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BIOAEROSOLS AND HEALTH: CURRENT KNOWLEDGE AND GAPS IN THE FIELD OF WASTE MANAGEMENT

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ABSTRACT

The development of biodegradable waste recycling leads to increased amounts of decaying organic materials handled, and encourages the conditions in which workers, households and neighbouring communities are potentially exposed to bioaerosols. The objective of this study was to assess the knowledge and gaps regarding the health risks associated to bioaerosols in the field of municipal solid waste (MSW) and commercial and industrial waste (C&IW) management. Additional objective was to identify priority issues for research in order to improve knowledge and prevention. Overall, 368 studies have been selected. Strong qualitative evidence links occupational exposure to bioaerosols in the waste industry to adverse effects on health including long-term respiratory disease, notably in the fields of composting, mechanical biological treatment (MBT) and materials recovery facilities (MRF). The literature review highlighted numerous gaps in knowledge about exposure and health effects of bioaerosols that need to be addressed to assess the risk. Most importantly, valid and standardized methods for quantitative exposure assessment are needed. Identification of environmental indicators, estimate of factors influencing the level of bioaerosol exposure at the workplace, well-designed epidemiological studies and validation of dispersion models are other priority issues.

1. INTRODUCTION

As an alternative to landfill disposal, processes are being developed that ensure recycling and energy recovery of biodegradable fractions of waste. In the European Union, the bio-fraction of municipal solid waste (MSW) and commercial and industrial waste (C&IW) has been estimated at 189 and 133 wet million tons, respectively, in 2014 (Arup URS Consortium, 2014).

Biodegradable fractions of waste include: (1) biowaste segregated by households and commercial and industrial activities and (2) the organic matter/waste fraction that remains in dry recovered waste and in residual waste when dry solid waste is segregated by households for separate collection. (Park et al., 2011a ; Schlosser et al., 2015 ; Tolvanen et al., 2001, 2004). Further processes aim at separating the organic wet fraction from the dry solid recovery waste, and to treat it mainly by composting, anaerobic digestion, or stabilisation. Consequently, the biodegradable fraction of waste is present in all MSW and C&IW management sectors.

The development of biodegradable waste recycling leads to increased amounts of decaying organic materials handled. The age of the waste, environmental conditions such as humidity and temperature, and some processes, such as composting, encourage the growth of micro-organisms in the biodegradable waste fraction and associated products. These factors encourage the conditions in which workers, households and neighbouring communities are potentially exposed to airborne biological agents, i.e., bioaerosols (Pankhurst et al., 2011a; Pearson et al., 2015; Schlosser et al., 2015; Wouters et al., 2000).

Bioaerosols consist of live and dead micro-organisms either as individual micro-organisms or as aggregates, fragments and micro-organisms products, such as bacterial endotoxins, β (1-3)-D glucans and mycotoxins. All these biological agents can also be carried by other particles (ACGIH, 1999). The interest of scientists and health authorities in bioaerosols has increased over the past two decades due to the wide range of adverse health outcomes associated with exposure in occupational and residential environments. These include infections, immuno-allergic, non-allergic inflammatory and toxic effects (ACGIH, 1999; ADEME, 2012; Douwes et al., 2003; Dutkiewicz, 1997; Swan et al., 2003).

The main objective of this study was to assess the knowledge and gaps relative to bioaerosol-related health issues in the field of MSW and C&IW management activities, and to have an insight into the weight of evidence from the literature and SUEZ experience. Additional objective

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was to identify priority issues for research in order to improve knowledge and prevention. As a preamble, is briefly given background information on bioaerosols and related health issues.

2. MATERIALS AND METHODS

A scoping review of the literature covering the topic of bioaerosols in the waste management field between 1990 and 2018 was carried out. The literature search for peer-reviewed scientific publications has been conducted on Medline, accessed via PubMed. In addition, technical and grey literature publications were searched using internet-wide search engines (Google, Google Scholar).

Studies were included in this review if they reported data in the MSW/C&IW management field on at least one of the following topics: biohazard identification, bioaerosol measurement, exposure assessment, health outcome in exposed people (case reports, epidemiological studies), quantitative microbial risk assessment, experimentation in humans, measures of prevention, regulation. Studies on bioaerosols from wastewater treatment plants and healthcare waste management activities were not included in the review. In addition to studies specific to the MSW and C&IW management field, articles about the measurement methods and the health effects of bioaerosols were included in the scoping review.

Overall, 368 studies were selected. Of these, 165 were related to bioaerosol monitoring in the field of MSW and C&IW, and 48 to epidemiology. Overall, 77% of the articles were related to the field of occupational exposure. For each of the waste management sectors, the identified studies were critically assessed in order to estimate whether or not hazard identification, exposure assessment and health effect (epidemiological studies, case reports) aspects were "sufficiently", "insufficiently" or "not" documented. An aspect was qualified as "sufficiently documented" if there were numerous studies that present similar conclusions, "insufficiently documented" if major gaps in knowledge still persisted regarding one or more issues, "not documented" if no documentation reporting the data mentioned above was found. It is noteworthy that industrial composting was by far the most investigated sector, accounting for 53% of the studies included. Inversely, in regards to food waste depackaging technology, as far as it could be established, only internal data was available.

3. BACKGROUND INFORMATION ON BIOAEROSOLS AND RELATED HEALTH EFFECTS

Bioaerosols are ubiquitous in nature, however some human activities such as animal farming, gain harvesting and handling, wood processing, the food industry, the textile industry, and waste management may substantially influence them both quantitatively and qualitatively (ACGIH, 1999; Douwes et al., 2003; Eduard et al., 2012; Oppliger and Duquenne, 2015; Rylander and Jacobs, 1994). Bioaerosols are airborne particles, and thus, strictly speaking, gaseous metabolites such as microbial volatile organic compounds (mVOC) are not considered as bioaerosols (ACGIH, 1999; Vilavert et al., 2012). Airborne biological agents can be free in air, such as mould spores, or carried by another particle, of organic or mineral content. Individual bioaerosols range in size from <0.01 µm to 100 µm in diameter (ACGIH, 1999).

Biological agents in aerosol can be transmitted through three routes:

- The inhalation route, which exposes the mucous membrane of the airways and the lungs to the agent impact according to the aerodynamic diameter (D_{ae}) of the particulate. The smaller the inhaled particle, the deeper the deposit into the lung. In addition, largest inhaled particles that impacted in upper airways (D_{ae} above 10 µm) can be swallowed in a second phase;
- the ingestion route, mainly by the contact of dirty hands to the mouth or through a direct projection of materials on face, and also from inhaled coarse particles as mentioned above;
- and the skin and eye contact mode.

