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Review

Review of biological risks associated with the collection of municipal wastes

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HIGHLIGHTS

- This review illuminates waste collection employees' biological working environment.
- Exposure increases with increasing temperatures and reduced collection frequency.
- Technical measures to reduce workers microbial exposure are identified.
- Microbial exposure correlates with reduced lung function at short and long term.
- Longitudinal studies are needed to better understand the potential health effects.

GRAPHICAL ABSTRACT

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ABSTRACT

In many countries, the management of household waste has recently changed with an increased focus upon waste sorting resulting in lower collection frequency for some waste fractions. A consequence of this is the potential for increased growth of microorganisms in the waste before collection, which can lead to an increased exposure via inhalation for waste collection workers. Through a review of the literature, we aimed to evaluate risks caused by waste collecting workers' exposure to bioaerosols and to illuminate potential measures to reduce the exposure. Across countries and waste types, median exposure to fungi, bacteria, and endotoxin were typically around 10^4 colony forming units (cfu)/m^3, 10^4 cfu/m^3, and 10 EU/m^3, respectively. However, some studies found 10–20+ times higher or lower median exposure levels. It was not clear how different types of waste influence the occupational exposure levels. Factors such as high loading, ventilation in and cleaning of drivers' cabs, increased collection frequency, waste in sealed sacks, and use of hand sanitizer reduce exposure. Incidences of

Abbreviations: FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; FEV1/FVC, Tiffeneau index; PEF, peak expiratory flow; MMEF, maximal mid-expiratory flow; IL-1β, Interleukin 1β; IL-6, Interleukin 6; IL-8, Interleukin 8,; TNF-α, alpha tumour necrosis factor; NO, exhaled nitric oxide; CC16, club cell protein.

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Household waste
Occupational exposure
Occupational health
Respiratory disease
Waste collectors

gastrointestinal problems, irritation of the eye and skin and symptoms of organic dust toxic syndrome have been reported in workers engaged in waste collection. Several studies reported a correlation between bioaerosol exposure level and reduced lung function as either a short or a long term effect; exposure to fungi and endotoxin is often associated with an inflammatory response in exposed workers. However, a better understanding of the effect of specific microbial species on health outcomes is needed to proceed to more reliable risk assessments. Due to the increasing recycling effort and to the effects of global warming, exposure to biological agents in this working sector is expected to increase. Therefore, it is important to look ahead and plan future measures as well as improve methods to prevent long and short-term health effects.

Contents

1. Introduction

Globally, a large number of people work with waste collection, and in Europe, on average, about 500 kg municipal waste is produced per person per year. Changes in waste handling strategies as well as improvements in waste management serve to increase the share of recycled waste. For example, in the EU in 2010, 36% of the waste production was recycled but by 2018 this was increased to 47% (eurostat, 2020). A main focus in Europe now is to recycle plastic and to develop and use biodegradable plastic. From 2015, Member States were obliged to collect paper, glass, metal, and plastic separately to foster high-quality recycling of these materials. Future targets include, that the preparation of municipal waste for re-use and the recycling shall be increased to a minimum by weight of 55% by 2025, to 60% by 2030 and 65% by 2035 (European-Environment-Agency, 2019). Recycling targets for packaging waste will also increase: 65% of all packaging waste will have to be recycled by 2025 and 70% by 2035 (European-Parliament, 2018). The new recommendation for extending the sorting instructions to include all plastic packaging such as covers or wraps for food trays, yoghurt or cream pots, and polyester trays used for meat or cheese etc., would probably further influence microbial communities of waste. A survey from a single European country, Denmark, indicates that extended waste sorting has caused a reduction in the waste collection frequency for some types of waste (Madsen et al., 2019). As an example, previously plastic packaging from meat was typically part of the mixed household waste, usually collected once a week, but may now be part of plastic waste collected less often (Madsen et al., 2019). The reduced waste collection frequency is to reduce costs and finance new collection schemes for recycling (Joe Papineschi et al., 2019). In Norway and Iceland residual waste is collected weekly while recyclable waste is collected three-weekly or monthly (Joe Papineschi et al., 2019). In some municipalities in England, the extended waste sorting has been associated with a reduced frequency of residual waste collection to offset the costs of the work caused by collection of more waste fractions (Goverment, 2019). Whether waste collection frequency has reduced generally in Europe has not been studied. In the USA the amount of municipal waste generated every year is increasing, but also the amount of recycled waste is increasing. In total 6×10^7 tons were recycled in 2005 and 7×10^7 tons in 2018, and especially paper is recycled (Agency, U.S.E.P, 2020).

Based on studies on the effect of collection frequency on e.g. concentrations of fungi in the airspace above waste in a container (Gladding and Gwyther, 2017) and common knowledge about microbial growth, it is expected that the numbers of microorganisms or microbial components in waste will increase as a consequence of reduced collection frequency. This may cause an associated increase in exposure level of workers handling the waste. Furthermore, some waste types, e.g. metal cans, seem now to be placed directly in the waste containers while previously these were bagged together with other residual waste (Madsen et al., 2019). This change in waste collection technique may also cause a higher exposure to bioaerosols.

In addition to the expected reduction in waste collection frequency, increases in temperatures possibly resulting from climate change (Union, 2020) are expected to affect the microbial growth rate in waste prior to collection, leading to an increased exposure level and possibly also changes to the composition of the microbial community. Conversely, better management of waste may serve to continuously reduce the amount of waste produced and the increased waste sorting may also mean that each waste collection may be smaller than a decade ago hence reducing the exposure levels.

