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Bioaerosol exposure from composting facilities and health outcomes in workers and in the community: A systematic review update

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ABSTRACT

Background: Rapid population growth and urbanisation around the world has led to increasing waste generation rates. Composting of organic waste in large-scale facilities is part of a growing trend in the UK, and elsewhere, to better manage and re-use the organic waste. However, composting inevitably generates bioaerosols, which have been associated with human health effects. In 2015, we reported that there was some, albeit limited, qualitative evidence linking bioaerosol emissions from composting facilities to poor respiratory health in nearby residents. However, the limited evidence precluded any quantitative assessment. Since then, the number of operational industrial-scale composting facilities in England has increased by 9% - nearly twice the growth from 2012 to 2014. At the same time, rapid urbanisation has led to expansion of city borders with more people living near large composting facilities and exposed to bioaerosol pollution. It is essential that regulatory authorities have access to the most up to date and accurate information.

Objective: In this update of a systematic review published in 2015, we review and summarise the evidence from more recent studies that have assessed bioaerosol exposures within and near composting facilities and their associated health effects in both community and occupational health settings. Specifically, we wanted to find out if new evidence has emerged since the previous review to strengthen and confirm its conclusions.

Material and methods: Two electronic databases (Medline and Embase) and bibliographies were searched for studies reporting on health outcomes and/or exposure to bioaerosols from composting facilities published between 1 January 2014 and 15 June 2018. Identification of relevant articles and data extraction was undertaken and studies were assessed for risk of bias.

Results: 23 studies met the inclusion criteria (15 exposure studies, 4 health studies, 4 health and exposure studies (one of which used an exposure proxy)). The majority of studies were conducted in occupational settings, and over short time periods. Some progress has been made in the characterisation of bioaerosol emissions from these composting facilities, with the application of molecular-based methods. Whilst the latest health studies do not rely solely on subjective self-reported measures of health status but include more objective health measures, these studies were almost exclusively carried out in compost workers and were characterised by profound methodological limitations. Only one community health study was identified and used a proxy measure of bioaerosol exposure.

Conclusions: Although this review identified an additional 23 studies since the earlier review, the conclusions remain largely unchanged. Given the absence of any consistent evidence on the toxicity of bioaerosols from composting facilities, there is insufficient evidence to provide a quantitative comment on the risk to nearby residents from exposure to compost bioaerosols. To improve risk assessment and to best advise on risk management, it is important to ensure that the research recommendations outlined in this review are addressed.

Abbreviations: ABAS, Ausschuss für Biologische Arbeitsstoffe (Committee on Biological Agents); ARG, Anti microbial Resistance Genes; DECOS, Dutch Expert Committee on Occupational Safety; EBC, Exhaled Breath Condensate; TBRA, Technischen Regeln für Biologische Arbeitsstoffe (Technical Rules for Biological Agents)

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1. Introduction

Around the world, waste generation rates are rising with rapid population growth and urbanisation. Worldwide, the amount of municipal waste generated is expected to triple by 2100 (Population matters, 2018). As a result, waste management has drawn increasing attention. In recent years, the UK has moved away from reliance on landfills towards more environmentally sustainable methods of managing waste and resources. A key driver in this has been the European Union Landfill Directive, which requires the UK (and other Member States) to reduce the biodegradable waste sent to landfill to 35% of the 1995 level by 2020 (Council of the European Union, 1999). Composting of organic waste in large-scale facilities is part of a growing trend in the UK and in 2017 there were 327 operational industrial-scale composting facilities in England, a 134% increase from the 2010 figure of 140 (Environment Agency, 2018c) (Fig. 1).

Commercial scale composting is conducted either in open-air turned windrows (long heaps of composting material), or in-vessel systems (also referred to as reactor systems and where the composting material is enclosed). Open windrow composting systems are employed by the vast majority (~70%) of facilities in the UK (Environment Agency, 2018c) The downside of composting is the biological air pollution (bioaerosols) released or produced, particularly as a consequence of agitation activities (such as shredding, turning and screening) (Taha et al., 2006). Bioaerosols, also known as primary biological airborne particles (PBAPs) have been linked to various health effects, affecting primarily the respiratory system, in a number of occupational settings, including composting (Pearson et al., 2015). The increased utilisation of composting as a sustainable waste management option, has led to increased public concern regarding potential health impacts within communities surrounding the sites. The Centre for Radiation, Chemical and Environmental Hazards (CRCE) within Public Health England (PHE) received 12 composting-related enquiries in August 2017 to August 2018, whereas there was only one composting-related enquiry in 2009–10 (PHE Environmental Hazards and Emergencies Department, personal communication, 6th September 2018).

We previously performed a systematic review of studies of bioaerosol exposures from waste composting and related health effects indexed in bibliographic databases up to July 2014 (Pearson et al., 2015). There was some, albeit limited, qualitative evidence linking bioaerosol emissions from composting facilities to poor respiratory health in nearby residents (Pearson et al., 2015). However, the limited evidence precluded any quantitative assessment. Rapid urbanisation has meant an expansion of city borders, and the boundaries of both rural and urban regions have becoming increasingly blurred (Eurostat, 2016) with more people likely to be living in the vicinities of industrial-scale composting facilities. In view of the potential health effects of nearby community exposure to composting bioaerosol and to ensure regulatory authorities have access to the most up-to-date information, this updated review looks at the evidence published since 2014.

1.1. Bioaerosol exposure at composting facilities

Composting results in elevated concentrations of bioaerosols, particularly during agitation activities (Taha et al., 2006). Bioaerosol concentrations and emissions are influenced by a number of biotic and abiotic factors (Brągoszewska et al., 2017). The continuation of an upward trend in the number of composting facilities is therefore likely to increase bioaerosol concentrations and diversity. Bioaerosols can stay suspended in the air for prolonged periods and potentially travel long distances from their source (Nygard et al., 2008) and as a result may pose health hazards to nearby communities with elevated exposures.

1.2. Potential health effects of bioaerosols at composting facilities

In many occupational settings, including composting, exposure to bioaerosols has been associated with a range of acute and chronic adverse health effects and diseases (Douwes, 2003; Pearson et al., 2015). The most commonly reported are respiratory system problems (e.g. rhinitis, asthma, bronchitis and sinusitis), through both atopic and non-atopic allergic mechanisms as well as non-allergic pathways (Douwes, 2003; Pearson et al., 2015). Other health problems reported include gastrointestinal (GI) disturbance, fatigue, weakness and headache (Douwes, 2003). Bioaerosol exposure occurs primarily through inhalation, although ingestion also contributes. Dependent on particle size, bioaerosols may penetrate into the lungs and become embedded in alveoli (Douwes, 2003; Ivens et al., 1999). While there is no conclusive evidence, several modes of action have been proposed to explain the association between occupational exposure to bioaerosols and health, such as airway inflammation and oxidative stress (Li et al., 2003; Qu et al., 2017; Samake et al., 2017). A robust systematic review of the literature (Pearson et al., 2015) found some, albeit limited, qualitative evidence of linkage between living near large-scale composting facilities and respiratory ill health. The annual report of the UK Chief Medical Officer, 2017 'Health Impacts of Air Pollution – what do we know?' also drew attention to the potential of public health risks from bioaerosol liberation at composting sites and highlighted the need for better understanding (Chief Medical Officer, 2017).

While there tends to be a bias towards the presumption of health risks from bioaerosols, the converse – beneficial health effects – may also

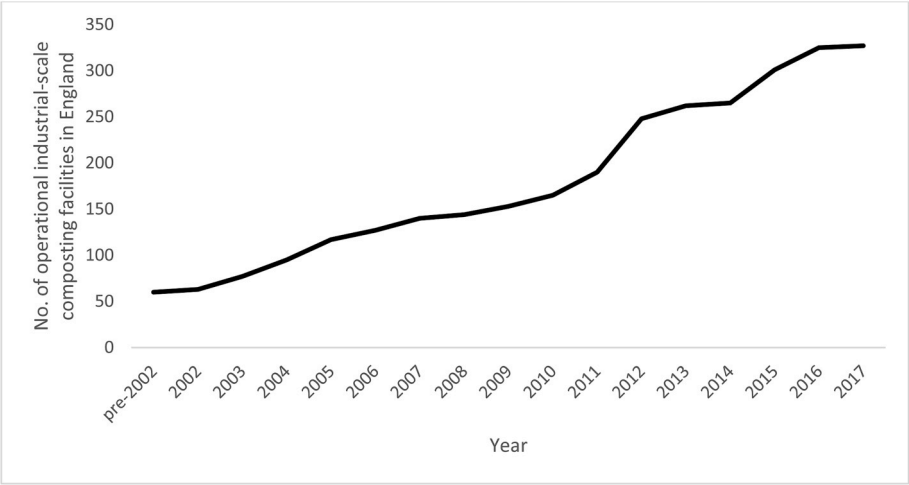


Fig. 1. Number of operational, industrial-scale composting facilities per year in England based on compost site permit data (Environment Agency, 2018c).

occur (e.g. increased microbial exposure, particularly during early life, may improve the immune system and reduce incidences of infection and allergic disease) (Bloomfield et al., 2016; Mirabelli et al., 2006).

1.3. Bioaerosol and composting legislation

At present, there are no quantitative dose-response estimates to inform legislation on bioaerosol emissions from composting facilities. The UK and several other countries, including Germany and the Netherlands, have developed regulatory guidelines to assess risk and control exposures to workers and nearby residents but these guidelines differ between countries. In England, the Environment Agency (EA) adopt a precautionary stance, and updated their guidance in January 2018 (Environment Agency, 2018a). In summary, composting facilities with 'sensitive receptors' (a place where people live or work for more than 6 h at a time) within 250 m of the site boundary are required to complete a site specific risk assessment, and monitor bioaerosols using the EA's Technical Guidance Note (M9) for the environmental monitoring of bioaerosols at regulated facilities (Environment Agency, 2018b). The M9 replaces the 2009 Association for Organics Recycling (AfOR) standardised protocol for the monitoring of bioaerosols at open composting facilities. Composting facilities should demonstrate that bioaerosols are maintained at 'acceptable levels' above background levels (Environment Agency, 2010, 2018a). The 'acceptable levels' are (Environment Agency, 2018a):

- 1000 colony forming units per cubic metre (CFU m^{-3}) for total bacteria;
- 500 (CFU m^{-3}) for Aspergillus fumigatus

Gram-negative bacteria levels are no longer required to be monitored (Environment Agency, 2018a). In the UK, there are no occupational exposure limits for bioaerosols. The Health and Safety Executive (HSE) 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 (Health and safety executive, 2016). Under these regulations, the duty holder is obliged to assess risk and control workers' exposure to as 'low as reasonably possible'. In Germany, the committee for Biological for Biological Agents (ABAS) have proposed a Technical Control Value of 50,000 CFU m^{-3} for mesophilic fungus (TBRA, 2019). A proposed occupational exposure limit of 90 endotoxin units per cubic metre (EU m^{-3}) has also been proposed in the Netherlands (8 h time weighted average) by the Dutch Expert Committee on Occupational Safety (DECOS) (DECOS, 2010). In Poland, the Polish Committee for the Highest Permissible Concentrations and Intensities of Noxious Agents in the Workplace have set limits of 100,000 CFU m^{-3} for mesophilic bacteria, 50,000 CFU m^{-3} for fungi and 200 ng m^{-3} – 2000 EU m^{-3} for endotoxin (Gutarowska et al., 2015).

1.4. Aim

The aim of this study was to undertake a systematic review of studies conducted in occupational and community settings measuring concentrations, and/or assessing the health effects associated with bioaerosol emissions within and nearby composting facilities. This is an update of an earlier systematic review (Pearson et al., 2015), which reported limited qualitative evidence of an association between living and/or working near large-scale composting facilities and ill health. Specifically, we wanted to find out if the relevant evidence that has accumulated over the last three years continue to support this position.

2. Material and methods

As per Pearson et al. (2015) the systematic review method was informed by Meta-Analyses and Systematic Reviews of Observational Studies (MOOSE) criteria (Stroup et al., 2000) and Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). The PROSPERO registration number is CRD42018089422.

2.1. Search strategy

A literature search was conducted across two electronic databases (Medline and Embase). The two search strings (provided in Appendix A) used to identify both health-based and exposure-based studies were identical to those developed by Pearson et al. (2015). The search strings were inputted within the title and abstract fields of the electronic database and adapted to each of the individual databases. The search was restricted to English-language papers published between 1 January 2014 and 15 June 2018. References were downloaded into the referencing software programme Endnote (version X8).

2.2. Study selection

After excluding duplicates, the selection of studies from the electronic databases was conducted in three stages; first by titles; next by abstract and then by full text (PD, EM, SR). A conservative approach was taken during the screening process. Any study with uncertain eligibility was taken forward for further consideration. To be included in the final analysis, studies had to fulfil all of the following inclusion criteria (adapted from Pearson et al. (2015)):

- The study was published in English between January 2014 and June 2018
- The study concerned exposure (studies that measured bioaerosol or used proxies) or health effects relating to bioaerosols emitted from composting sites
- The study was either peer reviewed or was published by a recognised institution

Studies were excluded if (adapted from Pearson et al. (2015)):

- They did not concern waste composting
- They did not concern bioaerosols
- They did not include 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
- Full texts were unavailable

Discrepancies were resolved by discussion between reviewers (PD, SR & EM) and, if necessary, referral to an independent reviewer (DJ).