3.1 Health outcomes of bioaerosols

Adverse health effects of inhaled bioaerosol can be divided into infectious diseases and non-infectious effects.

3.1.1 Infectious diseases

Bioaerosol inhalation is recognised as one of the main transmission routes for infectious diseases (Eames et al., 2009; Moretti et al., 2018; Qian and Zheng, 2018; Valade et al., 2015; Yates et al., 2016). Infection requires that a micro-organism (bacteria, viruses, fungi) be alive, and the severity of the disease depends on the virulence of the strain and individual risk factors, such as immune deficiency. Depending on the micro-organism, the reservoirs are humans, animals and/or the environment. The occurrence of airborne infectious diseases is facilitated by the clustering of people in close environments (e.g., influenza, tuberculosis) and by exposures that are specific to occupations (e.g., Q-fever in farmers, psittacosis in bird breeders) or environments (e.g., legionellosis, non-tuberculous mycobacterial pulmonary disease, histoplasmosis) (Cavalazzi et al., 2018; Clark et al., 2018; Drummond et al., 2019; Herwaldt et al., 2018; Hogerwerf et al., 2017; Maloney et al., 1995; McKinsey et al., 2011). Health care workers, veterinarians, farmers and biomedical workers have been identified as carrying out high risk occupations (Douwes et al., 2003).

Some micro-organisms are opportunistic pathogens; this means that infection occurs when the host defenses are compromised by disease or the treatment of the disease. Immune deficiency is the most common condition associated with opportunistic infection, including malignant disease, organ transplantation and human immunodeficiency virus (HIV) infection (Bunch and Crook, 1998). Opportunistic airborne micro-organisms include fungi (moulds, such as *Aspergillus fumigatus*, *Zygomycetes* species, *Fusarium*, *Coccidiodes immitis*, and yeasts such as *Cryptococcus neoformans* and *Pneumocystis jirovecii*) and bacteria (e.g., *Mycobacterium Avium* Complex, *Pseudomonas aeruginosa*, *Micrococcus*) (Brandt and Warnock, 2007; Clifton and Peckham, 2010; Lande et al., 2018; Lemonovich, 2018; Lin, 2009; Ma et al., 2018).

3.1.2 Non-infectious effects

Non-infectious effects of inhaled bioaerosols gather inflammation of airways from non-allergic mechanisms (usually cytokine-mediated effects), immuno-allergic respiratory diseases (asthma, rhinitis, hypersensitivity pneumonitis) that need previous sensitization to the allergenic compound(s) of the micro-organism, and toxic effects on organs (liver, kidney, central neurologic system, immune system, …) (ACGIH, 1999; Douwes et al., 2003; Rylander and Jacobs, 1994). Main non-infectious effects due to inhaled bioaerosols are summarized in Table 1. Non-infectious effects do not need the micro-organism to be alive; dead micro-organisms and fragments do keep pro-inflammatory and allergenic properties. Some mycotoxins (Aflatoxin B1) are classified as carcinogenic to humans (Group 1) by the International Agency for Research on Cancer (IARC, 2012). The critical route of exposure to mycotoxins is usually ingestion, however, there is growing evidence that lung can also be a target for aflatoxin B1 carcinogenicity (Donnelly et al., 1996; Jakšić et al., 2012; Marchese et al;, 2018; Massey et al., 2000).

Occurrence of immuno-allergic outcomes is influenced by both features of exposure to micro-organisms (the level and duration of exposure, occurrence of peaks of exposure), and the presence of individual risk factors, such as atopy for asthma, or asthma and cystic fibrosis for allergic bronchopulmonary aspergillosis (ABPA), which is the principal clinical disorder due to *Aspergillus* hypersensitivity (Denning et al., 2013; Knutsen and Slavin, 2011). In addition, sensitisation to *A. fumigatus* has also been associated with reduced lung function in severe asthma and chronic obstructive pulmonary disease patients (Denning et al., 2014; Fairs et al., 2010). The burden of allergic fungal airway disease is important. In a scoping review, Denning et al. (2013) estimated that the prevalence of ABPA in adults with asthma was 2.5%, whilst modelling suggests an ABPA global burden of 4.8 million adult patients. As regards severe asthma with fungal sensitisation, the global burden has been estimated at about 6.5 million patients (Denning et al., 2014). Furthermore, thermophilic actinomycetes and fungi are well-known causal agents of occupational hypersensitivity pneumonitis (ACGIH, 1999; Eduard, 2009; Quirce et al., 2016).

At the workplace, exposure to endotoxins has been associated with both acute and chronic respiratory outcomes, due to their pro-inflammatory properties (Rylander, 2006). Short-term respiratory and systemic outcomes can lead to sick leaves, and repeated exposure to high levels of endotoxins have been associated with chronic bronchopulmonary disorders and reduction in lung function (Searl et al., 2008). Endotoxin exposure substantially aggravates airways inflammation in patients with allergic rhinitis and atopic asthma (Michel et al., 1989; Rylander, 2006). Moreover, it has been shown that genetic variations in proteins that mediate endotoxin recognition impact the airways and immune response to endotoxin exposure (Holla et al., 2002). These data emphasize that the response to endotoxin exposure is not similar between individuals.

The results of workplace studies suggest that the development of respiratory symptoms as a result of exposure to bioaerosols is likely to lead to chronic respiratory illness following prolonged exposure (Rylander, 2006) and this negative effect is biologically plausible due to chronic inflammatory reaction of the respiratory tract (Bolund et al., 2017; Liebers et al., 2008). A recent meta-analysis of the association between organic dust (i.e., bioaerosol) exposure and decline in lung function, the first of its kind, showed a small significant excess loss in forced expiratory volume in the first second (FEV1) (on average 4.92 mL/year) among exposed compared with controls (Bolund et al., 2017). However, the authors highlight that this small excess decline could lead to possible important health issues after many years of exposure. Furthermore, the healthy worker selection bias (i.e., the potential bias caused by the phenomenon that more susceptible individuals may be excluded from employment or, once employed, may leave the job they do not tolerate) could be an evident problem in all the studies included in this review and may suggest that the associations found were underestimated (Bolund et al., 2017). Other symptoms associated with bioaerosol exposure are nausea, diarrhoea, headache and fatigue (Douwes et al., 2001; Gladding and Cloggins, 1997; Hambach et al., 2012; Ivens et al., 1999; Krajewski et al., 2004).

