

EXPOSURES AND HEALTH OUTCOMES IN RELATION TO BIOAEROSOL EMISSIONS FROM COMPOSTING FACILITIES: A SYSTEMATIC REVIEW OF OCCUPATIONAL AND COMMUNITY STUDIES

Clare Pearson¹, Emma Littlewood¹, Philippa Douglas¹, Sarah Robertson², Timothy W. Gant², Anna L. Hansell^{1,3}

¹Small Area Health Statistics Unit, MRC-PHE Centre for Environment and Health & NIHR HPRU in Health Impact of Environmental Hazards, Imperial College London, London, United Kingdom

²Centre for Radiation, Chemical and Environmental Hazards, Public Health England, Harwell Campus, Didcot, Oxfordshire, United Kingdom

³Public Health and Primary Care, Imperial College Healthcare NHS Trust, London, United Kingdom

The number of composting sites in Europe is rapidly increasing, due to efforts to reduce the fraction of waste destined for landfill, but evidence on possible health impacts is limited. This article systematically reviews studies related to bioaerosol exposures within and near composting facilities and associated health effects in both community and occupational health settings. Six electronic databases and bibliographies from January 1960 to July 2014 were searched for studies reporting on health outcomes and/or bioaerosol emissions related to composting sites. Risk of bias was assessed using a customized score. Five hundred and thirty-six papers were identified and reviewed, and 66 articles met the inclusion criteria (48 exposure studies, 9 health studies, 9 health and exposure studies). Exposure information was limited, with most measurements taken in occupational settings and for limited time periods. Bioaerosol concentrations were highest on-site during agitation activities (turning, shredding, and screening). Six studies detected concentrations of either *Aspergillus fumigatus* or total bacteria above the English Environment Agency's recommended threshold levels beyond 250 m from the site. Occupational studies of compost workers suggested elevated risks of respiratory illnesses with higher bioaerosol exposures. Elevated airway irritation was reported in residents near composting sites, but this may have been affected by reporting bias. The evidence base on health effects of bioaerosol emissions from composting facilities is still limited, although there is sufficient evidence to support a precautionary approach for regulatory purposes. While data to date are suggestive of possible respiratory effects, further study is needed to confirm this and to explore other health outcomes.

Waste management policy is rapidly evolving, largely because European countries are running out of space for landfill sites. Further, poor waste management contributes to climate change and threatens environmental sustainability. It is estimated that each tonne of food waste diverted from landfill to composting

reduces greenhouse gas emissions by the equivalent of 0.4 to 0.7 tonnes of carbon dioxide (Department for Environment, Food and Rural Affairs [DEFRA], 2011). Responding to the urgent need to improve waste management, the European Commission set tighter standards on Biodegradable Municipal Waste

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Address correspondence to Anna L. Hansell, Small Area Health Statistics Unit (SAHSU), Department of Epidemiology and Biostatistics, School of Public Health, Imperial College London, St Mary's Campus, Norfolk Place, London W2 1PG, United Kingdom. E-mail: a.hansell@imperial.ac.uk

(BMW) destined for landfill (Council Directive, 1999). Under the proposal, targets were set to recycle (including composting) at least 33% of household waste by 2015.

During the last decade there has been a rise in the number of large-scale composting facilities, as well as the introduction of a wide range of more advanced composting technologies. The majority of composting in the United Kingdom is completed in open windrows, and in 2007 approximately 90% of the total composting in the United Kingdom was undertaken using this method (Sykes et al., 2007). As material is in the open air, the process generates substantial potential emissions and exposures. Newer indoor facilities known as in-vessel composting facilities (IVC) still have some open-air processes, usually as part of the final maturation phase (Smith et al., 2009). Composting yields significant concentrations of bioaerosols (Wheeler et al., 2001; Taha et al., 2006). Bioaerosols are airborne biological particles, microbial fragments and constituents of cells, which may be viable or nonviable, and consist of fungi, bacteria, pollen, and fragments, constituents, particulate matter (PM₁₀), and by-products of cells (Douwes et al., 2003; Dowd and Maier, 2000; Viegas et al., 2014). A Health and Safety Executive (HSE) report in 2003 highlighted some studies where site workers demonstrated adverse health effects from occupational exposure to bioaerosols produced during composting (Swan et al., 2003). Further, there is increasing public concern regarding potential health impacts within communities surrounding the sites (Clapham, 2008; Gray, 2009).

BIOAEROSOLS EMITTED DURING COMPOSTING

The process of composting is often divided into three major stages (sanitization, stabilization, and maturation) and involves the interrelated activities of a diverse range of microorganisms (Searl, 2008; Taha et al., 2007). These microorganisms become airborne, giving rise to fugitive emissions during the composting process, particularly during agitation activities,

such as shredding, turning, and screening (Taha et al., 2006). The bioaerosol components studied and identified as potentially harmful (Searl, 2008; Swan et al., 2003) are:

- Fungi and fungal spores—including the thermotolerant species *Aspergillus fumigatus*.
- Bacteria—including gram-negative bacteria and the spore-producing gram-positive bacteria actinomycetes.
- Endotoxin—structural components of some bacteria released through cell wall damage, including lipopolysaccharides (LPS) or lipooligosaccharides (LOS).
- Dust or particulate matter (PM) containing microbial fragments.
- Beta (1→3) glucans—polysaccharides found in the cell walls of certain fungi, particularly *Aspergillus* species.

It is possible that mycotoxins, which are toxic secondary metabolites of fungi (one of the most potent of these is aflatoxin, which is mainly produced by *Aspergillus flavus*) (Searl, 2008; Swan et al., 2003), may also be emitted during the composting process. However, there is no firm evidence to suggest this.

The main routes of exposure to bioaerosols are through ingestion and inhalation. The risk of occupational exposure to bioaerosols via ingestion may be controlled by application of good hygiene practices (Swan et al., 2003). Exposure to bioaerosols through inhalation is of most concern. Once airborne, bioaerosols may travel considerable distances and be potentially inhaled by workers at the composting sites, as well as nearby residents.

ACCEPTABLE LIMITS FOR BIOAEROSOLS

Bioaerosols occur naturally in ambient air at highly variable concentrations, with mean and median background concentrations ranging from 1 to 100,000 colony-forming units per cubic meter (cfu/m³) for bacteria and fungi (Clark et al., 1983; Coccia et al., 2010; Crook et al., 2008; Deacon et al., 2009; Drew et al., 2007; Fischer et al., 2000, 2007; Herr et al., 2003b; Nadal et al., 2009; Nikaeen et al.,

2009; Reinthaler et al., 1999, 2004; Schlosser et al., 2009; Stagg et al., 2010; Swan et al., 2003; van Kampen et al., 2012; Williams et al., 2013).

The Environment Agency for England (and Wales until 2013; now referred to as the Environment Agency) published a position statement with provisional guidance for composting operators when applying for an operating permit (Environment Agency, 2010). It states that acceptable levels of bioaerosols, measured using the standardized sampling protocol (Association for Organics Recycling [AfOR], 2009), above upwind background concentrations, need to be maintained at 250 m or at the nearest sensitive receptor (such as a dwelling or place of work), whichever is closer, to protect public health, as bioaerosol concentrations are considered to generally reduce to near-background levels within 250 m (Wheeler et al., 2001). The acceptable levels are:

- 1000 cfu/m³ for total bacteria.
- 300 cfu/m³ for gram-negative bacteria.
- 500 cfu/m³ for *Aspergillus fumigatus*.

These levels are guidelines and are not based upon dose-response relationships or health measures. There are no current guideline levels for endotoxins in the United Kingdom.

There are no apparent existing guidelines for community levels in other countries to our knowledge, but a number of countries published occupational limit values. The Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BUNR) in Germany suggest a minimum distance of 300 m for enclosed installations, and 500 m for open-windrow composting for facilities processing 3000 kg or more, but do not provide any acceptable limits for bioaerosol components (BUNR, 2002). In 2010 the Dutch Expert Committee on Occupational Safety (DECOS) proposed an occupational exposure limit for airborne endotoxin of 90 Endotoxin per cubic meter (EU/m³) (8-h time-weighted average) (DECOS, 2010). The Federal Institute for Occupational Safety and Health (BAUA) in Germany have a regulatory occupational limit

for mesophilic fungus (includes *Aspergillus* sp.) of 50,000 cfu/m³ in breathable air in the workplace (BAUA, 2013). In the United Kingdom, there are no regulatory occupational limits for endotoxins or fungi, but the Health and Safety Executive (HSE) do provide composting facility employers with guidance on how to comply with the Control of Substances Hazardous to Health (COSHH) regulations to control exposure and protect workers' health (HSE, 2011), with guidance on respiratory protective equipment (HSE, 2013).