Evidence from several studies, mainly from the 1990s shows that exposure to microorganisms during waste handling was associated with allergic respiratory, skin, infectious, and gastrointestinal diseases (Poulsen et al., 1995a). Two papers from 1995 review the literature about occupational health of waste collection workers (Poulsen et al., 1995a) and waste sorting and recycling workers (Poulsen et al., 1995b). We expect the exposure levels as well as the physical activity level of waste workers to have changed since then. In this paper we have reviewed the literature from 1995 onwards concerning exposure to waste–associated microorganisms and the relationship between occupational exposure of waste collection workers and health. There is no standard method for measuring occupational exposure, and independently, but concurrent with the changes in waste sorting, development and/or application of newer methods for characterising workers exposure have occurred. These include methods for identification of microorganisms e.g.: real time PCR (rtPCR) (Rinsoz et al., 2008) and quantitative PCR (qPCR) (Alonso et al., 2015) for selected species, MALDI-TOF MS for viable species and next generation sequencing (NGS) for genera (Madsen et al., 2015). In addition, the methods for further characterization of isolates from workers exposure e.g. as testing for antibiotic resistance (Brągoszewska et al., 2020), viability (White et al., 2020), and allergens (Zahradnik and Raulf, 2014) have been applied. Endotoxin from bacteria has been measured for decades, and new methods have also been developed to measure this bioaerosol component (Liebers et al., 2019). With this development of methods, new knowledge concerning waste collection workers' exposure may be obtained forming the basis of a better understanding of the association between occupational exposure and health. This has also formed the basis for this renewed focus on reviewing the literature.

Based on the expected increases of occupational exposure to bioaerosols, it is important to investigate whether occupational exposure to bioaerosols during waste collection is associated with health effects. New types of waste containers and digital technologies are available, and it is also relevant to study whether they have been applied and how this might affect occupational exposure. To prevent health concerns associated with the collection of new waste fractions, it is important to learn from the studies which have already been performed concerning waste collection workers' exposure and to study whether the exposure can be reduced by technical or organisational solutions. The aim of this review is to evaluate the biological exposure risks for waste collecting workers and to consider potential measures to reduce their exposure.

2. Methods

The scope of this review, including the wording of the research questions and sub-topics, final search terms and inclusion and exclusion criteria, were agreed by the PEROSH (Partnership for Europe in Occupational Safety and Health) research group at the start of the project. PEROSH represents a network of 14 European occupational safety and health institutes. The search topics and questions guided which literature search terms were used (**Table A.1**) and guided the assessment of relevant evidence.

A literature search was carried out to collect evidence from peer reviewed studies, government, and industry reports and, where available, expert articles in professional journals. The searches focused on the period from January 1995 to October 2019, with some additional papers captured later, to assess supporting published evidence. Additional evidence was sought where available from stakeholders. Literature searches were undertaken using the researcher-led approaches outlined below, which included assistance from professional knowledge management staff within the research institutions authoring this paper. Additional information (e.g. details of experts, organisations, advisory panels etc.) was collated during this exercise.

To ensure that no sources of evidence were missed, the researchers used broad search terms to bring within scope a larger set of references. The searches were undertaken using relevant research platforms (**Table A.1.**) and other web sites hosted by relevant organisations, e.g. EU, government and regulatory bodies. Sources of information outside the EU were not excluded; however, any references identified were scrutinised to ensure they related to EU practices that were of relevance and if not, they were disregarded. The retrieved document titles and, where available, abstracts were collated and imported into the bibliographic software Endnote within which libraries of relevant documents were created (abstracts or full documents). Exclusion criteria were applied by a minimum of two researchers working together to reach a consensus opinion of each retrieved publication. This permitted the removal of irrelevant studies; for example, waste processing scenarios that were not within scope (e.g. radioactive waste) or publications that focused on exposures unrelated to recycling situations. Within secure Endnote library the PDF copies of relevant papers were retrieved and attached, then annotated with notes as required by the separate collaborating research teams.

The evidence in each document was assessed by two reviewers working collectively, to consider its relevance and quality. Information was summarized with respect to the agreed research questions and sub-topics, whilst considering the quality of the study design, methodology and data analysis used. The consistency of data across different studies was also considered important as this is indicative of any form of consensus of topic opinion. This evidence based approach also allowed for the identification of knowledge gaps, i.e. areas where the review questions could not be partially or fully answered, due to a lack of available information.

The quality of the studies in this structured literature review were assessed based on some of the principles used in systematic reviews.

However, some prior uncertainty over the expected number of directly relevant high-quality studies, and the fact that the publications can vary greatly in source and style, meant that a full systematic review was not appropriate. Some of the principles that can be applied to a structured, narrative review of the kind used here include the following questions:

- Does the research address the agreed research questions?
- Are the reported circumstances of testing/assessment relevant?
- Does the study provide sufficient information to address reproducibility of the results?
- Have appropriate methodology and data analysis been used?
- Were the conclusions justified based on the study design and results?
- Are there any uncertainties or biases in the study design and results and, if so, have these been identified?

In summary, this review considered, whether the available evidence was sufficient to usefully answer the research questions (**Table A.2**), describe the extent of any uncertainties and inform, whether there were specific knowledge gaps.

Where data were available the evidence summary addresses the requirements/questions based on identified topic areas of the review (**Table A.2**).

3. Results

The section is divided into seven main parts of which the first is about how waste is collected and handled (Fig. 1), followed by sections describing exposure routes, exposure levels, factors affecting workers exposure (Fig. 2), microbial species and risk evaluation, exposure related health effects, and medical survey and preventive measures.

3.1. How municipal waste is collected and handled

3.1.1. Definition of municipal waste

Municipal waste is defined as waste collected from households and waste from e.g. retail, administration, education, health services, accommodation as well as food and other services and activities, which are similar in nature and composition to waste from households (Eu, 2018). Municipal waste includes mixed waste and separately collected waste, including paper and cardboard, glass, metals, plastics, biowaste, wood, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators, and bulk waste, including mattresses and furniture. Biowaste contains biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants. In the USA the total amount of municipal waste has increased from 2×10^8 tons in 2000 to 3×10^8 tons in 2018 (Agency, U.S.E.P, 2020). Municipal waste constitutes approximately 10% of the total waste generated in the European Union (Eu, 2021), and it does not include wastes from industries and agriculture. Despite this, municipal waste collection and sorting employs many people in cities and urban communities.