On the other hand, it is worth noting that microbial exposure, and particularly exposure to endotoxins may have a protective effect against atopy and asthma, as suggested by epidemiological studies in farmers (Eduard et al., 2004; Riedler et al, 2001) and recent experimental works (Schuijs et al., 2015). Several epidemiological studies also support hypothesis that endotoxin exposure may protect against lung cancer, as a result of stimulation of cytokin release, and notably Tumor Necrosis Factor α (TNFα) (Ben

TABLE 1: Non-infectious effects from exposure to airborne micro-organisms.

Microorganisms	Constituents/Metabolites	Allergy	Non-allergic inflammation	Others [b]
Gram negative bacteria	Endotoxin		+	
Non-sporulated Gram positive bacteria	Peptidoglycans		+	
Fungi	Allergens β (1-3)-D-glucans Mycotoxins	+ a 	 + +	 c
Thermophilic actinomycetes	Allergens Peptidoglycans	+ 	 +	

a: Enhancement of the allergic response to inhaled allergens; b: Others: cytotoxic and carcinogenic effects; c: Limited evidence of systemic and carcinogenic effects of inhaled mycotoxins, in contrast with ingested mycotoxins.

Khedher et al, 2017; Lenters et al., 2010). However, optimal dose of exposure to endotoxin, if any, is unknown, as on the other hand long-term exposure to endotoxin is associated with chronic bronchopulmonary disorders as mentioned above.

3.2 Main gaps in knowledge on bioaerosol health effects

Several gaps remain in our knowledge of the potential health impact of exposure to bioaerosols generally, and notably from MSW and C&IW regardless of the specificity of the activity or process. These gaps concern each of the four steps of health risk assessment process (USEPA, 2018): hazard identification, exposure assessment, exposure-response relationship and health risk assessment.

3.2.1 Hazard identification

Exposure to bioaerosols is often estimated by analysis of microbial sum parameters in air samples using culture-based methods, and less frequently by microscope examination (ACGIH, 1999; Cartwright et al., 2009; Douwes et al., 2003; Eduard, 2009; Eduard et al., 2012). As highlighted above, bioaerosol in the organic waste management field is a complex mixture of microorganisms, constituents and metabolites. Moreover, bioaerosol exposure is associated with a large variety of symptoms and diseases. In fact, it is often not clear which agents are primarily involved in health outcomes that have been described by exposed groups. Many biological agents that may cause health effects are currently not identified. Even if a few studies carried out a large identification approach for microorganisms with molecular biology (quantitative PCR) (Le Goff et al., 2010; Pankhurst L.J. et al., 2012) or mass spectrometry (MALDI-TOF) (Madsen et al., 2016; Nasir et al., 2018a), or investigated specific antigens with enzyme immunoassays (van Kampen et al. 2014), data in most studies do not reflect the variety of different species. New biomolecular technologies such as next-generation DNA sequencing can help in informing on the microbial diversity and the relative abundance of airborne microorganisms and in identifying indicators for monitoring bioaerosols emission (Duquenne et al., 2018). Such indicators may help to distinguish the contribution of a specific source, such as a non-hazardous waste landfill, versus other sources (such as intensive poultry farming). They have been applied to the waste management field for a very few years (Degois et al., 2017; Dubuis et al., 2017; Mbareche et al., 2017, 2018; Wéry et al., 2018). In fact, there is a need for identification of indicator parameter(s) for exposure assessment and health risk assessment in the specific field of interest, depending on the goal of the study (Douwes et al., 2003). There is a need for clear demonstration of the relevance of the selected indicator parameter, according to the question to be answered. For example, to answer the question of assessing bioaerosol dispersion in the surroundings of composting facilities, a combination of three microbial indicators using culture-independent techniques (viable bacteria using solid-phase cytometry, and two bacterial phylotypes, affiliated to *Saccharopolyspora* sp and the *Thermoactinomycetaceae*, respectively, using qPCR) has been proposed as a relevant marker for monitoring composting aerosol (Le Goff et al., 2012). However, this combination would be would be of little interest for assessing the health effects of exposure of neighbouring residents to composting bioaerosols. To answer part of that question, the focus will rather be on micro-organisms such as *Aspergillus fumigatus*, which is a real concern for the health of susceptible individuals (Deacon et al., 2009a; Epstein, 1994; Kramer et al., 1989; Schlosser et al., 2016).

3.2.2 Exposure assessment

Exposure assessment is closely linked to the sampling strategy, which includes the selection of the collection and analysis methods and the sampling plan (stationary and personal sampling, sampling locations, sampling duration and sample size) (ACGIH, 1999; ADEME, 2012; Douwes et al., 2003; Eduard and Heederik, 1998). Measurement of bioaerosols should be performed according to a protocol representative of the exposure pattern and duration at the workplace or in the surrounding environment. Different factors may influence the pattern of exposure to bioaerosol components and the variability in exposure levels. The study design and the sampling strategy should take these factors into consideration. Furthermore, the particle size dispersion should be taken into account, for both health risk assessment process and bioaerosol dispersion modelling (Byeon et al., 2008; Galès et al., 2015; Rolph and Gladding, 2017).

As a major key point, there is a lack of valid methods to assess exposure, and of protocols that should include internationally accepted guidelines on sampling, transport and storage, and analytical procedures (Duquenne et al., 2013; Searl et al., 2008; Walser et al., 2015). This lack makes it difficult to compare the results of the different exposure studies, and of epidemiological findings. Several documents have been published by standardisation organisations or occupational health and safety institutes that describe protocols of bioaerosol measurement at the workplace. However, these protocols are not internationally recognised, and some of these documents should be reviewed to incorporate newly available knowledge (Duquenne et al., 2013). In Europe, the European Committee for Standardization (Comité Européen de Normalisation, CEN) published three standards in the early 2000s, EN 13098 (CEN, 2000), EN 14031 (CEN, 2003) and EN 14583 (CEN, 2004). EN 13098 and EN 14031 are currently being revised by the CEN technical committee 137.

Alongside the identification of appropriate indicator parameters, there is a need for developing standardized measurement methods and for harmonized approach to sampling strategy. There is also a clear need for developing continuous monitoring methods which provide real-time information (Nasir et al., 2018b; O'Connor et al., 2015; Robinson et al., 2013).

