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Use of dispersion modelling for Environmental Impact Assessment of biological air pollution from composting: Progress, problems and prospects

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ABSTRACT

With the increase in composting as a sustainable waste management option, biological air pollution (bioaerosols) from composting facilities have become a cause of increasing concern due to their potential health impacts. Estimating community exposure to bioaerosols is problematic due to limitations in current monitoring methods. Atmospheric dispersion modelling can be used to estimate exposure concentrations, however several issues arise from the lack of appropriate bioaerosol data to use as inputs into models, and the complexity of the emission sources at composting facilities. This paper analyses current progress in using dispersion models for bioaerosols, examines the remaining problems and provides recommendations for future prospects in this area. A key finding is the urgent need for guidance for model users to ensure consistent bioaerosol modelling practices.
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1. Introduction

Integrated waste management systems that recover resources are increasingly in use in the UK and across Europe encouraged by the EU landfill directive (2008/96/EC). Composting is a good example of such a process which produces nutrient rich fertiliser and prevents methane production. However, composting also results in elevated concentrations of biological air pollution (bioaerosols), particularly during agitation activities (Taha et al., 2006). Bioaerosols are airborne particles of biological origin. They include fungi, bacteria, pollen, organic particulate matter, and by-products of cells. These microorganisms may be viable and culturable, i.e. a living cell that is capable of growing on artificial culture media; or non-viable and not capable of growing on artificial culture media (Douwes et al., 2003; Dowd and Maier, 2000; Pearson et al., 2015; Viegas et al., 2014). Bioaerosol exposure is associated with various adverse health outcomes due to exposure to microorganisms and/or their components, and there is qualitative evidence suggesting that populations who live or work close to composting facilities are at risk of adverse health outcomes, particularly self-reported respiratory related symptoms (Herr et al., 2003; Pearson et al., 2015). The risk of exposure to bioaerosols has resulted in public health concerns. In response, the Environment Agency in England currently adopts a precautionary stance requiring composting facilities with sensitive receptors, e.g. houses or places of work within 250 m of the site boundary, to complete a site specific bioaerosol risk assessment to show that bioaerosols will be maintained at 'acceptable levels' above the ubiquitous bioaerosol background (Environment Agency, 2010). Each category has acceptable levels currently specified as 300, 1000 and 500 colony forming units per cubic metre (CFU m^{-3}) for gram-negative bacteria, total mesophilic bacteria and *Aspergillus fumigatus* respectively, as measured by the AfOR (2009) standard protocol. In Germany, the Federal Ministry for Environment, Nature, Conservation and Nuclear Safety (BUNR) suggest a minimum setback distance of 300 m and 500 m for enclosed and open-windrow facilities respectively that process 3000 Mg or more (BUNR, 2002). However, there are currently no quantitative dose-response estimates for bioaerosol exposure defined as the scientific understanding of the link between exposure and human health is limited (Pearson et al., 2015; Walser et al., 2015). There is a need for improved assessment of exposure to bioaerosol emissions from composting, to establish a clearer association between exposure, dose received and health outcomes, as highlighted by Sykes et al. (2007) and more recently by Douglas et al. (2016a).

Dispersion models are routinely used to provide reliable estimates of aerosol and other pollutant concentations over wide timescales and areas. There is also the potential for these to be used to estimate bioaerosol dispersion. A dispersion model set up to predict concentrations of bioaerosol would have a number of uses including:

- Estimating short and long term concentrations at sensitive receptors.
- Calculating set-back distances to assess locations for new facilities so as to reduce the risk of exposure of neighbouring sensitive receptors.
- As a risk management tool to inform site managers of predicted periods of high off-site concentrations and attribute these to specific activities. This enables the specification of mitigation measures to avoid exceedances of bioaerosol concentrations.
- Allowing regulators to assess emissions and evaluate the effectiveness of mitigation strategies prior to permitting operations.
- Determining the most appropriate siting of equipment for ambient monitoring strategies as well as determine locations where the highest off site bioaerosols concentrations are likely to be detected.
- Providing additional data to improve exposure assessment within epidemiological studies, e.g. developing work such as that by Douglas et al. (2016a). Used in conjunction with health data, this would improve knowledge of dose response relationships thus informing future regulation and guidance.