POTENTIAL HEALTH EFFECTS OF BIOAEROSOLS FROM COMPOSTING FACILITIES

Dependent on particle size, bioaerosols may penetrate deep into the lungs and become embedded in alveoli (Douwes et al., 2003; Ivens, 1999). For the species of bioaerosols emitted from composting facilities, principal types of health effects in humans have been identified (Lacey and Dutkiewicz, 1994). These include but are not limited to:

1. Allergic asthma, rhinitis, hypersensitivity pneumonitis (HP)/extrinsic allergic alveolitis, allergic bronchopulmonary aspergillosis (ABPA), eye and skin irritations
2. Toxic non-allergic asthma, rhinitis, mucous membrane irritations (MMI), chronic bronchitis, chronic airway obstruction such as chronic obstructive pulmonary disease (COPD), organic dust toxic syndrome (ODTS), toxic pneumonitis.
3. Infectious aspergillosis, zygomycosis; immunocompromised individuals are more susceptible at lower concentrations of the relevant pathogens.

Further animal studies suggested high levels of endotoxin exposure may result in elevated inflammatory response in pregnant rats (Huffman et al., 2004) and may also be damaging to an animal fetus (Duncan et al., 2002, 2003; Ando et al. 1988). Elevated inflammatory responses have also been found in humans

working in agricultural settings (May et al., 2012; Poole et al., 2010).

There are currently no apparent published systematic reviews available of health impacts from exposure to bioaerosols specific to composting, but a comprehensive report on health risks was conducted by the UK Institute of Occupational Medicine (IOM), published in 2008 (Searl, 2008). This reviewed literature on exposure and associated health effects from bioaerosol emissions from the waste management industry, including but not limited to waste composting (Searl, 2008). The report identified few studies of health impacts of bioaerosols, with most evidence derived from studies not specific to waste composting. More recently, a literature review by Wéry (2014) on bioaerosols from composting facilities has been published, which provides a broad overview of the issues in this subject area. The aim of this study was to provide an up-to-date systematic review of occupational and community studies measuring concentrations of bioaerosols and/or assessing health effects associated with bioaerosol emissions within and nearby composting plants.

METHODS

Methods were developed based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) criteria (Moher et al., 2009), and also informed by the Meta-analysis of Observational Studies in Epidemiology (MOOSE) criteria (Stroup et al., 2000).

Search Strategy

A literature search was conducted across six electronic databases, (Medline, Embase, PubMed, Science Direct, Web of Science, and Springerlink). Gray literature was identified using Internet-wide search engines (Google and Google Scholar) and one university database (Cranfield University, UK, included as the institution has conducted a number of relevant studies). Two searches were performed, to identify both health-based and exposure-based

studies; example search strings used are supplied in Appendices 1 and 2, respectively. The search strings were inputted within the title and abstract fields of the electronic databases. Hand searching of bibliographies of the papers identified was also conducted.

Search strategies were developed with assistance from an academic librarian for health and exposure studies relating to bioaerosols from composting, adapted to each of the individual databases. Search terms for general health and specific health outcomes (e.g., asthma, aspergillosis) were employed. References were downloaded into Endnote X7, a referencing software program, and duplicates were removed.

Study Selection

After excluding duplicates, the records identified by the searches were assessed for inclusion in two steps. All retrieved references were first screened for relevance on title and abstract using predefined inclusion and exclusion criteria. Full texts of potentially relevant articles were then retrieved and reassessed for eligibility. Each step was conducted by an independent reviewer (CP, EL, PD), and any uncertainties or disputes were resolved through discussion, or with an additional reviewer (AH).

Studies included in the review had to meet all of the following criteria:

- The study was published in English between January 1960 and July 2014.
- The study concerned exposure or health effects relating to bioaerosols (organisms and their cellular constituents) emitted from composting sites.
- The study contained results that could be extracted into one or both an exposure measurements table or a health effects table relating to monitored bioaerosol components.
- The study was either peer reviewed or was published by a recognized institution.

Studies were excluded if:

- They did not concern waste composting.

- They did not concern bioaerosols.
- They did not include any original data.
- They were review papers, although the reference list was still searched to identify any other potential relevant studies.
- They were unavailable in English.
- They were toxicological studies in animals.
- Full texts were unavailable.
- If the paper only concerned microbial volatile organic compounds (MVOCs).

Quantitative Quality Assessment

In order to evaluate quality and highlight biases in the cross-sectional and cohort health studies, a detailed quality assessment scoring tool suitable for environmental epidemiology was developed based on Shah and Balkhair (2011) (see Appendix 3 for details). Two reviewers (CP, EL) assessed each study with reported health effects for eight potential sources of bias: study design, selection, responder, confounder, exposure assessment, outcome assessment, sample size, and analytical. A third reviewer resolved any disputes. Scores were provided on a scale of 1 to 4; a score of 4 was given where there was low bias. Prospective cohort studies were scored as very low risk of study design bias; exposure assessment was scored at very low risk of bias if direct sampling involving measurement was conducted.

RESULTS

The study selection process is represented in Figure 1. Five hundred and thirty-six articles were identified through the electronic searches and either the abstracts or entire articles were fully examined by two of the reviewers (involving EL, CP, PD); 470 papers were excluded. This review first considered studies with measured exposures of bioaerosols and then health studies; occupational and community studies were considered separately for both categories. Figure 1 details how many articles fit into each category. Almost all health studies included corresponding exposure data, but data were not always supplied within the publication in an

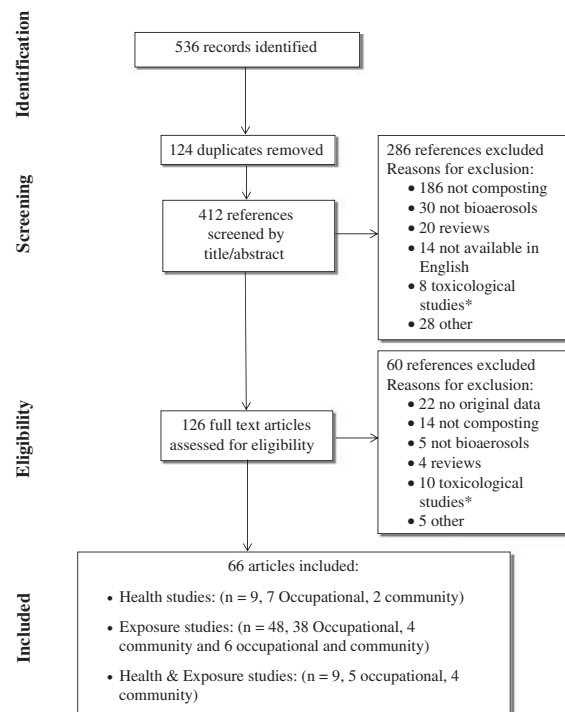


FIGURE 1. Flow chart showing the selection of studies analyzed in the review.

*The majority of toxicological studies were non-human lab-based studies.

extractable form (e.g., data were not provided in the paper, or had to be extracted from figures). Most of the 66 studies included were occupation based ($n = 51$).

Figure 2 shows the number of exposure and health studies where measurements were taken of different bioaerosols. Many bioaerosol components were monitored, of which total fungi, *Aspergillus fumigatus*, total bacteria, actinomycetes, and endotoxins are the most common, and the figure highlights how most studies occurred in occupational settings.