While most of the recycled waste is collected separately, other material comes from extracting recyclables from mixed municipal waste in sorting plants (Fig. 1). If the waste is pre-sorted, mainly on site where it is generated before collection, the risk of contamination of other recyclable material is reduced. The European Council adopted new rules in 2018 (Ec, 2018), which state that Member States have to ensure that by the end of 2023, biowaste (also called food waste or green waste) is either collected separately or recycled at source (e.g. home composting). This is important because separate biowaste collection and treatment play an essential part in the biobased circular economy (MacArthur and Economy, 2017).

3.1.2. Waste collection

The implementation of EU legislation is a prerequisite for the harmonisation and the improvement of waste management practices in Europe and EU members have to translate the principles of EU waste legislation at national, regional, and local level within their country. The EU also requires the collection of waste that is sorted at source and provides advice on good practices and recommendations for efficient waste management (Eu, 2020). In practice, there is a wide variety

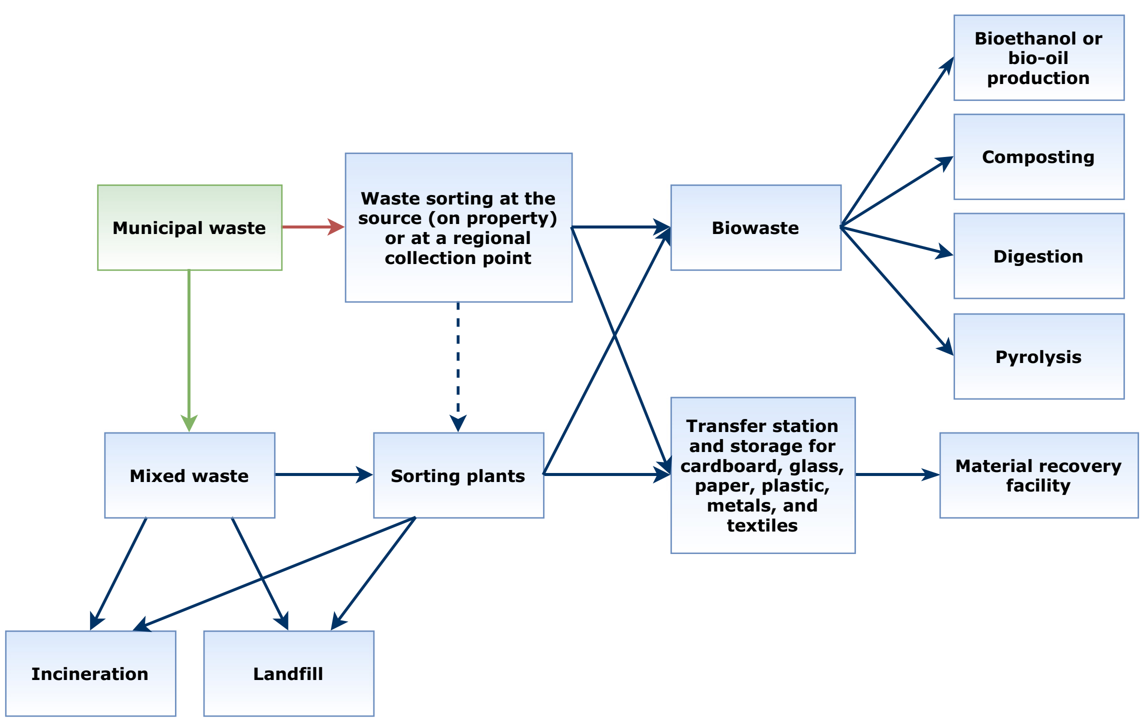

Fig. 1. Diagram of the most typical waste collection routes and handling sites within European countries. The red and green arrows show the two different routes the municipal waste can take, either being collected as mixed waste or being sorted at the source. The dashed line shows that some countries sort their waste at the source but still send it for further sorting in sorting plants.

Fig. 2. Summary of main working tasks for waste collection workers and potential determinants of exposure which will be considered further in this paper.

in collection schemes in Europe, as influenced by climate, population density, consumer habits, type of housing, as well as the history of waste collection in the municipalities (Bassi et al., 2017; Seyring et al., 2016). To sum-up, separate collection schemes of individual waste fractions can divided into 'door-to-door separate' (each types of waste are separated and collected from house to house), 'door-to-door co-mingled' (several types of waste are mixed and collected from house to house), 'drop-off points' (residents take their waste to the collection point, often in a communal container) and 'civic amenity sites' (residents take their waste to a collective waste disposal site, where it is separated) (Seyring et al., 2016; Ferreira et al., 2017).

Waste collection requires a collection truck and a team of workers typically composed of a driver and one or two loaders. Work tasks of waste collectors may vary from one country to another. Municipal waste collectors usually pick up waste or waste containers from domestic areas and transport them to the truck where waste is manually or mechanically loaded (Fig. 2). Loading can be done at the front, the rear end or side of the trucks. The operation is repeated from house to house and loaders usually climb into the truck cab to go from one collection area to another, if they are far apart; alternatively they may in some countries climb and stand at the rear end of the truck. Waste is transported to the treatment plant (incinerator, sorting centre etc.) to be unloaded in a generally dedicated area of the plant for material recovery or for energy production (Fig. 1).

A transfer station may be used for unloading of trucks followed by baling or the temporary deposition of recyclable waste before it is loaded into larger vehicles and transported to the material recovery facilities. Mixed waste not to be sorted is often transferred directly to the end point of disposal, previously mainly at landfills, but increasingly by incineration. Biodegradable waste or other waste containing organic material may not be deposited in landfills in several countries. For example, in Finland biowaste is collected separately for anaerobic digestion, composting or the conversion of biomass into liquid bio-oil or into other organic products (Kauriinoja, 2010).