Progress towards producing accurate estimates of downwind bioaerosol concentrations using dispersion models has been limited to date, primarily due to a lack of data on bioaerosol composition, emission rates and dispersal characteristics. These are difficult to quantify due to the varied and complex nature of the bioaerosol release, particularly at open windrow facilities. This in turn results in a lack of source term data for dispersion models used to assess sites. A summary of the complex nature of bioaerosol emissions from composting facilities is presented in Appendix A. The concentration, type (species) and timing of bioaerosol emissions from composting facilities vary by site due to differences in management practises and the processing techniques adopted.

Difficulties in quantification are further complicated by differing approaches to sampling used in past studies, amongst which there are no comparable relationships (Williams et al., 2013). The common bioaerosol sampling methods, and the advantages and disadvantages of each, are summarised in Appendix B. In England, there is a standardised sampling protocol (AfOR, 2009), which has recently been superseded by the 'M9' document (Environment Agency, 2017). Whilst this provides consistent data over time for the regulatory purposes it was designed to support, it currently provides a limited dataset, as the number of samples taken are limited (three samples; upwind, downwind and at the nearest sensitive receptor). This, like many sampling campaigns, was not designed to support dispersion modelling. Therefore at present insufficient data are available to validate the application of dispersion models to describe dispersion from composting sites. A further complication in interpreting bioaerosol data is that bioaerosols are ubiquitous in ambient air and background concentrations will vary depending on area and season (Maddelin, 1994; Swan et al., 2002). Therefore, determining whether concentrations are from composting or other sources of bioaerosols is difficult.

The aims of this paper are to:

(1) Review progress made to date in using dispersion models to estimate bioaerosol concentrations, summarising what input values have been used in the dispersion models, and assessing the quality of predictions.
(2) Highlight the key problems and challenges to dispersion modellers when attempting to predict bioaerosol concentrations from composting facilities.
(3) Identify future prospects and summarise the key areas where further research is necessary to close evidence gaps and improve model performance.

2. Review of progress and recognition of problems

2.1. Use of models

Dispersion models simulate the dispersion of a pollutant emitted to the atmosphere through the use of algorithms that describe the controlling atmospheric, physical and chemical processes (Holmes and Morawaka, 2006). There are various forms of dispersion models including box models, Gaussian, Lagrangian, and Eularian models and Computational Fluid Dynamic (CFD) models.

There have been a number of attempts to use dispersion models to predict bioaerosol dispersion, as summarised in Table 1. This

Table 1
A summary of the dispersion model and model inputs used in studies that have used dispersion models to predict bioaerosol concentrations nearby composting facilities. Numerical values are stated to one decimal place. NS denotes that the information was not stated in the study (Updated and modified from Douglas 2013).