Exposure Studies

There were 58 exposure studies examined (Figure 1), of which 49 examined worker and occupational exposure, some in addition to community exposures (see Appendix 4). The majority of the studies were located in Europe and North America. The full study

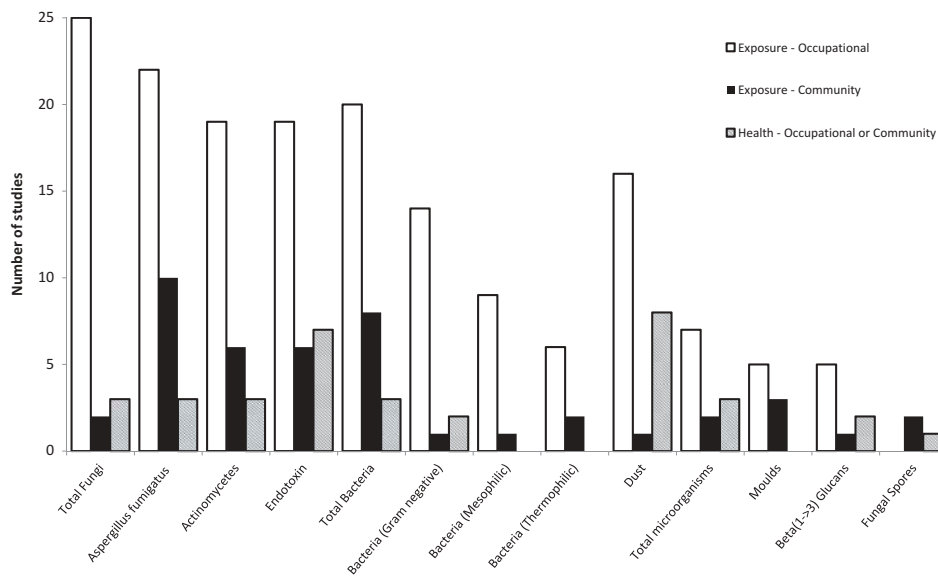


FIGURE 2. Bioaerosol components measured in articles with exposure measurements.

characteristics of occupational and community exposure studies are listed in Appendix 5 and Appendix 6, respectively. There were 10 components of bioaerosols commonly measured in exposure studies: viable total bacteria, gram-negative bacteria, actinomycetes, total fungi, and *Aspergillus fumigatus*, and also endotoxin, beta (1→3) glucans, organic dust, particulates, and total microbes.

The studies were heterogeneous in design, which may have affected concentrations detected; however, the majority of investigations provided the following information:

- Type and size of site (e.g., whether the site was open-windrow, IVC, or mixed).
- Whether agitation activities, such as shredding, turning, and screening, were taking place.
- Air sampling instrument used (e.g., filtration, liquid impingement and direct impaction).
- Sampling methodology (e.g., sample location and height, sampling time, laboratory culture methods).
- Meteorological variability, especially wind speed and direction.

Some studies also provided the following information, although this was less common:

- The age of compost (the amount and the microbiological composition of the composting material changes throughout the process) (Taha et al., 2007).
- Variations in sampled concentration with season (fungal concentrations were overall greater in summer than winter; Schlosser et al., 2009).

Most studies provided measurements of colony-forming units (CFU/M³) per cubic meter. Exposure sampling studies are reported here in two categories: occupational (including personal sampling for the assessment of workers exposure), and community exposure near composting facilities.

Occupational Exposure Studies Occupational median or mean concentrations (depending on what was reported in the original papers) from on-site locations at composting sites extracted from the reviewed literature were in the following ranges:

- Fungi, 10¹ to 10⁷ cfu/m³.
- *Aspergillus fumigatus*, <1 to 10⁶ cfu/m³.
- Bacteria, 10¹ to 10⁷ cfu/m³.
- Actinomycetes, 10¹ to 10⁶ cfu/m³.
- Organic dust, 0.1 to 56.14 mg/m³ (usually under 3 mg/m³).

- Endotoxin, 1 to 10⁴ EU/m³.
- Beta (1→3) glucans, <1 to 3400 ng/m³.

The highest bioaerosol concentrations were generally observed during compost agitation activities such as turning, shredding, and screening, but only around half of the studies specifically stated that measurements were taken during different compost site activities.

Thirteen occupational studies measured personal exposure of compost workers to different bioaerosol components (Bünger et al., 2007; Crook et al., 2008; Drew et al., 2007; Douwes et al., 1997; 2000; Epstein et al., 2001; Krajewski et al., 2002; Schlosser et al., 2009; Sigsgaard et al., 1994; Stagg et al., 2010; Sykes et al., 2011; Taha et al., 2007; Wheeler et al., 2001), detecting significantly high concentrations of actinomycetes, *Aspergillus fumigatus*, fungi, and endotoxin (Stagg et al., 2010), and elevated personal exposure levels of endotoxin in workers, particularly during composting agitation activities (Sykes et al., 2011). Four occupational studies measured mesophilic mould/fungi (Reinthal et al., 2004; Schlosser et al., 2009; Tolvanen et al., 2005; van Kampen et al., 2014). All mean/median (depending on metric reported) onsite measurements completed by Reinthal et al. (2004) and Schlosser et al. (2009) exceeded the 50,000 cfu/m³ occupational limit set by BAUA in Germany in 2006 (BAUA, 2006). Median on-site measurements by van Kampen et al. (2014) at sorting cabins, delivery places, and during processing also exceeded the BAUA limit. The mean/median values reported at the remainder of the on-site sampling locations in van Kampen et al. (2014) and the values reported in Tolvanen et al. (2005) did not exceed the BAUA limit, but the upper range did.

Total bacteria and *Aspergillus fumigatus* were the most consistently measured bioaerosol components, and their mean/medians (depending on metric reported, with range if provided) from occupational studies at selected sampling locations are shown in Figures 3 and 4, respectively. Both had wide variability in measured concentrations. Highest bioaerosol concentrations were experienced

on-site during agitation activities, with lower bioaerosol concentrations upwind. Measured *Aspergillus fumigatus* concentrations were more varied than total bacteria, ranging over eight orders of magnitude, compared to five orders of magnitude for total bacteria. Measured concentrations of total bacteria and *Aspergillus fumigatus* at the remaining sampling locations (such as at sorting areas and during periods of no activity) are provided in Appendices 7 and 8, respectively.

Community Exposure Studies The studies monitored bioaerosols at different distances from composting facilities, usually comparing concentrations measured downwind to the composting site with upwind concentrations, but also at points of interest, for example, at a sensitive receptor. There were wide ranges in measured concentrations of bioaerosol components in the studies, but this is difficult to interpret as studies were heterogeneous in design and presentation of results (some studies presented ranges and some presented medians or means).

Figures 5 and 6 show the median or mean (as reported) exposure values by distance upwind and downwind from the composting sites for total bacteria (nine studies) and *Aspergillus fumigatus* (eight studies), respectively, the most commonly measured bacterial and fungal components across the included studies. The solid line denotes the 250m boundary recommended by the Environment Agency (Environment Agency, 2010).

Figures 5 and 6 show that, as expected, generally the bioaerosol concentrations markedly increased immediately downwind of the composting facilities with concentrations gradually reducing on dispersion. However, it is important to recognize that not all studies measured concentrations at an upwind position, and therefore it is difficult to determine when concentrations returned back to background levels or to acceptable levels above background suggested by the Environment Agency.

In Figure 5, three (Herr et al., 2003b; Reinthal et al., 2004; Williams et al., 2013) of nine studies presented have measurements of total bacteria that exceed the

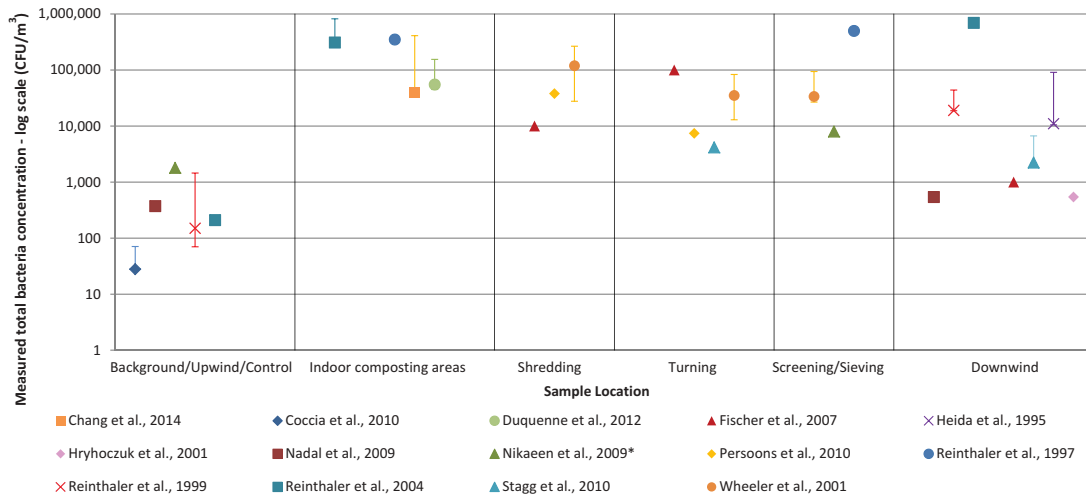


FIGURE 3. Mean/median airborne total bacteria concentrations at selected sampling locations in occupational exposure studies. If provided in the study, the range of values included is denoted by the error bars. Please refer to Appendix 5 for study characteristics. Measured concentrations of total bacteria at additional sampling locations are provided in Appendix 7.