Municipal waste is often collected in bins that can accommodate from 140 to 660 l of waste or in deep (e.g. 1–8 m^3) collection containers. The volume of the waste compactors for recyclable waste can be larger (e.g. 20 m^3) in the regional collection of urban areas. The emptying interval for waste bins varies within and between countries typically at the municipal level and depending on the type of the waste. Biowaste may be collected from waste bins more frequently than another waste due to the risk posed by microbial growth of microorganisms and subsequent environmental contamination. Biowaste is mainly collected weekly from apartment houses and at least every other week from single-family households (e.g. in Finland and Denmark). Within the UK biowaste collection frequency varies, depending on local authority, with a combination of weekly and two-weekly household collections in use. However, in general households on a weekly residual waste collection schedule captured far less food waste for recycling (14.7%) than those on a fortnightly residual waste service (33.7%) (Wrap, 2010). In Southern Europe, biowaste may be collected up to 2–4 times a week during the hotter summer periods. Other recyclable materials as e.g. glass and metal are usually collected after longer periods of time (Madsen et al., 2019).

3.2. Source, route, and place of exposure

3.2.1. Sources of exposure

The handling of waste is expected to be the main source of workers' exposure to microorganisms, which is also reflected in the overlap with species found in the rear end of the truck (Fig. 3**a**). The collected household waste generally consists of many different elements and materials, such as plastic, paper, cardboard, metal, glass, organic waste and the residual fraction, and this depends on the national or local consumer habits as well as sorting regulation for household waste collection (Gladding and Gwyther, 2017; Villalba et al., 2020). For example, studies from Denmark report that household waste could be divided into 48 material fractions and included among others 31% of vegetable waste, 10% of animal waste, 6.6% of diapers, 3.3% of yard waste, and 0.93% of vacuum cleaner bags (Riber et al., 2009), and the waste composition is different in single family and multi-family houses with single family houses having a larger fraction of food waste and smaller fractions of paper and glass (Edjabou et al., 2015). According to a review study, solid waste across Europe contains from 24% (Finland and Poland) to 67% (Turkey) organic/food waste, between 10% (Turkey) and 39% (Italy) paper/card board waste, and between 1% (Turkey) and 7% (UK) metal waste (Edjabou et al., 2015). A study from the USA has divided solid waste into 9 fractions and the largest fractions were paper (27%), food waste (15%), yard trimmings (14%), and plastic (13%) (agency, U.S.E.p, 2021). A study from Brazil shows that 51 to 57% of the municipal solid waste is organic matter, 4 to 13% paper/cardboard, 4 to 21% plastic, and 1 to 4% metal (Alfaia et al., 2017). So across countries and continents different fractions of waste which can together be called organic waste seems to constitute the largest fraction of household waste. Waste materials as well as the organic residues remaining on the waste provide the basis for the survival and growth of microbial communities in bulk waste. Water condensation forms inside containers and the bags due to variations of temperature and liquid spills from food packaging and may encourage microbial growth on papers and cardboard. As observed for biowaste (vegetable, fruit, garden waste etc.), the dynamic of microbial communities and the breakdown of the organic material in waste probably starts when the material is deposited within a container used for collection, and these materials deteriorate during prolonged storage (Ryckeboer et al., 2003). Thus, microorganisms were found at about 1.8×10^7 cfu/g of matter in fresh raw household solid waste collected in India, with an increase by a factor of 3 to 5 during storage (Atalia et al., 2015).

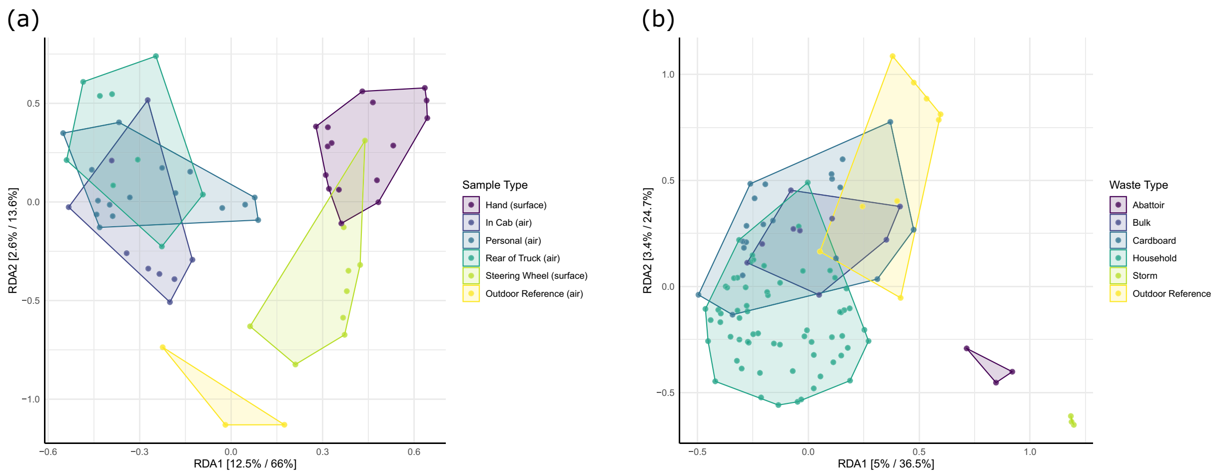

Fig. 3. ab: RDA (redundancy analysis) plotting of bacteria and fungi in waste collection workers' exposure constrained by the sample type (a) and by the waste type (b). For (a) Analysis of similarities (ANOSIM): $R^2 = 0.73$, $p = 0.001$; for (b) $R^2 = 0.28$, $p = 0.001$. If outdoor references, storm, and abattoir data were taken out of the analysis $R^2 = 0.15$ and $p = 0.004$. Based on data from (Madsen et al., 2019; Madsen et al., 2020b; Madsen et al., 2016; Angelakis et al., 2014; Ghattargi et al., 2019). 'Rear of Truck' are samples taken on the back end of the truck.

3.2.2. Route of exposure

The main routes of exposure of waste collectors are the inhalation of particulates including airborne microorganisms and microbial components and the contact of contaminated hands with the mouth and the eyes. Inhalation and hand contact with subsequent inhalation and the further ingestion of microbial pathogens and toxins may be the cause of gastrointestinal symptoms among sensitive workers (Poulsen et al., 1995a).