Author (year)	Dispersion model(s) used	Description of the dispersion modelling completed	Pollutant(s) modelled and emission rate (units)	Source type and geometry/height (m)	Meteorology	Other information
Millner et al. (1980)	Pasquill	Emission rate was back extrapolated based on measured downwind concentrations and used in a dispersion model to predict concentrations up to 2 km from a sewage sludge composting facility	*A.fumigatus* $2.3 \cdot 10^4$ – $6.7 \cdot 10^{10}$ (particles per second)	Point source, Height of 5.0 m	A wind speed of 2.1–3.6 m s^{-1} was inputted	
Danneberg et al. (1997)	AUSTAL-PC (v3.2)	Back extrapolated an emission rate based on measured airborne microbial concentrations captured 'near to a rotating sieve' and at 150 m downwind. Calculated emission rate was inputted into dispersion model and concentrations in the surrounding area were calculated	Total bacteria $1.3 \cdot 10^7$–$2.8 \cdot 10^8$ (CFU s^{-1}) *Aspergillus fumigatus* 4.6×10^6 (CFU/s)	Point source	NS	
Environment Agency (2001)	SCREEN 3	Modelled data were fitted to monitored data. Inputs were adjusted until the best match was achieved	Emission rate was adjusted until a good fit between modelled and monitored data was achieved	Volume source Source height was adjusted until a good fit between modelled and monitored data was achieved	NS	One-hour averaging time used
SWICEB (2005)	ADMS	Dispersion modelling was based on data collected from three composting sites	$6.0 \cdot 10^{-6}$ g m^{-2} s^{-1}	Area source Height 0.0 m Diameter 3.0 m	Wind speed 0.1 m s^{-1}	Temperature 11.0 °C Calculated deposition velocity, based on aerodynamic diameter, which ranged from $2.0 \cdot 10^{-5}$–$1.5 \cdot 10^{-3}$ m s^{-1}
Taha et al. (2005)	SCREEN 3	Static (un-agitated) compost windrows were monitored and modelled. The emission rate was calculated using an adapted emission rate equation (Jiang and Kaye, 2001)	*Aspergillus fumigatus* $3.6 \cdot 10^3$–$1.1 \cdot 10^4$ (CFU m^{-2} s^{-1}) Actinomycetes $5.5 \cdot 10^3$–$2.2 \cdot 10^4$ (CFU m^{-2} s^{-1})	Area Source Height 2.0 m Area 20.0 × 80.0 m	NS	
Taha et al. (2006)	SCREEN 3	Monitored static (un-agitated) windrows and agitation activities (screening, turning and loading operations). Emission rates for static emissions were calculated using an adapted odour emission rate equation (Jiang and Kaye, 2001). For agitation activities, emission rates were calculated via back extrapolation, estimated by using multiple candidate emission rates until the model outputs resembled measured data	*Aspergillus fumigatus* $8.8 \cdot 10^3$ (CFU m^{-2} m^{-1}) *Aspergillus fumigatus* $2.0 \cdot 10^5$–$8.9 \cdot 10^8$ (CFU s^{-1}) Actinomycetes $7.0 \cdot 10^5$–$8.6 \cdot 10^8$ (CFU s^{-1})	Area Source (static emissions) Height 1.5–2.0 m Point Source (agitation activities) Height 0.0 m Diameter 3.0 m	Ambient temperature 16.3–19.3 °C Wind speed 0.6–3.9 m s^{-1}	Source temperature 11.0 °C
Drew et al. (2007)	ADMS (v3.3)	Monitored static (un-agitated) windrows and agitation activities (screening, turning and loading operations)	*Aspergillus fumigatus* 0.0–$1.6 \cdot 10^5$ (CFU m^{-2} s^{-1}) Actinomycetes $8.0 \cdot 10^4$–$3.6 \cdot 10^5$ (CFU m^{-2} s^{-1}) *Aspergillus fumigatus* $1.8 \cdot 10^4$–$1.6 \cdot 10^5$ (CFU s^{-1}) Actinomycetes $7.9 \cdot 10^3$–$3.6 \cdot 10^5$ (CFU s^{-1})	Area source (static emissions). Static emissions were modelled as 4 point sources each with a diameter of 20 m Point source (agitation activities).	NS	Temperature of 15 °C for winter emissions and 30 °C for summer emissions

Table 1 (*continued*)

