated by a combination of dispersion modelling supported by measurements.

22. **While most published studies indicate that bioaerosols are reduced to background within that distance, some experimental studies and dispersion modelling exercises suggest that bioaerosols may exceed background concentrations at distances greater than 250 m under certain atmospheric conditions. Despite this, there is no published evidence that exposure to bioaerosols disseminated from compost facilities cause respiratory ill health in residents or workers at nearby (>200 - 250 m) locations, or that slightly greater than background bioaerosol levels represent a significant excess risk. However, in the absence of any agreed 'safe' value and range for background concentrations, with limited health and dose - response data, and with limitations to exposure measurement data as described above, it is recommended that no change should be made to the 250 m 'limit' prescribed by the Environment Agency until further research is completed which can validate the published findings in some areas of uncertainty or where published evidence is limited.**

The levels of airborne micro-organisms present on sites where compost is being handled may be several times greater than normal outdoor levels, but are generally lower than in some occupational industries, including some agricultural practices, which can expose workers to airborne micro-organisms regularly in excess of one million cfu/m^3. However, any exposure

of workers to elevated levels of airborne micro-organisms must constitute a respiratory health hazard and there is a need to assess and control the risks that are posed by work at composting facilities.

Millner *et al* (1994), reporting on the discussions at a workshop of experts, posed the question "Do bioaerosols associated with the operation of biosolids or solid waste composting facilities endanger the health and welfare of the general public and the environment?". They concluded that "Composting facilities do not pose any unique endangerment to the health and welfare of the general public". These conclusions were based on data showing that compost workers, who are exposed to greater bioaerosol concentrations than are others further away from the bioaerosol source, suffer from very few work related ill health effects. In the intervening nine years, further studies have been completed and published which highlight potential respiratory health concerns for workers on composting facilities but there is no published evidence to contradict their conclusions regarding the general public. While it is the opinion of the authors of the current review that the conclusions of Millner *et al* still are correct, there are concerns over respiratory health and these need to be evaluated and placed in the context of risks presented by other environmental hazards. Clearly further monitoring and epidemiological data are required.

13 APPENDICES

APPENDIX A: SUMMARY OF STUDIES CITED IN REPORT

APPENDIX B: COMPUTATIONAL MODELLING OF TEMPERATURE EFFECTS

APPENDIX C: PAPER BY GILBERT *ET AL* SUBMITTED FOR PUBLICATION IN 'BIOCYCLE'

APPENDIX A: SUMMARY OF STUDIES CITED IN REPORT

Report/paper	Section(s) referred	Review	Research report	Composting	Other waste disposal	Occupational exposure data	Environ - mental. exp. data	Occup. Health data	Env. health data	Dispersion modelling	Single site study	Multiple site study
Allmers et al. 2000.	10.5											
Breum et al 1997;	7.7, 9.4, 10.5											
Browne et al 2001,	8.4, 10.4											
Brown et al,1995,.	10.1											
Bunger et al 2000,.	10.1											
Cobb et al. 1995,.	10.4											
Conrad et al 1992,.	10.5											
Curtis et al 1999,.	7.2											
Danneberg et al 1997;	7.4, 8.4, 9.2, 9.4											
Darragh et al 1997,.	7.6											

Report/paper	Section(s) referred	Review	Research report	Composting	Other waste disposal	Occupational exposure data	Environ - mental. exp. data	Occup. Health data	Env. health data	Dispersion modelling	Single site study	Multiple site study
Deportes et al 1997;	9.2, 9.4											
Douwes et al 2000,.	10.2											
Douwes et al 1997,.	10.2											
Dowd et al 2000;	9.2											
Epstein et al 2001,.	7.7											
Fischer et al 1998;	7.7											
Fischer et al 1999,.	7.7											
Folmsbee, Strevett, 1999,.	7.2											
Gilbert, Ward,1999. .	8.4											
Gilbert,et al. 2001;	8.4											

Report/paper	Section(s) referred	Review	Research report	Composting	Other waste disposal	Occupational exposure data	Environ - mental. exp. data	Occup. Health data	Env. health data	Dispersion modelling	Single site study	Multiple site study
Haas et al 1999;.	7.2, 7.4											
Heida, Van der Zee 1995,.	7.4											
Hryhorczuk et al 1996:	7.2											
Hryhorczuk et al. 2001,	7.2											
Ivens et al 1997,.	10.5											
Ivens U et al 1999,.	10.5											
Kock et al. 1998	8.2											
Kothary et al 1984,.	7.6, 8.4											
Lacey 1997,	7.2											
Lavoie, Alie 1997,.	7.3											

Report/paper	Section(s) referred	Review	Research report	Composting	Other waste disposal	Occupational exposure data	Environ - mental. exp. data	Occup. Health data	Env. health data	Dispersion modelling	Single site study	Multiple site study
Marchand et al 1995	7.3											
Maricou et al 1998,.	7.4											
Marth et al 1997,.	10.4											
Millner et al. 1980:	7.6, 8.4, 9.2, 9.4											
Millner,et al. 1994,	8.4											
Nielsen et al 1997;	7.3, 9.4											
Passman, 1983,	8.4											
Recer et al 2001,.	8.4, 10.4											
Reinthaler,et al 1998/99,	8.4											
Schilling et al 1999,.	7.4, 8.4											

Report/paper	Section(s) referred	Review	Research report	Composting	Other waste disposal	Occupational exposure data	Environ - mental. exp. data	Occup. Health data	Env. health data	Dispersion modelling	Single site study	Multiple site study
Sigsgaard et al 1997,.	10.5											
Syzdek, Haynes 1995,.	8.4											
Tolvalen et al 1998,.	7.3											
Vincken, 1984,.	10.1											
Weber et al 1993,.	10.1											
Wheeler et al 2001,	7.2, 8.4, 9.2, 9.4, 10.4											

APPENDIX B: COMPUTATIONAL MODELLING OF TEMPERATURE EFFECTS

Energy from a bucket of hot compost

Volume of air in bucket = $3.5m^3$

Assuming ambient temperature is 15^oC and the material in the bucket is at 55^oC.
Density of air at 55^oC and atmospheric pressure, ρ = 1.08 kg/m^3
Assuming a constant specific heat capacity, c_p = 1010 J/kg K

Energy to raise temperature of air in bucket from ambient to 55^oC

= $c_p \Delta T$ = 1010 * 40

= 40,000 J/kg

Mass of air in bucket = 3.5 x 1.08 = 3.76 kg

Energy to raise temperature of mass of air in bucket from ambient to 55^oC

= 40,000 * 3.76

= 152,000 J

Giving a heat flow rate = 2.5 kW at one bucket per minute

Assuming this is introduced over an equivalent area to the mouth of a bucket ($1.4mx2m=2.8m^2$) and knowing the volume of heated air a velocity can be calculated through this area

3.5/2.8/60 = 0.02 m/s

Similarly at a rate of 5 buckets per minute, heat flow rate = 12.5 kW at a velocity of 0.1 m/s.

Energy from hot compost surface

Assuming that at any time a 4.5m long strip of a 4.5m wide windrow remains at a raised temperature during the turning process and that the emission of bioaerosols occurs over this surface.

For an equivalent horizontal area, A = 4.5m x 4.5m and a heat transfer coefficient of 10 $W/m^2/^oC$

Rate of heat flow Q, with the surface at 55^oC and an ambient of 15^oC

Q = 4.5 x 4.5 x 40 x 10 = 8kW

Knowing the area, A, over which this energy is introduced

$Q=VA \rho c_p$

The velocity, V, can be found:

$V=Q/(A \rho c_p)$= 8000/ (4.5 x 4.5 x 1.08 x 1010) = 0.37 m/s

With the surface at 35^oC the heat flow is half the above, 4kW, and the velocity is 0.17m/s.

APPENDIX C: FINAL PAPER BY GILBERT *ET AL* SUBMITTED TO 'BIOCYCLE', MAY 2002

Preliminary Results of Monitoring the Release of Bioaerosols from Composting Facilities in the UK:

Interpretation, Modelling and Appraisal of Mitigation Measures

E Jane Gilbert[1], Adrian Kelsey[2], Jon D Karnon[2], Jillian RM Swan[2], and Brian Crook[2]

1. The Composting Association, Avon House, Tithe Barn Road, Wellingborough, NN8 1DH, UK
2. Health and Safety Laboratory, Broad Lane, Sheffield, S3 7HQ, UK

This paper describes the measurement of concentrations of total culturable mesophilic bacteria and *Aspergillus fumigatus* downwind from two composting facilities in the United Kingdom. A rural site, distant from a commercial composting facility, and an arable farm were used to obtain reference data. Background concentrations were shown to vary considerably during the study period, with minimum concentration of bacteria and *A. fumigatus* of 0 and 1 cfu / m^3 respectively, and maxima of 2,968 and 249 cfu / m^3, respectively. Concentrations of bioaerosols at composting facilities decrease approximately exponentially with distance from the source, reaching measured background levels within 200 m of the source, although earthen bunding surrounding one of the composting sites appeared to impede dispersal. Calculated decimal reduction distances (D values) calculated fell within the range 26 – 96 m at the composting sites. Inherent difficulties in modelling bioaerosol dispersal are discussed.