2.3. Data extraction

The standardised checklist developed by Pearson et al. (2015) was used to extract data from studies that met the inclusion criteria. Information collected from all the studies were: study aims, study setting, statistical analysis, main findings and limitations. In studies containing health data, study design, study population, health metrics and outcome assessment were also extracted. In studies containing exposure information, the bioaerosols measured, bioaerosol sampling details and laboratory methods were also extracted, as well as any quantitative concentration data. The data extraction was conducted independently by two authors (exposure information by PD and EM, and health information by PD and SR).

2.4. Bias assessment

We used the quality assessment scoring tool from Douglas et al. (2018) which was itself previously developed from Shah et al. (2011).

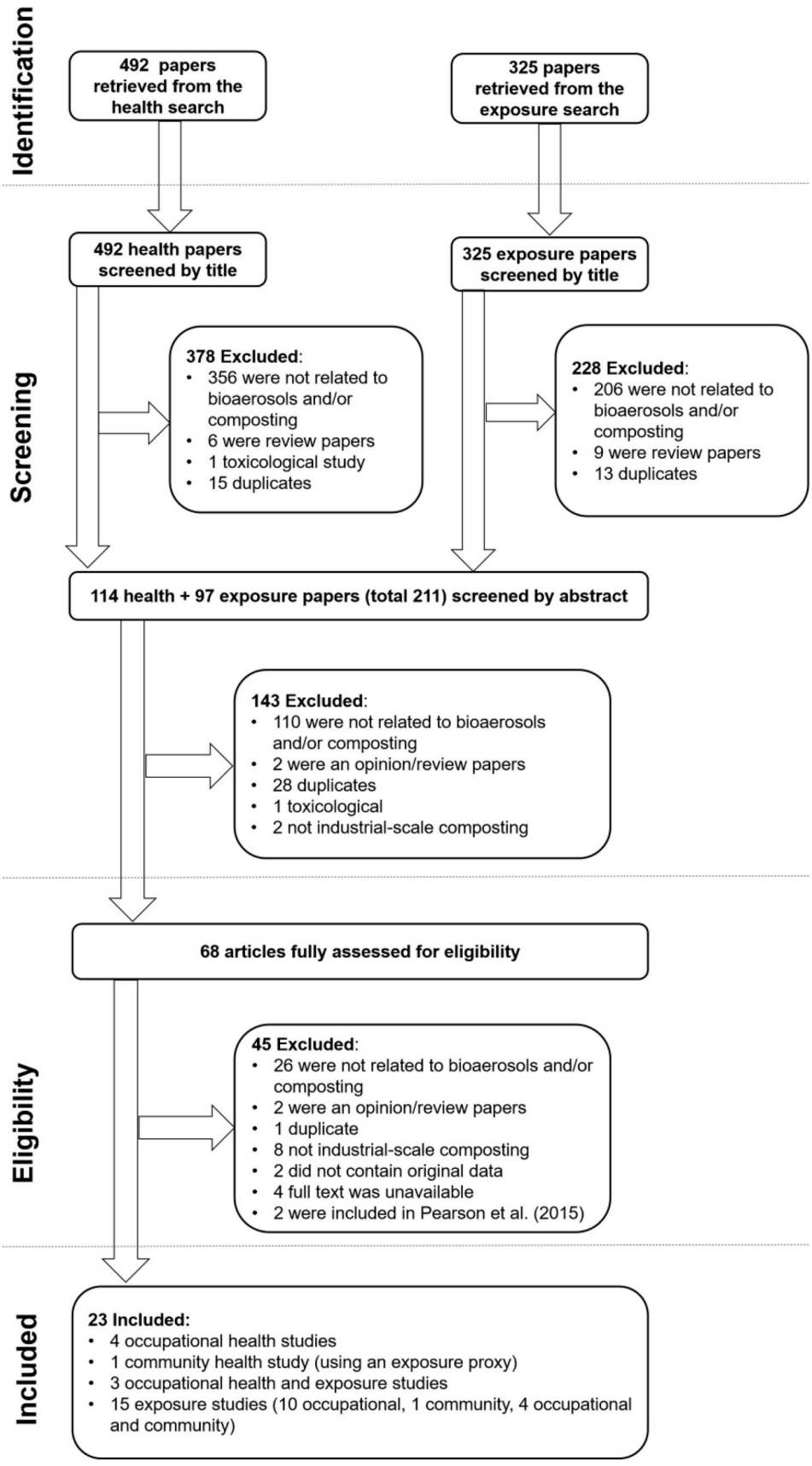


Fig. 2. Flow diagram summarising the study selection and exclusion process.

This scoring tool, which was originally designed to assess bias from cross-sectional and cohort studies, was adapted to allow bias from experimental and quasi-experimental studies (Appendix B). Two reviewers (PD, SR) independently 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 analysis. A third reviewer (EM, DJ) resolved any disputes. Scores were provided on a scale of 1–4; a score of 4 was given where there was a low risk of bias.

3. Results

3.1. Study selection

The study selection process is represented in Fig. 2.

After removing duplicates, the search strategies identified 817 citations, of which 606 were excluded on title screening. After screening for relevance on abstracts and full text, 23 papers remained. The most frequent reasons for exclusion were: did not concern bioaerosols, did not publish original data or did not concern composting. This review considered studies that measured exposures of bioaerosols and/or assessed the health effects associated with bioaerosol emissions within and nearby composting facilities; occupational and community studies were considered separately for both categories. Fig. 2 details the number of studies within each category.

Among the final set of 23 papers, there were 18 exposure studies, of which 17 examined occupational exposure (4 also looked at community exposure data). Eight health studies were reviewed, the majority of which were occupation-based (n = 7). Only three of the health studies included corresponding bioaerosol exposure data and all were conducted in an occupational setting (Gutarowska et al., 2018; Heldal et al., 2015, 2016; a fourth community health-based study used distance from site as a proxy of exposure (Douglas et al., 2016). The majority of studies were located in Germany, Canada, France, and England; studies involving these countries were included in the earlier review (Pearson et al., 2015). However, a number of papers were identified in previously unstudied regions of Europe, (Ireland, Hungary, Switzerland), as well as in non-European countries (India, China).

The full study characteristics of the exposure and health studies are listed in Table 1 and Table 2, respectively.

3.2. Exposure studies

Eighteen exposure studies (with measured exposures of bioaerosols) were reviewed; 13 of these were conducted in an occupational setting (Bonifait et al., 2017; Conza et al., 2014; Duquenne et al., 2015; Feeney et al., 2018; Gutarowska et al., 2015; Gutarowska et al., 2018; Heldal et al., 2016; Heldal et al., 2015; Mbareche et al., 2017; O'Connor et al., 2015; Rashidi et al., 2017; Sebok et al., 2016; Veillette et al., 2018), one in a community setting (Gales et al., 2015) and four in both an occupational and community setting (Gao et al., 2018; Pahari et al., 2016; Pasciak et al., 2014; Tamer Vestlund et al., 2014). Only two of the 18 exposure studies also assessed health outcomes (Heldal et al., 2015, 2016, with a further study investigating the *in vitro* cytotoxicity of settled dust collected from a composting facility (Gutarowska et al., 2018).

The methods used in the exposure studies varied, with different bioaerosol types and species being measured, using different sampling methods and analytical techniques. It was not possible to extract exposure data on airborne levels when values were not included in the manuscript, or qualitative analyses were used.

3.2.1. Sampling methods and analytical techniques

Studies were heterogenous in design, and the bioaerosols were sampled, and analysed using different methods, as summarised in Table 1.

The majority of studies used a combination of different samplers. Coriolis liquid impinger samplers (n = 4), Andersen impaction samplers (n = 5) or filter samplers (n = 4), sampling for short periods of time (Coriolis: 4–10 min, Andersen: 2–15 min, Filter: 30–360 min). Two studies adopted longer-term (> 24 h) sampling methods (Feeney et al., 2018; O'Connor et al., 2015). These studies used Wideband Integrated Bioaerosol Sensors (WIBS) to sample fluorescent particles or a spore watch spore counter (to count spores per hour) (Feeney et al., 2018). However, sampling times remained relatively short (7 days). In some studies it was not clear what sampling time was used (e.g. sampling time was reported for one sampling method but not another); and three studies did not report a sampling time (Pasciak et al., 2014; Rashidi et al., 2017; Sebok et al., 2016).

Many different analytical techniques were used to quantify/identify bioaerosols in the collected samples, with all 18 studies performing some type of microbial characterisation. The majority of studies (n = 10) used culture based methods; seven of which complemented the culture methods with further verification methods (such as microscopic imaging; biochemical, physiological, antibiotic susceptibility or chemotaxic testing; immunofluorescence assays; mass spectroscopy; or microbial DNA sequencing). The different analytical techniques used by the studies are summarised in Appendix C.

Five studies extracted DNA directly from air samples or settled dust to analyse the wider (culture independent) microbial characteristics of bioaerosols; using polymerase chain reaction (PCR)-based methods and/or next generation sequencing (NGS) for downstream microbial identification. Four studies used PCR to detect bacteria (Bonifait et al., 2017; Gales et al., 2015; Gao et al., 2018; Veillette et al., 2018). Two of these studies (Bonifait et al., 2017; Gales et al., 2015) also used PCR to detect fungal species. Four studies used NGS to amplify 16S rRNA and/or rDNA ITS1/2 regions to identify bacteria and fungi, respectively (Gao et al., 2018; Gutarowska et al., 2018; Mbareche et al., 2017; Veillette et al., 2018). No studies used whole genome sequencing to analyse all of the microbial DNA (metagenome) within collected samples. One study (Gao et al., 2018) detected antimicrobial resistance genes (ARGs).

In addition, nine studies performed some type of other (non-microbial) bioaerosol characterisation. Seven studies used spectroscopy, gravimetry or WIBS to measure inhalable dust/particulate matter (PM). Four studies, including two studies that also included health data (Heldal et al., 2015, 2016), used the Limulus amoebocyte lysate (LAL) assay (Duquenne et al., 2015; Heldal et al., 2015, 2016) or mass spectroscopy (Gutarowska et al., 2015) to quantify endotoxin concentrations. One study used the MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assay to measure the cytotoxicity of settled dust in human lung cells (Gutarowska et al., 2018). While cytotoxicity is not a microbial characteristic *per se*, it may be related to microbial and/or non-microbial bioaerosol characteristics.

3.2.2. Bioaerosols/pollutants measured

Most studies reported bioaerosol concentrations, although it was not always possible to extract this data from the study (e.g. data was only presented in graphs/figures). There was no one bioaerosol characteristic that was consistently measured across all of the studies. However, eleven studies enumerated total bacteria, eight total fungi, eight Actinobacteria, four endotoxins, and eight measured inhalable dust/particulate matter/fluorescing particulate concentrations. Seven of these studies also measured the size distribution of microbial particles and/or inhalable dust/particulate matter (see section 3.2.3).

Where possible, the concentrations of total bacterial and total fungi, the most commonly measured bioaerosols enumerated from the different studies, are summarised in Figs. 3 and 4 respectively.

Overall total bacteria concentrations were higher than total fungi, and both were highly variable, with measurements of total bacteria and total fungi ranging across eight orders of magnitude (~10–~1,000,000,000 CFU m^{-3} for total bacteria and ~1 to ~100,000,000 CFU m^{-3} for total fungi). There was evidence of considerable within site variability from replicates as denoted by the error bars in the graph, which represent minimum and maximum reported

Table 1
Characteristics of the exposure studies included in the review (excludes Douglas et al., 2016 as this study used an exposure proxy).