3.2.3 Exposure-response relationship

Regarding bioaerosols, exposure-response relationship is lacking for most agents (ACGIH, 1999, Eduard, 2009, Searl et al., 2008; Walser et al., 2015). Indeed, establishing exposure-response relationships for bioaerosols is difficult due to: (1) the definition of exposure (e.g., what indicator parameter? what exposure time scale? what exposure unit?), (2) the definition of the response (what critical effect as the relevant endpoint? threshold versus non-threshold response?), and (3) the complexity of the mixture of micro-organisms and components in bioaerosols. Moreover, the combined effects of biological agents (such as endotoxin and specific allergens) should not be ruled out. Neither should interactive effects between bioaerosols and chemical hazards such as ammonia and volatile organic compounds (Viegas et al., 2017). These points highlight potential differences in response to an environmental indicator depending on the occupational sector (e.g., differences in response to endotoxin exposure in pig farming versus paper and cardboard recycling depending on other associated air pollutants).

Establishing exposure-response relationships also faces difficulty associated with variation between individuals and within individual (i.e., over-time) in the response to a particular inhaled biological agent. There is a need for investigating the issue of individual susceptibility to allergens, endotoxin and other bioaerosol components, and the potential influence on the shape of the exposure-response relationships.

There is a need for further research on exposure–response relationships for most bioaerosol components.

3.2.4 Health risk assessment

According to the above sub-sections, it is obvious that health risk characterization regarding bioaerosols, and in the waste industry particularly, is seriously hampered by several major gaps in each of the constitutive steps of the process. That means we cannot precisely predict the risk of a particular health outcome associated with a specific job, nor can we for general community. Owing to the lack of established exposure-response relationship for inhaled biological agents, quantitative microbial risk assessment (QMRA) cannot be performed.

As an alternative to a predictive approach with risk characterization, epidemiological studies provide observational results and risk measurement estimate. However, regarding bioaerosols, available epidemiological studies do not provide strong evidence that would allow establishment of exposure-response relationships and subsequent exposure limits (Walser et al., 2015). There is a need for further epidemiological studies, particularly prospective cohort studies, which allow consideration of both exposure level and individual risk factors as covariates. If ethically feasible, experimental studies involving human subjects may also help to establish health-based guidelines for airborne biological agents, such as endotoxin (Health Council of the Netherlands, 2010).

Whatever the risk assessment approach, large uncertainties in exposure assessment (mainly due to the lack of reliable and standardized quantitative exposure assessment methods) greatly hamper the development of legal health-based exposure limits for most bioaerosols (Douwes et al., 2003). A few specific components are exceptions, such as subtilisin, which is an enzyme produced by Bacillus subtilis and used in detergents, and endotoxin, as mentioned above (Douwes et al., 2003; Eduard et al., 2012). In the Netherlands, 90 EU m^{-3} has been proposed as a health-based recommended limit (8-hr time-weighted average) for endotoxins at the workplace, which affords adequate protection against the effects of both acute and chronic exposure (Health Council of the Netherlands, 2010). Otherwise, regulatory occupational exposure limits have been set for cotton, grain, wood, and flour dust, however these limits do not consider specific components present in the dust (Eduard et al., 2012).

4. BIOAEROSOLS FROM MSW AND C&IW MANAGEMENT AND HEALTH: WHAT WE KNOW AND WHAT WE DO NOT KNOW

This section synthetizes knowledge and gaps related to bioaerosols in the MSW and C&IW management field. Some data are specific to this sector, other ones are more generic as they apply to other occupational and environmental fields.

4.1 What are the target groups regarding exposure to bioaerosols from MSW and C&IW management activities?

Main target groups are workers, households and nearby residents of waste management facilities. Additional target groups are represented by occasional visitors of the facility (school pupils, municipal representatives, …) and since recently by pupils and teachers in schools where an on-site composting program has been implemented (Brown, 2005; Garden Organic, 2018; Green Mountain Farm to School, 2010). There are marked differences in features of target groups and in respective exposure patterns that can influence the response of individuals to bioaerosols. Workers in MSW and C&IW management activities are clearly the target group with highest levels of exposure. Workers are adults, generally healthy (although some of them may present asthma and/or be smokers), and high levels of exposure to bioaerosols from waste are limited to the working time. Households may be exposed to MSW bioaerosols from separate storage of biowaste and home composting. Households' exposure is intermittent, but may occur over the lifetime. Individuals may obviously be ill and present risk factors. Residents living or working nearby open air waste management facilities (composting plants, non-hazardous waste landfill sites) may be exposed to bioaerosol emissions from the facility. Residents' exposure is irregular, depending on the on-site activity, and may potentially occur all over the lifetime. These individuals may also be ill and present risk factors.

As a result, although exposed to highest concentrations of bioaerosols, waste workers should not be considered as a "sentinel group" for surveillance programs on health impact of bioaerosols. In other words, the absence of reported health problems among workers does not mean there is no risk among household members, neighbouring residents and school pupils. Waste workers are not representative of the general population, as they may be markedly different with regard to individual risk factors and exposure patterns.

4.2 What do we know about waste workers' exposure to bioaerosols?

MSW and C&IW materials present in the waste management sectors contain micro-organisms from biodegradable fraction of incoming waste, and from the growth of bacteria and fungi favoured by humidity and temperature (Miller and Clesceri, 2002; Pahren, 1987; Palmisano and Barlaz, 1996). Microorganism occurring in bioaerosol from MSW and C&IW are mainly fungi and bacteria, and are divided into four major groups: Gram-negative bacteria, Gram positive bacteria, actinomycetes and fungi (Dutkiewicz, 1997) (Table 2). The composition of bioaerosols depends on the nature of the feedstock and the processed used. For example, in the composting process, mesophilic bacteria and fungi in feedstock are succeeded by thermophilic actinomycetes and fungi species as the temperature rises above 45°C (Millner et al., 1994; Swan et al., 2003). Exposure to viruses in solid waste processing facilities is poorly documented. Human adenovirus and Torque teno virus (which has been proposed as an indicator of viral faecal contamination in the environment) have been detected in the air of waste disposal and recycling plants (Carducci et al., 2013). Most of human adenovirus positive air samples were able to grow in cell culture and were thus considered infective. In another study, human adenovirus genome could not be quantified in any of the air samples from biomethanization facilities (Traversi et al., 2018).