Introduction

The identification and quantification of airborne micro-organisms and their constituent parts (bioaerosols) formed at composting facilities has been well documented (Millner et al, 1994; Swan et al, 2002). Inhalation of large concentrations of bioaerosols has been shown to elicit allergic and immunotoxic respiratory diseases and occasionally respiratory infection (Lacey and Dutkiewicz 1994, Dutkiewicz 1997). Adverse health effects have been reported in workers where high concentrations of bioaerosols are known to occur, such as agricultural and food processing industries, as well as at composting facilities (Lundholm and Rylander 1980; Malmros 1990; Bunger et al, 2000). At least two case studies of acute respiratory illnesses associated with handling compost have been reported (Brown et al, 1995; Weber et al, 1993).

Composting in the UK has increased significantly over the past decade and is set to grow further, primarily as a result of European, UK and national legislation (Slater et al, 2001) . A necessary consequence of this is the need to establish and regulate new facilities, however, public concern and opposition to composting facilities often lies in apprehension about chronic exposure to emissions from such sites, in particular bioaerosols (Millner et al, 1994; Browne et al 2001). A number of studies have set out to assess the impacts composting facilities may have, however, monitoring bioaerosols in an outdoor environment is beset with practical difficulties (Lacey et al, 1996). Consequently, there have been few detailed studies reported in the scientific literature that relate specifically to composting and the spread of bioaerosols. By contrast, there are numerous reports on the dispersal of pollen and spores, especially those that are of agronomic importance (see, for example, McCartney 1994). These aerosols are thought to decrease in concentration away from the source following either the power law or exponential models (Fitt et al 1987).

There are a number of reasons why the use of mathematical models provide uncertain results when used to predict bioaerosol dispersal. Most have been developed to simulate

atmospheric transport of particles over medium to long ranges (for example, estimating the release of particles from smoke stacks), with little information available on short range (< 1 km) dispersal. Determining the emission rate (source term) is complex, which stems from the fact that it is often moving and intermittent, and little information has been gathered to date by direct measurements, most being based on estimates of emission concentrations (Danneberg et al 1997; Millner et al 1980). Additionally, buoyancy effects caused by the release of hot air from the composting piles into the cooler atmosphere have not yet been accounted for within any reported models. Coupled with the high degree of variability of naturally occurring background concentrations (Jones and Cookson 1983) and the effects of traffic movements and neighbouring bioaerosol sources, such as agricultural activities (Reinthaler et al, 1998/99), the impacts composting facilities have on neighbouring populations remain uncertain.

In England and Wales the regulatory body, the Environment Agency, stated in 2001 that: "*There will be a presumption against permitting [and to object to any planning application] of any new composting process [or any modification to an existing process] where the boundary of the facility is within 250 metres of a workplace or the boundary of a dwelling, unless the application is accompanied by a site-specific risk assessment, based on clear, independent scientific evidence which shows that the bioaerosol levels are and can be maintained at appropriate levels at the dwelling or workplace."(*Environment Agency 2001*)*. Mitigation measures that either contain the emission or enhance dispersal from the site have been suggested as risk management options, however, the cost and benefits (to both workers and neighbours) of these have not been characterised to date. The relatively low tipping fees at landfill sites currently act as a disincentive towards the widespread implementation of more capital and resource intensive enclosed hall and in-vessel composting systems within the UK.

The aim of this study was to monitor and model the dispersal of bioaerosols from composting facilities in order to assess the potential impacts the sites may have on neighbouring populations.

Methods

Sampling was carried out at two open-air turned-windrow composting facilities in the UK during 1997 and 1998. One composted approximately 5000 tonnes per annum of green waste (yard trimmings) and kerbside collected green waste / botanical kitchen waste from households (Site A). The other composted approximately 12,000 tonnes per annum green waste (Site B). Site A was located on a flat industrial site, with the nearest building over 400 m away, and was surrounded by a chain link fence. Site B was located adjacent to an active biodegradable waste landfill site and duck farm. Its perimeter was bordered by an earth bund at least 3 – 4 m high.

To act as reference data, samples were also taken at a rural site distant from a commercial composting facility (Site C), and on an arable farm (Site D). Samples were taken during the shredding, turning (using a front-end loader) and screening processes at sites A and B; when spreading compost using a small garden chipper to simulate a static source (Site C); and adjacent to crop harvesting using a combine harvester (Site D). At all sites samples were collected both upwind and at various distances downwind from the emission sources. The positions of both the sources and the samplers were determined using a differential Global Positioning System (Trimble ProXR), which was accurate to within 1 m. More details of this are given in Gilbert *et al.* (manuscript in preparation).

Culturable *Aspergillus fumigatus* and total mesophilic bacteria were collected in parallel using single stage (N6) viable impactor Andersen samplers (Graseby Andersen; [Jones et al 1985]) fitted with an aluminium hemi-cylindrical baffle, described by May (1966) according to the method described by Gilbert and Ward (1999).

A portable weather station (Skye Instruments, Wales) was used to continually log wind speed (every 10 seconds), wind direction (every 10 seconds), air temperature (every 10 minutes), relative humidity (every 30 minutes), atmospheric pressure (every 30 minutes) and solar insolation (every 10 minutes). Weather data were downloaded into a portable computer

at the end of every sampling day and were used to calculate the atmospheric stability class (Pasquille and Smith 1983).

The temperature of the composts or shredded feedstocks was determined at least three discrete points within the mass of material handled on the sampling day using a hand held thermometer with a 1.5 m probe. The moisture content of at least two representative samples was determined by heating the composts in a forced aeration oven at 550 °C for 24 h until a constant mass had been achieved.

Results

Background levels of culturable mesophilic bacteria and *Aspergillus fumigatus* were determined during the study period either upwind of composting site activities, or at the reference sites. The range of measured concentrations is shown in Table 1.

TABLE 1
Range of measured background concentrations

	Concentration of culturable mesophilic bacteria (cfu / m^3)	Concentration of culturable *Aspergillus fumigatus* (cfu / m^3)
Median	48	8
Arithmetic mean	237	17
Minimum	1	0
Maximum	2968	249
n	120	99

Despite numerous attempts, only seven days' worth of sampling (across all sites) yielded sufficient numbers of downwind samples to estimate dispersal. This was due to either precipitation, damage to equipment, changes in site management practices on the day, activities adjacent to the site, or overloading of the nutrient agar plates.

Concentrations were plotted on a semi-logarithmic ($\log_{10}$) scale against the distance from source (Fitt et al 1987; McCartney 1994); an example is shown in Figure 1. The data were used to estimate the source concentration, the decimal reduction distance (D value; the downwind distance required to reduce concentrations by one order of magnitude) and the distance to reach background concentrations (both measured on the day and the medians estimated from samples taken throughout the year; Table 1). Data for culturable mesophilic bacteria and *A. fumigatus* are shown in Table 2 and 3, respectively. Weather data are shown in Table 4.

FIGURE 1 Concentrations of culturable *Aspergillus fumigatus* measured at distances downwind from a 'turning' operation at Site A (sample code A2)

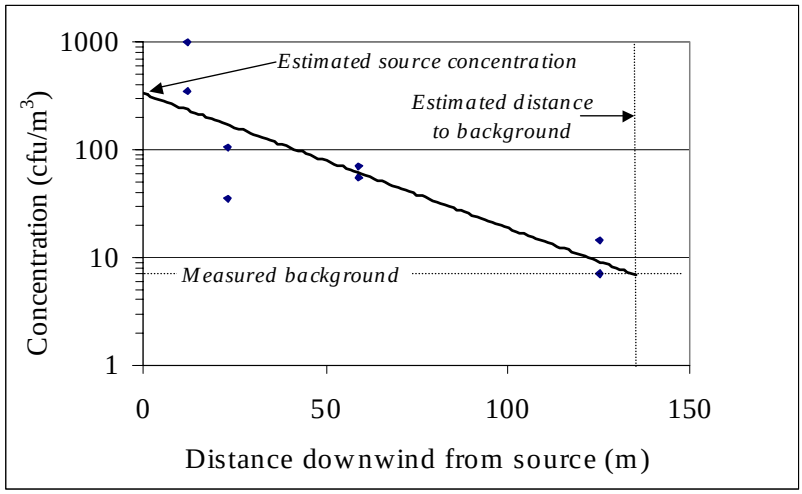


TABLE 2: Modelled dispersal of culturable mesophilic bacteria

Date	Site and code number	Site activity	Estimated source strength (cfu / m^3)	Measured background concentration (cfu / m^3)	D value (m)	Distance to assumed median background of 48 cfu /m^3 (m)	Distance to measured background (m)	Number of down wind sampling locations	Number of down wind samples taken	Regression equation	R^2	Notes
15-Dec-97	A1	Shredding	21,653	61	49	131	126	2	8	y = 21653e-0.0467x	0.91	1
13-Jan-98	A2	Turning	936	23	57	74	92	4	20	y = 935.75e-0.0404x	0.39	
14-Jan-98	A3	Turning	656	45	96	109	112	5	10	y = 656.05e-0.024x	0.68	
14-Jan-98	A4	Shredding	11,749	48	72	171	171	2	6	y = 11749e-0.0321x	0.26	
2-Feb-98	B1	Turning	20,829	1613	84	222	93	4	13	y = 20829e-0.0274x	0.08	2
10-Mar-98	C1	Spreading	6,186	45	48	102	103	4	19	y = 6185.6e-0.0477x	0.65	
10-Aug-98	D1	Harvesting	1,922	150	93	149	103	7	7	y = 1922e-0.0247x	0.05	
11-Aug-98	D2	Harvesting	8,263	97	102	229	198	10	19	y = 8262.8e-0.0225x	0.44	