Author (year)	Dispersion model(s) used	Description of the dispersion modelling completed	Pollutant(s) modelled and emission rate (units)	Source type and geometry/height (m)	Meteorology	Other information
Taha et al. (2007)	SCREEN 3 and ADMS (v3.3)	Monitored static (un-agitated) windrows and agitation activities (screening, turning and loading operations). Emission rates calculated using an adapted odour emission rate equation (Jiang and Kaye, 2001) for static emissions. Agitation activity emission rates were calculated by back extrapolation of the measured data	*Aspergillus fumigatus* $5.5 \cdot 10^4$–$1.6 \cdot 10^7$ (CFU s^{-1}) Actinomycetes $4.8 \cdot 10^4$–$1.1 \cdot 10^7$ (CFU s^{-1})	Area source (static emissions) Area 80.0 × 20.0 m Height 2.0 m Point source Diameter 3.0 m Height 3.0 m	Roughness length of 'rural' and 0.1 metres was used in the SCREEN3 and ADMS 3.3 models respectively Atmospheric stability class D was used	Exit velocity 0.3 m s^{-1}* Source temperature of 9.9 or 15.0 °C
SNIFFER (2007)	SCREEN 3 and ADMS (v3.3)	Monitored static (un-agitated) windrows and agitation activities (screening, turning and loading operations). Bioaerosol emission rate for passive emissions was estimated using adapted odour emission rate equations (Jiang and Kaye, 2001) Emission rates for agitation activities were estimated by back extrapolation	*Aspergillus fumigatus* and Actinomycetes Emission rates NS	Area (Passive emissions) Point (Agitation activities) Volume (Emissions from buildings)	Atmospheric stability class D was used	
Tamer Vestlund (2009)	ADMS (v3.3)	Monitored static (un-agitated) windrows and agitation activities (screening, turning and loading operations)	Actinomycetes $2.6 \cdot 10^2$–$6.4 \cdot 10^3$ (CFU m^{-2} s^{-1}) Actinomycetes $5.8 \cdot 10^7$–$8.1 \cdot 10^7$ (CFU s^{-1})	Area (passive emissions)Height 3.0 m Point (agitation activities) Height 3.0 m Diameter 3.0 m	Atmospheric stability class D was used	Various temperatures modelled (19.7–28.5 °C and a 'high temperature scenario 55 °C) Various exit velocities modelled (0.5– .7 m s^{-1})
Williams et al. (2013)	ADMS(v4 and 5)	Modelled composting activities at four composting sites over short and long time periods. Emissions rates were back calculated	10^3–10^6 CFU s for point sources, 10^5 CFU m s for line sources and 10^2–10^3 CFU m^2 s for area sources Bioaerosol fractions modelled NS	Line source to represent turning activities, Area source to represent composting activities and point sources to represent screening and shredding activities	Used data collected on site and data obtained from the Met Office	Used an emission velocity of 1.2 m s^{-1} and emission temperature equal to the ambient temperature plus 3 °C
Douglas et al. (2016b)	ADMS (v4.2)	Calibration and validation study to determine the optimal model inputs which result in modelled outputs which best represent measured bioaerosol data	*Aspergillus fumigatus* Various tested (ranging from $1 \cdot 10^6$–$9 \cdot 10^9$ g m^2 s^{-}**). Optimal value was $9 \cdot 10^6$ CFU g m^2 s^{-}**	Area source Various heights (0–5 m) and geometries were tested Optimal value was with a geometry relating to the size of a typical windrow (44 × 9.5 m) and height of 2.65 m	Used data obtained from the Met Office	Various temperatures (0–60 °C) and emission exit velocities (0–25 m s^{-1}) tested Optimal values when using an emission temperature of 29 °C and velocity of 2.95 m s^{-1}. Optimal values also included using Background concentrations equivalent to the limit of detection of the sampling method were used

* Taha et al. (2007) state an exit velocity with units in m. As the standard unit for exit velocity is m/s, a typographical error has been assumed and thus has been altered as such within the table.

** Douglas et al. (2016b) used gas a proxy for CFU.

shows that the dispersion models used in this context are typically Gaussian (i.e. they assume that the air pollutant disperses and advects from the source in such a way that its concentration around a centre-line follows a Gaussian distribution determined by local meteorological conditions and aerosol characteristics). Such models are well validated for aerosol modelling and are widely recognised and accepted. The most recent and extensive modelling studies with regard to bioaerosols from composting (Douglas et al., 2017; Drew et al., 2007; SNIFFER, 2007; SWICEB, 2005; Taha et al., 2005, 2006, 2007; Tamer Vestlund, 2009; Williams et al., 2013) have used the ADMS dispersion model.

Confidence in model outputs is determined by the quality and accuracy of the input data (Douglas et al., 2016b). Table 1 highlights the limitations and justifications for model inputs used a number of studies to date. While there are valid reasons for deficiencies, uncertainty is evident in model inputs and thus model predictions in this context have large uncertainties. Definition of the pollutant source term within the model has a major influence on model accuracy, specifically:

- What is the most appropriate method for defining bioaerosols as a pollutant within the model (particle characteristics)?

- What is the buoyancy and mass of bioaerosols under atmospheric conditions (particle characteristics)?
- How should the source term geometry be defined to represent emissions from composting activities?
- How should time varying emission factors be used to address variability in emission releases from sources over time?
- What background levels of bioaerosols should we expect, and how should this be accounted for in a dispersion model?
- What averaging times should be used?