Author (year)	Country	Number/type of sites studied	Exposure sampling location/ activity	Exposure sampling methods[a]	Bioaerosols/pollutants measured & analytical methods[b]	Comments
Occupational exposure studies						
Bonifait et al. (2017)	Canada	3 composting facilities: ● domestic (green waste) ● manure (manure & hay) ● carcasses (pig carcasses & placenta)	5 locations/activities per facility: ● on-site, no work activities ● on-site, beginning of work activities ● on-site, middle of work activities ● on-site, end of work activities ● outdoor, upwind	Samplers: ● Coriolis μ® liquid impinger (300 L min^{-1}, 10 min) ● Six stage Andersen impactor (28.3 L min^{-1}, 2 min) Numbers: ● n = 1 per location/activity per facility per visit ● total samples = 70 Timing: ● 4–5 visits per facility ● Apr 2014–Mar 2015	Culture + morphological identification **(1B)**: ● mesophilic bacteria ● mesophilic moulds ● thermophilic Actinomycetes ● A. fumigatus qPCR **(2E)**: ● total bacteria ● total mycobacteria ● total *legionella* ● *L. pneumophilia* ● *Penicillium/Aspergillus/Paecilomyces varioti* ● *A. fumigatus/Neosartorya fischeri* ● *S. rectivirgula*	● On-site exposure to total fungi exceeded German occupational exposure limits ● May have sampled at some of the same facilities as Mbareche et al. (2017)
Conza et al. (2014)	Switzerland	8 open windrow green waste composting facilities: ● 4 in Southern Switzerland ● 4 in Northern Switzerland Plus 5 communal outdoor green waste storage centres in Southern Switzerland (3 short term & 2 long term storage)	3 or 4 locations from steaming compost piles up to a maximum distance of 5 m per facility Plus 1–5 compost samples per facility & 1–2 compost samples from 2 short term & 2 long term storage centres (~1 kg, 30 cm depth)	Sampler: ● Coriolis μ® liquid impinger (250 L min^{-1}, 4 min) Numbers: ● n = 1 per location per facility ● total samples = 31 Timing: ● 1 visit per facility ● Southern facilities – May–Aug 2009 ● Northern facilities – May–Aug 2010	Culture + DNA sequencing **(1E)**: ● free-living amoebae Co-culture + MALDI-TOF mass spectroscopy/ slide agglutination **(1C/D)**: ● Legionella Co-culture + immunofluorescence assay **(1D)**: ● *Legionella pneumophila*	● Sampling methods and locations also described in Conza (2013)
Duquenne et al. (2015)	France	15 composting facilities processing one or a combination of: ● wastewater sludge ● green waste ● household organic waste ● residual household waste ● faecal matter	5-35 locations close to the main composting activities per facility	Sampler: • closed-face three-piece cassette filter connected to a GilAir® pump (2 L min-1, 36–210 min (median 90 min), height of 1.7 m) Numbers: ● total samples = 281 (270 analysed) Timing: ● 9 facilities were visited once ● 6 facilities were visited twice ● Jun 2009–Jan 2012	LAL assay **(3C)**: ● endotoxin	● Omitting deposits on the inner surfaces of the cassette filters from analysis underestimated the concentrations measured ● 35% of the samples were above the OEL of 90 EU m^{-3} proposed by the Dutch Expert Committee on Occupational Standards in 2010
Feeney et al. (2018)	Ireland	1 green waste open windrow composting facility	1 location at the North West corner of the facility during high, low or no activity	Samplers: ● WIBS-4A (7 days, 0.5–15 μm) ● spore watch electronic spore & pollen sampler (10 L min^{-1}, tape surface moved 2 mm h^{-1}, 7 days, height of 3 m) Numbers: ● continuous sampling over 7 days with a resolution of 1 h Timing: ● 1 visit ● 29th Feb-7th Mar 2016	Spore sampler + optical microscopy **(2A)**: ● fungal spores WIBS-4A **(2B/3B)**: ● bioaerosols (fluorescent) ● non-fluorescent dust ● size & shape data	● Two methods show some correlations & overlap ● Sampled at the same facility as O'Connor et al. (2015)

(*continued on next page*)

Table 1 (*continued*)

Author (year)	Country	Number/type of sites studied	Exposure sampling location/ activity	Exposure sampling methods[a]	Bioaerosols/pollutants measured & analytical methods[b]	Comments
Gutarowska et al. (2015)	Poland	4 composting facilities: • 2 green waste (urban areas, fruit & vegetable markets, horticultural facilities) • 2 producing substrates for industrial cultivation of button mushrooms (wheat & rye straw, chicken & horse manure)	3 locations/activities per facility: • mushroom substrates 1 – seeding/sell halls • mushroom substrates 2 – loading/transfer/sell halls • green waste 1 – open air area • green waste 2 – sorting area/ loading hall/machine room • offices (internal background) • atmospheric air (external background, 5–10 km from facility) Plus dust samples from green waste 2 waste sorting area, & green waste 2 seeding/sell halls	Samplers: • MAS-100 Eco air sampler (according to PN-EN 13098:2007 standard, 50 & 100 L, height of 1.5 m) • six-stage Andersen impactor (28.3 L min^{-1}, 5 min, height of 1.5 m, in production hall of 1 mushroom compost producing facility during activity & following cleaning plus internal & external backgrounds) Numbers: • MAS-100 – n = 16–18 per location/ activity, total samples = 70 • Andersen – n = 3 per location/activity, total samples = 24 Timing: • 1 visit per facility • Feb–Mar 2013	MAS-100 sampler + culture **(1A)**: • total bacteria • total fungi MAS-100 sampler + culture + morphological & biochemical identification **(1B)**: • bacterial diversity • fungal diversity MAS-100 sampler + culture + NGS **(1F)**: • bacterial indicators of microbiological contamination (16S rRNA) • fungal indicators of microbiological contamination (ITS1/2 rDNA) Andersen impactor + culture **(1A)**: • size distribution of bacteria • size distribution of fungi GCMS **(3D)**: • endotoxin	• Bacteria were the predominant group of airborne microorganisms in composting facilities producing button mushroom substrates (78–88%) while fungi dominated in green waste composting facilities (53–56%) • Total microorganisms did not exceed quantitative. Polish thresholds, although the highest measured upper limit exceeded BAUA limits • May have sampled at some of the same facilities as Pasciak et al. (2014)
Mbareche et al. (2017)	Canada	2 composting facilities: • domestic (green waste) • animal (pig carcasses & placenta)	5 locations/activities per facility: • on-site, prior to any activity • on-site, beginning of work activities • on-site, middle of work activities • on-site, end of work activities • off-site, upwind Plus compost samples (1 L)	Sampler: • Coriolis μ® liquid impinger (300 L min^{-1}, 10 min) Numbers: • n = 1 per location/activity per facility per visit • total samples = 30 Timing: • domestic facility – 4 visits (2 in spring & 2 in summer) • animal facility – 2 visits (1 in summer & 1 in autumn)	NGS (ITS1/2 genes) **(2D)**: • fungal diversity	• Some fungi were enriched in the air (compared to compost) • Recommend taking action to reduce worker exposure
O'Connor et al. (2015)	Ireland	1 green waste open windrow composting facility	3 locations/activities: • ~20 m South-East of outdoor product compost area & ~20 m North-East of deliver/loading/green waste area during heavy, light & no activities (WIBS-4 only) • ~100 m upwind (Andersen only) • ~100 m downwind (Andersen only)	Sampler: • WIBS-4 (7 days, height of 1.5–2.0 m, < 13 μm) • Andersen grab sampler (15 min) Numbers: • WIBS – continuous sampling over 7 days • Andersen – n = 1 per location, total samples = 2 Timing: • WIBS – 30th Sep-1st Oct 2014 (1 day heavy activity), 10th-13th Oct 2014 (3 day no activity) & 15th-17th Oct 2014 (3 day light activity) • Andersen – 13.00–14.00 on 16th Oct 2014	WIBS-4 **(2B/3B)**: • bioaerosols (fluorescent) • non-fluorescent dust • size & shape data Andersen sampler + culture (following M9 sampling protocol) **(1A)**: • mesophilic bacteria • *A. fumigatus*	Total fungi & bacteria counts during light activity were below expected ambient levels
Rashidi et al. (2017)	Iran	1 municipal waste composting facility (food waste, paper, wood, street wastes, ferrous & non-ferrous metals, glass, plastic, etc)	4 locations with high worker traffic: • screen • conveyor belt • aerated pile • static pile	Sampler: • multi-stage QuickTake 30 impactor (according to ASTM E884-82 (2001) guidelines, 28.3 L min^{-1}, height of ~1.5 m) Numbers: • n = 4 per location • total samples = 20 Timing: • summer & winter 2015	Culture **(1A)**: • total bacteria • total fungi • *S. aureus* • *Klebsiella*	• Concentrations of bacteria & fungi were higher than the microbial standard for inhaled air • Recommend methods to reduce worker exposure

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Table 1 (*continued*)

Author (year)	Country	Number/type of sites studied	Exposure sampling location/ activity	Exposure sampling methods[a]	Bioaerosols/pollutants measured & analytical methods[b]	Comments
Sebok et al. (2016)	Hungary	3 composting facilities: ● municipal waste (paper, food residuals, plastics, etc) ● agricultural waste (plant residues) ● horticultural waste (plant residues, potting soil, green waste)	1 location per facility: ● 1 m from composting piles ● plus 1 unspecified natural (pasture) off-site environment (background for all facilities) Plus compost samples (~ 1 kg)	Sampler: ● Andersen impactor (28.3 L min^{-1}, height of 1.5 m) Numbers: ● n = 3 (3 days of 3 consecutive weeks per month visited) per facility per visit ● total samples = 48 Timing: ● 4 visits ● Oct 2011, & Jan, Apr & July 2012	Culture **(1A)**: ● thermophilic fungi Culture + morphological identification + confirmation with NGS (ITS region) **(1B/1F)**: ● fungal diversity	
Veillette et al. (2018)	Canada	3 composting facilities: ● domestic waste (green waste) ● vegetal waste (manure, cow bedding) ● animal waste (pig carcasses & placenta with spinet)	2-4 locations/activities per facility: ● domestic waste – 1–2 m from sorting or sieving ● vegetal waste – 1–2 m from filling, transfer, maturation or spreading ● animal waste – 1–2 m from filling or brewing Plus compost samples (10 L)	Sampler: • Coriolis μ® liquid impinger (300 L min-1, 10 min) Numbers: ● n = 3 per location/activity per facility per visit ● total samples = 60 (only 38 analysed) Timing: ● domestic facility – 4 visits (2 in Apr & 2 in July) ● vegetal facility – 2 visits (Jun–Aug) ● animal facility – 2 visits (Jun–Sep)	qPCR **(2E)**: ● total bacteria ● total mycobacteria ● *S. rectivirgula* NGS (16S V6—V8 region) **(2D)**: ● bacterial diversity	● Some species seem to have a preference for aerosolisation ● Source material composition may not be a good proxy of the composition & nature of bioaerosols ● May have sampled at some of the same facilities as Mbareche et al. (2017)
Gutarowska et al. (2018)	Poland	1 composting facility Plus 4 other non-composting facilities (cement plant, poultry farm, cultivated area)	1 location (homogenisation hall) with 1–5 workers Plus settled dust (1.5 m, 24 h)	Sampler: ● DustTrak™ DRX aerosol monitor 8533 portable laser photometer (3 L min^{-1}, 1 s sampling interval over 24 h, height of 1.5 m, 0.1–15 μm, 0.001–150 mg m^{-3}) Numbers: ● n = 3 ● total samples = 3 (+n = 3 settled dust samples) Timing: ● 1 visit ● 9th Sep 2017	Spectrometry **(3B)**: ● PM_1 ● $PM_{2.5}$ ● PM_4 ● PM_{10} ● total PM Culture (settled dust) **(1A)**: ● total bacteria ● total fungi ● xerophilic fungi ● Actinomycetes ● haemolytic *Staphylococcus* ● *Staphylococcus* spp ● *Pseudomonas fluorescens* ● *Enterobacteriaceae* NGS (settled dust) **(2D)**: ● bacterial diversity (16S rRNA V3—V4 region) ● fungal diversity (ITS region) MTT assay (settled dust) **(3E)**: ● cytotoxicity	● Fungal & bacterial diversity measured in settled dust ● Sampled the same composting facility as Gutarowska et al. (2015)
Occupational exposure studies that also contain health data						
Heldal et al. (2015)	Norway	10 composting facilities (organic household waste, sewage sludge, organic food industry waste): ● 5 open windrow ● 5 closed reactors	2 locations/activities: ● compost workers' personal environment ● 37 office workers' personal environment Plus 44 sewage workers	Sampler: ● personal PAS-6 cassette filter connected to an air pump (2 L min^{-1}, ~6 h single shift) Numbers: ● n = 47 compost workers ● n = 37 office workers ● n = 2 per worker (for different measurements) ● total samples = 168	Gravimetry **(3A)**: ● inhalable dust Fluorescence microscopy **(2A)**: ● non-branching bacteria SEM **(2A)**: ● Actinomycetes spores ● fungal spores LAL assay **(3C)**: ● endotoxin	All samples exceeded BAUA limits

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Table 1 (*continued*)