1 GPS not used to determine distances from source. Temperature of materials determined immediately after shredding

2 Sampling carried out inside bunded area

TABLE 3: Modelled dispersal of *Aspergillus fumigatus*

Date	Site and code number	Site activity	Estimated source strength (cfu / m^3)	Measured background concentration (cfu / m^3)	D value (m)	Distance to assumed median background of 8 cfu /m^3 (m)	Distance to measured background (m)	Number of down wind sampling locations	Number of down wind samples taken	Regression equation	R^2	Notes
13-Jan-98	A2	Turning	9170	8	26	81	81	5	16	9170.1e-0.087x	0.46	
14-Jan-98	A3	Turning	333	7	80	129	134	4	8	332.63e-0.0288x	0.71	
10-Mar-98	C1	Spreading	141	181	43	54	-5	4	16	140.75e-0.0531x	0.83	3

3 High background concentrations due to adjacent farming activities (muck spreading)

TABLE 4
Weather data on sampling days

Date	Site and code number	Atmospheric stability class*	Mean temperature of compost (°C)	Mean moisture content of compost (% m/m)	Mean atmospheric temperature (°C)	Mean wind speed during sampling (m/s)	Solar Insolation**	Atmospheric pressure (mB)
15-Dec-97	A1	A-B	5.2	ND	5.2	1.7	Slight	1030
13-Jan-98	A2	C	49.5	61	6.8	2.5	Slight	980
14-Jan-98	A3	C	49.5	54	ND	4.8	Slight	971
14-Jan-98	A4	D	7.5	65	ND	5.1	Slight	995
2-Feb-98	B1	ND	71.0	59	4.7	ND	ND	ND
10-Mar-98	C1	D	5.7	28	6.4	5.1	Slight	1008
10-Aug-98	D1	A	ND	ND	26.2	1.6	Strong	1011
11-Aug-98	D2	A-B	ND	ND	26.6	2	Strong	998

* A, extremely unstable; B, moderately unstable; C, slightly unstable; D, neutral; E, slightly stable; F, moderately stable
** Strong > 581 W / m^2; medium 291 – 581 W / m^2; Slight <291 W / m^2

Discussion

There are a number of inherent difficulties in sampling bioaerosols outdoors, that are not generally encountered during indoor aerobiological measurements (Lacey et al 1996). For example, wind movements and precipitation can affect sampling characteristics (inlet sampling efficiency and collection efficiency) and may also result in damage to equipment. Combined they mean that sampling is not only time consuming, but costly. For this reason, comprehensive data on bioaerosol concentrations surrounding composting facilities have rarely been reported. During this study extensive sampling was performed over a period of a year; however, dispersal data were only obtained on seven days.

Replicate samples showed considerable variability, especially close to the source when bioaerosol concentrations were high and sampling times short to prevent overloading the nutrient medium agar plates. Similar observations have been made elsewhere (Lembke et al 1981; Wheeler et al 2001; Smid et al 1989). In addition, the effects of vehicular movements and other adjacent activities can emit their own bioaerosols and add to downwind concentrations (Reinthaler et al 1998/99; Wheeler et al 2001). This was noted on a number of occasions due to muck spreading by a nearby farmer (sample C1, which resulted in higher upwind concentrations of *A. fumigatus*), delivery vehicle movements on and off the sites, landfill site operations and movement of hay bales (data not shown).

Fluctuations in bioaerosol plumes (due to changes in wind direction, possible thermal uplift and turbulence) during the sampling period often meant that the Andersen samplers were not located directly in the centre of the plume. Close to the source, separated flow and associated recirculation between windrows may also have affected the ability of the samplers to collect a representative sample of the true concentration of bioaerosol being released.

When turning windrows with a front-end loader, the emitting source was rarely static, and by nature emitted bioaerosols in discrete ‘puffs’, such that the emission rate varied considerably. Additionally, sample durations were not constant, and needed to be changed by more than one order of magnitude dependent on the proximity to the bioaerosol sources, in order to prevent overloading of collection plates by colonies at high concentrations and too few colonies at low concentration to make counting accurate. Shorter readings were likely to show

greater variability, due to the actual variation in concentrations, whilst longer readings tended to average out the variations.

Aerosolisation affects the survival and culturability of viable micro-organisms, which is a function of solar incidence, temperature, relative humidity, particle aggregation size and time (Lighthart and Mohr 1987; Lighthart 1997). Loss of culturability has therefore been cited as a potential problem that may result in under sampling (Wheeler et al 2001). However, as both *A. fumigatus* and actinomycetes produce resistant spores, and thermophilic composting has been shown to select for gram-positive bacteria (Dees and Ghiorse 2001; Ghazifard et al 2001) which are inherently more resistant than gram-negatives, it was assumed that loss of culturability would be negligible during the relatively short dispersal times. A similar assumption has been made elsewhere (Millner et al 1980).

Concentrations of both culturable mesophilic bacteria and *A. fumigatus* downwind of source activities decreased approximately exponentially with distance from the source, and generally attained background levels (measured and estimated from the median sampled throughout the study period) within 200 m of the source activities. The two exceptions to this were samples B1 and D2 (bacteria) and C1 (as noted previously).

The measured background concentrations of mesophilic bacteria at site B1 were, however, high (1613 cfu / m^3) and far greater than the median estimate of 48 cfu / m^3; consequently the estimated distance to this assumed concentration was 222 m. This was probably caused by the high earth bunding surrounding the site, which acted to contain the bioaerosol emissions by impeding airflow through site. In this instance, emissions of bioaerosols from site B could probably have been treated as an area source, rather than a point source as at the other sites.

Wind turbulence is thought to play a key role in the dispersal of airborne micro-organisms (Millner et al 1980; Lighthart and Mohr 1987). Millner *et al*. monitored concentrations of *A. fumigatus* at a sewage sludge composting facility and applied a Pasquill dispersion model to the data. This predicted that background concentrations of *A. fumigatus* would be attained between 500 – 600 metres from the source under unstable (turbulent) conditions, with distances in excess of 1 km under stable conditions. Lighthart and Mohr used a simulated virus (whose properties were derived from two actual viruses) and applied a Gaussian model. Their data suggested that turbulence dramatically affected downwind concentrations, with dilutions of 10^{-4} suggested within 30 m downwind from the source.

Unfortunately downwind monitoring of bioaerosols outside of the perimeter of site B was not possible due to the neighbouring landfill site and farm. An estimate of the effect of this type of structure may have had on long range dispersal was therefore not possible. The high measured background concentrations did, however, suggest that worker exposure would have been greater at site B than at site A, which was surrounded by a chain link fence.

The D values calculated within this study fell within the range 26 – 96 m at sites A, B and C, although higher D values were calculated at site D (93 and 102 m for bacteria), which might have been due to the different source term (mechanical harvesting of crops). It is worth noting that concentrations of *A. fumigatus* were low at site D and not different from background levels, even close to the harvester (data not shown). However, the presence of smuts and rusts was noted on the crops being harvested and it is probable that total airborne concentrations of fungal spores were raised. The detection of fungi other than *A. fumigatus* would have required culturing methods which was beyond the scope of the project.

Similar decreases in concentrations of bioaerosols at composting facilities have been noted elsewhere. For example, Lacey and Williamson (1995) measured a 10-fold reduction in airborne fungi and bacteria 10 – 12 m from a turned pile of compost (D value of approximately 10 m). Beffa et al (1998), however, noted a 100 – 1000-fold decrease in concentrations of *A.*

fumigatus 10 m from a turning machine (D values between 0.1 – 1 m); at 500 m down wind, concentrations of between 0 – 20 cfu / m^3 were measured.

Samples of *A. fumigatus* collected 150 m downwind of composting facilities in Maine, USA, were not above background concentrations, whilst at one site, background concentrations were measured at 90 m downwind (Passman 1983). Measured concentrations of airborne micro-organisms at a number of waste handling and treatment facilities in Austria were reported by Reinthaler et al (1998/99). At one composting site, concentrations of bacteria were greater at 700 m than at 500 and 600 m, which was attributed to vehicle movements. Increased counts in residential areas adjoining the facility were ascribed to neighbouring farms. However, based on the data collected, the authors concluded that significantly lower counts were measured at distances greater than 200 m from the source.

Some studies have, however, suggested that elevated concentrations of bioaerosols occur at greater distances from composting facilities than those observed during this study. For example, Recer et al (2001) measured concentrations of thermophilic actinomycetes and *A. fumigatus* downwind of a yard waste composting facility in New York State, USA, and found significantly increased levels at 500 m.