Levels of exposure to bioaerosols in the MSW/C&IW industry are highly variable between sectors and within individual sectors, and between workers and within workers (variation in personal exposure over time) (Spaan et al., 2008; Wouters et al., 2006) (Figure 1). Measurement uncertainty might be factor of variation; however, waste composition, extended residual waste collection cycles, enclosed vs. open air facility, types of process, season, tasks being performed and control measures in place are major potential determinant factors of bioaerosol concentration in the air (Gladding et al., 2003; Gladding and Gwyther, 2017; Persoons et al., 2010, Schlosser et al., 2009, 2015; Sykes et al., 2011; Wouters et al., 2006). Processes that are particularly associated with high levels of exposure to bioaerosols are all sources of mechanical agitation (waste unloading, stored waste handling, shredding, screening, windrow turning, material transfer operations, truck loading) or tasks involving manual agitation of waste (manual sorting of waste, cleaning and maintenance operations, blockage clearing) (Millner et al., 1994; Persoons et al., 2010; Sanchez-Monedero et al., 2005; Schlosser et al., 2009, 2015; Taha et al., 2006). In addition, vehicle traffic on dirty roadways contributes to bioaerosol emission (Epstein et al., 2001; Millner et al., 1994; Reinthaler et al. 2004). All these processes and activities generate dust, which contains biological agents. In a recent multivariable study, the level of inhalable dust has been shown to be the factor that most influenced within-site variability in endotoxin and culturable bacteria concentration in the air in sewage sludge composting facilities (Schlosser et al., 2018). These findings suggest that measurement of dust can efficiently assist decision making for prevention measures against endotoxin and bacteria in sludge composting plants. Further work could help to determine whether inhalable dust may be used as a marker of exposure to endotoxin and other airborne biological agents in other fields of waste management.

The highest levels of exposure to airborne bacteria and

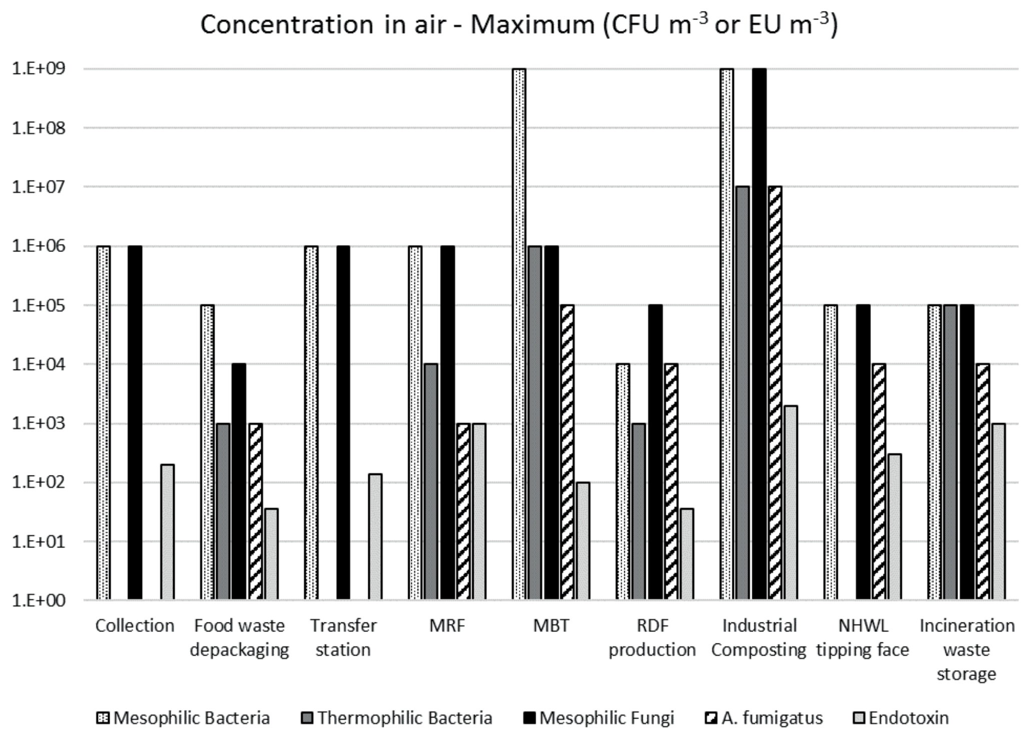

FIGURE 1: Maximum concentrations (orders of magnitude) of bioaerosols in waste management activities reported in the literature and from internal measurements.

fungi have been reported at composting sites and mechanical biological treatment (MBT) facilities (Pearson et al., 2015; Persoons et al., 2010; Schlosser et al., 2009; Searl, 2008; Sykes et al., 2011; Tolvanen and Hänninen, 2005; Wouters et al., 2006) , followed by material recovery facilities (MRFs) and during waste collection operation (Cerna et al., 2017; Gladding and Coggins, 1997; Lavoie et al., 2002; Madsen et al., 2016; Neumann et al., 2002; Nielsen et al., 1995; Schlosser et al., 2015; Würtz and Breum, 1997) (Figure 1). These exposure levels were 100 to 100,000 times higher than highest outdoor background levels. Levels of exposure to endotoxins reached several tenths or hundreds Endotoxin Units m^{-3} in most sectors. These exposure levels were 10 to 1000 times higher than outdoor background levels.

4.3 What do we know about bioaerosol-related risk for waste workers' health?

In the MSW and C&IW field, associated microorganisms are mostly not pathogens, i.e. they are not infectious for healthy people. However, a few are real pathogens, such as *Legionella* species (Conza et al., 2013; Currie et al., 2014) or enteric pathogens in pet excrements and disposable diapers (Gerba et al., 1995, 2011). Some airborne microorganisms (mainly fungi, such as *Aspergillus fumigatus* and *Zygomycetes* species) may act as opportunists in fragile people, that are immunocompromised or present lung damages often associated with prescription of steroids (Cornillet et al., 2006; Latgé, 1999; Roden et al., 2005). These individual risk factors are significant determinants of the risk of severe fungal infection. However, it is worth stressing that huge levels of exposure to *A. fumigatus* spores have been associated with severe *Aspergillus* infection in immunocompetent persons (Arendrup et al., 2006; Jung et al., 2014; Russell et al., 2008; Zuk et al., 1989). These atypical cases are rare.