2.2. Particle characteristics

The biological pollutants that have been modelled are *Aspergillus fumigatus* (Douglas et al., 2017; Drew et al., 2007; Millner et al., 1980; SNIFFER, 2007; Taha et al., 2005, 2006, 2007), Actinomycetes (Danneberg et al., 1997; Drew et al., 2007; SNIFFER, 2007; Taha et al., 2005, 2006, 2007; Tamer Vestlund, 2009), and Total bacteria (Danneberg et al., 1997). The properties of bioaerosols that will determine their dispersion in the atmosphere include their size or aerodynamic diameter and weight, which influences their deposition rate. Their movement within the atmosphere will also be influenced by whether they are single cells, groups of cells (aggregates) or attached to other particles (dust, compost, and so on).

Research examining bioaerosol size distribution and aggregation (or coalescence) from composting emissions is limited. Byeon et al. (2008) found that aerodynamic diameters of microorganisms were larger than expected and attributed this to the possibility that they were suspended as aggregates with other bioaerosols and/or with dust particles. Reinthaler et al. (1997) showed that typical sizes of particles was approximately 4 μm. However, Tamer Vestlund et al. (2014) and Gales et al. (2015) found that bioaerosols were released mainly as single spherical cells with diameter <1 μm. Kanaani et al. (2008) found that deposition rates for bioaerosols and non-biological particles were a function of particle size, not the nature of the particle. At present, the lack of clear evidence on bioaerosol particle sizes and aggregation tendencies means that is difficult to define an accurate deposition velocity to be used within a dispersion model, and further research is needed in this area.

Two further issues that are not clearly understood are bioaerosol die-off (Tong and Lighthart, 1997; 1998) within the plume (where the microorganism becomes non-viable); and drop out from the plume, in other words, dry or wet deposition which occurs where the particle density is heavier than air. ADMS and other models are capable of calculating wet and dry deposition, if the particle density is known. Typically this data is not available or is inconsistent for bioaerosols and neither do we have sufficient data on changes to viability within the plume, making it difficult to appropriately factor in issues such as UV, OH and other radicals, and even humidity (Haddrell and Thomas, in press). Given the limited data available, the best option available at present is to model an "envelope" of plausible concentrations, which can be used subsequently for Environmental Impact Assessment purposes.

2.3. Source term geometry

Composting facilities represent complex, mobile and intermittent sources (see Appendix A). Research to date has shown that compost process activities, such as agitation (screening, shredding and turning), are responsible for peak bioaerosol emissions at composting sites (Pankhurst, 2010; Pankhurst et al., 2011; Taha et al., 2006). At a typical composting facility, there can be multiple emission sources of differing rates and concentrations, and the number and location of sources can also change depending on the activities taking place on site. Representing these within a model is complicated, with modellers testing different options (Table 1), which ultimately all result in a simplification of reality.

Source geometries from composting have been represented by point, area, line and volume dimensions, although use of point and area geometries are the most common methods of defining the source. Typically point sources have been used to represent agitation activities (e.g. turning, screening shredding – see Appendix A) whereas area sources have been used to represent emissions from static windrows (Drew et al., 2007; SNIFFER, 2007; Taha et al., 2005, 2006, 2007; Tamer Vestlund, 2009). A recent validation study suggests that model outputs are more representative of measured concentrations when representing emissions as an area source (Douglas et al., 2017). This is compatible with the physical reality of open windrow sites, where while the peak emission might be associated with the location at which turning occurs, this location migrates down the length of the windrows on the site. This may also be influenced by the averaging time of the emission, with short term peak concentrations from activities better represented as point sources. However, further work is required to confirm that this is the optimal way to represent biological pollutant emissions from composting facilities.

2.4. Emission rates

In most studies, emission rates of bioaerosol released from agitation activities have been calculated through back extrapolation of measured ambient concentrations, by comparing model outputs to these values and adjusting emission rate to match the observed concentrations. This method is used because directly measuring bioaerosols from these activities is restricted by the use of front end loaders and similar machinery that pose safety hazards to those undertaking the sampling. These estimated rates have been found to vary greatly depending on the source type, the bioaerosol modelled and the on-site process in progress: For point sources emission rates these have been determined to vary from $7.90 \cdot 10^3$ to $8.60 \cdot 10^8$ and $1.80 \cdot 10^4$ to $6.70 \cdot 10^{10}$ CFU s^{-1}; and for area sources from $2.60 \cdot 10^2$ to $3.60 \cdot 10^5$ and 0.00 to $9.00 \cdot 10^6$ CFU m^{-2} s^{-1} for Actinomycetes and *Aspergillus fumigatus* respectively (Table 1).