The D values calculated in this study provided a useful measure of the rate at which bioaerosol concentrations decreased, although they did not, however, provide any indication of the range of applicability of the results, or the mechanisms involved in dispersal. A number of authors have attempted to model dispersal. As noted above, Millner et al (1980) applied a Pasquill dispersal model to measured concentrations of *A. fumigatus* downwind of a sewage sludge composting facility. Danneberg et al (1987) collected bioaerosol samples adjacent to a biofilter and trommel screen and at a single downwind sampling point at 150 m at a composting facility in Germany, then used the data to predict dispersal using a German TA Luft model. The authors concluded that typical background concentrations would be reached at 500 m. Wheeler *et al*. (2001) monitored bioaerosol dispersal from three composting facilities in England. Samples were collected downwind at the facilities using filters held in personal dust samplers designed for use in occupational exposure assessments. The USEPA SCREEN3 model was then used to try and model the data. Emission rates and effective source height were varied to attempt to obtain a fit between the model and measurements, although no satisfactory agreement between model and measurements could be produced. Instead a straight line fit to a semi-log plot of the data was used to estimate the distance to reference concentrations. The reference concentrations used were 1000 cfu / m^3 for total bacteria, 1000 cfu / m_3 for total fungi and 300 cfu / m^3 for gram-negative bacteria. The authors concluded that concentrations generally reached the reference levels within 250 m of the source. They also noted that neither bioaerosol viability nor the presence of aggregates large enough to exhibit non-gaseous behaviour were modelled in SCREEN3. It was suggested that the rate of decline of actual concentrations would be faster than that predicted by SCREEN3.

There are a number of reasons why the use of mathematical models provide uncertain results when used to predict bioaerosol dispersal. Most have been developed to simulate atmospheric transport of particles over medium to long ranges (for example, estimating the release of particles from smoke stacks), with little information available on short range (< 1 km) dispersal. Determining the emission rate (source term) is complex, which stems from the fact that it is often moving and intermittent, and there are no direct methods available at present to measure it directly (most are based on estimates of emission concentrations [Danneberg et al 1997; Millner et al 1980]). Additionally, buoyancy effects caused by the release of hot air into the cooler atmosphere have not yet been accounted for within any reported models. Coupled with the high degree of variability of naturally occurring background concentrations (Jones and Cookson 1983) and the effects of traffic movements and neighbouring bioaerosol sources, such as agricultural activities, the impacts composting facilities have on neighbouring populations

remain uncertain. Measuring the potential for composts to produce bioaerosols (for example, by using a dustiness drum) is an approach that could be tried.

The predicted increase in large-scale composting across the UK over the next decade will result in increasing pressures being placed on the industry to identify new sites for composting facilities. As such, the respective land use planning and waste regulators will require further guidance on suitable 'buffer' distances between site boundaries and neighbours, the ways in which site engineering and system design may mitigate emissions either by containing emissions or enhancing dispersion. These, however, come at a cost, and the respective benefits to both workers and the general public have not been evaluated to date.

In order to address these issues calculations will be performed using the ADMS dispersion model (CERC 1999). This has been widely employed in the UK for regulatory purposes. This model incorporates an up to date understanding of the boundary layer, there are also sub-models available to allow the effects of structures, such as windrows, and concentration fluctuations to be examined. Since estimation of emission rate has proved difficult calculations will be performed to demonstrate the reduction in concentration over distance for unit emissions. A cost-benefit analysis will also be undertaken to assess the benefits to society that the use of various composting systems may provide.

Acknowledgements

The authors wish to thank Chris Ward and Sue Thompsett, Coventry University, for assisting with the sampling and providing technical support throughout the course of the field work; Norfolk Environmental Waste Services Ltd and Erewash Borough Council for allowing access to their composting sites, and HRI Wellesbourne for access to the farm land. This work was supported through the Landfill Tax Credit Scheme by Norfolk Environmental Waste Services Ltd and by a grant from the Health and Safety Executive (Project R52143).

References

Beffa, T., Staib, F., Lott Fischer, J., Lyon, P. F., Gumowski, P., Marfenina, O. E., Dunoyer-Geindre, S., Georgen, F., Roch-Susuki, R., Gallaz, L., Latgé, J.-P. Mycological Control and Surveillance of Biological Waste and Compost Medical Mycology 1998, 36, 137-145.

Browne ML, Ju CL, Recer GM, Kallenbach LR, Melius JM, Horn EG, Prospective Study of Health Symptoms and *Aspergillus fumigatus* Spore Counts Near a Grass and Leaf Composting Facility, Compost Science & Utilization., 2001, 9, 241-249.

Brown JE, Masood D, Couser JI, Patterson R, Hypersensitivity pneumonitis from residential composting: residential composter's lung. Annals of Allergy, Asthma and Immunology, 1995, 74**,** 44-47.

Bunger J, Antlauf-Lammers M, Schulz TG, Health complaints and immunological markers of exposure to bioaerosols among biowaste collectors and compost workers. Occup Environ Med, 2000, 57**,** 458-464.

CERC (1999) ADMS User Guide CERC, Cambridge, UK

Danneberg G, Grueneklee E, Seitz M, Hartung J and Driesel A J Microbial and endotoxin immissions in the neighborhood of a composting plant Annals of Agricultural and Environmental Medicine 1997; 4, 169-173

Dees, P. M., Ghiorse, W. C. Microbial Diversity in Hot Synthetic Compost as Revealed by PCR-Amplified rRNA Sequences from Cultivated Isolates and Extracted DNA. FEMS Microbiology Ecology 2001, 35, 207-216

Dutkiewicz J. Bacteria and fungi in organic dust as potential health hazard. Ann Agric Environ Med, 1997, 4**,** 11-16.

Environment Agency. Agency Position on Composting and Health Effects, Bristol, 2001.

Fitt, B. D. L., Gregory, P. H., Todd, A. D., McCartney, H. A., MacDonald, O. C. Spore Dispersal and Plant Disease Gradients: a Comparison Between Two Empirical Models Journal of Phytopathology 1987, 117, 227-242

Ghazifard, A., Kasra-Kermanshahi, R., Far, Z. E. Identification of Thermophilic and Mesophilic Bacteria and Fungi in Esfahan (Iran) Municipal Solid Waste Compost Waste Management and Research 2001, 19, 257-261

Gilbert, E. J., Ward, C. W. Standardised Protocol for the Sampling and Enumeration of Airborne Micro-organisms at Composting Facilities. 1999. The Composting Association, Coventry

Jones, B. L., Cookson, J. T. Natural Atmospheric Microbial Conditions in a Typical Suburban Area Applied and Environmental Microbiology 1983, 45, 919-934

Jones W, Morring K, Morey P, Sorensen W. Evaluation of the Andersen viable impactor for single stage sampling. Amer. Ind. Hyg. Assoc. J. 1985; 46: 294-298.

Lacey J, Dutkiewicz J . Bioaerosols and occupational lung disease J. Aerosol Sci. 1994, 25, 1371-1404

Lacey, J., Williamson, P. A. M. Airborne Microorganisms Associated with RDF Fines at Castle Bromwich, CWM/110/93, Report to UK Department of the Environment Wastes Technical Division, 1995.

Lacey, J., Williamson, P. A. M., Crook, B. Microbial emissions from composts and associated risks In Aerobiology (Muilenberg, M. and Burge, H., eds.), 1996, 1-17, CRC Press, Boca Raton, Florida

Lembke LL, Kniseley RN, van Nostrand RC, Hale MD. Precision of the all glass impinger and the Andersen microbial sampler for air sampling in solid waste handling facilities. Appl. Env Microbiol. 1981; 42: 222-225.

Lighthart B. The ecology of bacteria in the alfresco atmosphere. FEMS Microbiology Ecology 1997; 23: 263-274.

Lighthart B, Mohr A J. Estimating downwind concentrations of viable airborne microorganisms in dynamic atmospheric conditions. Applied and Environmental Microbiology 1987, 53, 1580-1583

Lundholm M, Rylander R. Occupational symptoms among compost workers. J. Occup.Med 1980; 22: 256-257.

Malmros P. Problems with the working environment in solid waste treatment. The National Labour Inspectorate of Denmark report 1990.

May KR. Multistage liquid impinger. Bacteriol. Rev. 1966; 30: 559-570.

McCartney, H. A. Dispersal of Spores and Pollen from Crops Grana 1994, 33, 76-80

Millner P D, Bassett D A and Marsh P B. Dispersal of *Aspergillus fumigatus* from sewage sludge compost piles subjected to mechanical agitation in open air. Applied and Environmental Microbiology 1980: 39, 1000-1009

Millner, P. D., Olenchock, S. A., Epstein, E., Rylander, R., Haines, J., Walker, J., Ooi, B. L., Horne, E., Maritato, M. Bioaerosols Associated with Composting Facilities Compost Science and Utilization 1994, 2, 6-57

Pasquill F, Smith FB. Atmospheric Diffusion. 3rd Ed. 1983: Ellis Horwood, Chichester

Passman, F. J. Recovery of *Aspergillus fumigatus* Aerospora from Municipal Sewage Sludge Composting Operations in the State of Maine Mycopathologia 1983, 83, 41-51

Recer GM., Browne ML, Horn E., Hill K., Boehler W. Ambient air levels of *Aspergillus fumigatus* and thermophilic actinomycetes in a residential neighbourhood near a yard waste composting facility. Aerobiologia, 2001, 17**,** 99 - 108.

Reinthaler, F. F., Haas, D., Feierl, G., Schlacher, R., Pichler-Semmelrock, F. P., Köck, M., Wüst, G., Feenstra, O., Marth, E. Comparative Investigations of Airborne Culturable Microorganisms in Selected Waste Treatment Facilities and in Neighbouring Residential Areas Zentralblatt für Hygiene und Umweltmedizin 1998/99, 202, 1 – 17

Slater RA, Frederickson J, Gilbert EJ. The State of Composting 1999. Composting Association, Wellingborough, 2001.

Smid T, Scokkin E, Boleij JSM, Heederik D. Enumeration of viable fungi in occupational environments; a comparison of samplers and media. Amer. Ind. Hyg. Assoc. J. 1989; 50: 235-239.