Gloves as mechanical protection used by waste sorting workers were found to be contaminated by fungi and mycotoxins (Viegas et al., 2020) but we have not found similar studies for waste collectors. However, in a recent study by Madsen et al., microorganisms were found on the palmar side of the workers' hands and on the steering wheels in their waste collection trucks (Madsen et al., 2020a). This confirmed that route of exposure by direct contact should be taken into account in the evaluation of biological risk among waste collectors (Madsen et al., 2020b).

During the collection of domestic waste, workers usually pull and push the containers, walk quickly and sometimes run, which may result in an increased pulmonary ventilation and heartbeat as compared to normal. Such an increased physiological activity may induce the deposition of particles further down in the lungs as well as increase the inhaled dose of microbial particles (Madsen et al., 2019; Poulsen et al., 1995a).

3.2.3. Places of exposure

The occupational exposure to bioaerosols occurs during loading and unloading of waste as workers stand next to the waste during these operations and it also may occur during non-loading times in the collection round if workers stand on the back of the truck (Fig. 3). As described later, exposure may also occur in the truck cab which may be contaminated by airborne microorganisms from the outdoor unloading process by waste loaders entering inside with contaminated clothes (Madsen et al., 2016). During epidemics, such as the current SARS-CoV-2 pandemic, another issue to consider is the risk of infecting colleagues by traveling in the same truck cab, but also by sharing the truck with other teams. Furthermore, leachate may occur in trucks, particularly if the collected waste is of organic origin and has a high water content. Published studies have suggested that splashes during waste collection may be a significant source of bioaerosols, even when the trucks are empty (Lavoie and Dunkerley, 2002a; Nielsen et al., 2000) and during the crushing process.

3.3. Exposure

3.3.1. How assessment of waste collection workers' exposure has been done

In this section, the methods used in most studies to characterise waste collection workers' exposure are summarized. In order to measure the occupational exposure of waste collection workers to bioaerosols studies have been carried out using personal samplers; these are necessary because the workers move around. Most studies have used methods for sampling on filters for a full work shift. However, a few studies have used a shorter sampling time, and in our presentations of data in this paper we will also take into consideration these different sampling times. Samplers such as GSP (e.g. (Madsen et al., 2016; Wouters et al., 2006a), PAS (Personal Air Sampler) (Neumann et al., 2002), and different closed-face cassettes (Lavoie et al., 2006; Ivens et al., 1999) are often used, and the most commonly used flow rates are 2 or 3.5 l/min.

Occupational exposure of waste collection workers has focused on endotoxin, (1 → 3)-β-D-glucans, fungi, bacteria, and mass of dust as main categories, specific selected microbial genera or species, and more recently also on identification of a wider community of microorganisms. Within studies, significant correlations have been found between exposures to bacteria vs endotoxin (Madsen et al., 2020a; Heldal and Eduard, 2004; Park et al., 2011), bacteria vs fungi (Madsen et al., 2020a), endotoxin vs dust (Heldal and Eduard, 2004; Park et al., 2011; Gladding et al., 2003), endotoxin vs fungi (Madsen et al., 2020a), endotoxin vs (1 → 3)-β-D-glucans (Gladding et al., 2003), (1 → 3)-β-D-glucans vs dust (Gladding et al., 2003), fungi vs dust (Park et al., 2011), and house dust mite allergens vs dust (Neumann et al., 2015). In a paper, which analyzed data across several studies with workers collecting various types of waste, only moderate correlations between different exposures were found (Nielsen et al., 1997a), and thus the measurement of one component cannot substitute measurement of another.

While some studies have used one agar medium for fungi and one for bacteria, other studies have used several different growth media and temperatures to allow for growth of different groups of microorganisms. Thus, MacConkey agar has been used for detection of gram-negative bacteria (Park et al., 2011), Trypticase soya agar and Nutrient agar for bacteria in general (Madsen et al., 2020a; Lavoie and Dunkerley, 2002b), and Malt Extract Agar (Krajewski et al., 2002), Sabouraud Dextrose Agar (Lavoie and Dunkerley, 2002b), and DG18 agar (Madsen et al., 2019) for fungi. Some studies have identified selected bacterial genera containing pathogens based on microscopy and biochemical methods (Krajewski et al., 2002; Nielsen et al., 1995), selected isolates of bacteria using PCR (Gladding and Gwyther, 2017), other studies have identified fungi and bacteria in general using MALDI-TOF MS (Madsen et al., 2020b), or measured antigens for selected fungi (Neumann et al., 2015). A metagenomics approach has not been executed to characterise waste collection workers' personal exposure, but it has been carried out to characterise the airborne components in waste sorting plants (Degois et al., 2017; Degois et al., 2021). Furthermore, we have found no studies measuring exposure to viruses during waste collection, however a study has detected airborne viruses in waste processing facilities using PCR based methods (Carducci et al., 2013).

In most published studies endotoxin has been measured using the Limulus amoebocyte lysate assay (e.g. (Madsen et al., 2020a; Heldal and Eduard, 2004; Park et al., 2011)), also called the LAL assay. By contrast, the variant of the assay using a recombinant version of the Limulus hemolymph factor C (rFC) as well as chemical methods have, to our knowledge, not been used for waste collection workers' exposure. While endotoxin has been measured using the same assay in many studies, the treatment of samples before analysis differs and e.g. only some research groups mention that they use a detergent, e.g. Tween, for extracting endotoxin from the filters (e.g. (Neumann et al., 2002; Nielsen et al., 1997a)), and this makes comparison of studies from different research groups difficult. Therefore data here are also presented relative to outdoor references within the same study. The fungal component (1 → 3)-β-D-glucan is measured in few studies only, and it has been measured using different methods: the modified LAL method (Thorn et al., 1998), an inhibition Enzyme Immuno Assay (Wouters et al., 2006a), and a two-site enzyme immunoassay based on monoclonal antibodies (Neumann et al., 2015).