*The study by Nikaeen et al. (2009) presented only maximum values, and no mean/median or minimum values

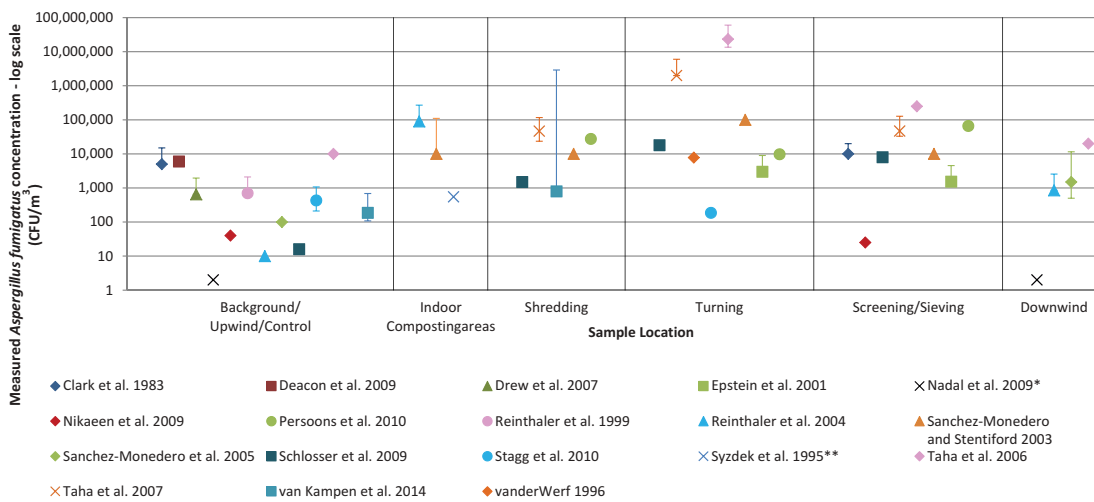


FIGURE 4. Mean/median airborne *Aspergillus fumigatus* concentrations at selected sampling locations in occupational exposure studies. If provided in the study, the range of values included is denoted by the error bars. Please refer to Appendix 5 for study characteristics. Measured concentrations of *Aspergillus fumigatus* at additional sampling locations are provided in Appendix 8.

*The measured concentration at the downwind and background locations in Nadal et al. (2009) were quoted as '<2'.

**The results in Syzdek and Haines (1995) were presented as spores/m³.

Environment Agency’s acceptable level of 1000 cfu/m³ above background concentrations beyond 250 m downwind (Environment Agency, 2010). Measurements by Hryhorczuk et al. (2001) and Reinthaler et al. (1999) may have also exceeded the Environment Agency’s

acceptable levels beyond 250 m, but background values are not provided in these studies.

In Figure 6, only two (Reinthaler et al., 2004; Williams et al., 2013) of eight studies presented show concentrations of *Aspergillus fumigatus* higher than Environment Agency’s

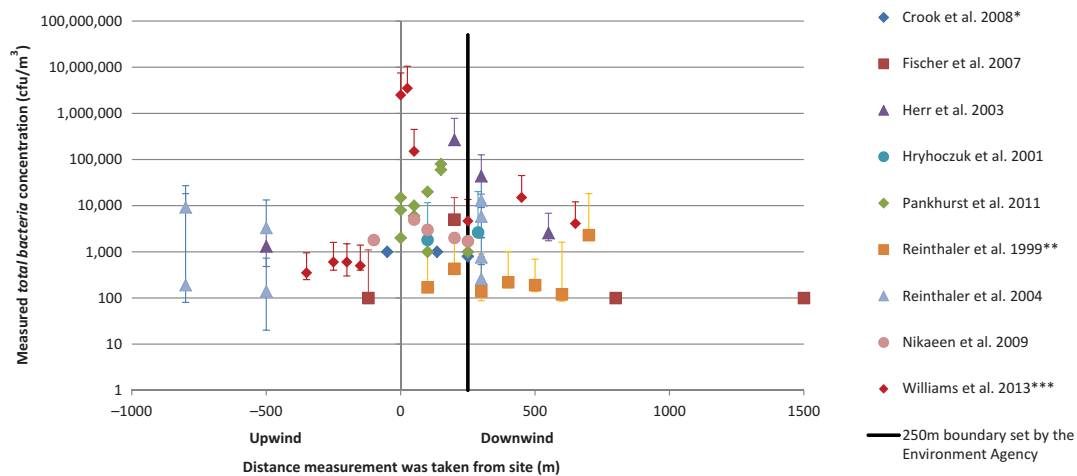


FIGURE 5. Mean/median airborne total bacteria concentrations in communities near composting facilities. If provided in the study, the range of values included is denoted by the error bars. Concentrations that appear to have been measured at 0m were taken on-site or on the site boundary. Please refer to Appendix 6 for study characteristics.

*Crook, Stagg, and Uwagboe (2008) stated that one of their measurements was collected at 120-150m downwind. These measurements are presented at 135m downwind on the graph.

**Reinthal et al. (1999) stated that measurements were taken at different distances from compass points around the site. It was not clear whether these measurements represented upwind or downwind measurements, and have been assumed to have been downwind within this graph.

***Results from Williams et al. (2013) were estimated from graphs, and therefore the exact locations and concentrations has not been replicated.

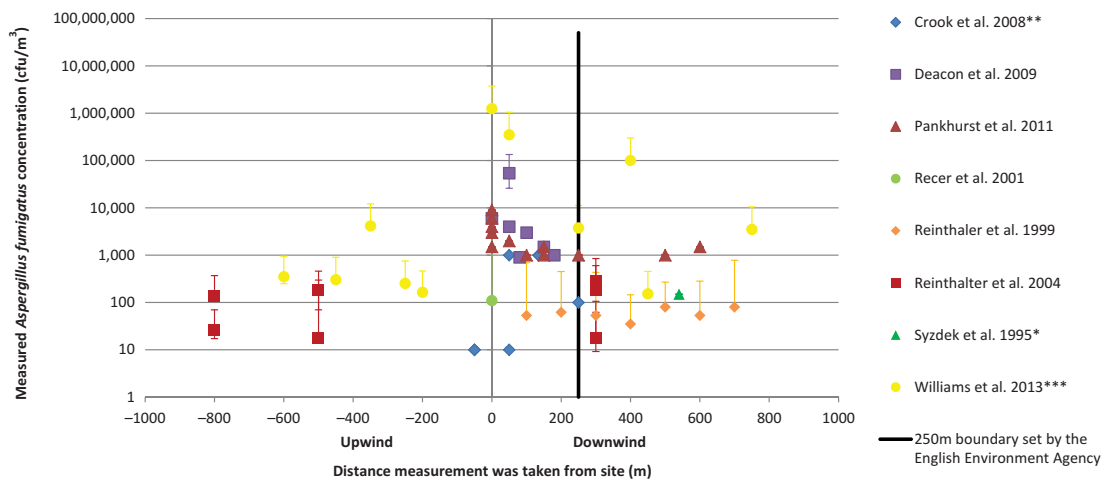


FIGURE 6. Mean/median airborne *Aspergillus fumigatus* concentrations in communities near composting facilities. If provided in the study, the range of values included is denoted by the error bars. Concentrations that appear to have been measured at 0m were taken on-site or on the site boundary. Please refer to Appendix 6 for study characteristics.

*The results in Syzdek and Haines (1995) were presented as spores/m³.

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***Results from Williams et al. (2013) were estimated from graphs, and therefore the exact locations and concentrations has not been replicated.

acceptable level of 500 cfu/m³ above background concentrations beyond 250 m downwind (Environment Agency, 2010). Measurements by Pankhurst et al. (2011) and Reinthaler et al. (1999) may also have exceeded the Environment Agency's acceptable levels beyond 250 m, but background values are not provided in these studies.

Health Studies

Eighteen health studies relating to bioaerosols from composting facilities were reviewed, the majority of which were conducted in Europe (Appendix 4). The full characteristics for both occupational and community based studies are displayed in Tables 1 and 2, respectively.