Swan JRM, Crook B, Gilbert EJ. Microbial emissions from composting sites. In: Issues in Env. Sci & Tech. R Harrison, ed. 2002: Royal Soc. Chemistry, Cambridge.

Weber S, Kullman G, Petsonk E, Jones WG, Olenchock S, Sorenson W, Parker J, Marcelo-Baciu R, Frazer D, Castranova V. Organic dust exposure from compost handling: case presentation and respiratory exposure assessment. Am. J. Ind. Med. 1993, 24, 365-374.

Wheeler PA., Stewart I, Dumitrean P, Donovan B. Health effects of composting. - A Study of Three Compost Sites and Review of Past Data Environment Agency R&D Technical Report P1-315/TR, 2001, Environment Agency, Bristol

14 REFERENCES

ACGIH. Bioaerosols; Assessment and Control. ACGIH Press, Cincinnatti 1999.

Allmers H., Huber H, Baur X. Two year follow-up of a garbage collector with allergic bronchopulmonary aspergillosis (ABPA). American Journal of Industrial Medicine, 2000, 37**,** 438 - 442.

Beaumont F, Kauffman HF, Sluiter HJ, DeVries K. Sequential sampling of fungal air spores inside and outside the homes of mould sensitive, asthmatic patients. Ann. Allergy 1985; 55: 740-746.

Beffa, T., Blanc, M., Lyon, P.-F., Voght, G., Marchiani, M., Lott Fischer, J., Aragno, M. Isolation of Thermus Strains from Hot Composts (60 to 80 ºC), Applied and Environmental Microbiology 1996, 62, 1723-1727.

Beffa, T., Staib, F., Lott Fischer, J., Lyon, P. F., Gumowski, P., Marfenina, O. E., Dunoyer-Geindre, S., Georgen, F., Roch-Susuki, R., Gallaz, L., Latgé, J.-P. Mycological Control and Surveillance of Biological Waste and Compost Medical Mycology 1998, 36, 137-145.

Blainey AD, Topping MD, Ollier S, Davies RJ. Allergic respiratory disease in grain workers: the role of storage mites. J Allergy Clin Immunol, 1989, 84, 296-303.

Blanc, M., Marilley, L., Beffa, T., Aragno, M Thermophilic Bacterial Communities in Hot Composts as Revealed by Most Probable Number Counts and Molecular (16 S rDNA) Methods. FEMS Microbiology Ecology 1999, 28, 141-149.

Blomquist G. Sampling of biological particles. Analyst 1994, 119, 53-56.

Bovallius A, Bucht B, Roffey R, Anas A. Three-year investigation of the natural airborne bacterial flora at four localities in Sweden. Appl. Environ. Microbiol 1978, 35, 847-852.

Breum N O, Nielsen B H, Nielsen E M Midtgaard U and Poulsen O M Dustiness of compostable waste: a methodological approach to quantify the potential of waste to generate airborne micro-organisms and endotoxin. Waste Management & Research 1997; 15, 169-187

Browne ML, Ju CL, Recer GM, Kallenbach LR, Melius JM, Horn EG, Prospective Study of Health Symptoms and *Aspergillus fumigatus* Spore Counts Near a Grass and Leaf Composting Facility, Compost Science & Utilization., 2001, 9, 241-249.

Brown JE, Masood D, Couser JI, Patterson R, Hypersensitivity pneumonitis from residential composting: residential composter's lung. Annals of Allergy, Asthma and Immunology, 1995, 74**,** 44-47.

Bunger J, Antlauf-Lammers M, Schulz TG, Health complaints and immunological markers of exposure to bioaerosols among biowaste collectors and compost workers. Occup Environ Med, 2000, 57**,** 458-464.

Carpenter-Boggs, L., Kennedy, A. C., Reganold, J. P. Use of Phospholipid Fatty Acids and Carbon Source Utilization Patterns to Track Microbial Community Succession in Developing Compost Applied and Environmental Microbiology 1998, 64, 4062-4064.

CEN (1999) Soil Improvers and Growing Media – Guidelines for the Safety of Users, the Environment and Plants PD CR 13455 : 1999.

CERC (1999) ADMS User Guide CERC, Cambridge, UK

Chan-Yeung M, Enarson DA, Kennedy SM. The impact of grain dust on respiratory health. Am. Rev. Respir. Dis. 1992, 145, 476-87.

Chaumont JP, Berrard N, Simeray J, Leger D.Fungal spores in the atmosphere at Besancon, France: seasonal and annual variations during 1988 and 1989 Ann Pharm Fr 1990; 48:136-44

Clapp WD, Becker S, Quay J, Watt JL, Thorne PS, Frees KL, Zhang X, Koren HS, Lux CR, Schwartz DA. Grain dust-induced airflow obstruction and inflammation of the lower respiratory tract. Am. J. Resp. Crit Care Med. 1994, 150, 611-7.

Cobb N, Sullivan P, Etzel R. Pilot study of health complaints associated with commercial processing of mushroom compost in Southeastern Pennsylvania. Journal of Agromedicine, 1995, 2**,** 12-25.

Conrad DJ, Warnock M, Blanc P, Cowan M, Golden JA, Microgranulomatous aspergillosis after shoveling wood chips: report of a fatal outcome in a patient with chronic granulomatous disease. American Journal of Industrial Medicine, 1992, 22**,** 411-418.

Crook B. Aerobiological investigation of occupational respiratory allergy in agriculture in the UK. Grana 1994, 33, 81-4.

Crook B. Chapter 9 - Inertial samplers: biological perspectives. In: Cox CS and Wathes CM, eds. Bioaerosols Handbook. 1995(a) CRC/Lewis Publ., Boca Raton, USA; 247-267.

Crook B. Chapter 10 - Non-inertial samplers: biological perspectives. In: Cox CS and Wathes CM, eds. Bioaerosols Handbook. 1995 CRC/Lewis Publ., Boca Raton, USA; 269-283.

Crook B, Olenchock SA. Chapter 19 - Industrial Workplaces. In: Cox CS and Wathes CM , eds. Bioaerosols Handbook. 1995 CRC/Lewis Publ., Boca Raton, USA; 531-545.

Crook B, Lacey J. Airborne allergenic micro-organisms associated with mushroom cultivation. Grana 1991; 30: 446-449.

Crook B, Swan JRM. Bacteria and other bioaerosols in industrial workplaces. In: Micro-organisms in Home and Indoor Work Environments; Diversity, Health Impacts, Investigation and Control. Flannigan B, Samson RA, Miller JD (Editors) 2001; Harwood Publ. Harwood Publ. 69-82

Curtis L, Ross M, Chung J, Scheff P, Persky V, Wadden R, Ramakrishnan V, Hryhorczuk D. Characterisation of bioaerosol emissions from a suburban yard waste composting facility. In: Bioaerosols, fungi and mycotoxins: health effects, assessment, prevention and control. Ed. Johanning E. 1999, Eastern NY Occup. Env Health Centre Publ. New York., 254-257.

Danneberg G, Grueneklee E, Seitz M, Hartung J and Driesel A J Microbial and endotoxin immissions in the neighborhood of a composting plant Annals of Agricultural and Environmental Medicine 1997; 4, 169-173

Darke CS, Knowelden J, Lacey J, Milford-Ward A. Respiratory disease of workers harvesting grain. Thorax 1976, 31, 294-302.

Darragh A, Buchan RM, Sandfort D, Coleman R.. Quantification of air contaminants at a municipal sewage sludge composting facility. Appl. Occup. Environ. Hyg, 1997, 12**,** 190 - 194.

DECOS Dutch Expert Committee on Occupational Standards. 1998, Gezondheidsraad.

Dees, P. M., Ghiorse, W. C. Microbial Diversity in Hot Synthetic Compost as Revealed by PCR-Amplified rRNA Sequences from Cultivated Isolates and Extracted DNA. FEMS Microbiology Ecology 2001, 35, 207-216

Deportes I, Zmirou D, Benoit-Guyod J-L Modelling composting plant dust exposure in a neighbouring population. Annals of Agricultural and Environmental Medicine 1997; 4: 175-176

Douwes J, Wouters I, Dubbeld H, Upper airway inflammation assessed by nasal lavage in compost workers: A relation with bio-aerosol exposure. American Journal of Industrial Medicine, 2000, 37**,** 459-468.

Douwes J, Dubbeld H, van Zwieten L, Wouters I, Doekes G, Heederik D. Work related acute and subchronic airways inflammation assessed by nasal lavage in compost workers. Ann. Agric. Environ. Med. 1997, 4, 149-151.

Douwes J, Heederik D. Int. J. Occ. Environ. Health 1997, 3, S37-S41.

Dowd S E, Gerba C P, Pepper I L and Pillai S D Bioaerosol transport modeling and risk assessment in relation to biosolid placement. Journal of Environmental Quality 2000; 29, 343-348

Droffner, M. L., Brinton Jr., W. F., Evans, E. Evidence for the Prominence of Well Characterized Mesophilic Bacteria in Thermophillic (50-70oC) Composting Environments. Biomass and Bioenergy 1995, 8, 191-195

Dutkiewicz J. Bacteria and fungi in organic dust as potential health hazard. Ann Agric Environ Med, 1997, 4**,** 11-16.