3.3.2. Occupational exposure relative to outdoor references

In total, 26 published scientific papers have been found referencing measurements of exposure to bioaerosols during waste collection. Most studies have included reference measurements, which are typically air samples taken outdoors and away from major bioaerosol sources. In general, occupational exposure levels are considerably higher than these reference measurements. Occupational exposures were reported to be around 30 times greater for endotoxin, 20 to 100 times for bacteria, typically 100 times for fungi, 20 times for (1→3)-β-D-glucan, and around 5 times greater for dust compared to outdoor references (Table A.3). *Penicillium* typically constitutes a larger fraction of the fungi in the occupational exposure compared with reference measurements (Madsen et al., 2020b). Reanalysis of species composition in published studies from Denmark, India, and South Arabia reveals that the composition of waste collection workers' exposure differs from that of outdoor references as measured using MALDI-TOF MS (Fig. 3ab).

3.3.3. Exposure levels

Average (median or geometric mean) values of exposure to endotoxin during waste collection are presented in Fig. 4, and similar data are presented for bacteria in Fig. 5 and for fungi in Fig. 6. The studies behind the data in Figs. 3–5 are of different sizes and different sampling periods have been used. To account for that the sizes of the bubbles illustrate the size of the studies behind each exposure level. Most waste collection workers were exposed to around 10 EU/m^3 however, in some studies the average exposure levels were much higher and even above 500 EU/m^3 (Fig. 4). The average exposures to bacteria are very distinct in the different studies, but for most workers the exposure to bacteria and fungi are around 10^4 cfu/m^3 (Figs. 5–6). Included in these median exposure levels there are also individuals who are exposed to higher levels as e.g. a max of 1090 EU/m^3, 7.5×10^5 cfu/m^3 for bacteria (Krajewski et al., 2002) and 1.0×10^5 cfu/m^3 for fungi (Lavoie et al., 2006).

Studies, which have measured exposure to mass of dust, show median or average levels between 0.11 and 0.76 mg dust/m^3 (Nielsen et al., 1997a), 0.36 and 0.43 mg dust/m^3 (Nielsen et al., 1995), 0.58 mg/m^3 (Wouters et al., 2002), and 0.6 and 0.8 mg/m^3 (Neumann et al., 2015). The fungal species *Aspergillus fumigatus* has been measured in some studies, and the following exposure levels have been found (values as cfu/m^3): below detection (bd) to 7×10^3 (Madsen et al., 2020a), bd to 6×10^3, and 100 to 2×10^3 (Nielsen et al., 1995). β-glucan has also been measured in some studies but different methods have been used; examples of levels as follows: 10.8 to 36.4 ng/m^3 (Limulus assay) (Thorn et al., 1998), 1.0–3.4 ng/m^3 (ELISA based on monoclonal antibodies) (Neumann et al., 2015), and 0.8 and 1.6 μg/m^3 (Enzyme Immuno Polyclonal Assay) (Wouters et al., 2006a).

3.3.4. Size distribution of bioaerosol components

Data regarding the size distribution of airborne microorganisms emitted during waste collection are very scarce. Thus, one study among those reviewed reported measurement of sizes of culturable bacteria and fungi (Madsen et al., 2019). Short-term measurements (4 to 7 min) were made at a waste plant using an Andersen six stage cascade impactor (ASCI) before or during unloading of the cardboard waste. The ASCI was mounted with Petri dishes containing either a Nutrient agar medium or a DG-18 agar medium, and microbial isolates from all the sampler's stages were identified using MALDI-TOF MS. The results indicated that microorganisms carrying particles were primarily collected on the first five stages of the ASCI sampler, which corresponds to a potential deposition of particles from oral and nasal cavities to terminal bronchi. The geometric mean diameters for particles with bacteria were from 3.0 to 5.2 μm and particles with fungi were from 3.8 to 6.0 μm. Both the total concentration of microorganisms and the number of species (species richness) were increased during unloading of waste as compared to before unloading, but no changes were observed for the size distribution of microbial particles and their deposition in lungs. In total, 81 different bacterial species and 25 fungal species were found in emitted bioaerosols and microbial species were not associated with any particular particle size fraction (Madsen et al., 2019). Human bacterial pathogens (*Bacillus cereus*, *B. circulans*, *Salmonella* sp., etc.) were found in the coarser fraction of particles. They may be deposited in the upper airways of the respiratory tract (nasal cavity and pharynx) and then swallowed, which could be associated with symptoms such as diarrhoea that were reported in previous published studies among workers handling waste. Fungal allergenic and opportunistic pathogens (*Penicillium chrysogenum*, *A. niger*, *Cladosporium* spp. etc.) were also found in the same size fraction. A small fraction of the airborne microorganisms could potentially deposit in the alveoli, and the deposition of microorganisms in alveoli could be exacerbated during intense physical activity (Madsen et al., 2019). The deposition in the alveoli is particularly relevant since antibiotic resistant bacteria have been found in household waste samples (Akter et al., 2020).

3.4. Factors affecting workers' exposure and steps towards its reducing

In the hierarchy of exposure control to hazards, the primary consideration is elimination of the hazard, followed by engineering and organisational controls, with the use of personal protective equipment as a last resort or to support the other measures. In waste and recycling where there is the potential for exposure to bioaerosols, the opportunity to eliminate hazards is limited as microbial colonisation will always be present in organic waste that requires processing and handling. While in theory, methods to limit microbial proliferation in stored waste could be feasible, in practice, the move towards less frequent collection of household waste for example fortnightly instead of weekly, leads to greater potential for microbial proliferation. Consequently, other interventions are required. These include equipment and collection vehicle designs, spatial segregation, and hygiene interventions. Several factors