Case reports of respiratory disease in waste workers, with either immune-allergic, non-allergic inflammatory or infectious mechanism, provide evidence in support of an association with bioaerosol exposure in composting plants and in MRFs (reviewed by: ADEME, 2012; Schlosser et al., 2009, 2015; Swan et al., 2003). However, case reporting does not mean a confirmed excess of risk, and epidemiological investigations are necessary to estimate whether the risk is significantly increased in exposed workers and how large this increase may be. In the field of MSW/C&IW management, most epidemiological studies are of cross-sectional design (29 out of the 48 studies identified). Most of these studies agree in indicating an excess of upper airway (nose and throat), eye and respiratory tract irritation symptoms in exposed workers (e.g., Athanasiou et al., 2010; Bünger et al., 2000; Gladding et al., 2003; 2010; Hambach et al., 2012; Heldal and Eduard, 2004; Heldal et al., 2015; Hoffmeyer et al., 2014; Ray et al., 2005; Schantora et al., 2015). These findings support the hypothesis of an inflammatory effect of bioaerosol exposure in waste workers, which is confirmed by the association between inflammatory symptoms of the airway and increases in inflammation cells and markers in nasal lavage or induced sputum samples (Douwes et al., 2000; Heldal et al., 2003; Wouters, 1999). Furthermore, several studies showed a cross-shift decline in respiratory function in waste workers exposed to bioaerosols (Heldal et al., 2003, 2015; Sigsgaard et al., 1994). However, quantitative evidence of an excess risk of chronic respiratory disease following long-term exposure to bioaerosols in the waste industry is limited. In a 5-year follow-up study in composting workers, a slight decline of the Forced Vital Capacity in percent of predicted (FVC%) of the non-smoking compost workers was observed during the observation period compared to control subjects (Bünger et al., 2007). Conversely, in a prospective study over 5 years in garbage collectors in Switzerland, the respiratory function was not altered (Tschopp et al., 2011). The authors emphasize that the lack of effect of bioaerosols in this population probably resulted from low exposure levels due to good working conditions. In a 13-year follow-up study in Germany, van Kampen et al. (2016) demonstrated that working as a compost worker for more than 5 years significantly increased the risk of coughing by an average of 28% and that for cough with phlegm by an average of 32%, suggesting an increased risk of chronic bronchitis. However, compared to controls, no higher inci-

TABLE 2: Micro-organism genera or species most often isolated from bioaerosols in the MSW management field.

Group of micro-organisms	Origin	Microorganism genera or species
Gram-negative bacteria	Fresh and stored plant materials	*Pantoea, Pseudomonas, Klebsiella, Aeromonas, Rahnella, Flavobacterium*
	Animal products	*Acinetobacter*
Gram-positive bacteria	Animal products and stored plant materials	Coryneform bacteria (*Arthrobacter, Corynebacterium, Brevibacterium, Microbacterium*), cocci (*Staphylococcus, Micrococcus, Streptococcus*), spore forming bacilli (*Bacillus*), *Listeria*
Actinomycetes	Stored plant materials	Thermophilic species (*Saccharopolyspora rectivirgula, Thermoactinomycetes vulgaris, Saccharomonospora viridis, Thermomonospora spp*)
	Soil and vegetable materials	Mesophilic species (*Streptomyces, Rhodococcus, Agromyces*)
Fungi	Saprophytic and pathogen plant fungi	*Cladosporium, Alternaria, Fusarium, Davidiella, Didymella, Curvularia, Drechslera*
	Decaying organic matter	*Penicillium, Aspergillus, Acremonium, Paecilomyces, Zygomycetes* species *(Rhizopus, Mucor, Absidia)*
	Low-moisture food waste	*Wallemia*

Sources : ADEME, 2012 ; Cerná et al., 2017; Degois et al. 2017 ; Dutkiewicz, 1997 ; Huang et al., 2002 ; Kalwasinska et al., 2014 ; Krajewski et al., 2002 ; Lis et al., 2004 ; Madsen et al., Mbareche et al., 2018 ; 2016 ; Nielsen et al., 1997 ; Pinto et al., 2015 ; Rahkonen et al., 1990 ; Viegas et al., 2014 ; Wéry, 2014.

dence of loss of respiratory function during the follow-up was observed in compost workers. A distinct improvement in health protection measures during the 13 years of study (which reduced the level of exposure to bioaerosols) and a potential healthy worker effect are limitations of the study. To date, no other long-term prospective epidemiological studies have been published.

It is important to stress that several factors may suggest that prevalence of respiratory disorders in the waste industry is under-reported. Some of these factors are associated with potential selection bias due to the healthy worker effect, the employment patterns in the waste industry, the low specificity of most symptoms, and the time scale over which chronic respiratory disease usually develops.

Nevertheless, as supported by exposure data in the waste industry and epidemiological findings in other sectors such as agriculture, farming, and textile industry, strong qualitative evidence links occupational exposure to bioaerosols in the waste industry to adverse effects on health including long-term respiratory disease, notably in the fields of composting, MBT and MRF (Pearson et al., 2015; Schlosser et al., 2009, 2015; Searl, 2008). In a richly documented report delivered to DEFRA in UK in 2008, strong warnings were issued about the potential for bioaerosols to cause major respiratory health problems to waste workers in the future (Searl, 2008; Letsrecycle.com news, 2009).

These data emphasize the need for appropriate preventive measures against bioaerosols at the workplace in the MSW and C&IW industry, even if the epidemiological evidence is limited. As highlighted by the literature review, the levels of exposure to dust and bioaerosols vary within individual waste management sector, suggesting that there is potential to reduce exposures through good practice and prevention measures. These measures involve facility and process design, operational activities and, as a last resort, personal protection. The positive effect of vehicle technical factors has been demonstrated in the waste collection field (Breum et al., 1996; Neumann et al., 2002, 2005). At MRFs, several prevention measures have been recommended, such as adopting a site layout that uses separate areas for different processes, adopting a first in-first out order of treatment of the incoming waste, installing appropriate ventilation and dust capture systems in the processing areas, and installing adequate ventilation systems in the sorting rooms (Felten et al., 2001; INRS, 2011; Rapp et al., 2009; Schlosser et al., 2015; Stagg et al., 2013). Furthermore, in order to reduce microbial growth in the incoming waste, households are requested to dispose raw waste and biowaste into the container for separate collection and use containers with a cover in order to protect waste from the rain (INRS, 2011; Schlosser et al., 2015). In composting plants, several preventive measures have been recommended, such as dust control measures that include moisture control of the feedstock and composting, screening operation in a separate area from composting operations, sealing of the turning machinery with rubber mats, dust capture systems, adequate ventilation in buildings, regular cleaning and wetting of driveways, and protection of the vehicle cab with a pressurisation and high efficiency particulate air (HEPA) filtration system (Epstein, 1996, 2001; Millner et al., 1994; Reinthaler et al., 2004, Schlosser et al., 2012; Spencer and Alix, 2006; Sykes et al., 2007). Furthermore, frequent windrow turning has been shown to reduce *A. fumigatus* on the compost surface due to improved thermohygienisation, resulting in a reduction in cumulative health risk despite more frequent turnings (Fischer et al., 1998). In all waste management sectors, the use of respiratory protective equipment (at least a FFP2/N95 filtering half mask) is recommended for tasks during which workers are most exposed, such as cleaning and maintenance. All these recommendations are based on common sense, however, quantitative data on their efficiency is limited (Breum et al., 1996; Epstein et al., 2001; Neumann et al., 2002, 2005; Park et al., 2011a; Rapp et al., 2009; Schlosser et al., 2012, 2015). Moreover, there is no consensus on the advantages (control of dust emission)-disadvantages (e.g., microbial growth due to humidity, dirty equipment) balance of the use of water spray misters in the waste management field and quantitative data is lacking (Epstein et al., 1996, INRS, 2011, Millner et al., 1994; Schlosser et al., 2015; Spencer and Alix, 2006; Stagg et al., 2013). Further research, and notably intervention studies, is needed in order to better assess the efficiency of prevention measures against bioaerosols at the workplace.