Dutkiewicz J. Studies on endotoxin of Erwinia herbicola and their biological activity. Zbl. Bak. I. Abt. Orig. 1976, 236, 487-508.

Dutkiewicz J Bacteria in farming environment. Eur. J. Resp. Dis. 1987, 71, 71-88

Dutkiewicz J Bacteria and fungi in organic dust as a potential health hazard. Ann Agric Environ Med 1997 4, 6-11.

Dutkiewicz J, Kus L, Dutkiewicz E, Warren CPW. Hypersensitivity pneumonitis in grain farmers due to sensitization to Erwinia herbicola. Ann Allergy 1985, 54, 65-68.

Dutkiewicz J, Olenchock SA, Sorenson WG, Gerencser VF, May JJ, Pratt DS, Robinson VA. Levels of bacteria, fungi, and endotoxin in bulk and aerosolised corn silage. Appl Environ Microbiol 1989, 55,

Eduard W Exposure to non-infectious microorganisms and endotoxins in agriculture Ann Agric Environ 1997, 4., 179-186

Eitzer B. Emissions of volatile organic chemicals from municipal solid waste composting facilities. Environ Sci Technol, 1995, 29**,** 896 - 902.

Epstein E., Epstein J.I. Biocycle 1989, 30, 50-53.

Epstein E., Wu N, Youngberg C., Croteau G. Dust and Bioaerosols at a Biosolids Composting Facility. Compost Science and Utilisation, 2001, 9, 250 - 255.

Farmer SG. A comparison of methods of estimating stability category and boundary layer depth using routine surface observations. Met. Office Internal report SITN37, 1984. Met Office, Bracknell UK.

Fink JN. Hypersensitivity pneumonitis J Allergy Clin Immunol 1973, 52, 309-17

Finstein M.S., Miller F.C. Composting of Agricultural and other Wastes. 1985, Elsevier Applied Science, Barking UK. 13-26.

Fischer J L, Beffa T, Lyon P-F and Aragno M. *Aspergillus fumigatus* in windrow composting: effect of turning frequency. Waste Management & Research 1998; 16, 320-329

Fischer G., Ostrowski R., Dott W. Airborne fungi and their secondary metabolites in working places in a compost facility. Mycoses, 1998, 41**,** 383 - 388.

Fischer G., Ostrowski R., Dott W. Mycotoxins of Aspergillus fumigatus in pure culture and in native bioaerosols from compost facilities. Chemosphere, 1999, 38**,** 1745 1755.

Fischer G., Moller M., Ostrowski R., Dott W. Species-specific production of microbial volatile organic compounds (MVOC) by airborne fungi from a compost facility. Chemosphere, 1999, 39**,** 795 - 810.

Fitt, B. D. L., Gregory, P. H., Todd, A. D., McCartney, H. A., MacDonald, O. C. Spore Dispersal and Plant Disease Gradients: a Comparison Between Two Empirical Models Journal of Phytopathology 1987, 117, 227-242

Flannigan B, McCabe EM, McGarry F. Allergenic and toxigenic micro-organisms in houses. J. Applied Bacteriol. 1991; 70: 61s – 73s

Fogelmark D, Rylander R. Pulmonary inflammation induced by repeated inhalations of (1-3)β-D-glucans and endotoxin Int.J. Exp. Pathol. 1994, 74, 85-90.

Folmsbee M, Strevett KA. Bioaerosol concentration at an outdoor composting center. J. Air and Waste Management Association, 1999, 49**,** 554 - 561.

Ganio L M, Mohr A J and Lighthart B. A comparison between computer modelled bioaerosol dispersion and a bioaerosol field spray event. Aerobiologia 1995; 11, 183-188

Ghazifard, A., Kasra-Kermanshahi, R., Far, Z. E. Identification of Thermophilic and Mesophilic Bacteria and Fungi in Esfahan (Iran) Municipal Solid Waste Compost Waste Management and Research 2001, 19, 257-261

Gilbert, E. J., Ward, C. W. Standardised Protocol for the Sampling and Enumeration of Airborne Micro-organisms at Composting Facilities. 1999. The Composting Association, Coventry.

Gilbert, E. J., Riggle, D., S., Holland, F. D. Large-Scale Composting - A Practical Manual for the UK 2001; The Composting Association, Wellingborough, UK

González-Vila, F. J., Almendros, G., Madrid, F Molecular Alterations of Organic Fractions from Urban Waste in the Course of Composting and their Further Transformation in Amended Soil. The Science of the Total Environment 1999, 236, 215-229

Goodley JM, Clayton YM, Hay RJ Environmental sampling for aspergilli during building construction on a hospital site. J Hosp Infect 1994;26:27-35

Gravesen S., Frisvad J.C., Samson R.A. Microfungi, 1994, Munksgaard, Copenhagen.

Grundy, A.C., Green, J.M. and Lennartsson, M. (1988). The Effect of Temperature on the Viability of Weed Seeds in Compost. Compost Science and Utilisation 6 (3), 26-33.

Haas DU, Reinthaler FF, Wust G, Skofitsch G, Degenkolb T, Schumann P, Marth E. Emission of thermophilic actinomycetes in composting facilities, their immediate surroundings and in an urban area. Centr. Eur. J. Publ. Health 1999; 2: 94-99.

Haug, R. T. The Practical Handbook of Compost Engineering, 1993, Lewis, Boca Raton, Florida

Heida H, Van der Zee S, Occupational exposure and indoor air quality monitoring in a composting facility. American Industrial Hygiene Association, 1995, 56**,** 39 - 43.

Heisler, G. M., Dewalle, D. R. Effects of Windbreak Structure on Wind Flow Agriculture, Ecosystems and Environment 1988, 22/23, 41-69

Heldal K, Eduard W, Bergum M. Bioaerosol exposure during handling of source separated household waste. Ann Agric Environ Med, 1997, 4**,** 45 - 51.

Hellmann, B., Zelles, L., Palojärvi, A., Bai, Q. Emission of Climate-Relevant Trace Gases and Succession of Microbial Communities during Open Windrow Composting Applied and Environmental Microbiology 1997, 63, 1011-1018

Herrmann, R. F., Shann, J. F. Microbial Community Changes During the Composting of Municipal Solid Waste. Microbial Ecology 1997, 33, 78-85

Hofman R, Bohm R, Danneberg G, Gerbi-rieger S, Gottlich E, Koch A, Kuhner M, Kummer V, Leibl K, Martens W, Missel T, , Neef A PU, Rabe R, Schilling B, Tilkes F, Wieser P. Schriftenr. Ver Wasser Boden Lufthyg. 1999, 104, 1 - 80.

Holben WE. Isolation and purification of bacterial community DNA from environmental samples. In: Manual of Environmental Microbiology, eds Hurst CJ, Knudsen GR, McInerney MJ, Stetzenbach LD, Walter MV. Amer. Soc. Microbiol. Press, Washington, 431- 436.

Hryhorczuk D, Curtis L, Keys N, Chung J, Rizzo M, Lewis C. Environmental characterization of bioaerosol emissions from the dk recycling systems, inc composting facility in lake forest Illinois. Illinois: Occupational Health Service Institute, 1996: 1 - 94.

Hryhorczuk D. , Scheff P., Chung J., Rizzo M., Lewis C., Keys N., Moomey M. Bioaerosol emissions from a suburban yard waste composting facility. Ann Agric Environ Med, 2001, 8**,** 177 - 185.

HSE. Guidance MDHS 81, Dustiness of powders and materials, HSE Books 1996

HSL Health and Safety Laboratory. 1999 Swan, JRM, Unpublished data.

Hunter CA, Lea RG. The airborne fungal population of representaive British homes. In: Air Quality Monographs Vol 2; Health Implications of Fungi in Indoor Environments. Samson RA,, Flannigan B, Flannigan ME, Verhoeff AP, Adan BCG, Hoeckstra ES. 1994; Elsevier New York; 141 - 153.

Ivens U, Hansen J., Breum N.O., Ebbehoj N., Nielsen M., Poulsen O, Wurtz H., Skov T. Diarrhoea among waste collectors associated with bioaerosol exposure. Ann Agric Environ Med, 1997, 4**,** 63 - 68.

Ivens U, Ebbehoj N, Poulsen O, Skov T. Gastro intestinal symptoms among waste recycling workers. Ann Agric Environ Med, 1997, 4**,** 153 - 157.

Ivens U, Breum N.O., Ebbehoj N., Nielsen B.H., Poulsen O., Wurtz H. Exposure-response relationship between gastrointestinal problems among waste collectors and bioaerosol exposure. Scand. J. Work Environ. Health 1999, 25**,** 238-245.

Jacobs RR, Heederik D, Douwes J, Zähringer U. Endotoxin structure Int. J. Occ. Environ. Health. 1997, 3, S6-S7.

Johansson, C., Kron, E., Svensson, S-E. Compost Quality and Potential for Use. AFR Report 154, Swedish Environmental Protection Agency 1997.

Jones, B. L., Cookson, J. T. Natural Atmospheric Microbial Conditions in a Typical Suburban Area Applied and Environmental Microbiology 1983, 45, 919-934

Jones JR, Hodgson JT, Clegg TA, Elliott RC. Self reported work related illness in 1995; results from a household survey. HSE Books, 1998.

Jones JR, Huxtable CS, Hodgson JT. Self reported work related illness in 1998/99; results from EUROSTAT ill health module in the 1999 Labour Force Survey summer quarter. HSE Books, 2001.