For each study, only a small number of conditions of those examined showed statistically significant associations as reported in Tables 3 and 4 for occupational and community-based health studies, respectively (nonsignificant health effects are presented in Appendix 9). As the majority of health studies were cross-sectional in design and too diverse to permit a quantitative meta-analysis, a narrative synthesis and table of significant health effects from occupational and community-based health studies are presented.

Bias Assessment

Table 5 presents results of bias assessment for health studies. The risk of bias was assessed using the tool presented in Appendix 3, based on Shah and Balkhair (2011). Sample sizes were generally low, introducing the possibility of statistical power issues. Many studies were also assessed as being at high risk of response bias, usually due to lack of explanation of follow-up of initial nonresponders. In addition, earlier published occupation-based studies were less likely to have taken relevant confounders into account (such as age, gender, and deprivation).

Occupational Health Studies There were two occupational case reports (of two patients

in total) reviewed, both of which were of HP in compost workers (Vincken and Roels, 1984; Brown et al., 1995). Ten further occupational studies. . . . (quasi-experimental design, i.e., a nonrandomized pre-post intervention study; Harris et al., 2004), one lab based study, one experimental study, and one was a cohort study (see Appendix 4 for details). Studies generally reported upper respiratory symptoms, eye and nose irritation, and skin and intestinal symptoms in exposed workers (see Table 3 for statistically significant health effects and Appendix 9 for all non-statistically significant health effects). This was supported by evidence from studies examining inflammatory markers and two further lab studies of human airway cells.

Three small studies examined inflammatory markers using experimental and quasi-experimental designs. Two were occupational studies, with nasal lavage measurements pre- and postshift (Douwes et al., 2000) or three days of work (Heldal, 2003) on 25 and 31 composting workers, respectively, while a third examined peripheral blood pre and post 2-h exposure in 17 healthy young adult volunteers (Müller et al., 2006). Both occupational studies found elevations in neutrophils and inflammatory markers of myeloperoxidase and interleukin-8 (IL-8) in nasal lavage fluid post shift; one of the studies (Heldal, 2003) also noted a rise in eosinophil cationic protein (ECP). Both studies reported some evidence for associations between exposures to endotoxin, beta (1→3) glucan and fungal spores (Heldal et al., 2003), but inflammatory responses were not specific to measured components of the bioaerosol dust. Müller et al. (2006), found elevated levels of blood neutrophils postexposure, but not inflammatory cytokines of tumor necrosis factor- α (TNF- α), interleukin-1 β (IL-1 β), or interleukin-6 (IL-6).

Two lab studies of inflammatory markers were identified. Chang et al. (2014) examined expression of airway remodeling genes in human lung mucoepidermoid NCI-H292 cells exposed to airborne bioaerosols from sampling filters used in a composting plant. Postexposure there were elevations in IL-6, transforming

TABLE 1. Occupational Health Articles—Study Characteristics

Author (year)	Study characteristics	Number and type of sites	Exposure assessment	Outcome assessment	Bioaerosols studied
Brown (1995)	United States; case report in compost site worker	1 site	Not reported	Clinical examination	Organic dust
Bünger (2000)	Germany; cross-sectional study in compost and biowaste workers	Multiple sites, details not reported	Standardized interview questionnaire about bioaerosol occupational exposure	Standardized occupational questionnaire Symptoms of respiratory system; skin; gastrointestines; atopy	Bacteria, actinomycetes, fungus spores
Bünger (2007)	Germany; cohort study of acute and chronic respiratory disorders and lung function in site workers at 41 open and in-vessel composting (IVC) sites	41 open, IVC and mixed sites	Personal air sampling of workers at 6 of 41 studied sites from which respirable dust, cultivable microorganisms, and endotoxins were extracted.	Clinical examination; Interview with standardized questionnaire; spirometric measurements of lung function Symptoms of upper respiratory system; eyes; effect of exposure on lung function	Organic dust; total microorganisms; endotoxin
Chang (2014)	Location not specified; laboratory based study whereby human lung mucoepidermoid cells were cocultured with <i>Aspergillus fumigatus</i> samples collected from a composting hall	1 IVC composting plant	A single stage ambient microbe sampler was used at a rate of 28.3 L/min at 1.5 m above ground. For cytotoxicity assay of particulate matter a filter sampler was used at a flow rate of 4 L/min. For endotoxin assay, a five-stage cascade impactor was used at a flow rate of 9 L/min at a height of 1.5 m above ground. All sampling was conducted for 8 h.	Laboratory-based study whereby human lung mucoepidermoid cells and <i>Aspergillus fumigatus</i> collected from the “composting hall” were cocultured to mimic exposure to inflammatory factors in vivo. Results confirmed that the cells showed increased proinflammatory responses.	<i>Aspergillus fumigatus</i> , bacteria, mould, particulate matter, endotoxin
Douwes (2000)	Netherlands; two cross-sectional studies and quasi-experimental studies conducted 12 mo apart in site workers	1 IVC site	Personal air sampling; endotoxin and $\beta(1,3)$ -glucan extractions; impactor sampling (Andersen) for ambient total bacteria	Nasal lavage (NAL) sampling for inflammatory markers; self-reported questionnaire; standardized health questionnaire of reported respiratory symptoms	Organic dust; endotoxin; beta (1→3)glucans
Hambach (2012)	Belgium; cross-sectional study in compost facility workers in 3 indoor composting sites	3 indoor sites—vegetable, garden and fruit facilities.	N/A. Those exposed worked almost exclusively in the compost hall and therefore exposed to organic dusts.	Questionnaire incorporated into annual medical examination. Respiratory symptoms (dry cough, phlegm, wheezing, dyspnoea, chest tightness); irritation (runny eyes, blocked/running nose, sore throat, sneezing/tickly nose); gastrointestinal (nausea, pyrosis, lack of appetite); skin	Occupational bioaerosols—organic dust

(Continued)

TABLE 1. (Continued)

Author (year)	Study characteristics	Number and type of sites	Exposure assessment	Outcome assessment	Bioaerosols studied
Heldal (2003)	Norway; quasi-experimental study in waste workers (including compost workers)	1 IVC site	Personal air sampling full-shift; analyses for endotoxin, $\beta(1-3)$ glucan, bacteria, fungi, organic dust;	Nasal lavage sampling; acoustic rhinometry pre-shift twice per week; self-reported nonstandardized symptom and occupational questionnaire;	Organic dust; endotoxin; beta (1→3) glucans
Lundholm (1980)	Sweden; cross-sectional study among workers at a composting plant	1 open air site, feedstock and sewage sludge	Impactor sampling (Anderson 6 stage)	Interview questionnaire, nonstandardized subjective symptoms of upper respiratory system; eyes; gastrointestinal; headache; fatigue	Gram-negative bacteria
Müller (2006)	Germany; experimental study in healthy, young previously unexposed volunteers, shoveling compost for 2 hours	1 open air compost site	Personal dust sampler worn by participants	Standardized questionnaire, lung function tests (spirometry) and blood samples (inflammatory markers) taken just before and 3 h after exposure period.	Endotoxin, organic dust
Sigsgaard (1994)	Denmark; cross-sectional study in compost workers	Open green compost sites, unknown number	Filter sampling for personal and ambient inhalable dust; endotoxin extractions; impinger sampling for ambient total bacteria and fungi	Interview questionnaire, standardized and skin prick tests for inhalant allergens and antigens. Symptoms of respiratory system, lung function; gastrointestinal; skin	Organic dust; total microorganisms; gram-negative bacteria; total fungi; endotoxin
van Kampen (2012)	Germany; cross-sectional study of current and former compost workers at 31 sites	31 mixed sites	Standardized interview questionnaire about occupational exposure to bioaerosols	Clinical examination; standardized interview questionnaire; spirometric measurements of lung function; serum levels of specific IgG antibodies to antigens used as immunological biomarkers of 4 fungus species Upper respiratory system; eyes; skin; gastrointestinal; atopy; other influenza-like symptoms; lung function	Occupational bioaerosols
Vincken (1984)	Belgium; case report in compost site worker	1 site	Not measured	Clinical examinations; chest radiograph; spirometry; blood test; bronchial washings	<i>Aspergillus fumigatus</i>

growth factor (TGF)- β 1 and cyclin-dependent kinase inhibitor 1 (p21^{WAF1/CIP1}) but not matrix metalloproteinase (MMP)-9. Liu et al (2011) showed elevated inflammatory cytokine production in cultured human D562 pharyngeal epithelial and MM6 monocytic cell cultures exposed to airborne endotoxin samples from active on-site areas, but not where samples

displayed low endotoxin levels, including those collected upwind, downwind at 100 m or more from composting site boundary, or when composting sites were inactive. Liu et al. (2011) suggested that airborne endotoxin levels of >50 EU/m³ may have the potential to induce proinflammatory responses in airway epithelial cells.