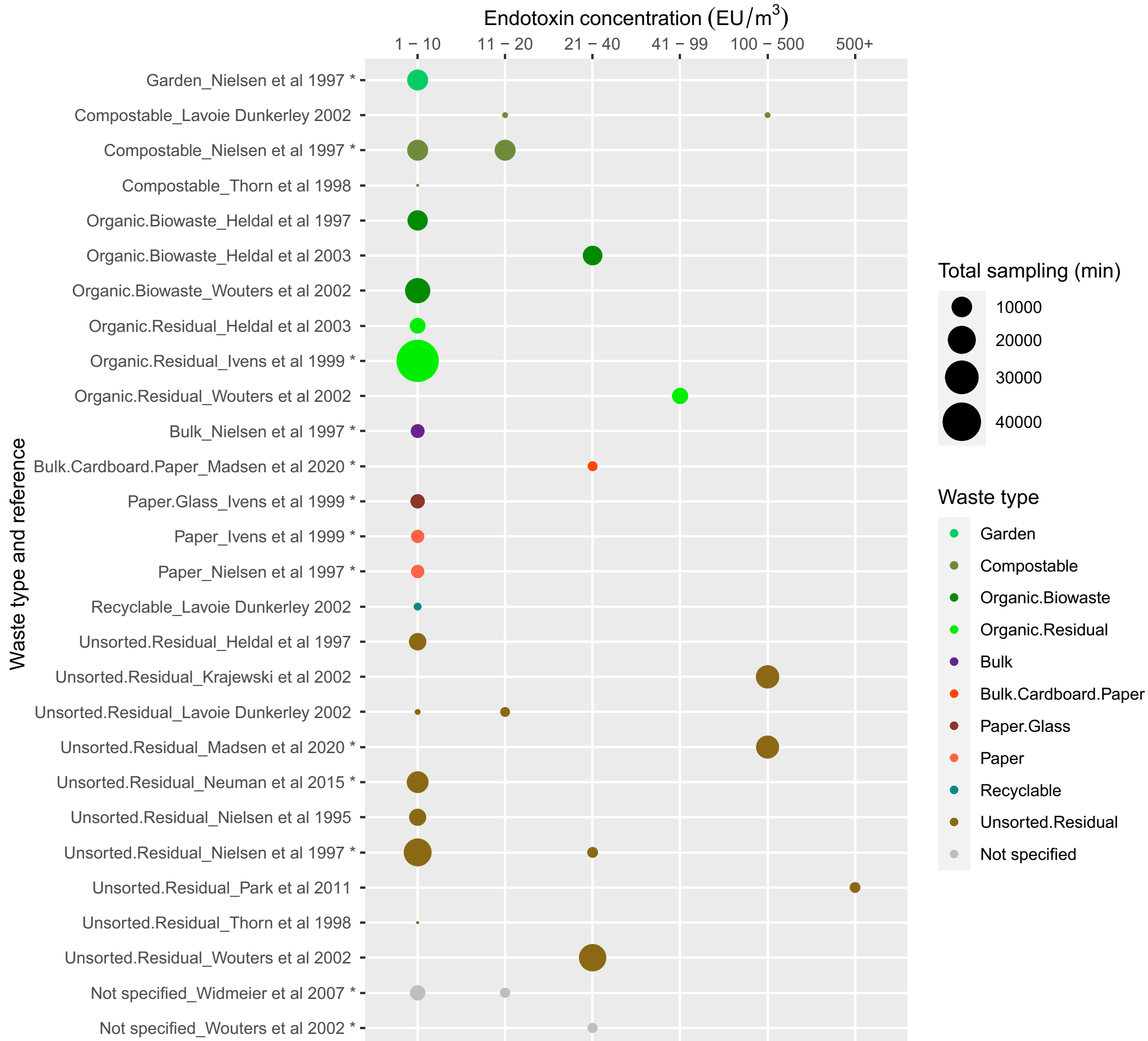

Fig. 4. Personal exposure to endotoxin (median or geometric mean) sorted by study and the waste fraction collected. The colour shows the waste fraction and the size of the bubbles illustrates the total sampling time of the study, which was estimated by multiplying the number of samples with the time sampled for each study. The * in y axis indicates whether Tween was used for analyte extraction.

affect the exposure levels and in the following sections these will be reviewed.

3.4.1. Work task

In some studies, it has been possible to subdivide workers into drivers and waste loaders. In general, loaders are exposed to considerably higher concentrations of endotoxin, bacteria, and/or fungi than drivers (Neumann et al., 2002; Ivens et al., 1999; Park et al., 2011; Widmeier et al., 2007). For example, in one study exposures were around 2–10×, 10–60×, and 4× higher concerning endotoxin, bacteria, and fungi, respectively, for loaders than for drivers (Neumann et al., 2002). However, in another study no difference was found in exposure between the two tasks (Krajewski et al., 2002). In a further study, three workers associated with the same truck comprised one driver, one front runner, and one loader. The loader was exposed to the highest levels of endotoxin and fungi (Ivens et al., 1999). Often workers in the same team help each other with all tasks. One study showed that there was no significant correlation between exposures to fungi, bacteria, and endotoxin, and the inflammatory potential of the exposures of workers within the same team, although there was a tendency towards correlation for fungi (Madsen et al., 2020a).

Although the exposure of the driver is often lower than that of the loader, the exposure in the truck cab is often higher than outdoor reference measurements (Madsen et al., 2020a; Madsen et al., 2016; Nielsen et al., 1995; Ncube et al., 2017), which may be a result of inadequate vehicle hygiene (Madsen et al., 2020a). The potential release of microorganisms from 'dirty' clothing inside the truck cab has not been studied. However, the microbial species composition in the truck cabs resembles that of the waste collection workers' exposure and is different from the outdoor air (Fig. 3**a**).

3.4.2. Type of waste

In Figs. 4–6 exposure levels during collection of different types of waste are presented in categories. In a study no significant difference in exposure level to inhalable dust, endotoxin, and (1 → 3)-β-D-glucan has been found between workers collecting organic waste vs. residual waste (Wouters et al., 2002). Similarly no significant difference in exposure to fungi and endotoxin has been found for workers collecting biowaste vs unsorted waste (Heldal et al., 1997). Another study measured exposure during collection of mixed household waste, sorted household waste, paper waste, compostable household waste, bulk waste for incineration, paper and glass waste, and garden waste. No