Kateman E., Heederik D., Pal T.M., Smeets M., Smid T., Spitteler M.. Relationship of airborne microorganisms with the lung function and leucocyte levels of workers with a history of humidifier fever. Scand. J. Work Environ. Health 1990, 16, 428-433

Kleyn JG, Johnson WM, Wetzler TF.. Microbial aerosols and actinomycetes in aetiological considerations of mushroom workers lungs. Applied and Envir. Microbiol 1981; 41**,** 1454 - 1460.

Kleyn, J. G., Wetzler, T. F. The Microbiology of Spent Mushroom Compost and its Dust. Canadian Journal of Microbiology 1981, 27, 748-753

Kock M, Schlacher R, Pichler-Semmelrock FP, Reinthaler FF, Eibel U, Marth E, Friedl H. Air-borne microorganisms in the metropolitan area of Graz, Austria. Cent Eur J Public Health 1998;6: 25-8

Kondrój, J., van Elsas, J. D. Structural Diversity of Microorganisms in Chemically Perturbed Soil Assessed by Molecular and Cytochemical Approaches Journal of Microbiological Methods 2001, 43, 197-212

Kothary M., Chase T, Macmillan J. Levels of *Aspergillus fumigatus* in air and in compost at a sewage sludge composting site. Environmental Pollution, 1984, 34**,** 1 - 14.

Lacey J, Actinomycetes in Composts. Ann Agric Environ Med, 1997, 4**,** 113 - 121.

Lacey J The microflora of grain dusts In**:** Dosman JA, Cotton DJ :Occupational pulmonary disease: focus on grain dust and health, 1980, 189-200.

Lacey J. Grain dust and health Postharvest. News. and. Information. 1990, 1, 113-7.

Lacey J. Airborne agents of occupational lung disease and their detection Ann Agric Environ Med 1995, 2, 31-35.

Lacey J, Crook B. Fungal and actinomycete spores as pollutants of the workplace and occupational allergens Ann Occup Hyg 1988, 32, 513-533.

Lacey J., Dukiewicz J. Isolation of actinomycetes and fungi from mouldy hay using a sedimentation chamber. J. Appl. Bacteriol. 1976; 41: 315-319.

Lacey J, Dutkiewicz J . Bioaerosols and occupational lung disease J. Aerosol Sci. 1994, 25, 1371-1404

Lacey, J., Williamson, P. A. M. Airborne Microorganisms Associated with RDF Fines at Castle Bromwich, CWM/110/93, Report to UK Department of the Environment Wastes Technical Division, 1995.

Lacey, J., Williamson, P. A. M., Crook, B. Microbial emissions from composts and associated risks In Aerobiology (Muilenberg, M. and Burge, H., eds.), 1996, 1-17, CRC Press, Boca Raton, Florida

Lavoie J, Alie R. Determining the characteristics to be considered from a worker health and safety standpoint in household waste sorting and composting plants. Ann Agric Environ Med, 1997, 4**,** 123 - 128.

Leenders A, Behrendt M, Luijendijk A, Verbrough H, Density and molecular epidemiology of Aspergillus in air and relationship to outbreaks of Aspergillus infection. Journal of Clinical Microbiolgy, 1999, 1752 - 1757.

Liesivuori J, Kotimaa M, Laitinen S, Louhelainen K, Ponni J, Sarantila R, Husman K. Airborne endotoxin concentrations in different work conditions. Am. J. Ind. Med. 1994 25, 123-4,

Lighthart B, Mohr A J. Estimating downwind concentrations of viable airborne microorganisms in dynamic atmospheric conditions. Applied and Environmental Microbiology 1987, 53, 1580-1583

Lighthart, B. The Ecology of Bacteria in the Alfresco Atmosphere FEMS Microbiology Ecology 1997, 23, 263-274

Lynch, J. M. In Science and Engineering of Composting: Design, Environmental, Microbiological and Utilization Aspects (Hoitink, H. A. J. and Keener, H. M., eds.), 1993, 24-35, Renaissance Publications, Worthington, Ohio.

Marchand G, Lavoie J, Lazure L. Evaluation of bioaerosols in a municipal solid waste recycling and composting plant. Air and Waste Management Association, 1995, 45**,** 778 - 781

Maricou H., Verstraete W, Mesuere K. Hygienic aspects of biowaste composting; airborne microbial concentrations as a function of feedstock, operation and season. Waste Management Res, 1998, 16:4**,** 304 - 311.

Marth E., Reinthaler F.F., Schaffler K., Jelovcan S., Haselbacher S., Eibel U., Kleinhappl B. Occupational health risks to employees of waste treatment facilities. Ann. Agric. Env. Med. 1997, 4, 143-148.

Maule A. Survival of verocytotoxigenic Escherichia coli O157 in soil, water and on surfaces. Symp Ser Soc Appl Microbiol 2000; 29:71S-78S

McCartney, H. A. In: Species Dispersal in Agricultural Habitats (Bunce, R. G. H. and Howard, D. C., eds.), 1990, Belhaven Press, London

McCartney, H. A. Dispersal of Spores and Pollen from Crops Grana 1994, 33, 76-80

Michel O, Duchateau J, Sergysels R. Effect of inhaled endotoxin on bronchial reactivity in asthmatic and normal subjects. J. Appl. Physiology 1989; 66: 1059-64.

Michel O, Gianni R, Duchateau J, Vertongen F, Le Bon B, Sergysels R. Domestic endotoxin exposure and clinical severity of asthma Clin. Exp. Allerg. 1991, 21, 441-448.

Michel O, Gianni R, Le Bon B, Content J, Duchateau J, Sergysels R. Inflammatory response to acute inhalation of endotoxin in asthmatic patients Am. Rev. Resp. Dis. 1992, 146, 352-357

Michel O, Gianni R, Le Bon B, Content J, Duchateau J, Sergysels R. Dose-response relationship to inhaled endotoxin in normal subjects. Am. J. Resp. Crit. Care Med. 1997, 145, 1157-1164

Miller, F. C. In Microbiology of Solid Waste (Palmisano, A. C. and Barlaz, M. A., eds.), 1996, 115-154, CRC Press, Boca Raton

Millner P D, Bassett D A and Marsh P B. Dispersal of *Aspergillus fumigatus* from sewage sludge compost piles subjected to mechanical agitation in open air. Applied and Environmental Microbiology 1980: 39, 1000-1009

Millner, P. D., Marsh, P. B., Snowden, R. B., Parr, J. F Occurrence of *Aspergillus fumigatus* During Composting of Sewage Sludge Applied and Environmental Microbiology 1977, 34, 765-772

Millner, P. D., Olenchock, S. A., Epstein, E., Rylander, R., Haines, J., Walker, J., Ooi, B. L., Horne, E., Maritato, M. Bioaerosols Associated with Composting Facilities Compost Science and Utilization 1994, 2, 6-57

Milton DK, Amsel J, Reed CE, Enright PL, Brown LR, Aughenbaugh GL, Morey PR. Cross-Sectional Follow-Up of a Flu-Like Respiratory Illness among Fiberglass Manufacturing Employees:Endotoxin Exposure Associated with Two Distinct Sequelae Amer. J.Ind. Med. 1995, 28, 469-488.

Meyer JD, Holt DL, Chen Y, Cherry NM, McDonald JC. SWORD '99; surveillance of work-related and occupational respiratory disease in the UK. Occup. Med. 2001; 51: 204- 208.

Mouilleseaux A, Squinazi F. Airborne fungi in several indoor environments. In: Air Quality Monographs Vol 2; Health Implications of Fungi in Indoor Environments. Samson RA,, Flannigan B, Flannigan ME, Verhoeff AP, Adan BCG, Hoeckstra ES. 1994; Elsevier New York 155-162.

Mullins J. Micro-organisms in outdoor air. In: Micro-organisms in Home and Indoor Work Environments; Diversity, Health Impacts, Investigation and Control. Flannigan B, Samson RA, Miller JD (Editors) Harwood Publ. Harwood Publ. 3-16.

Mullins J, Hutcheson P, Slavin RG. *Aspergillus fumigatus* spore concentrations in outside air: Cardiff and St Louis compared. Clin Allergy 1984; 14: 351-354.

Neef A., Albrecht A., Tilkes F., Harpel S., Herr C., Liebl K., Eikmann T., Kampfer P. Measuring the spread of airborne microorganisms in the area of composting sites. Schriftenr. Ver Wasser Boden Lufthyg. 1999, 104, 655-664.

Nielsen B H, Würtz H, Breum N O, Poulsen O M. Microorganisms and endotoxin in experimentally generated bioaerosols from composting household waste. Annals of Agricultural and Environmental Medicine 1997; 4, 159-168

Nevalainen A, Hyvarinen A, Pasanen AL, Reponen T. Fungi and bacteria in normal and mouldy buildings. In: Air Quality Monographs Vol 2; Health Implications of Fungi in Indoor Environments. Samson RA,, Flannigan B, Flannigan ME, Verhoeff AP, Adan BCG, Hoeckstra ES. 1994; Elsevier New York 163-168.

NRAES . On-farm Composting Handbook. NRAES, New York 1992

Ogden LD, Fenlon DR, Vinten AJ, Lewis D. The fate of Escherichia coli O157 in soil and its potential to contaminate drinking water. Int J Food Microbiol 2001;66:111-7

Ogram A, Feng X. Methods of soil microbial community analysis In: Manual of Environmental Microbiology, eds Hurst CJ, Knudsen GR, McInerney MJ, Stetzenbach LD, Walter MV. Amer. Soc. Microbiol. Press, Washington, 422- 430.