TABLE 2. Community Health Articles—Study Characteristics

Author (year)	Study characteristics	Number and type of sites	Exposure assessment	Outcome assessment	Bioaerosols studied
Aatamila (2011)	Finland; cross-sectional study in residents near to 5 mixed landfill and compost sites	5 sites; details not available	Not measured	Standardized telephone interview questionnaire of odor-related self-reported health complaints; Respiratory tract; gastrointestinal (GI); eyes; nose/throat; headache; fever; nausea/vomiting; joint/muscular pain; general health of last 12 months	Not studied: odour annoyance investigated
Browne (2001)	United States; panel study of residents living 540 m downwind from a green waste composting site	1 grass and leaf composting facility	Burkard–Hirst 7-day volumetric spore trap 1.5 m above ground	Self-reported symptom diary containing daily checklists for a week Allergy symptoms and asthma symptoms	<i>Aspergillus fumigatus</i>
Herr (2003b)	Germany; cross-sectional study of residents stratified: 150–200 m, 200–400 m, 400–500 m of 1 compost site	1 mixed (open and IVC) site	Filter samplers 1.5 m above ground level, 10 m collection time, 3 repeated measurements for each of the 3 fractions of culturable microorganisms	Self-reported standardized questionnaire of health complaints over past year; doctors' diagnoses; odour annoyance Symptoms of respiratory tract; eye; skin; gastrointestines; general health	Total bacteria; total fungi; thermophilic actinomycetes
Herr (2003a)	Germany; cross-sectional study of 3 groups of residents near (150 m, 1500 m, and 1500 m) to 3 compost sites; controls from 3 matched unexposed areas	3 sites; details not available	Concentrations of bioaerosols fractions measured in residential air; sampling methods not reported	Self-reported standardized questionnaire of somatic health complaints over past 2 years Somatic symptoms including pains and discomfort in head, face, back, legs, arms, stomach; breathlessness; nausea	Total viable microorganisms; total fungi; thermophilic fungi; thermophilic actinomycetes
Kramer (1989)	United States; case report in an asthmatic resident within 250 m of a site	1 site; details not available	Impactor sampler (Andersen)	Skin reactivity test; serum measurement of total and Af-specific IgE; chest radiograph	<i>Aspergillus fumigatus</i>
Liu (2011)	United Kingdom, laboratory-based study assessing the inflammatory potential of airborne endotoxins in nearby residential areas of composting sites using in vitro human pharyngeal epithelial culture models	2 large-scale green waste open windrow composting facilities	SKC filter samplers used at a flow rate of 2.2 L/min for 30–120 min at a height of 1.7 m. Samples were taken upwind (up to 400 m), on-site, at the site boundary and downwind (up to 600 m).	Inflammatory cytokine production was assessed from cultured human pharyngeal epithelial cells exposed to airborne endotoxins collected from neighboring residential areas of composting sites. Similar to untreated cells, samples containing low endotoxin concentrations did not induce secretion of cytokines.	Endotoxin

TABLE 3. Significant Health Results From the Occupational-Based Health Studies (Laboratory-Based Studies Have Been Excluded)

Author (year)	Study population		Effects estimates
	Country	Subjects	<i>p</i> Values or adjusted OR/RRs (and 95% confidence intervals)
Respiratory system			
Sigsgaard* (1994)	Denmark	Garbage handlers (<i>n</i> = 40), compost workers (<i>n</i> = 8), paper sorting workers (<i>n</i> = 20), controls (<i>n</i> = 119); 20 paper sorting workers; 119 controls	Decrements in lung function associated of all refuge workers with exposure to organic dust over the course of a shift (<i>p</i> < .05) (not exclusively compost workers)
Bunger (2000)	Germany	Compost workers (<i>n</i> = 58), bio-waste collectors (<i>n</i> = 53), male control subjects (<i>n</i> = 40)	Significantly more diseases and symptoms of the airways in compost workers compared with controls (<i>p</i> = .003)
Muller (2006)	Germany	Subjects exposed for 2 h (<i>n</i> = 17) and subjects analyzed on control (<i>n</i> = 12)	Lung function did not significantly change during exposure or control day
Bunger (2007)	Germany	Employees at 41 composting sites (<i>n</i> = 218) and unexposed controls (<i>n</i> = 66) Lost 95 exposed and 18 unexposed in follow-up after 5 years	FVC (% of predicted) decreased significantly decreased in non-smoking composters compared with controls (<i>p</i> < .05) Increase in number of composters suffering from chronic bronchitis (RR = 1.41 (1.28–1.55))
Hambach (2012)	Belgium	Compost facility workers in 3 indoor VGF (vegetable, garden, and fruit) composting sites (<i>n</i> = 62, 31 exposed, 31 nonexposed)	Respiratory symptoms: work related or not = 3.7 (1.1–12.0), work related = 17.4 (1.7–178.4)
Van Kampen (2012)	Germany	Workers from 31 composting plants (<i>n</i> = 190), former compost workers (<i>n</i> = 58), office employee controls (<i>n</i> = 38)	FVC significantly lower in compost workers than controls (<i>p</i> = .01)
Skin complaints			
Bunger (2000)	Germany	As above	More symptoms and diseases of the skin in the compost workers (<i>p</i> = .02)
Hambach (2012)	Belgium	As above	Skin symptoms: work related or not = 7.3 (1.0–52.0)
Gastrointestinal (GI) diseases			
Sigsgaard (1997)	Denmark	Garbage handlers (<i>n</i> = 40), Compost workers (<i>n</i> = 8), Paper sorting workers (<i>n</i> = 20), controls (<i>n</i> = 119)	GI symptoms (ever vomiting, diarrhea in relation to work) composting industry = 7.51 (1.17–48.1)
Hambach (2012)	Belgium	As above	GI symptoms: work related or not = 4.4 (1.2–15.5), work related = 8.4 (1.3–52.9)
Eye/nose/throat irritation			
Bunger (2007)	Germany	As above	Watering eyes; itching eyes; conjunctivitis reported more frequently in compost workers than in control subjects (<i>p</i> < .05)
Van Kampen (2012)	Germany	As above	Watering eyes; foreign body sensation in eyes reported more frequently in compost workers than in control subjects (<i>p</i> = .008 and .013, respectively)
Hambach (2012)	Germany	As above	Irritation ⁺ (work related) = 4.7 (1.8–25.3) ⁺ runny eyes, blocking of nose, runny nose, sore throat, ticking nose or sneeze aggregated

Note. Nonsignificant health results are presented in Appendix 9.

*The study information from Sigsgaard, Hansen, and Malmros (1997) is from a conference paper, as the results were not reported in Sigsgaard et al. (1994).

TABLE 4. Significant Health Results From the Community-Based Health Studies (Laboratory-Based Studies Have Been Excluded)