Author (year)	Country	Number/type of sites studied	Exposure sampling location/ activity	Exposure sampling methods[a]	Bioaerosols/pollutants measured & analytical methods[b]	Comments
				Timing: • 1 measurement between two health examinations (1 prior to, & 1 following, exposure)		
Heldal et al. (2016)	Norway	10 composting facilities • 5 open windrow • 5 closed reactors Plus 8 sludge treatment facilities (4 with driers & 4 without)	2 locations/activities: • compost workers' personal environment • 38 office workers' personal environment	Sampler: • personal PAS-6 cassette filter connected to an air pump (2 L min^{-1}, 4–5 h single shift) Numbers: • n = 47 compost workers • n = 38 office workers • n = 2 per worker (for different measurements) • total samples = 170 (3 lost due to disrupted pump flow) Timing: • 1 measurement between two health examinations (1 prior to, & 1 following, exposure)	Gravimetry **(3A)**: • inhalable dust Fluorescence microscopy **(2A)**: • total bacteria SEM **(2A)**: • Actinomycetes spores • fungal spores LAL assay **(3C)**: • endotoxin	• Measured upper levels exceed BAUA limits • Used the same compost workers as described in Heldal et al. (2015)
Occupational and community exposure studies						
Gao et al. (2018)	China	4 composting facilities (mixture of manures from cattle, poultry & swine, mushroom residue & corn straw)	5 locations/activities per facility: • composting area (n = 9) • packaging area (n = 7) • office area (n = 8) • ~250 m downwind (n = 4) • plus 1 sample ~250 m upwind (background for all facilities)	Sampler: • total suspended particulate impactor (100 L min^{-1}, 24 h) Numbers: • n = 1–3 per location/activity per facility • total samples = 29 Timing: • 1 visit per facility • Oct 2014–Oct 2015	NGS (16S rRNA V3−V4 region) **(2D)**: • bacterial diversity ddPCR **(2E)**: • *Escherichia coli* • Staphylococcus spp • class 1 integron: intl1 • 4 ARG types: - β-lactam - tetracycline - sulphonamides - erythromycin • 22 ARG subtypes: - β-lactam: blaCARB-4, blaOXA-18, blaOXA1, blaOXAII, blaOXAIII, blaPSE, blaTEM - tetracycline: tetQ, tetM, tetS, tetT, tetW, tetA/P, tetG, tetL, tetZ, tetX - sulphonamides: sul1, sul2, sul3, dfrA1 - erythromycin: ermB	
Pahari et al. (2016)	India	1 waste treatment facility with an open windrow composting area (vegetable market waste & municipal solid waste [organic matter, plastic, rubber, cloth, wood, paper, glass, metal, sand/ stone])	7 locations/activities: • on-site, morning, high activity in waste receiving & pre-sorting section • on-site, lunch break, no/low activity • on-site, afternoon, high activity in the compost windrow, & compost refinement & bagging sections • off-site, afternoon, ~200 m East • off-site, afternoon, ~120 m North-West	Samplers: • six-stage Andersen impactor (28.3 L min^{-1}, 2 min, height of 1.2 m) • EnviroTech high volume sampler (1.2 L min^{-1}, 30–95 min, height of 1.2 m, < 10 μm) • three-stage Siotus personal cascade impactor (9 L min^{-1}, 30–95min, height of 1.2 m, 0.5–2.5 μm & > 2.5 μm) • used simultaneously Numbers: • Andersen – n = 2 per location/activity, total samples = 14 • EnviroTech – n = 1 per location/activity, total samples = 7	Andersen sampler + culture **(1A)**: • non-fastidious bacteria • Actinomycetes Andersen sampler + culture + biochemical tests + NGS (16S rDNA) **(1B/1F)**: • bacterial diversity EnviroTech sampler **(3A)**: • > PM_{10} Siotus impactor **(3A)**: • $PM_{0.5\text{-}2}$ • > $PM_{2.5}$	• Observed good correlation between total bioaerosols & aerosols (PM_{10}) collected using the Andersen impactor & EnviroTech sampler, respectively • Observed bioaerosols levels near the slum area exceeded the recommended values • Facility possibly contributed to elevated concentrations of bioaerosols in the nearby slum area

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Table 1 (*continued*)

Author (year)	Country	Number/type of sites studied	Exposure sampling location/ activity	Exposure sampling methods[a]	Bioaerosols/pollutants measured & analytical methods[b]	Comments
			• off-site, afternoon, ~190 m South-East • off-site, lunch break & afternoon, ~150–200 m West near slum area	• Siotus – n = 1 per location/activity, total samples = 7 Timing: • 1 visit • Dec 2014–Mar 2015		
Pasciak et al. (2014)	Poland	1 facility producing compost for mushroom growing	7 locations/activities: • production & sales halls (n = 9) • offices & laboratories (n = 7) • entrance (n = 2) • facility owners' house (100 m from the facility) (n = 9) • facility owners' house entrance (n = 2) • facility owners' car (n = 2) • outdoor, ~2 km from facility (n = 5) Plus n = 3–5 surface samples (walls & equipment of the production hall) & compost samples	Sampler: • MAS-100 Eco Air sampler (50 or 100 L) Numbers: • n = 3–5 per location/activity • total samples = 36 Timing: • 1visit • Nov 2008–Feb 2009	Culture **(1A)**: • total bacteria Culture + biochemical, morphological identification **(1B)**: • aerial mycelium actinobacteria • bacterial diversity Culture + physiological, antibiotic susceptibility, chemotaxic & 16S rRNA sequencing based identification **(1B/F)**: • predominant actinobacterial strain	One case of hypersensitivity penumonitis in an office worker (&, although not clinically confirmed, chronic headaches & weakness of other workers and the owner's family members) reported
Tamer Vestlund et al. (2014)	England	1 open windrow composting site	10 locations/activities: • source (windrow) using a wind tunnel (static source) • source (windrow) from agitation activities (agitation) • 2 by the screening area • 2 at source (windrows) • 10 m downwind of windrows • 50 m downwind of windrows • 100 m downwind of windrows • 50 m upwind	Sampler: • personal SKC filter sampler (2 L min-1, 30 min, height of 1.8 m) Numbers: • n = 3 • total samples = 30 Timing: • 1 visit	SEM **(2A)**: • particle: - number - size (0.5–10 μm) - shape - type - aggregation status	
Community exposure studies						
Gales et al. (2015)	France	One green waste open windrow composting facility	2 locations during agitation activities: • 50 m downwind • 100 m upwind	Samplers: • 11-stage ELPI™ electrical low pressure impactor (10 L min^{-1}, 90 min, 3 nm-10 μm) • GRIMM optical particle counter (1.2 L min^{-1}, 90 min, 0.3–20 μm) Numbers: • ELPI™ – n = 1 (50 m downwind location only) per visit, total samples = 3 • GRIMM n = 1 per location per visit, total samples = 8 Timing: • ELPI™ – 3 visits, 11th, 12th & 18th Sep 2012 • GRIMM – 8 visits, 10^{th}-13th & 17^{th}-20th Sep 2012	Real-time spectroscopy **(3B)**: • particle: - number - size (0.3–20 μm) Culture **(1A)**: • size distribution of thermophilic cells qPCR **(2E)**: • size distribution of: - total bacteria - S. rectivirgula & relatives - A. fumigatus Flow cytometry **(2C)**: • size distribution of total microbial cells	

[a] Where values are not provided for specific sampling parameters (such as flow rate, sampling time, sampling height etc.), they were not reported.
[b] Numbers correspond to the sampling method as detailed in Appendix C.

Table 2
Characteristics of the health studies included in the review.

Author (year)	Study design	Setting	Population/subjects studied	Exposure assessment[a]	Outcome assessment	Bioaerosols/pollutants studied
Douglas et al. (2016)	Cross-sectional small area ecological study (community study)	All permitted industrial-scale composting facilities operating 2008–2010, with an outdoor composting component, in England (n = 148; of which 117 open windrow and 31 in-vessel)	34,963 respiratory hospital admissions in 4656 census output areas within 250–2500 m of a compost site	Distance from site was used as a proxy for bioaerosol exposure (pre-defined distance bands of 0–250, 250–750, 750–1500 and 1500–2500 m; distance as a continuous measure was also examined)	Emergency and non-emergency hospital admissions for postcode areas (from Hospital Episode Statistics), with a respiratory-related primary diagnosis for admission (according to International Classification of Disease (ICD10) code) (also stratified into respiratory infections, asthma, and chronic obstructive pulmonary disease (COPD))	None (distance used as a proxy for bioaerosol exposure)
Gutarowska et al. (2018)	Lab-based toxicological study (occupational study)	A composting facility, two cement facilities, a poultry farm and a cultivated area located in Poland	No subjects – the A-549 cell line (human adenocarcinoma lung epithelial adherent cells) was used to analysis the toxicity of dust collected from 4 working environments	Measurement technique: Airborne dust concentration was measured by using a DustTrak™ DRX Aerosol Monitor 8533 portable laser photometer (TSI). Measurements obtained at a height of 1.5 m from ground level in triplicate for each location, with a sampling rate of 3 L min and a sampling interval of 1 s. Also, settled dust samples (part of airborne particulate matter (PM) that fell down onto sampling surface during work activities) was collected onto 5 glass plates (positioned 1.5 m from ground level) for 24 h. Identification/enumeration of microbial community Identification of bacteria and fungi by cell culture methods and by using polymerase chain reaction (PCR) amplification and sequencing of ribosomal RNA.	The MTT assay was used to analyse the cytotoxicity and cell viability of human lung adenocarcinoma epithelial cells (A-549) exposed to dust samples.	Xerophilic fungi and non-xerophilic species, total number of bacteria, haemolytic *Staphylococcus*, Actinomycetes, mannitol-positive *Staphylococcus* spp, *Pseudomonas fluorescens*, *Enterobacteriaceae*; sequencing regions of rRNA genes from bacteria (16S) and fungi (ITS); mass concentrations of size-segregated particles (PM_{total}, PM_{10}, PM_4, $PM_{2.5}$ & PM_1)
Heldal et al. (2015)	Occupational quasi-experimental (pre-post shift)	5 Windrow (mainly outdoor) composting sites and 5 reactor (composting mainly indoors) facilities in Norway	47 workers (20 windrow compost workers; 27 reactor facility workers) and 37 unexposed controls (mainly white collar workers from the administration at the facilities)	Personal filter samplers (PAS-6 cassettes) at a flow rate of 2 L min^{-1} 2 different filters were used: (1) polycarbonate filter (pore size 0.8 μm) for microbiological analysis (total bacteria, fungal & Actinomycetes spores); (2) glass fibre filters for endotoxins	Self-administered questionnaire, spirometry, acoustic rhinometry, blood samples collected (post-shift only) for measurement of blood pneumoproteins (CC16; SP-A; SP-D)	Endotoxin, fungal spores, Actinomycetes spores, non-branching bacteria, inhalable dust
Heldal et al. (2016)	Occupational quasi-experimental (pre-post shift)	10 compost facilities (5 windrow facilities & 5 reactor facilities)and 8 sewage sludge treatment facilities in Norway	47 compost workers (as described in Heldal et al. (2015)), 44 sewage facility workers (19 from 4 facilities using sludge drying, 25 from 4 facilities that didn't use sludge drying), 38 unexposed controls (all administrative staff from the facilities; 28 from the compost facilities & 9 from the sewage treatment facilities)	Personal filter samplers (PAS-6 cassettes) at a flow rate of 2 L min^{-1} for approx. 4–5 h 2 different filters were used: (1) polycarbonate filter (pore size 0.8 μm) for microbiological analysis (total bacteria, fungal & Actinomycetes spores); (2) glass fibre filters for endotoxins Personal filter samplers (PAS-6 cassettes) at a flow rate of 2 L min^{-1} for approximately 5–6 h Exposure assessment not conducted	Post-shift only Self-administered questionnaire spirometry, blood samples collected for measuring levels (concentrations) of biomarkers of inflammation (CRP; ICAM-1, VCAM), coagulation (fibrinogen, D-dimer) and allergen-specific IgE antibodies	Inhalable dust, total bacteria, fungal spores, Actinomycetes spores, endotoxin Exposure assessment not conducted

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Table 2 (*continued*)

Author (year)	Study design	Setting	Population/subjects studied	Exposure assessment[a]	Outcome assessment	Bioaerosols/pollutants studied
Hoffmeyer et al. (2014)	Occupational cross-sectional study	31 composting sites in north-western Germany	190 currently exposed compost workers, 59 former compost workers, 38 white-collar workers without occupational exposure		Self-administered questionnaire diagnosis of chronic bronchitis, rhinitis and conjunctivitis was based on the proportion of self-reported symptoms, spirometry was used to diagnose COPD and the GOLD classification system was used to categorise disease severity (I-IV), score-based diagnosis of asthma (included a questionnaire & examination for clinical measures of asthma & atopy)	
Hoffmeyer et al. (2015)	Occupational cross-sectional study	31 composting sites in north-western Germany	119 currently exposed compost workers, stratified by smoking and atopy (from same cohort as used in Hoffmeyer et al. (2014))	Self-administered questionnaires (daily time per task, personal protective device uses) and results of ambient monitoring at workplaces was used to categorise subjects into 2 exposure groups: high and low level exposure	Airway inflammation/oxidative stress using: (1) exhaled breath condensate (EBC) collection for pH & concentrations of eicosanoids and (2) fractional exhaled nitric oxide (FeNO) Blood samples collected for measuring levels (concentrations) of allergen-specific IgE antibodies	None
Raulf et al. (2015)	Occupational cross-sectional study	31 composting sites in north-western Germany	140 currently exposed compost workers, 49 former compost workers and 29 white-collar workers from same cohort as used in Hoffmeyer et al. (2014)	Exposure assessment not conducted	Self-administered questionnaire, diagnosis of chronic bronchitis was based on a combination of the proportion of self-reported symptoms and spirometry test; blood samples collected for allergen-specific IgE test (allergy detection), induced sputum was analysed for total and differential cellular counts and for concentrations of total protein, soluble CD14, MMP-9, 8-iso-$PGF_{2\alpha}$ and IL-8	Exposure assessment not conducted
van Kampen et al. (2016)	Occupational cohort study 13-year follow-up (1996/7–2009)	31 composting sites in north-western Germany	74 currently exposed compost workers, 42 former compost workers (who had left during the 13-year follow-up) and 37 non-exposed controls (from same cohort as used in Hoffmeyer et al. (2014))	Exposure assessment not conducted	Exposure groups (current, former, controls) categorised into cough, cough with phlegm or chronic bronchitis based on proportion of self-reported symptoms, blood samples collected for allergen-specific IgE test (allergy detection), indices derived from spirometry were used to diagnose COPD	Exposure assessment not conducted

[a] See Table 1 for details. Where values are not provided for specific sampling parameters (such as flow rate, sampling time, sampling height etc.), they were not reported.