Most dispersion modelling studies to date (Taha et al., 2006; Douglas et al., 2017) have focussed on estimating bioaerosol concentrations based on traditional culture methods. However, atmospheric conditions and sampling techniques can reduce the viability of bioaerosols. For example, high throughput filtration samplers can cause bioaerosols to dry out (Nielsen et al., 1997). Atmospheric conditions, such as temperature, relative humidity and ultraviolet radiation can also impact on viability of bioaerosols (Dowd and Maier, 2000; Tong and Lighthart, 1997). Bioaerosols clumped together as aggregates may be protected from effects such as dessication, and are more likely to be viable as the inner cells are protected (Carrera et al., 2005; Duncan and Ho, 2008; Lighthart and Schaffer, 1994; Marthi et al., 1990; Thomas et al., 2008; Tong and Lighthart, 1997). These methods are thus known to underestimate true bioaerosol concentrations, as only those that are culturable are sampled.

Most dispersion models, including ADMS, now have the functional to include time varying emissions factors. This has the potential to address issues such as the intermittent nature of activities such as shredding, turning and screening, potential variation in emissions due to compost age and the return of compost windrow to a steady state following an agitation activity such as turning, compost volume at a facility due to seasonal variations, and the movement of agitation activities within sites. However, the lack of data and understanding surrounding variability in emission rates from composting sources has resulted in the function being rarely used in modelling studies for bioaerosols and composting, as no published study to date has utilised these options.

2.5. Bioaerosol background

Bioaerosols are ubiquitous in the atmosphere, arising from a wide range of natural and anthropogenic processes. Just as there is limited evidence on bioaerosol concentrations related to composting sites, there is also limited evidence for other potential sources that may contribute to background concentrations of bioaerosols. Outdoor background bioaerosol concentrations have been found in ranges of up to 10^3–10^4 cfu/m^3 orders of magnitude, but vary significantly, depending on factors such as the of bioaerosol, location and the time of year (ACGIH, 1999; Swan et al., 2003).

Most dispersion models have the ability to account for the presence of naturally occurring background concentrations. Accounting for background concentrations is important for determining the total impact on receptors. Without knowing if the background contribution represents a minor or significant proportion of the total pollutant concentration, it is difficult for epidemiologists to determine the component of adverse health impact that might be attributable to a site-specific bioaerosol emission. To date, only two studies (Douglas et al., 2017; Williams et al., 2013) has accounted for background concentrations when using a dispersion model to estimate bioaerosol concentrations in the surrounding environment of composting facilities.

2.6. Exposure averaging time

Traditional pollutants have air quality objectives defined for specific periods, which define the averaging time for modelling concentration assessment. For example, the PM_{10} objectives are an annual mean of 40 $\mu g\ m^{-3}$ and a 24-h mean of 50 $\mu g\ m^{-3}$ for background not to be exceeded more than 18 times a year, while sulphur dioxide has an objective set as a 15-min mean (Department for Environment, Food and Rural Affairs, 2007). These times are based on the timescale over which exposures are known to result in adverse health effects. The dose-response evidence to date for bioaerosols, and from composting specifically, is insufficient to allow us to define such parameters and subsequently set the averaging time in the dispersion modelling interface.

2.7. Other inputs

Information regarding the values used for other model inputs is sparse, and in some cases, not supported with evidence. For example, only 8 studies (Douglas et al., 2017; Millner et al., 1980; SNIFFER, 2007; SWICEB, 2005; Taha et al., 2006, 2007; Tamer Vestlund, 2009; Williams et al., 2013) stated what meteorological inputs were used and only 4 studies define the pollutant exit velocity that was input into the model (Douglas et al., 2017; Taha et al., 2007; Tamer Vestlund, 2009; Williams et al., 2013). These inputs are essential source information within the model. A recent sensitivity analysis found that pollutant exit velocity was one of the most sensitive inputs, i.e. small changes in exit velocity result in large changes to off-site emission concentrations, thus demonstrating the importance of accurate input values (Douglas et al., 2016b).