4.4 What are the main gaps in knowledge about exposure to bioaerosols and related risks for waste workers' health?

As a general rule, most studies investigated microbial sum parameters (e.g., mesophilic fungi), endotoxins, and mainly *A. fumigatus* as a micro-organism species. There is a lack in hazard identification in all sectors, as mentioned above, and exposure to some biological agents such as mycotoxins and *Legionella* is poorly documented. Workers' exposure to bioaerosols is not or insufficiently documented in several fields: this is the case for activities in household waste recycling centres (HWRC), waste transfer stations, MBT facilities, non-hazardous waste landfill sites(NHWL), incineration plants, and for those associated with refuse-derived fuel (RDF) production or food waste depackaging. Importantly, there are major knowledge gaps in all sectors about identification of determinant factors of bioaerosol exposure at the workplace and the size effect of these determinants. Most exposure studies are descriptive works, or only bivariable statistical analysis was performed. Another gap is the limited data on personal sampling, as compared to results of stationary sampling. These personal measurement results are necessary for estimating actual worker's exposure. Moreover, most personal samplings were full-shift and resulted in time-weighted averaged exposure estimates. Information on task-specific exposure is needed in most sectors for appropriate health risk management. Finally, most of epidemiological studies in the waste industry are cross-sectional designed, generally involving small numbers of subjects, and they provide limited information for exposure-response relationship. Prospective cohort studies are lacking, for both short-term health adverse effects and long-term ones (Bünger et al., 2007; Tschopp et al., 2011; van Kampen et al., 2016).

4.5 What do we know about households' exposure to bioaerosols and associated health risk, and what are the major gaps?

Limited data suggests that separate storage of biowaste by households could increase exposure to bioaerosols and health effects in susceptible individuals (Herr et al., 2004; Naegele et al., 2016; Wouters et al. 2000). However, data on personal exposure associated with separate storage of biowaste by households is lacking. Potential impact that could be associated with changes in collection regime (switch for fortnightly collection of residual waste, extension of the sorting instruction of plastic packaging) would deserve attention; however, it is extremely poorly documented (Gladding and Gwyther, 2017; Schlosser et al., 2015). In particular, it should be stressed that home composting raises the question of potential health risk for susceptible individuals, mainly because of potential exposure to high concentrations of *A. fumigatus*. This hypothesis is supported by two severe infection case reports (Jung et al., 2014; Russel et al., 2008), and the occurrence of a deadly invasive pulmonary aspergillosis associated with gardening in the UK reported by Russel et al. (2008) has been given a lot of media coverage (National Health Service, 2008). However, households' personal exposure to *A. fumigatus* during compost agitation is not documented. To our knowledge, no epidemiological study is available.

In addition to home composting, urban community composting and composting programs at school are being developed. However, there is very little work on associated health issues (Pankhurst et al., 2011a), and to the best of our knowledge personal exposure is not documented. Strong evidence supports causality between exposure to moulds and the development and exacerbation of asthma in children (ANSES, 2016). Implementing an on-site composting program at school can expose vulnerable children to mould spores when turning and handling compost and further research is needed.

4.6 What do we know about nearby residents' exposure to bioaerosols from MSW/C&IW treatment facilities and associated health risk?

Regarding bioaerosols, potential health impact on nearby residents is primarily relevant for open-air composting facilities (Pankhurst et al., 2011b; Taha et al., 2006) and NHWL sites (Reinthaler et al., 1999; Schlosser et al., 2016). This issue can also be addressed for on-site waste handling in the open as it generates bioaerosol emission, and for enclosed composting facilities and MRFs as biofilter exhaust contains bioaerosols (Ibanga et al., 2018; Sanchez-Monedero et al., 2003).

A. fumigatus and thermophilic actinomycetes species have been identified as relevant indicators for monitoring of bioaerosols in the surrounding areas of large-scale outdoor composting facilities (Albrecht et al., 2008; Environment Agency, 2018; Le Goff et al., 2012). Data on bioaerosol monitoring in the surrounding environment of open-air composting facilities shows that concentrations generally drop to near-background levels within 300 m, although raised levels of exposure may occasionally arise at distance of up to 500 m from composting facilities (Pankhusrt et al., 2011b; Recer et al., 2001). Data on bioaerosol measurements in the surroundings of NHWL sites is limited. A recent study suggested that mesophilic moulds and *A. fumigatus* may be transported beyond 500 m from the property boundary at concentrations above those found locally upwind of the landfill site (Schlosser et al., 2016). In addition to distance from the facility, other mitigation factors linked to the facility design have been the focus of published studies. These measures contribute to reduce the off-site transport of bioaerosols and include site enclosure, negative pressure of the air above the composting process, installation of biofilters, bioscrubbers equipped with a droplet separator, or equipment with a dielelectric barrier discharge reactor (Ibanga et al., 2018; Millner et al., 1994; Morey et al., 2003; Park et al., 2011b; Sanchez-Monedero et al., 2003; Schlegelmilch et al., 2005). Removal efficiency was different depending on the equipment and the micro-organism, however, it did not reach 2 log removal (i.e., 99% reduction in concentration). Building berms and planting trees at appropriate locations on the site have been recommended as measures that can alter wind dispersion patterns and off-site transport of bioaerosols (Millner et al., 1994). The benefit of forest barriers on particulate dispersion has been demonstrated experimentally (Raynor et al., 1974) and highlighted regarding composting (Millner et al., 1994). Forest barrier both dilutes the particulate concentration in the plume and induces impaction and deposition of particles onto foliage.