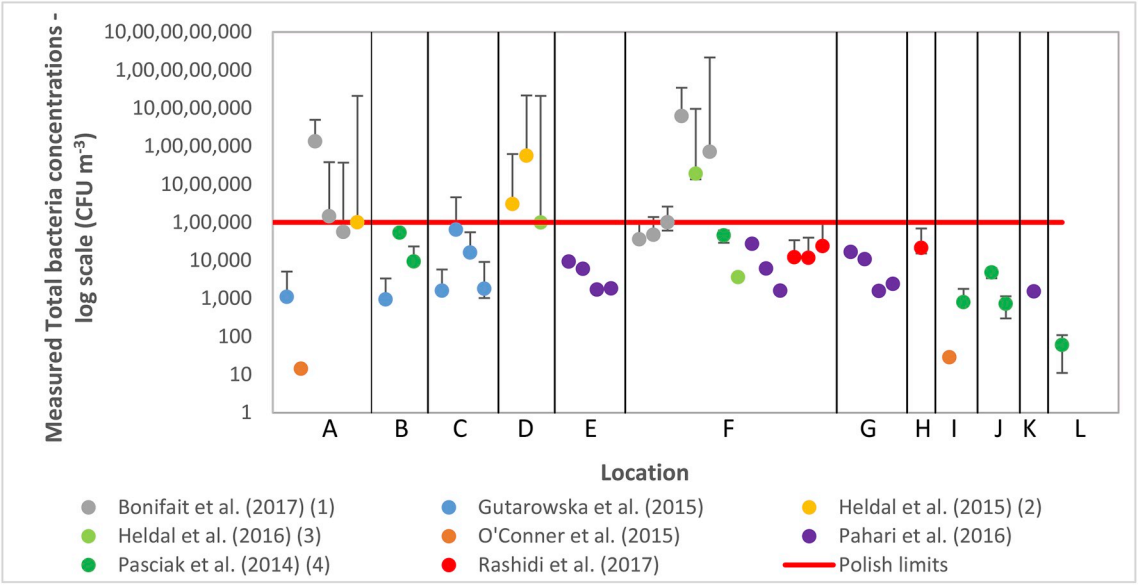


Fig. 3. Mean (or median if mean is not reported) airborne total bacteria concentrations at different location reported in studies with exposure data. Error bars represent minimum and maximum concentrations (or standard deviation if minima and maxima not reported), if reported in the study. Location A = Background/Upwind, B = Office, C = Compost Hall, D = Personal, E = Waste receiving area, F = On Site, G = Bagging area, H = Screening, I = Downwind (at an unspecified distance), J = Downwind 100 m, K = Downwind 200 m, L = Downwind 2000 m. Results from Gutarowska et al. (2018) are not included as they measured settled (not airborne) dust. The red line represents the Polish Committee for the Highest Permissible Concentrations and Intensities of Noxious Agents in the Workplace limit for mesophilic bacteria, which is 100,000 CFU m^{-3} (Gutarowska et al., 2015). See Table 1 for exposure study characteristics. (1) Some measurements in Bonifait et al. (2017) were reported as genomes m^{-3}. (2) Results in (Heldal et al., 2015) were reported as cells m^{-3}. (3) Results in Heldal et al. (2016) were reported as bacteria m^{-3}. (4) Pasciak et al. (2014) reported measurements taken at offsite locations and provided approximate distances from site, but did not explicitly state these measurements were taken downwind. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

measured values. The highest concentrations of total bacteria were measured on personal samplers worn by workers and on site (Fig. 3). A similar pattern was observed for total fungi concentrations (Fig. 4). Not all studies measured or reported upwind/background concentrations, so it was not always possible to tell if on-site concentrations were directly attributable to composting activities. Four studies (Bonifait et al., 2017; Gutarowska et al., 2015; Heldal et al., 2015, 2016 report that some levels exceeded Polish limits of 100,000 CFU m^{-3} for mesophilic bacteria. All samples reported by Heldal et al. (2015) exceeded the Polish limits, although one of these is a background measurement indicating that there are high levels of naturally occurring bacteria, and reported bacterial cells, not CFU, which may not be mesophilic or completely comparable. High background measurements were also observed for Bonifait et al. (2017). One of the two (Heldal et al., 2016) samples exceeded Polish limits, but background values were not provided. The upper limits of one sample exceed the Polish limits in Gutarowska et al. (2015), but as the mean concentration does not exceed this limit, the authors concluded that total microorganisms did not exceed quantitative thresholds. Four studies (Bonifait et al., 2017; Gutarowska et al., 2015; Heldal et al., 2015, 2016 report some levels that exceeded German occupational technical control values of 50,000 CFU m^{-3} for mesophilic fungi (TBRA, 2019) and Polish limits for fungi, which is also 50,000 CFU m^{-3} (Gutarowska et al., 2015). All samples reported by Heldal et al. (2015), and the upper limits of Heldal et al. (2016) exceeded German technical control values/Polish limits, although one of the Heldal et al. (2015) samples is a background measurement indicating high levels of naturally occurring fungi, and fungal spores are presented in this study, which are not necessary

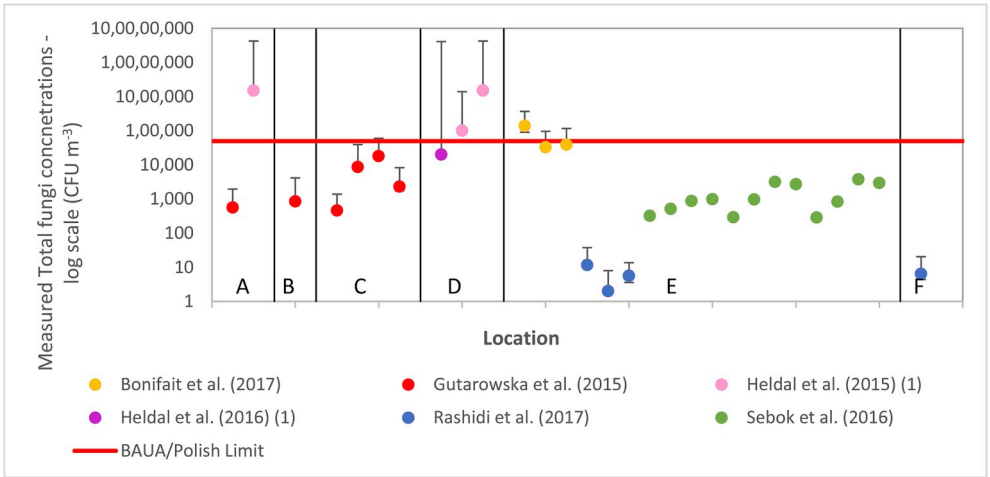


Fig. 4. Mean (or median if mean is not reported) airborne total fungi concentrations at different location reported in studies with exposure data. Error bars represent minimum and maximum concentrations, if reported in the study. Location A = Background/Upwind, B = Office, C = Compost Hall, D = Personal, E = On Site, F = Screening. Results from Gutarowska et al. (2018) are not included as they measured settled (not airborne) dust. The red line represents the German technical control value of 50,000 CFU m^{-3} for mesophilic fungi (TBRA, 2019) and the Polish Committee for the Highest Permissible Concentrations and Intensities of Noxious Agents in the Workplace limit for fungi, which is also 50,000 CFU m^{-3} (Gutarowska et al., 2015). See Table 1 for exposure study characteristics. (1) Presented results as spores m^{-3}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.).

mesophilic. One sampling point and the upper limits of two sampling points in Bonifait et al. (2017) who did present results for mesophilic mould exceed German technical control values/Polish limits, however, upwind values are not provided. The measured levels in Gutarowska et al. (2015) exceed the German technical control value; airborne fungi was measured in this study, which may or may not include mesophilic fungi.

It was only possible to extract endotoxin concentrations from two studies (Heldal et al., 2015, 2016. Both studies measured personal endotoxin exposures from composting workers. Heldal et al. (2015) reported mean concentrations of 4–38 EU m^{-3} (range 0–730 EU m^{-3}), and Heldal et al. (2016) reported a median concentration of 3 EU m^{-3} (range 1–310 EU m^{-3}). The upper limits of endotoxin concentrations reported in these studies exceed proposed Dutch limits of 90 EU m^{-3} (DECOS, 2010), however, both studies sampled for less than 8 h, and the proposed Dutch limits are an 8 h time weighted average.

As there were only five studies that included community exposure measurements, it was not possible to determine how bioaerosol concentration may deplete downwind from the composting facilities. Pasciak et al. (2014) reported measurements from several offsite locations, and detected total bacteria and Actinobacteria 2 km from the site. However, it was not clear whether these were taken downwind or upwind of composting activities, and therefore whether these were naturally occurring bioaerosols, or emitted from the composting site.

The studied bioaerosol characteristics are summarised in Table 1, including (but not limited to) total bacteria, endotoxin, actinomycetes, *Legionella,* total fungi/mould, and *Aspergillus fumigatus.* The levels of microorganisms detected by the exposure studies are summarised in Appendix D, and the microbial genera detected in two or more studies is summarised in Fig. 5. The key fungal genera detected were *Aspergillus*, *Penicillium*, and *Cladosporium*. The predominant bacterial general were mostly gram-positive (*Staphylococcus, Bacillus* and *Kocuria*) with some gram-negative genera such as *Pseudomonas.* The inhalable dust/particulate matter concentrations ranged from 2.29×10^{-1} – 5.00×10^{4} µg m^{-3}.

3.2.3. Bioaerosol size distribution

Six studies examined the size distribution of the microbial constituent of bioaerosols. Two observed that the majority of fluorescing particles were small, with a diameter of < 2 µm (Feeney et al., 2018) or 0.5–3.0 µm (O'Connor et al., 2015); and generally elongated to ellipsoidal/spherical in shape (O'Connor et al., 2015). Likewise, four studies reported that the predominant bacterial particles were small and thus in single cell form, in the range of 0.95–2.40 µm (mean 1.3 µm) (Gales et al., 2015); < 1 µm (Tamer Vestlund et al., 2014); 0.65–1.1 and 1.2–2.1 µm (Gutarowska et al., 2015); or 0.65–2.1 µm (Pahari et al., 2016); and spherical (Tamer Vestlund et al., 2014). Only one study also measured the size distribution of fungal particles (Gutarowska et al., 2015). They demonstrated that, in contrast to bacterial particles, fungal particles within the facility were heavily influenced by those present in the atmospheric air, with particles of 1.1–2.1 and 2.1–3.3 µm predominating in both indoor and outdoor air (Gutarowska et al., 2015).

Five studies collected data on the size distribution of inhalable dust/particulate matter. However, only two reported full analysis of this data, both of which observed an increase in small particulate matter < 1 µm (Gutarowska et al., 2018) or 0.6–1.8 µm (Gales et al., 2015). These particles could be of both non-microbial and microbial origin, and in combination with the data above suggest that much of the small particulate matter may be single bacterial cells. Two studies used the data to demonstrate that there was increase in fluorescent bioaerosols over non-fluorescent particles during compost facility activity reporting the ratio/difference only (Feeney et al., 2018); or that there was a greater association of bacteria with PM > 2.5 µm (Pahari et al., 2016). The remaining study failed to report any (non-fluorescent) dust data (O'Connor et al., 2015).

3.3. Health studies

Eight health studies relating to bioaerosols from composting facilities were published since (Pearson et al., 2015). All were conducted in Europe. The majority (6 out of 8) were in occupational groups (i.e. compost workers). Of the eight health studies, four were cross-sectional in design (Douglas et al., 2016; Hoffmeyer et al., 2014, 2015; Raulf et al., 2015), two were pre-post exposure, quasi-experimental in design (Heldal et al., 2015, 2016), one was a prospective cohort (van Kampen et al., 2016), and one was a laboratory-based study (Gutarowska et al., 2018), examining the cytotoxicity of compost dust samples in human epithelial A-549 cells. Only three of the health studies combined bioaerosol exposure data with health information and all were on compost workers (Gutarowska et al., 2018; Heldal et al., 2015, 2016). A fourth community health-based study used distance from site as a proxy of exposure (Douglas et al., 2016). The full characteristics for both occupational and community based studies are displayed in Table 2.

3.3.1. Occupational health studies

For the six occupational-based health studies, sample sizes ranged from 84 to 262 compost workers. Various outcome measures or endpoints were used, but chiefly related to respiratory health. The studies typically used a combination of both subjective (based on self-report, usually questionnaires) and objective measures (based on direct physiological measurement). For each study, only a small number of the total endpoints examined showed statistically significant association as reported in Table 3 and described further in the text below.

3.3.1.1. Baseline lung function. Three papers including one prospective cohort study (van Kampen et al., 2016) and two quasi-experimental studies (Heldal et al., 2015, 2016), reported baseline spirometry indices. All three (Heldal et al., 2015, 2016; van Kampen et al., 2016) reported a lower FEV_1/FVC ratio (ratio of the forced expiratory volume in the first 1 s to the forced vital capacity of the lungs) at baseline in compost workers compared to non-exposed controls; although only one found significant ($p < 0.05$) differences (Heldal et al., 2015). The non-exposed control groups consisted of administrative staff from within (Heldal et al., 2015, 2016) or outside (van Kampen et al., 2016) the composting facilities. The study by van Kampen and colleagues included current and former compost workers and observed no difference in the FEV_1/FVC ratio measured at baseline (van Kampen et al., 2016).