3. Future prospects

To date, it has been difficult to respond to the issues identified above due to:

- A lack of data with which to evaluate model performance
- Lack of a meaningful averaging time for considering exposure, which may vary by bioaerosol component and between the types of health outcome within a bioaerosol component (e.g., *A. fumigatus*-related immunoallergic outcomes versus infection)

Despite the considerable steps forward in understanding bioaerosol source terms over recent years, we lack a statistically robust data for model validation and for determining emission characteristics as model inputs. In the absence of site-specific emission information, the development of a comprehensive bioaerosol emissions inventory and guidance on bioaerosol modelling would provide greater consistency in the modelling approaches taken. This would aid both regulators and operators to determine potential impacts on nearby receptors.

Table 2 provides a summary of current gaps in knowledge together with recommendations for further studies in this area. Without further data, the current knowledge gaps are unlikely to be met in the near future. Yet bioaerosols modelling offers benefits as described above and needs to progress if that value is to be realised. In moving forward, the sector needs guidelines for a consistent approach to dispersion modelling of bioaerosol from composting facilities. This should be driven by a scientifically robust risk-based management approach, with guidance on determining best input values. Defaults might be suggested to support professional judgement in the absence of detailed information, provided that some indication is given on the uncertainities associated with this approach. Such guidance might be achieved by a multi-disciplinary collaboration or working group, including dispersion modellers, microbiologists, and epidemiologists from academia, the regulatory bodies and composting site operators.

Table 2
A summary of the identified gaps in bioaerosol science and dispersion modelling, with associated recommendations for future studies.

Knowledge Gap	Recommendation for future studies
Lack of data suitable for modelling purposes, including appropriate source terms, background data and downwind data for model validation	• Monitoring programmes that are designed with the end use purpose of providing input into dispersion models • Determination of pollutant exit velocity and temperature • Long term ambient monitoring programmes ideally with detailed spatial and temporal features. This would include ongoing monitoring simultaneously at various positions on and around several composting facilities, using a consistent approach and methodology. Innovative and novel monitoring techniques should be incorporated and tested. • Monitoring data supported by additional data including local meteorological conditions, site activities and processing information, local topography and land use surrounding the facilities
Inability to define bioaerosols as a pollutant within dispersion models	• Further studies to understand bioaerosol composition, key bioaerosol properties, including viability, size and shape, aggregation tendencies and link to proxy pollutants, such as PM_{10}. Understanding of how these properties can be used to define bioaerosols within dispersion models
Lack of appropriate health-based limit values to define model output settings, including reference exposure limits and averaging times	• Need for community based health studies – A recent systematic review (Pearson et al. 2015) identified only six health studies in community settings. Health studies are needed to develop a biomarker for bioaerosols to better understand long term effects of bioaerosol exposure and to help provide dose-response estimates
Inconsistencies in modelling approaches and lack of justification of input values	• Development of a modelling protocol or best practice guidance, support by industry and regulators

4. Impacts and implications

The application of dispersion modelling methods to the assessment of ambient bioaerosol exposure plays a significant role in the regulation of composting facilities and the protection of human health, if the barriers identified above can be overcome. From an operator's perspective, information derived from bioaerosol emission modelling can demonstrate compliance with regulatory frameworks, help design new facilities to minimise their impact and support healthy relationships with nearby communities.

This paper shows that, whilst progress has been made in modelling bioaerosols from composting, most studies have been limited by lack of robust model input values, and the paucity of reliable ambient monitoring data for model validation and source term analysis. The key challenge remains how to increase the available pool of source term data.

While, this paper focusses on composting, most of the issues raised here are relevant for other sources of bioaerosols, such as intensive agriculture, recognising that the components of bioaerosol may differ markedly between different sources.

5. Conclusions

Dispersion models are in principle capable of estimating levels of exposure to ambient bioaerosol. At present their ability to do so is limited by uncertainties in source term definition and dispersal characteristics. Until we have a better understanding of the mechanisms by which bioaerosols might cause adverse health outcomes there is no clear indication as to appropriate averaging times for model outputs.

We suggest that the key areas to prioritise are:

- Monitoring studies designed specifically to provide inputs for, and validation of dispersion models.
- Determination and dissemination of robust emissions factors for bioaerosols from composting. This should be extended to other anthropogenic sources of bioaerosols (such as intensive agriculture).
- A greater understanding of bioaerosol background concentrations to provide a full environmental context of process emissions.
- A set of guidelines for consistent bioaerosol modelling.

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Appendices A and B. Supplementary materials

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2017.08.023.

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