Community-based epidemiological data is very limited. In a cross-sectional study in Germany, health questionnaires were collected from residents near a large-scale composting site and from unexposed controls (Herr et al, 2003). Residents exposed to bioaerosol pollution were shown to report irritative respiratory complaints independently of perceived odours. Recently, a national-scale study in England showed that it is unlikely that there is an increased risk of severe respiratory health outcome in healthy nearby residents of large-scale composting facilities (Douglas et al., 2016). However, such a conclusion cannot be drawn for minor respiratory health problems and for vulnerable groups.

4.7 What are the main gaps in knowledge about bioaerosol exposure of nearby residents of MSW/C&IW treatment facilities and related health impact?

There is a lack of information on dispersion of biological agents from waste facilities that may be of health concern for nearby residents. This is especially the case for opportunist *Zygomycetes* mould species and pathogenic species of *Legionella* from composting sites. Data on dispersion of endotoxin in the surrounding environment of waste processes is quite limited (Danneberg et al., 1997; Deacon et al., 2009b). Moreover, sampling strategies that have been performed (short sampling time that provides only a snapshot of concentrations at the time of sampling) do not provide information on long-term exposure, which is particularly important for community-based health studies (Pearson et al., 2015). Real-time bioaerosol sensors based on light-induced fluorescence techniques, such as SIBS (spectral intensity bioaerosol sensor), are being developed, however, SIBS equipment is still in its infancy and further research is needed (Nasir et al., 2018b). To the best of our knowledge, there is as yet no large-scale prospective study on adverse health effects on residents of bioaerosols emitted from composting facilities that has been conducted, and no data is available on the potential health impact of bioaerosols on nearby residents of NHWL sites and other plants with waste handling in the open. Importantly, there is no information on the potential impact of bioaerosols (and mainly *A. fumigatus*) from waste management plants on vulnerable groups such as immunocompromised, patients with lung damage and asthmatics.

Attempts have been made to use atmospheric dispersion models for predicting bioaerosol concentration in the surrounding environment of composting facilities. However, despite recent improvement, there is still limited confidence in these predictions due to uncertainties in source term definition and dispersal characteristics (Douglas et al., 2017).

The definition of a "safe" buffer distance from the site has been proposed as one of the responses to manage potential health risks for nearby residents of waste management sites. At that distance, bioaerosol concentrations should be reduced to the background levels. The principle is that if at this distance the outdoor background levels are not exceeded, there is no threat of excess health risk linked to the facility's presence (Schlosser, 2017). However, this statement raises two problems. First, outdoor background levels of bioaerosols need better characterization as they vary both temporally and spatially (Pearson et al., 2015; Schlosser et al., 2017). Secondly, the setting of a hypothetic "safety boundary" around waste management facilities is based on the non-rejection of null hypothesis in difference tests. That is to say, the setting of the safe buffer distance is linked to the power of the statistical test, and notably to the number of measurement results. A study designed with a large sampling plan may lead to conclude that at a given distance, bioaerosol concentrations are still significantly higher than background levels, even if this increase is low and does not suggest an unacceptable risk for health. On the other hand, the absence of a rejection of the null hypothesis could be linked to a lack of the power of the statistical test, especially because the sample size was too low. There is a need to explain what is meant by "bioaerosols concentration should be reduced to background levels" and to stress that the definition of a safety distance is based on a statistical approach (Schlosser et al., 2017).

4.8 What do we know about visitors' exposure to bioaerosol and associated risk for health?

To the best of our knowledge, this issue has not been addressed and neither published article nor grey literature is available.

5. CONCLUSIONS AND PROSPECTS

The synthesis of data from the literature on the health outcomes of bioaerosol exposure and exposure patterns in the MSW and C&IW industry highlights the following key points:

- Levels of exposure to fungi, bacteria and endotoxins at the workplace can be very high if appropriate prevention measures are not taken. The highest levels of exposure are a real concern for the respiratory health of workers in the long term;
- The literature review does not provide evidence of an excess risk to the health of nearby residents of open-air waste management facilities, such as composting plants or non-hazardous waste landfill sites. However, one of the key aspects when addressing this issue is the potential presence of at-risk individuals among nearby residents, such as patients with immune deficiency or severe lung damage. Fungal opportunistic pathogens, such as *Aspergillus fumigatus* or *Zygomycetes* species, are ubiquitous and not specific to organic waste decomposition and the waste management field. In the absence of exposure-response relationships, the relevant question is whether the level of exposure to airborne biological agents of interest is significantly increased by the presence of the facility, as compared to the outdoor background levels. Facility siting and design, operational changes and dispersion control measures can help to reduce bioaerosol emission and transport off-site;
- Waste handling may be of concern for the health of households if they have individual risk factors for adverse effects related to fungal exposure (e.g., immunodeficiency, asthma, severe lung damage, cystic fibrosis). This question is especially relevant for home composting. Urban community composting and composting at-school raises the same question.

However, this scoping review also highlighted numerous gaps in knowledge.

First, there are general needs for further research on the bioaerosol and health topic, regardless of the waste industry field. There are needs particularly for hazard identification and definition of relevant environmental indicators, for identification of health endpoints as the dependent variable in health studies, for standardized measurement methods, for better characterization of background bioaerosol levels, for investigation of impacts in vulnerable groups, and for more knowledge on interaction of bioaerosols with chemical pollutants and on potential protective effects of bioaerosols on atopic diseases and cancers.

Then, there are specific needs for further research in the field of the MSW/C&IW industry. Several knowledge gaps should be filled as a priority: identification of relevant indicators for exposure and health studies, reliable and detailed assessment of personal exposure, estimate of factors influencing the level of exposure at the workplace, estimate of the benefit of the control measures that have been implemented on sites to reduce exposure to bioaerosols, well-designed epidemiological studies that would especially estimate the health risk over long time scales, validation of dispersion models predicting concentration in the surrounding environment of open-air sites and especially composting plants. Several sectors have been poorly investigated, such as HWRC, food waste depackaging technology, MBT, RDF production, NHWL and incineration.

Most importantly, valid and standardized methods for quantitative exposure assessment are needed to better assess health risk and contribute to establish reliable health-based guidelines for bioaerosols. However, available exposure and health data emphasize the need for appropriate preventive measures against bioaerosols in MSW and C&IW handling and treatment activities, including workers training, medical examination prior to employment and regular surveillance. Furthermore, information should be given to susceptible individuals about potential biohazards associated with home composting and on-site composting at school.

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