3.3.1.2. Post-shift decline in lung function. One study investigated acute cross-shift changes in lung function among compost workers (Heldal et al., 2015). Heldal and co-workers reported a lower FEV_1/FVC ratio in 47 Norwegian compost workers (20 employed at five windrow facilities and 27 employed at five reactor facilities) (Heldal et al., 2015). Personal samplers were used to measure full-shift exposure measurements at the same time as health examinations and this indicated that the cross-shift decline in the FEV_1/FVC ratio was associated with exposure to actinomycetes spores ($p = 0.003$).

3.3.1.3. Long-term decline in lung function. One study examined changes in lung function in workers (74 currently exposed compost workers, 42 former workers and 37 controls) over a 13-year follow-up (van Kampen et al., 2016). There was no difference in the magnitude of changes in FVC or FEV_1 during the follow-up period in active and former German compost workers compared with non-exposed control subjects (administrative employees from outside the composting operations), after taking into account smoking status.

3.3.1.4. Cough, chronic bronchitis and COPD. A quasi-experimental (Heldal et al., 2015) and cross-sectional (Hoffmeyer et al., 2014) study measured self-reported cough symptoms with prevalence's ranging from 14.6% to 45% and odd ratios (ORs) ranging from 4.1 to

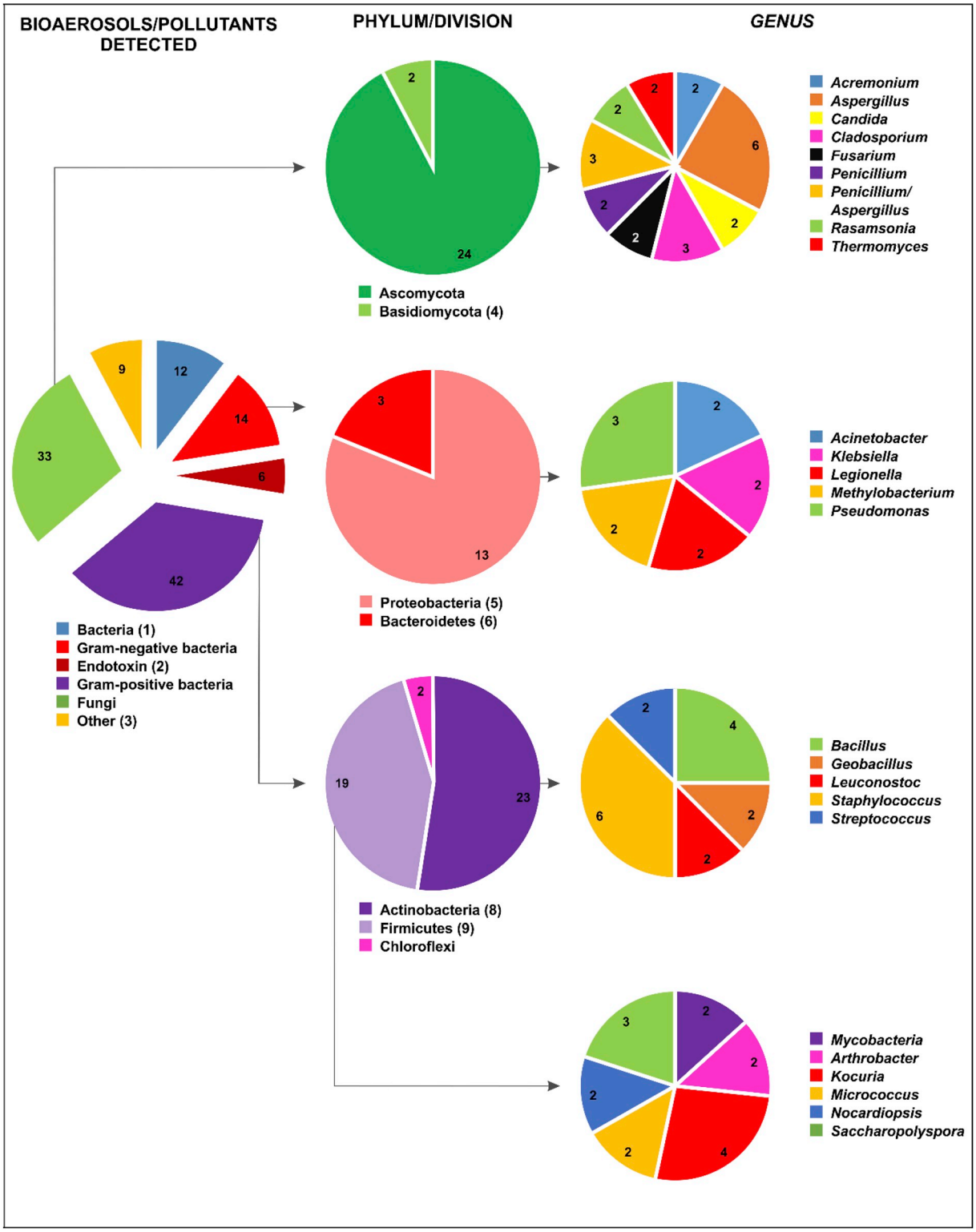


Fig. 5. The number of studies detecting bioaerosols/pollutants (left), and microorganisms (middle and right), measured in studies with exposure measurements. Some studies classified microbes at phylum/division level (middle), but some classified further to genus level (right). See Appendix D for a full list of the microorganisms detected by the exposure studies. Only microorganisms that were measured in two or more studies are included. (1) Total bacteria (n = 10) and mycobacteria (n = 2). (2) Endotoxin are molecules found in the outer membrane of gram-negative bacteria. (3) Dust/particulates (n = 6), fluorescing particles (n = 2). (4) All (n = 2) were Ustilaginomycetes class. (5) n = 2 measured to phylum/division level only. (6) All (n = 3) were of the *Bacteroides* genus. (7) All (n = 2) were of the Ktedonobacteria class. (8) n = 8 measured to phylum/division level only (9). n = 3 measured to phylum/division level only. NOTE: Heldal et al. (2015) and Heldal et al. (2016) may have reported results from the same samples, and counted twice in the figure, although this is not clear in the manuscripts.

Table 3
Significant results from the health studies.

Author (year)	Subject information	Health outcome	Confounders	Significant findings	Comments
				Odds ratios (ORs)/relative risks (RR) and p-values and 95% confidence intervals (CI) where reported	
Occupational studies					
Heldal et al. (2015)	47 workers (20 windrow compost workers; 27 reactor facility workers) and 37 unexposed controls mainly white collar workers from the administration at the facilities	Same day self-reported questionnaire to assess pulmonary, gastro-intestinal (GI), and general symptoms/illnesses Spirometry (FEV_1, FVC) measurements taken pre- and post- shift. Acoustic rhinometry measured pre- and post- shift.	Adjusted for age and smoking Adjusted for smoking, age and atopy Adjusted for smoking and age	Cough in windrow site workers (OR: 4.3 (CI: 1.0–18.2)). One or more work-related symptoms in windrow site workers (OR: 4.0 (CI: 1.1–14.7, $p < 0.05$)). Symptoms were increased in the middle exposure category of Actinomycetes spores for cough (OR: 4.3 (CI: 1.1–16.0, $p < 0.05$)), upper airway irritation (OR: 6.2 (CI: 1.5–25.0, $p < 0.05$)), nose irritation (OR: 6.1 (CI:1.5–25.0, $p < 0.05$)), one or more airway symptoms (OR: 3.8 (CI: 1.1–13.0, $p < 0.05$)), and one or more work-related symptoms (OR: 4.5 (CI:1.2–17.0, $p < 0.05$)), Cough was also increased with the middle exposure category of bacteria (OR: 3.9 (CI:1.1–14.0, $p < 0.05$)), endotoxins (OR: 4.7 (CI:1.2–19.0, $p < 0.05$)), and dust (OR: 4.9 (CI:1.3–19.0, $p < 00.5$)) Predicted FVC% lower for all compost workers (102.2%) and reactor facility workers (102.3%) compared to controls (109.5%) ($p < 0.05$). Cross-shift decrease in FEV_1/FVC ratio in the middle exposure category for Actinomycetes (−3.2%, $p < 0.05$) Cross-shift decrease in the outer volume of the nasal cavity (TVOL1) among all workers ($-0.22\,cm^3$ $p < 0.05$) and reactor facility workers ($-0.28\,cm^3$ $p < 005$).	Administrative staff at the sites are not true population-based controls – i.e. subjects likely to be more exposed than general population. A slight exposure among the controls would result in an underestimation of effects. There was also a higher proportion of females in the control group. The use of respiratory protection (which was not controlled for) was most prevalent in workers in the highest exposure category and explain the lower risk for self-reported symptoms in this group compared to the middle exposure category Subjects were not blinded to the exposure condition and the duration of employment of the workers was not specified. The statistical power was also limited by the small size of the respondent population.
Heldal et al. (2016)	47 compost workers (as described in Heldal et al. (2015)), 44 sewage facility workers (19 from 4 facilities using sludge drying, 25 from 4 facilities that didn't use sludge drying), 38 unexposed controls (all administrative staff from the facilities; 28 from the compost facilities & 9 from the sewage treatment facilities)	Spirometry (FEV_1, FVC) measurements taken pre- and post- shift Post-shift blood sample for the determination of biomarkers of inflammation (IL-6, ICAM-1, VCAM-1, CRP) and coagulation (D-Dimer, fibrinogen) specific allergens	Adjusted for age, smoking, gender and atopy	All (compost & sewage workers combined) exposed subjects had lower FVC (100.3%) than controls (109.5%) CRP, fibrinogen and ICAM-1 significantly ($p < 0.05$) higher in all exposed compared to controls. When stratifying into sewage or compost workers, fibrinogen ($p < 0.05$) and ICAM-1 ($p = 0.01$) remained significantly higher in compost workers compared to the controls. Nonlinear associations between serum CRP and FEV_1 and FVC were observed (decline in FEV_1 starting at a CRP concentration of approximately $2\,mg\,L^{-1}$). Serum concentrations of ICAM-1 were associated with CRP concentrations when considering all workers (ICAM-1 = 290 + 62.5 IgCRP, $p < 0.01$) (and for the sewage and compost workers separately) ICAM-1 concentrations were positively associated with dust ($\beta = 38.6$, $p < 0.05$) and bacteria ($\beta = 23.0$, $p < 0.05$) exposure among all exposed workers.	Administrative staff at the sites are not true population-based controls – i.e. subjects likely to be more exposed than general population. A slight exposure among the controls would result in an underestimation of effects. Inflammatory markers may be confounded by obesity (BMI was not measured) Subjects were not blinded to the exposure condition and the duration of employment of the workers was not specified. The statistical power was also limited by the small size of the respondent population.

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Table 3 (*continued*)

Author (year)	Subject information	Health outcome	Confounders	Significant findings Odds ratios (ORs)/relative risks (RR) and p-values and 95% confidence intervals (CI) where reported	Comments
Hoffmeyer et al. (2014)	190 currently exposed compost workers, 59 former compost workers, 38 white-collar workers without occupational exposure	Self-administered questionnaire diagnosis of chronic bronchitis Eye and nose irritation assessed by self-administered questionnaire Spirometry was used to diagnose COPD and the GOLD classification system was used to categorise disease severity (I-IV)	Before adjustment After adjustment for the effect of age, smoking habits, BMI and atopy Before adjustment After adjustment for the effect of age, smoking habits, BMI and atopy Before adjustment	Chronic bronchitis was highest amongst former workers (25.5%) compared to current workers (4.5%) and controls (9.1%). Prevalence of chronic bronchitis differed significantly from control subjects for former workers ($p < 0.0001$), but not current workers. Compared to never smokers, prevalence of chronic bronchitis was significantly higher in current smokers. Current compost workers identified as atopic demonstrated a significantly enhanced OR for chronic bronchitis (6.25; CI: 1.19–32.90) Compared to controls, former compost workers reported more eye irritation ($p = 0.03$) Eye irritation was associated with chronic bronchitis in current compost workers (OR 7.22, CI: 1.12–46.8) and former workers (OR 38.6, CI: 1.33- > 1000.0) Nose irritation was associated with cough in current compost workers (OR 3.51, CI: 1.07–11.6) and chronic bronchitis in former workers (OR 25.0 CI: 1.21–513.0) Co-morbidity of chronic bronchitis and COPD was more apparent in former workers (13.7%) compared to current workers (0.6%) and controls (3.0%) ($p < 0.0001$)	25 subjects previously diagnosed with allergic asthma were excluded from further analysis (further analyses conducted on 178 current workers, 51 former workers and 33 controls) Administrative staff at the sites are not true population-based controls – i.e. subjects likely to be more exposed than general population. A slight exposure among the controls would result in an underestimation of effects. The control group were also significantly older ($p < 0.0001$) and had been employed for longer ($p < 0.0001$) Increased prevalence of chronic bronchitis, and severe airflow limitations in former workers but not current workers may be due to healthy worker affect. Subjects were not blinded to the exposure condition. The statistical power was also limited by the small size of the respondent population
Hoffmeyer et al. (2015)	119 currently exposed compost workers, stratified by smoking and atopy (from same cohort as used in Hoffmeyer et al. (2014))	pH and levels of eicosanoids in EBC Fractional exhaled nitric oxide (FeNO) Blood samples collected for measuring levels (concentrations) of allergen-specific IgE antibodies	Before stratification After stratification on atopy and smoking habits After stratification on atopy and smoking habits	Levels of 8-iso-$PGF_{2\alpha}$ (marker of oxidative stress) in EBC was higher in workers classified as high exposure compared to the low exposure group ($p = 0.047$). pH of EBC was lower in smoking compared to non-smoking subjects in both the low and high exposure groups ($p = 0.049$ and 0.009 respectively). Smoking demonstrated a significant negative impact on FeNO levels both in low ($p = 0.0001$) and high ($p < 0.0001$) exposed workers. Both current and cumulative cigarette exposure was negatively correlated to FeNO ($p < 0.001$, each). There was also a statistically significant correlation between FeNO and both time worked under clean air supply ($p = 0.0071$) and duration of employment in atopic subjects ($p = 0.041$)	Study did not include a reference group (i.e. non-exposed control group). The statistical power was also limited by the small size of the respondent population Subgroups under study had different distributions for age and duration of employment in the composting facility – neither of these were adjusted for in the main analysis