Author (year)	Study population		Effects estimates
	Country	Subjects	<i>p</i> Values or adjusted ORs (and 95% confidence intervals)
Respiratory system			
Browne (2001)	USA	Residents living 540 m downwind of green waste composting site (<i>n</i> = 63), controls (<i>n</i> = 82)	No significant associations between <i>A. fumigatus</i> and asthma or allergy
Herr (2003b)	Germany	356 residents stratified: within 150–200 m (<i>n</i> = 82), within 200–400 m (<i>n</i> = 76), within 400–500 m (<i>n</i> = 56) of 1 mixed IVC/open compost site; <i>n</i> = 356 (unexposed <i>n</i> = 142)	Exposed vs. unexposed: Bronchitis = 3.59 (1.40–9.47), Waking up due to coughing = 6.59 (2.57–17.73), Coughing on rising or during the day = 3.18 (1.24–8.36) Most exposed vs. near background exposure levels: bronchitis = 3.02 (1.35–7.06), waking up due to coughing = 2.70 (1.23–6.10), coughing on rising or during the day = 2.67 (1.17–6.10), shortness of breath at rest = 3.99 (1.31–15.19), shortness of breath on exertion = 4.23 (1.74–11.34) >5 yrs residency: Frequency of colds = 4.72 (1.1–31.83); bronchitis = 2.91 (1.29–7.03); waling up due to coughing = 2.51 (1.19–5.53); wheezing = 2.95 (1.22–7.99)
Aatamila (2011)	Finland	Residents near 5 waste treatment centers, within 1.5 km (<i>n</i> = 672), 1.5–3.0 km (<i>n</i> = 253), and 5 km (<i>n</i> = 217)	By distance band <1.5 km vs. 3–5 km: cough/phlegm = 1.3 (1.0–1.8); In those annoyed by the odor: unusual shortness of breath = 1.5 (1.0–2.2), hoarseness/dry throat = 1.5 (1.1–2.0)
Eye/nose/throat irritation			
Browne (2001)	United States	Residents living 540 m downwind of green waste composting site (<i>n</i> = 63) Controls (<i>n</i> = 82)	No significant associations between <i>A. fumigatus</i> and eye/nose irritation
Herr (2003b)	Germany	As above	Most exposed vs. near background exposure levels: smarting eyes (>10 per year) = 2.44 (1.02–6.22) >5 yr residency: Itching eyes (>10 per year) = 2.85 (1.31 – 6.50); smarting eyes (>10 per year) = 2.42 (1.06–5.86) Odor annoyance in the residential area: itchy eyes (>10 per year) = 4.97 (1.8–15.67); smarting eyes (>10 per year) = 10.40 (2.87–66.96)
Aatamila (2011)	Finland	As above	By distance band <1.5 km vs. 3–5 km: nose irritation/stuffy nose = 1.5 (1.1–2.1); hoarsness/dry throat = 1.3 (1.0–1.8) in those annoyed by the odor: eye irritation = 1.5 (1.1–2.1)
Other illnesses			
Browne (2001)	United States	Residents living 540 m downwind of green waste composting site (<i>n</i> = 63), controls (<i>n</i> = 82)	No significant associations between <i>A. fumigatus</i> and nausea/upset stomach, joint pain, cold & flu
Herr (2003b)	Germany	As above	Exposed vs. unexposed: excessive tiredness = 4.27 (1.56–12.15), current medication intake = 2.64 (1.08–6.60) Most exposed vs. near background exposure levels: excessive tiredness = 2.80 (1.22–6.72), shivering = 4.63 (1.44–20.85) >5 yrs residency: Nausea/vomiting = 4.10 (1.28–18.44); shivering = 3.67 (1.32–12.20) Odor annoyance in the residential area: joint trouble (>10 per year) = 4.30 (1.55–14.17); muscular complaints (>10 per year) = 2.99 (1.02–11.08)

(Continued)

TABLE 4. (Continued)

Author (year)	Study population		Effects estimates
	Country	Subjects	<i>p</i> Values or adjusted ORs (and 95% confidence intervals)
Herr (2003a)	Germany	3 groups of residents near (150 m, 1500 m, and 1500 m) to 3 compost sites of unspecified type; controls were residents in 3 matched unexposed areas; <i>n</i> = 496	Total complaint index (TCI) Difference between those living 150 m away from site and controls (<i>p</i> = .001)
Aatamila (2011)	Finland	As above	By distance band <1.5k m vs. 3–5 km: fever/shivering = 1.7 (1.0–2.8); By distance band 1.5–3 km vs 3–5 km: joint pain = 1.6 (1.1–2.4) In those annoyed by the odor: toothache = 1.4 (1.0–2.1), unusual tiredness = 1.5 (1.1–2.0), fever/shivering = 1.7 (1.1–2.5), joint pain = 1.5 (1.1–2.1), muscular pain = 1.5 (1.1–2.0)

Note. Nonsignificant health results are presented in Appendix 9.

TABLE 5. Risk of Bias in Health Studies (excluding case report and lab based studies), with the Risk of Bias assessed using the tool presented in Appendix 3, based on Shah and Balkhair (2011)

Author (year)	Risk of bias								
	Study design	Selection	Responder	Confounder	Exposure assessment	Outcome assessment	Sample size	Analytical	Total
Occupational health studies									
Lundholm (1980)	2	2	1	1	3	2	1	1	13
Sigsgaard (1994)	2	4	3	2	2	4	1	3	21
Bünger (2000)	2	2	1	2	1	3	2	3	16
Douwes (2000)	2	2	1	2	4	3	1	3	18
Heldal (2003)	2	1	1	2	2	3	1	2	14
Muller (2006)	2	3	3	1	3	3	1	3	19
Bünger (2007)	1	3	2	2	2	3	2	3	18
van Kampen (2012)	2	2	1	3	1	3	2	4	18
Hambach (2012)	2	2	4	3	1	3	1	3	19
Community health studies									
Browne (2001)	3	3	2	2	3	3	2	3	21
Herr (2003b)	2	4	1	4	3	3	3	4	24
Herr (2003a)	2	2	1	1	2	4	3	3	18
Aatamila (2011)	2	4	3	4	1	4	4	3	25

Note. The scores are provided on a scale of 1 to 4; the maximum score is 32 (best quality study) and the minimum score is 8 (lowest quality study).

Community Health Studies

One case report of allergic bronchopulmonary aspergillosis (ABPA) produced by *Aspergillus fumigatus* in a patient with a history of asthma was identified (Kramer et al., 1989). The patient lived 250 ft from a municipal leaf composting site. There were no reported cases of invasive aspergillosis of residents living near compost plants (Kramer et al., 1989).

Three cross-sectional community-based studies, two of which also measured exposure (Herr et al., 2003a, 2003b), examined health effects in residents of communities at various distances to composting facilities (see Table 4 for statistically significant health effects and Appendix 9 for all non-statistically significant health effects). Three studies used questionnaires to assess symptoms, one in Finland (Aatamila et al., 2011) and two in Germany (Herr et al., 2003a, 2003b), also assessing odor

(Aatamila et al., 2011; Herr et al., 2003a, 2003b) and bioaerosol concentrations (Herr et al., 2003a, 2003b). A fourth study in the United States used daily symptom diaries (Browne et al., 2001) in relation to *Aspergillus fumigatus* spore counts, comparing residents (oversampling those with allergic rhinitis and asthma) near a composting facility with those from a reference area. The three questionnaire-based studies reported adverse health effects, predominantly respiratory and irritated eye and nose symptoms, but may have been prone to reporting and selection biases (Table 5). However, the symptom diary study did not find marked associations between allergy and asthma symptom symptoms and *A. fumigatus* spore counts (Browne et al., 2001).

The community-based health effect studies provided limited evidence of increased exposure levels at distances greater than 200 m to 300 m. The zone widths (1.5 km) in Aatamila et al. (2011) were most likely too large for this type of stratification, and distance zones in the study were not consistently associated with the observed symptoms (although symptoms were with reported odor annoyance).

DISCUSSION

The aim of this systematic review was to evaluate the current evidence relating to possible health impacts associated with bioaerosol emissions from composting facilities, and this is the first systematic review to focus entirely on bioaerosol emissions from composting facilities. The exposure studies were heterogeneous in design and analysis, with limited details provided in many studies, but did identify a wide range of possible exposures to bioaerosol components. Highest bioaerosol concentrations were reported most frequently during agitation activities, such as turning, screening, and shredding. Most of the health studies were occupational. These studies provided qualitative evidence linking occupational exposure to bioaerosols to gastrointestinal (GI), skin, and respiratory-tract symptoms, supported by objective evidence from occupational and lab

studies showing small decrements in lung function and elevation in inflammatory markers, but there were too few studies and designs were too heterogeneous to determine exposure-response relationships. There were four community health studies, three of which were prone to response bias. As with any review, some studies may have not been retrieved, but a comprehensive search strategy was employed that also incorporated gray literature to attempt to include all evidence currently available.

Exposure Studies

The exposure studies included in the review demonstrated a wide variation in the types of bioaerosols sampled and concentrations measured both on-site and at various distances from sites in community studies. The variability in measured concentrations is likely due, in part, to different methods of sampling and measurement.