Olenchock SA, Christiani DC, Mull JC, Ye TT, Lu PL . Airborne endotoxin concentrations in various work areas within two cotton textile mills in the People's Republic of China. Biomed Environ Sci. 1990, 3, 443-451.

Otten L, Voroney R, Winter J, Andrews S, Lee H, Trevors J, Health effects of composting. Oxfordshire: A E A Technology, 1999: 1 - 109.

Palchak RB, Cohen R, Ainslie M, LaxHoerner C. Airborne endotoxin associated with industrial-scale production of protein products in gram-negative bacteria. Am. Ind. Hyg. Assoc. J. 1988, 8, 420-1.

Parvaneh S, Johansson E, Elfman LH, van Hage-Hamsten M. An ELISA for recombinant Lepidoglyphus destructor, Lep d 2, and the monitoring of exposure to dust mite allergens in farming households. Clin Exp Allergy 2002;32: 80-6

Pasquill F. The estimation of the dispersion of windborne material. Meteorological Magazine 1961; 90, 33-49

Pasquill F, Smith FB. Atmospheric Diffusion. 3rd Ed. 1983: Ellis Horwood, Chichester

Passman, F. J. Recovery of *Aspergillus fumigatus* Aerospora from Municipal Sewage Sludge Composting Operations in the State of Maine Mycopathologia 1983, 83, 41-51

Peters, S., Koschinsky, S., Schweiger, F., Tebbe, C. C. Succession of Microbial Communities during Hot Composting as Detected by PCR-Single-Strand-Conformation Polymorphism-Based Genetic Profiles of Small-Subunit rRNA Genes Applied and Environmental Microbiology 2000, 66, 930-936

Rainer J, Peintner U, Poder R. Biodiversity and concentration of airborne fungi in a hospital environment. Mycopathologia 2001;149: 87-97

Recer GM., Browne ML, Horn E., Hill K., Boehler W. Ambient air levels of *Aspergillus fumigatus* and thermophilic actinomycetes in a residential neighbourhood near a yard waste composting facility. Aerobiologia, 2001, 17**,** 99 - 108.

Reinthaler, F. F., Haas, D., Feierl, G., Schlacher, R., Pichler-Semmelrock, F. P., Köck, M., Wüst, G., Feenstra, O., Marth, E. Comparative Investigations of Airborne Culturable Microorganisms in Selected Waste Treatment Facilities and in Neighbouring Residential Areas Zentralblatt für Hygiene und Umweltmedizin 1998/99, 202, 1 – 17

Roepstorff V, Sigsgaard T. Cytotoxic effect of organic dust extracts from different working environments; an in vitro assay. Ann Agric Environ Med, 1997, 4**,** 195 - 201.

Roepstorff V, Sigsgaard T. The cytotoxic potential of household waste during composting. Waste Management and Research, 1997, 15**,** 189 - 196.

Rylander R. Organic Dusts and Lung Disease: The Role of Inflammation Ann. Agric. Environ. Med.1994, 1, 7-10.

Rylander R. Evaluations of the risks in endotoxin exposures Int. J. Occ. Environ. Health. 1997, 3, S32-S36.

Rylander R, Bake B, Fischer JJ, Helander IM. Pulmonary function and symptoms after inhalation of endotoxin Am. Rev. Resp. Dis. 1989, 140, 981-986.

Schilling B, Heller D, Graulich Y, Gottlich E. Determining the emission of microorganisms from biofilters and emission concentrations at the site of composting areas. Schriftenr Ver Wasser Boden Lufthyg. 1999, 104:685-70.

Semple, K. T., Reid, B. J., Fermor, T. R. Impact of composting strategies on the treatment of soils contaminated with organic pollutants. Environmental Pollution 2001, 112, 269-283

Shelton BG, Kirkland KH, Flanders WD, Morris GK. Profiles of airborne fungi in buildings and outdoor environments in the United States. Appl. Env. Microbiol. 2002; 68: 1743-1753.

Sidhu, J., Gibbs, R. A., Ho, G. E., Unkovich, I. The Role of Indiginous Microorganisms in Suppression of Salmonella Regrowth in Composted Biosolids Water Research 2001, 35, 913-920

Sigsgaard T, Malmros P, Nersting L, Pedersen C. Work related symptoms and lung function among Danish refuse workers. Am. Rev. Respir. Dis. 1994, 149, 1407-1412.

Sigsgaard T, Hansen JC, Malmros P. Biomonitoring and work related symptoms among garbage handling workers Ann. Agric. Environ. Med. 1997, 4, 107-112.

Simpson JCG, Niven RMcl, Pickering CAC, Oldham LA, Fletcher AM, Francis HC. Comparative Personal Exposures to organic dusts and endotoxin Ann Occ Hyg 1999, 43,107-115.

Slater RA, Frederickson J, Gilbert EJ. The State of Composting 1999. Composting Association, Wellingborough, 2001.

Stentiford E. Composting Control: Principles and Practice. In: Bertoldi M, Sequi P, Lemmes B, Papi T, eds. The Science of Composting. Blackie Acad. Publ., London.1996.

Streifel AJ, Lauer JL, Vesley D, Juni B, Rhame FS *Aspergillus fumigatus* and other thermotolerant fungi generated by hospital building demolition.Appl Environ Microbiol 1983;46:375-8

Strom, P. F. Effect of Temperature on Bacterial Species Diversity in Thermophilic Solid-Waste Composting, Applied and Environmental Microbiology 1985, 50, 899-905

Strom, P. F. Identification of Thermophilic Bacteria in Solid-Waste Composting Applied and Environmental Microbiology 1985, 50, 906-913

Stutzenberger, F. J., Kaufman, A. J., Lossin, R. D. Cellulolytic Activity in Municipal Solid Waste Composting Canadian Journal of Microbiology 1969, 16, 553-560

Swan JRM, Crook B. Airborne microorganisms associated with grain handling. Annals of Agricultural and Environmental Medicine 1998, 5, 7-15.

Syzdek L. , Haynes JH. Monitoring *Aspergillus fumigatus* aerosols from a composting facility. Aerobiologia, 1995, 11**,** 87 - 93.

Thorn PS, Rylander R, Airways inflammation and glucan in a rowhouse area Am. J. Resp. Crit. Care. Med. 1998, 157, 1798-1803

Thorpe A., Gould JR, Brown RC, Crook B. Investigation of the performance of agricultural vehicle cab filtration systems against grain dust. J. Agric. Eng. Research: 1997; 66; 135-149.

Tolvalen O, Veijanen A, Villberg K. Occupational hygiene in biowaste composting. Waste Management and Research, 1998, 16**,** 525 - 540.

Tuomela, M., Vikman, M., Hatakka, A., Itävaara, M. Biodegradation of Lignin in a Compost Environment: A Review Bioresource Technology 2000, 72, 169-183

USEPA. SCREEN3 Model User's Guide. United States Environment Protection Agency, EPA-454/B-95-004; 1995.

van den Bogart HGG, van den Ende G, van Loon PCC, van Griensven LJLD. Mushroom workers lung; serologic reactions to thermophilic actinomycetes present in the air of compost tunnels. Mycopathologia 1993; 122**:** 21-28

Verhoeff AP, van Wijnen JH, Brunekreef B, Fischer E, van Reenen Hoekstra E, Samson RA. Presence of viable mould propagules in indoor air in relation to house damp and outdoor air. Allergy 1992; 47: 83-91.

Vincken W., Hypersensitivity pneumonitis due to Aspergillus fumigatus in compost. Thorax, 1984, 39**,** 74 - 75.

Weber S, Kullman G, Petsonk E, Jones WG, Olenchock S, Sorenson W, Parker J, Marcelo-Baciu R, Frazer D, Castranova V. Organic dust exposure from compost handling: case presentation and respiratory exposure assessment. Am. J. Ind. Med. 1993, 24, 365-374.

Weppen, P. Process Calorimetry on Composting of Municipal Wastes Biomass and Bioenergy 2001, 21, 289-299

Wheeler PA., Stewart I, Dumitrean P, Donovan B. Health effects of composting. - A Study of Three Compost Sites and Review of Past Data Environment Agency R&D Technical Report P1-315/TR, 2001, Environment Agency, Bristol

Zuskin E, Schachter EN, Kanceljak B, Mustajbegovic J, Wiltek T. Immunological and respiratory reactions in workers exposed to organic dusts Int. Arch. Occup. Environ. Health. 1994, 66, 317-24.

Printed and published by the Health and Safety Executive
C1.25 06/03

MAIL ORDER
HSE priced and free
publications are
available from:
HSE Books
PO Box 1999
Sudbury
Suffolk CO10 2WA
Tel: 01787 881165
Fax: 01787 313995
Website: www.hsebooks.co.uk

RETAIL
HSE priced publications
are available from booksellers

HEALTH AND SAFETY INFORMATION
HSE Infoline
Tel: 08701 545500
Fax: 02920 859260
e-mail: hseinformationservices@natbrit.com
or write to:
HSE Information Services
Caerphilly Business Park
Caerphilly CF83 3GG

HSE website: www.hse.gov.uk

RR 130

£20.00

ISBN 0-7176-2707-1