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Table 3 (*continued*)

Author (year)	Subject information	Health outcome	Confounders	Significant findings Odds ratios (ORs)/relative risks (RR) and p-values and 95% confidence intervals (CI) where reported	Comments
Raulf et al. (2015)	140 currently exposed compost workers, 49 former compost workers and 29 white-collar workers (from same cohort as used in Hoffmeyer et al. (2014))	Cellular and soluble markers in induced sputum	Before stratification After stratification of the 3 subject groups by smoking After stratification by clinical symptoms and smoking habits	Compared with white-collar workers, concentrations of sCD14 and 8-isoprostane concentrations in induced sputum samples were lower in current (sCD14: $p < 0.05$; 8-isoprotane: $p < 0.001$) and former sCD14: $p < 0.001$; 8-isoprotane: $p < 0.001$compost workers Total cell count was lower in former compost workers than in current compost workers ($p = 0.001$) and in white-collar workers ($p < 0.01$). Percentage of neutrophils was higher in current workers compared with the white-collar workers ($p < 0.01$). There was also high correlation between the IL-8 concentration and the number of neutrophils ($p < 0.0001$) Non/ex-smokers in the group of former workers showed lower biomarker concentrations (MMP-9: $p < 0.001$; sCD14: $p < 0.05$) compared with the non/ex-smoker group of current workers. Significant differences in prevalence of chronic bronchitis ($p = 0.018$) between former compost workers (24.5%), current workers (5%), and white-collar workers (10.3%). A significantly higher ($p < 0.05$) percentage of neutrophils was measured in induced sputum of smoking subjects suffering from chronic bronchitis. There was higher IL-8 concentrations in the smokers in each group (current/former/white-collar) and increasing of IL-8 concentration with an augmentation of respiratory symptoms. MMP-9 also significantly increased in each group with augmentation of respiratory symptoms but was not influenced by smoking habits.	Administrative staff at the sites are not true population-based controls – i.e. subjects likely to be more exposed than general population. A slight exposure among the controls would result in an underestimation of effects. Subjects were not blinded to the exposure condition. The statistical power was also limited by the small size of the respondent population
van Kampen et al. (2016)	74 currently exposed compost workers, 42 former compost workers (who had left during the 13-year follow-up) and 37 non-exposed controls (from same cohort as used in Hoffmeyer et al. (2014))	Prevalence of self-reported symptoms (questionnaire data) Lung function (via spirometry)	Before adjustment After adjustment for smoking habits, exposure group, severity of respiratory symptoms and duration of employment Before adjustment	Compared to 1996/97, the number of current and former compost workers reporting cough increased in 2009 ($p = 0.013$ & $p = 0.003$ respectively). Former compost workers showed a higher risk of cough and cough with phlegm ($p = 0.024$ & $p = 0.012$, respectively) during the follow-up period. Working as a compost worker for > 5 years significantly increased the risk of cough and cough with phlegm ($p < 0.001$ for both). Similarly, smoking increased the risk of cough and cough with phlegm ($p = 0.002$ & $p = 0.004$, respectively). Lung function measures deceased significantly during the time of follow-up in the 3 groups ($p < 0.001$)	Did not adjust for growing use of protective measures (e.g. respiratory masks) during the 13-year follow-up period (this is likely to confound exposure response associations) Subjects were not blinded to the exposure condition. The statistical power was also limited by the small size of the respondent population

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Table 3 (*continued*)

Author (year)	Subject information	Health outcome	Confounders	Significant findings Odds ratios (ORs)/relative risks (RR) and p-values and 95% confidence intervals (CI) where reported	Comments
Community studies					
Douglas et al. (2016)	34,963 respiratory hospital admissions in 4656 census output areas within 250–2500 m of a compost site	Emergency and non-emergency hospital admissions for postcode areas (from Hospital Episode Statistics), with respiratory-related primary diagnosis for admission (according to International Classification of Disease (ICD10) code; all respiratory disease, respiratory infections, asthma & COPD)	After adjustment for age and sex After adjustment for age, sex, socio-economic deprivation and tobacco sales	Small increased risk for of admissions for all respiratory disease and COPD for those living nearer a composting sites when assessed by distance band (p for trend = 0.01 & 0.04, respectively) Using log-transformed distance from site there was a small significant decreasing risk for respiratory admissions with increasing distance from site (p = 0.054)	Study did not account for changes in seasonality and did not have information on individual-level smoking or co-morbidities. The study did not also consider other potential sources of bioaerosol exposures (e.g. intensive farms) Hospital admissions represent a severe end of the spectrum of potential health effects of bioaerosol exposures. It is unlikely that severe impacts would have been reliably demonstrated if infrequent

* Where values are not provided for specific sampling parameters (such as flow rate, sampling time, sampling height etc.), they were not reported.

4.3, when comparing compost workers, especially windrow composting workers, to non-exposed controls (administrative staff from within (Heldal et al., 2015) or outside (Hoffmeyer et al., 2014) the composting facilities). However, only one study found differences (Heldal et al., 2015) greater than would be expected by chance ($p < 0.05$). Heldal et al. (2015) also found increased prevalence of self-reported cough with increasing exposure of compost workers to endotoxin, bacteria or actinomycetes spores as measured by personal samplers. Of note, the middle tertile but not the highest tertile, of exposure to endotoxin, bacteria or actinomycetes spores had significantly increased adjusted (for age and smoke) OR's for cough prevalence. However, the analyses did not include a trend test. In the 13-year follow-up study by van Kampen et al. (2016) the occurrence of symptoms was examined using modified Poisson regression. Former – but not current – compost workers had a significantly increased risk of cough and cough with phlegm (relative risk (RR) and 95% confidence intervals (CI), 2.46; 1.13–5.38, $p = 0.024$; and RR, 2.93; Cl, 1.27–6.76, $p = 0.0.012$, respectively) compared with non-exposed controls (administrative staff from outside the composting facilites).

Three papers, including one prospective cohort study (van Kampen et al., 2016) and two cross-sectional studies (Hoffmeyer et al., 2014, 2015, showed increased prevalence and incidence of chronic bronchitis in compost workers, with the highest levels among former compost workers. Findings reached conventional levels of significance in two of the studies (Hoffmeyer et al., 2014, 2015).

Two studies reported on COPD (Hoffmeyer et al., 2014; van Kampen et al., 2016). Spirometry was used to classify subjects into COPD and its GOLD (Global Initiative of Chronic Obstructive Lung Disease) severity stages (stages I-IV). A cross-sectional study by Hoffmeyer et al. (2014) in 190 current compost workers, 59 former workers and 28 control subjects reported no statistical significant differences in the prevalence of COPD between groups. Likewise in the 13-year follow-up study by van Kampen et al. (2016) there was no statistical differences in the prevalence of COPD among current compost workers, former workers and control subjects.

3.3.1.5. Asthma and asthma symptoms. One cross-sectional study reported on asthma (Hoffmeyer et al., 2014). A score-based diagnosis of allergic asthma was less common in the current (12/190; 6.3%) compared to former workers (8/59; 13.6%), and to the control subjects (5/38. 13.2%) (Hoffmeyer et al., 2014). However, a quasi-experimental analysis (Heldal et al., 2015) of data on 47 Norwegian workers employed at five windrow ($n = 20$) and five reactor facilities ($n = 27$) found increased odds of symptoms of asthma in the compost workers compared with control subjects. This difference, however, did not reach statistical significance.

3.3.1.6. Antigen-specific immunoglobulin (IgE) levels. Two cross-sectional studies on German compost workers detected no differences in the prevalence of atopic sensitisation in workers formerly and currently exposed (Hoffmeyer et al., 2014, 2015. Furthermore, median total serum IgE concentrations at baseline and 13-year follow-up for current and former compost workers were similar to the control group (van Kampen et al., 2016). Also, the percentage of participants with elevated specific IgG levels against *Aspergillus fumigatus*, *Penicillium* spp., *Saccharopolyspora rectivirgula* and *Thermoactinomyces vulgaris* was similar at baseline and 13-year follow-up in all groups (van Kampen et al., 2016). Serum IgE and IgG concentrations in compost workers were unrelated to duration of employment at the compost facility (van Kampen et al., 2016).

3.3.1.7. Eye and nose irritation. One cross-sectional study comparing compost workers and controls reported increased occurrence of eye irritation, especially among former workers ($p = 0.03$) (Hoffmeyer et al., 2014). In the same study, prevalence of nose irritation was lower in current compost workers, whereas it was higher in former

Table 4
Risk of bias in the health studies (excluding Gutarowska et al. (2018), a lab-based study), using the risk of bias assessment tool presented in Appendix B. Scores are provided on a scale of 1–4, a maximum possible score of 32 represented the best quality study with minimal bias. Explanations for the scores are provided in Appendix E.

Author (year)	Study design	Selection	Responder	Confounders	Exposure assessment	Outcome assessment	Sample size	Analysis	Total
Occupational health studies									
Heldal et al. (2015)	3	3	4	2	4	3	2	4	25
Heldal et al. (2016)	3	3	4	3	4	3	2	4	26
Hoffmeyer et al. (2014)	2	3	1	3	1	3	3	4	20
Hoffmeyer et al. (2015)	2	3	1	2	1	3	2	3	17
Raulf et al. (2015)	2	3	1	3	1	3	2	3	18
van Kampen et al. (2016)	4	3	2	3	1	3	2	4	22
Community health studies									
Douglas et al. (2016)	2	4	4	3	2	3	4	4	26

workers (Hoffmeyer et al., 2014). A quasi-experimental analysis comparing compost workers and controls reported no increased prevalence's of nose irritation or eye irritation (Heldal et al., 2015). However, there was a positive and statistical significant relationship between measured exposure to *Acinomycetes* ($0.02–0.3 \times 10^6$ spores/m^3) and reported nose irritation ($p < 0.05$) and increased swelling in the outer part of the nose measured using acoustic rhinometry among compost workers when measured across shift (Heldal et al., 2015). There were no changes in the narrowest area of the nasal cavity, deemed the most accurate measure of inflammatory response (Heldal et al., 2015).

3.3.1.8. Lung and systemic inflammation. Induced sputum evaluation revealed lower values of soluble biomarkers (sCD14 and 8-isoprostane) in current and former German compost workers compared to controls (administrative staff from outside the composting facility) (Raulf et al., 2015). Former workers had a significantly lower total cell count compared to current compost workers ($p = 0.001$) or to the control workers ($p < 0.01$) (Raulf et al., 2015). The percentage of neutrophils were significantly higher in the current compost workers, as compared to the control group ($p < 0.01$) (Raulf et al., 2015). Furthermore, neutrophil levels correlated positively with IL-8 ($r = 0.669$, $p < 0.0001$) (Raulf et al., 2015). Subgroup analysis showed that these changes in induced sputum were most pronounced in current than ex/non-smokers and in those with chronic bronchitis. (Raulf et al., 2015). This was true for all groups of subjects: current compost workers, former compost workers and control workers (Raulf et al., 2015).

Heldal and co-workers (Heldal et al., 2016) showed that serum intracellular adhesion molecule-1 (ICAM-1) and fibrinogen levels (after adjustment for age and smoking habits) were significantly higher among Norwegian compost workers compared with the control group (administrative staff from the composting facilities). Elevated CRP levels were found to be associated with lower values of FEV_1/FVC when data from both compost workers and sewage workers were analysed in a mixed model (Heldal et al., 2016). Similarly, a statistically significant positive association between both dust and bacteria with ICAM-1 was also observed (Heldal et al., 2016). High levels of fractional exhaled nitric oxide (FeNO; considered a surrogate marker of airway inflammation) in compost workers were reported to correlate with the intensity of exposure, but only in atopic compost workers (Hoffmeyer et al., 2015).

3.3.2. Community health studies

One cross-sectional community-based study (Douglas et al., 2016) examined health effects in residents of communities at various distances to composting facilities (see Table 2 for details).

Analysing 34,963 respiratory hospital admissions in 4656 census output areas (COAs) within 250–2500 m of a large open-air composting facility in England, there were no significant trends using pre-defined distance bands of > 250–750 m, > 750–1500 m and > 1500–2500 m. Using a continuous measure of distance, there was a small non-statistically significant ($p = 0.054$) association with total respiratory admissions corresponding to a 1.5% (95% Cl: 0.0–2.9%) decrease in risk if moving from 251 m to 501 m. There were no significant associations for subgroups of respiratory infections, asthma or COPD. In summary, this national study does not provide evidence for increased risks of respiratory hospital admissions in those living beyond 250 m of an outdoor composting area perimeter.