Several countries have issued recommendations for sampling methods and equipment, but these all differ, which affects study comparisons. In the United Kingdom, the Association for Organics Recycling (AfOR), now the Organics Recycling Group (ORG), published a standardized protocol for monitoring bioaerosols at open (but not IVC) composting facilities in 1999, updated in 2009 (AfOR, 2009). The protocol recommends the use of Andersen impaction samplers and IOM filter samplers enumerate colonies of total bacteria and *Aspergillus fumigatus* only. However, a comparison of different sampling techniques, including Andersen impaction samplers and IOM filter samplers (as well as others), found that there was no consistent relationship between the concentrations of bioaerosols measured with the AfOR standard sampling methods (Williams et al., 2013). In Germany, BAUA published recommendations of how to sample airborne biological particles in an occupational setting, covering but not specific to composting processes (BAUA, 2006; Meffert and Blome, 2011), and recommended the sampling equipment to be used. The National Institute for Occupational Safety and Health

(NIOSH) produced a sampling method when measuring bioaerosols in indoor air (Lonon, 1998), which is different again. In 2013, The European Intergovernmental Panel on Climate Change (IPCC) called for a technical working group to review the biowaste industry's best available techniques (BAT) reference document (BREF) (Collins, 2013, ORG, 2013). A BREF for biowaste is underway, but not yet available, although a BREF for waste treatment industries is (European Commission, 2006).

Analysis of total microbial cell numbers is also an area of differences in bioaerosol concentrations reported between studies. Only a proportion of microbial cells within a bioaerosol are capable of being cultured, with the remainder being either dead but intact cells, or "viable but non culturable" (VBNC)—live cells not capable of being cultured either because they have entered a metabolically dormant state or because the agar medium used does not support their growth. However, these microorganisms may also pose a health risk and need to be taken into consideration in human health impact assessment. Sampling techniques that rely on microbiological cultures are also subject to upper and lower limits of detection. Impaction samplers are capable of capturing lower concentrations of bioaerosols, but become overloaded when sampling in areas where higher concentrations are expected (such as on-site or during agitation activities) (Williams et al., 2013). Therefore, the sampling technique used needs to be carefully considered and be appropriate for the study needs. The weaknesses in the sampling techniques also provide challenges for dispersion modellers attempting to predict bioaerosol exposure.

Perhaps most importantly, the current sampling regimes do not provide information on long-term exposures, which is particularly important for community health studies. The AfOR protocol has short sampling times (up to 45 min, but usually 10–30 min, depending on the location and sampler used) (AfOR, 2009) that provide only a short snapshot of emissions at the time of sampling. However, recently continuous sampling techniques have

become available, for example, Wideband Integrated Bioaerosol Sensors (WIBS) (Droplet Measurement Technologies [DMT], 2014), which operate using light scattering and fluorescence detection. These bioaerosol sensors are capable of operating over long periods of time and detect VBNC cells, providing the potential to complete chronic exposure studies. Measurement of PM₁₀ (particulate matter 10 μm in diameter; the diameter of a bioaerosol may also be 10 μm , as they range in size from 0.02 to 100 μm [Dowd and Maier, 2000]) may also allow an estimation of continuous bioaerosol concentrations (Brown et al., 2009, Williams et al., 2013). However, Williams et al. (2013) demonstrated a poor correlation between PM₁₀ and bioaerosol concentrations, and therefore additional research needs to be completed before PM₁₀ measurements can be used solely as a proxy for bioaerosol concentrations.

Many of the exposure studies included in this review did not measure a background concentration. Further, where a background concentration was measured it was not clear whether concentrations determined downwind of the composting site had taken into account the background levels. This lack in reporting of background concentrations may, in part, reflect difficulties in obtaining background measurements. For example, the site might be located in an area where there are many sources of bioaerosols. As bioaerosols are ubiquitous and highly variable, defining a "true" background concentration is problematic. In addition, in areas where the site is located near multiple sources of bioaerosols, downwind measurements may be influenced by other sources. This causes difficulties when defining exposure levels and apportioning bioaerosol exposure to a source.

Health Studies

Our review suggests that information in relation to health risks from compost facilities has expanded in recent years, but is still limited. The evidence base is not sufficient to

provide quantitative dose-response estimates—and is limited by lack of evidence base relating to dose.

Workers at compost sites are those exposed to the highest levels of bioaerosol components. Health studies provide some evidence of potential short-term respiratory, gastrointestinal, and proinflammatory effects at high levels of exposure, but respiratory protection is recommended for compost site workers to minimize impacts on health (HSE, 2013). The strength of inferences that may be drawn from the available studies was weakened by the small sample sizes and short-term nature of the investigations. Only one occupational cohort study was identified, and this was suggestive of higher risks of chronic bronchitis and reduced lung function with ongoing bioaerosol exposure. There were no studies identified that would enable the estimation of incidence rates of occupational allergic disease, one of the most frequent occupational respiratory disorders. However, respiratory and allergic disease following elevated exposures to some bioaerosols, such as endotoxin and *Aspergillus fumigatus* (Rautiala et al., 2003), was noted in other occupations including agricultural workers (May et al., 2012; Poole et al., 2010) and domestic waste collectors that were not considered in this review. The lack of longitudinal studies is most likely due to the practical difficulties of longitudinal studies in these settings, and the difficulty in obtaining historical data due to the relatively recent development of the composting industry. More studies are needed to determine if chronic effects can be confirmed, particularly if respiratory protection has been used.

Only five community health studies were identified; one was a case report and four were cross-sectional studies (therefore limiting interpretation of causality) and reliant on self-reported symptoms (which may be prone to recall and reporting bias). There are as yet no large-scale longitudinal investigations of adverse health impacts on residents of bioaerosols emitted from composting facilities. None of the community studies provided information on the relationship between

emission rates of bioaerosols on site and resulting concentration of bioaerosols at distances from source. The potentially harmful microbes identified in this review and diseases associated with them are tabulated in Appendix 10, but of the nine health studies that also measured exposure, *Aspergillus fumigatus*, endotoxin, and gram-negative bacteria were the only specific organisms for which exposure sampling measurements were conducted. Selection of participants in the community studies is also a potential source of bias, and the chosen distance bands (0–<1500, 1500–<3000, and 3000–<5000 m) in Aatimila et al. (2011) are too large, given that exposure studies demonstrated that most bioaerosol concentrations fall to near-background levels at 250 m.

No studies provided direct evidence relevant to vulnerable members of the population such as the immunocompromised, who are potentially at risk of invasive respiratory fungal infection from *Aspergillus fumigatus* at lower concentrations than are healthy individuals (Stagg et al., 2010), or asthmatics, who occasionally were reported to suffer increased risk of hypersensitivity to fungi at concentrations found in ambient air (Searl, 2008). The developing fetus may also be considered potentially sensitive to environmental exposures, but no apparent studies of reproductive outcomes were found.

CONCLUSIONS

Overall, the results reported in this systematic review endorse those previously noted by Searl (2008). Current evidence on both exposure to bioaerosol emissions from composting facilities and potential for associated health effects remains limited. All of the exposure studies included in this review have involved short-term sampling, which provides little insight into long-term exposures. The health studies have design limitations, generally involving small numbers of subjects and, in the community studies, reliant on self-reported outcomes that may be prone to bias. Further, with the exception of one cohort study that was

undertaken over the course of 5 years (Bünger et al., 2007), studies were either of short time scales or cross-sectional in design, which limits interpretation.

The health studies provide no quantitative dose-response estimates, and therefore evidence to date is insufficient to inform risk-based regulation. However, occupational and community health studies do provide qualitative evidence of adverse health outcomes that is sufficient to justify the current approach to prevent community exposures to elevated bioaerosol levels. This is the current position adopted by the Environment Agency (Environment Agency, 2010). Results from studies to date do not provide clear guidance as to where the distance boundaries from site should be placed, or what elevation in bioaerosol levels is harmful. Three studies have detected concentrations of total bacteria, and two investigations detected concentrations of *Aspergillus fumigatus* above the Environment Agency's recommended threshold levels above background beyond 250 m from the site, which might potentially be of concern to susceptible individuals and argues against reducing the current boundary, although studies certainly indicate lower exposures beyond 250 m compared with closer to the site. An additional problem is that background levels of bioaerosols are not well defined and are likely to vary both spatially and temporally.

To address current limitations in the evidence base, more detailed and longer term monitoring of various components of bioaerosols, better characterization of background bioaerosol levels, examination of the health effects over longer time scales and in larger numbers of individuals, use of objective measures of health outcomes (such as biomarkers, functional assessments such as lung function, and outcomes validated by examination of health records), and investigation of impacts in potentially sensitive groups (children, elderly, those with chronic illness, and reproductive health) is suggested. An initial research focus on respiratory and allergic disease is supported by the literature. Our paper summarizes available information on bioaerosol exposure profiles in relation to composting, and this may facilitate

comparisons with health studies in other settings (such as intensive agriculture) when exposure profiles are found to be comparable.

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