3.3.3. Bias assessment

Table 4 presents results of the bias assessment. Explanations for the scores agreed for each study are presented in Appendix E. A high score denotes a low risk of bias and a low score denotes a high risk of bias. The highest possible score is 32, and the lowest possible score is 8. Overall studies included in this systematic review scored 17–26 a score of 25–26 for the two occupational studies measuring exposure, 17–20 for the four occupational studies that did not assess occupational exposures, and a score of 26 for the 1 community study (using an exposure proxy).

The majority of studies used statistical tests appropriate for the type of question and study design and in general, an adequate description of the methodology was provided. The occupational epidemiological studies were prone to selection bias, related to studying only current workers (i.e. healthy worker survival bias). Three of the studies (Hoffmeyer et al., 2014; Raulf et al., 2015; van Kampen et al., 2016) attempted to correct partially for this by including workers formerly and currently exposed. The two studies from Heldal et al., 2015, 2016 scored higher on study design (quasi-experimental designs as opposed to cross-sectional design) and exposure assessment (as measured). In all six occupational studies, sample size was small and none of the studies presented sample size calculations. The one community study (Douglas et al., 2016) had a higher sample size and was less vulnerable to the effects of selection bias (included all composting facilities with an outdoor composting component in England) and response bias (outcome data were objectively collected and independently coded hospital admissions to NHS hospitals rather than self-reported health questionnaires), with control for relevant confounders (age, sex, area-level deprivation and tobacco sales). While both community and occupational studies adjusted for a number of confounders such as age, sex and smoking status, the community study (Douglas et al., 2016) was the only study to include socio-economic status as a potential confounder. However, it was cross-sectional in design and did not measure exposure directly.

4. Discussion

This timely review serves as a comprehensive update of what new evidence has emerged on exposures and health outcomes in relation to bioaerosol emissions from composting facilities. Composting facilities are a major source of bioaerosols and in 2015 we reported that there was some, albeit limited, evidence linking bioaerosol emissions from composting facilities to poor respiratory health in nearby residents (Pearson et al., 2015). However, the limited evidence precluded any

quantitative assessment. Since then, the number of operational industrial-scale composting facilities in England has increased by 9% - nearly twice the growth from 2012 to 2014. At the same time, rapid urbanisation has led to expansion of city borders. It is therefore likely that more and more people are living near large composting facilities and being exposed to bioaerosol pollution.

Although this review identified a number of new studies, the conclusions remain largely unchanged to those of our earlier review (Pearson et al., 2015). Bioaerosol concentrations in recent studies conducted in occupational settings remain similar to those reported in the previous review. Furthermore, many of our research recommendations have not yet been fully implemented. While some progress has been made characterising bioaerosol emissions from composting facilities, relatively little headway has been made regarding the potential public health risks associated with these bioaerosol emissions.

Studies included in the previous review (Pearson et al., 2015) mostly relied on traditional methods, such as culture and/or morphological identification by microscopy, for analysing the microbial characteristics of bioaerosols (Appendix F). Advances in molecular technologies have enabled a more comprehensive characterisation of the bacterial and fungal components, providing greater microbial resolution and diversity. Since only a small percentage of bacteria (around 2%) and fungi (around 5–17%) can be readily grown in the laboratory, culture-based methods greatly underestimate diversity (Stefani et al., 2015; Wade, 2002). Microscopy is less prone to bias; however, classification remains challenging as many microorganisms share similar morphological characteristics. Methods analysing the microbial DNA (metagenome) directly extracted from samples without any prior culture are culture-independent, thereby enabling the identification of all microbes (unculturable, culturable, viable and non-viable). This further maximises clinical relevance, as microorganisms do not need to be viable nor culturable to elicit a response. Although over half (55%) of the exposure studies analysing the metagenome were culture-independent, these represent only 30% of the total exposure studies. Thus, the microbial characterisation of bioaerosols currently remains culture-dependent.

Metagenome analyses were based on the NGS and/or PCR of amplified regions (amplicons) containing sections unique to a specific microbial genera or species, providing improved microbial resolution and diversity data. Such molecular methods are not without their own caveats. Results of amplicon-based analyses are often presented as relative abundance of microorganisms within a sample, suggesting that the number of amplicons (or sequences) designated to a particular microorganism relates to its abundance. This is not necessarily true – different species (and even strains) of bacteria and fungi can contain different numbers of the same genes, so called copy number variation. Thus, a specific microorganism may appear to have greater abundance, simply because it has a greater number of copies of the analysed DNA region. Likewise, some microbial spores contain greater/lesser amounts of DNA and/or be easy/more difficult to break open, thus leading to results that could be incorrectly interpreted as actual abundance. While this is a problem when attempting to quantitatively compare the abundance of different microorganisms within a particular sample, it is not necessarily an issue when monitoring temporal or spatial changes in the same microorganism. Fortunately, the latter is probably of more immediate interest with respect to composting facilities; particularly since the exposure studies to-date largely rely on short duration “snapshot” sampling. Subsequent targeted validation of microorganisms of interest, for example by qPCR, may be useful in future studies. Furthermore, sequencing generates vast amounts of data, but requires robust bioinformatics for accurate microorganism identification. Identification is only as good as the reference database used. Sequences that cannot be assigned to a reference, because the database lacks sequences from particular genera or species, will remain unclassified or worse still, be misclassified. As the use of microbial metagenomics continues to increase, the molecular analysis methods, associated databases and thus microbial identification will also improve. Indeed, it is worth noting that the results of a two four-year Natural Environment Research Council (NERC; the UK's leading public funder of environmental science) funded program, which has involved developing, testing and comparing traditional and molecular methods, are due to be published soon. This will help to inform on the use of such methods and drive improved and standardised bioaerosol characterisation protocols.

To evaluate the exposure and the dispersal of bioaerosols beyond the composting site, it is necessary to know their background concentrations in air from unaffected areas. One of the shortcomings of the earlier studies was the lack of background measurements. This problem remains. Only eight of the 18 bioaerosol exposure studies (44%) measured bioaerosol concentrations at a background location, although this is an improvement compared to our previous review (32%) (Pearson et al., 2015). As with other pollutants, untangling the contribution of an individual source (in this case a composting site) from background bioaerosol concentrations is a challenge. For example, the composting site might be located in an area where there are many sources of bioaerosols. It is therefore very difficult to assess the potential risk to health arising from bioaerosols emitted from composting sites on nearby communities.

This review underscores once again that far too little is known about whether exposure to bioaerosol emissions from composting facilities can contribute to poor health outcomes. Bioaerosol exposures and health outcomes among communities living within the vicinity of the composting site has not been sufficiently investigated. The few epidemiological studies that were identified were almost exclusively carried out in compost workers and were characterised by significant methodological limitations (for example, small sample size and short time frames). Furthermore, the results of such studies have been mixed, with some reporting adverse effects, and others reporting no effect or even a protective effect. It is impossible to determine whether a potential effect is a true causal effect of exposure or a reflection of the selection bias in occupational epidemiological studies (also known as the healthy worker effect). In almost all cases, effect-sizes were small, and there was no discernible pattern of whether effects may subside over time in the studies comparing current and former compost workers. Studies focussed mainly on respiratory health with even less information available on other outcomes such as cardiovascular and gastrointestinal outcomes. While health data on occupationally exposed workers can provide some insight into the allergenicity, toxicity, infectious and inflammatory processes, or lack thereof, resulting from bioaerosol exposure in the general population, caution should be exercised in making any inferences. There tends to be a bias towards the presumption of health risks from bioaerosols. However, the converse – beneficial health effects – may also occur. The hygiene hypothesis (Stiemsma et al., 2015; Strachan, 1989), a somewhat misleading term (Bloomfield et al., 2016), proposes that exposure to microbial agents during early life may lead to lower level of allergy and asthma.

The available evidence reveals some progress has been made regarding health outcome assessment. Rather than relying solely on self-reported measures of health status, most studies included clinical outcome measurements, such as spirometry. However, given the (1) limited number of studies; (2) small associations observed; (3) methodological issues; and (4) potential for selection bias, a conclusive interpretation of these studies remains challenging. There was one community study and this study relied on distance as a proxy for bioaerosol exposure (Douglas et al., 2016). One key advantage of this study is that it used objective data, analysing respiratory-related hospital admission rates for small geographical areas in England from 2008 to 2010. However, this was an ecological study, may not reflect individual-level effects, is likely to have been hampered by exposure misclassification (due to the use of distance as an exposure proxy), and did not account for bioaerosol levels or meteorological effects. The study also looked at respiratory-related hospital admissions as the health outcome, which may represent the more severe effects of potential bioaerosol-related health effects. Collection of health data in the community, or use of primary care data (not currently available at national level in the UK) would be more suitable.

4.1. Impact

It is hoped that this review will provide support to help guide environmental health decision-makers. This review not only examines past research, but also identifies research gaps and argues for the need for further research to better characterise composting-associated bioaerosol exposures and health. This review is particularly topical in the UK as bioaerosol emissions and their potential impacts on health was identified as an ongoing concern in the latest annual report from the Chief Medical Officer (Chief Medical Officer, 2017). The information provided at the time of this review does not provide evidence to support a change from the Environment Agency's current permit guidance of at least 250 m (Environment Agency, 2010, 2018a). However, this should be re-reviewed pending acquisition of further data.

4.2. Recommendations for future work

To address the gaps in knowledge highlighted above, studies that incorporate the following are required:

1. Larger sample sizes

More studies with sufficient power are needed to draw meaningful conclusions from the data. No studies included details of power calculations, making it difficult to identify which studies were sufficiently powered to detect a meaningful difference. Sample size and power considerations should therefore be an essential component of planning future studies.

2. More varied populations

The majority of studies have been conducted in occupational settings, which can be male-dominated and liable to healthy worker bias. There is a need for detailed studies to be conducted in community settings. Future studies should include a more representative sample of individuals of, for example; men and women, a wide age range (children, adults and the elderly), and different health status (asthmatics, immunocompromised individuals). This would also help to identify any susceptible populations.

3. Longer time scales

The majority of studies take a snapshot of a population and measure the exposure and health outcomes over a very short time period. Longer-term studies are essential to capture the longer-term effects of acute and chronic bioaerosol exposure. This would be important for understanding whether there are synergetic or interactive effects of temperature and bioaerosol exposure on human health. Since the previous review, there has been modest improvements in the characterisation of bioaerosols associated with the advent of new sampling and analysis technologies. However, due to the lack of long-term sampling the spatial and temporal variability of bioaerosol composition and concentration remains largely unknown. Longer-term bioaerosol measurement methods are not well established, but as highlighted in this review, there are developments with the use of WIBS technology (although studies included in this review only monitored bioaerosols over seven days). Homogeneity in the sampling methods used to quantify and characterise bioaerosols would also be advantageous to allow easier comparison between studies, particularly in studies conducted in different countries.

4. Quantification of background concentrations

To evaluate the exposure and the dispersal of bioaerosols beyond the composting site, it is necessary to know their background concentrations in air from unaffected areas. Less than half of the exposure studies measured a bioaerosol concentration at a background location. These measurements are needed to help determine which bioaerosol components and concentrations are released as a direct result of compositing.

5. Clearer health outcome definition

While health studies are starting to use objective health measurements, supplemented by questionnaire data, clearer definition of the health outcomes under study is required. This is difficult given the nature of bioaerosols, as different components may give rise different health effects, and biochemical measurements alongside objective health measurements should be considered.

6. Consideration of confounders

It is essential in all epidemiology studies studying environmental effects of health outcomes to account for potential confounding factors. Health studies included in this review typically adjusted for age and sex but many important potential confounding factors were overlooked (for example, socioeconomic status, quality of housing and other lifestyle factors).

7. Use of experimental studies to assess mechanisms

To identify the health effects of bioaerosols without confounding effects, and to determine the specific bioaerosol components that lead to specific health outcomes, more experimental work in model systems is required. Mechanistic studies will improve our understanding of the biological links between exposure and effect, enabling causal associations to be established.

While all of these recommendations would greatly benefit this area of research, it is unlikely that all will be applied in a single study. Therefore, we suggest, in the first instance, that future studies focus on well-powered, long-term studies, using standardised methods to measure both bioaerosol exposure and associated health outcomes in community settings.

5. Conclusions

Although this review identified an additional 23 studies since July 2014, our conclusions remain largely unchanged (Pearson et al., 2015). Unfortunately, studies have not yet had the chance to implement many of our research recommendations from Pearson et al. (2015). While some progress has been made characterising the bioaerosol emissions from composting facilities, with the increasing use of molecular methods, relatively little headway has been made regarding the potential public health risks associated with these bioaerosol emissions. Only one community health study was identified and used an imprecise measure of bioaerosol exposure. Given the absence of any consistent evidence on the toxicity of bioaerosols from composting facilities, there is insufficient evidence to provide a quantitative comment on the risk to nearby residents from exposure to composting bioaerosols. To improve risk assessment and to best advise on risk management a holistic approach is required to provide a more comprehensive understanding of both bioaerosol characteristics and their associated health effects in nearby residents, within the same study.

Conflicts of interest

The authors report no conflicts of interest.

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Apendices

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