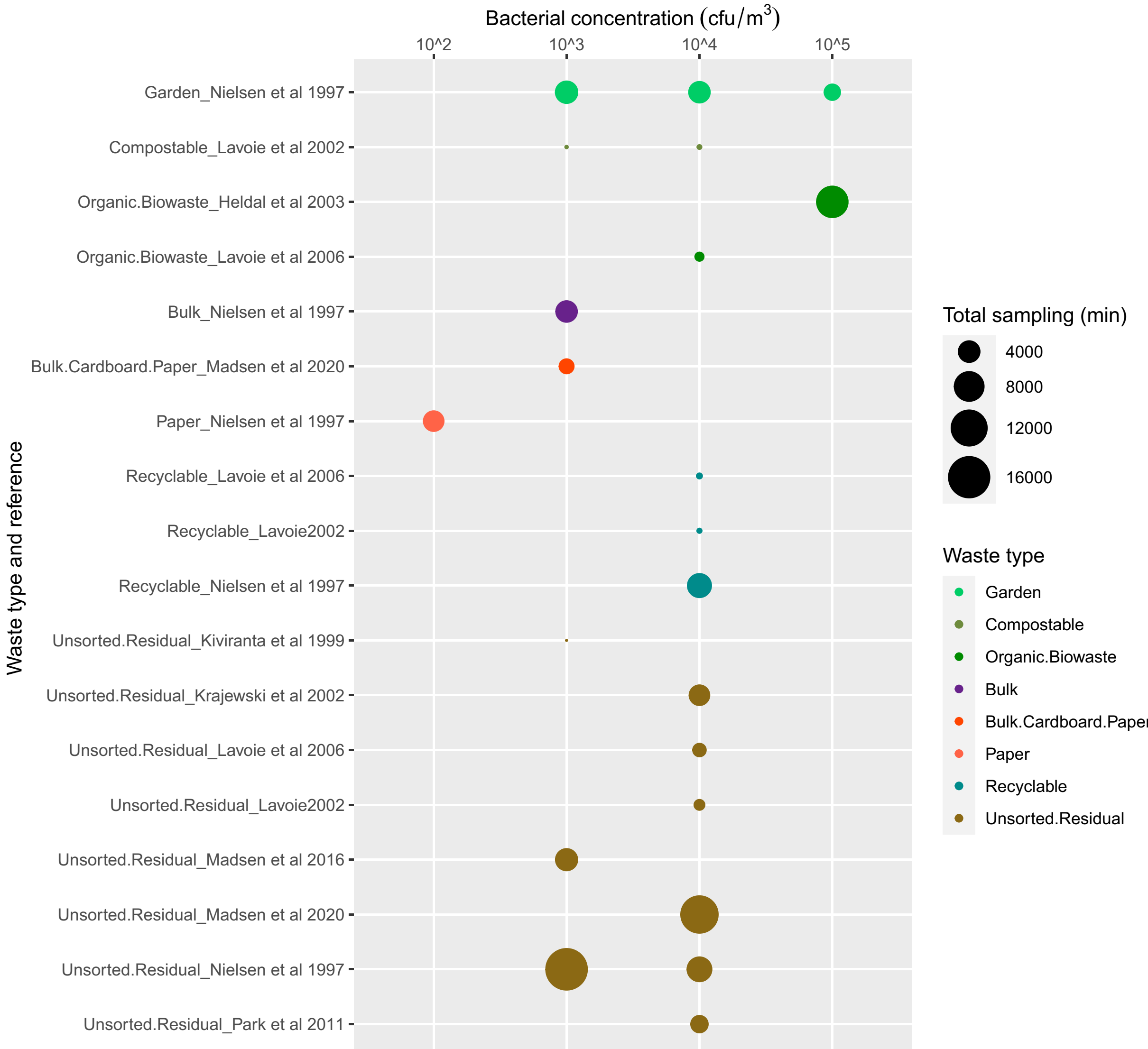

Fig. 5. Personal exposure to bacteria (median or geometric mean) sorted by study and the waste fraction collected. The colour shows the waste fraction and the size of the bubbles illustrates the total sampling time of the study, which was estimated by multiplying the number of samples with the time sampled for each study.

major differences in exposure level were found related to the waste type except that workers collecting garden waste were exposed to higher levels of actinobacteria and *Aspergillus fumigatus* than the other workers (Nielsen et al., 1997a). It should be noted that the waste was present in different containers and sacks and collected using different types of trucks. In contrast, mixed household waste has been associated with higher exposure to endotoxin, bacteria, and fungi than cardboard, paper, and bulk waste considered together (Madsen et al., 2020a). In one study, a type of waste called recyclable, which was described as lightweight packaging materials, was associated with lower exposures to fungi, bacteria, and endotoxin than collection of domestic waste (Neumann et al., 2002).

A re-analysis of published data shows that the microbial communities associated with collection of bulk waste, cardboard, or household waste are statistically different, although an overlap of these different communities occurs (Fig. 3**b**). We have found no studies on exposure to bioaerosols during collection of some of the newer waste fractions as e.g. plastic waste and metal waste, and measurement of the impact of each of the waste types on exposure may also be difficult as waste is sometimes collected in two or three room containers with a separated spaces for each waste type.

A positive intervention to achieve greater recycling targets is augmented use of household pre-sorting and widening the scope of materials accepted for recycling. However this could impact on worker exposure. Schlosser et al. (Schlosser et al., 2015) looked at how extending sorting instructions for householders could affect the exposure of workers working at materials recovery facility (MRF) to dust, endotoxin, fungi and bacteria. The inclusion of pots, trays and film with other recyclable plastic packaging led to an increase in exposure to endotoxin, fungi and bacteria at MRFs.

3.4.3. Season, temperature, and relative humidity

In general, higher levels of exposure to endotoxin, gram-negative bacteria, and fungi have been associated with higher outdoor temperatures (Madsen et al., 2019; Madsen et al., 2020a; Neumann et al., 2002; Park et al., 2011; Nielsen et al., 1997a; Heldal et al., 1997; Breum et al., 1996a). No clear seasonality or association with outdoor temperature has been found for exposure to dust and bacteria in general (Madsen et al., 2020a; Park et al., 2011; Nielsen et al., 1997a; Heldal et al., 1997), but in two studies higher bacterial exposures were associated with higher temperatures inside waste collection containers (Madsen et al., 2019) or outside but only for containers with organic waste

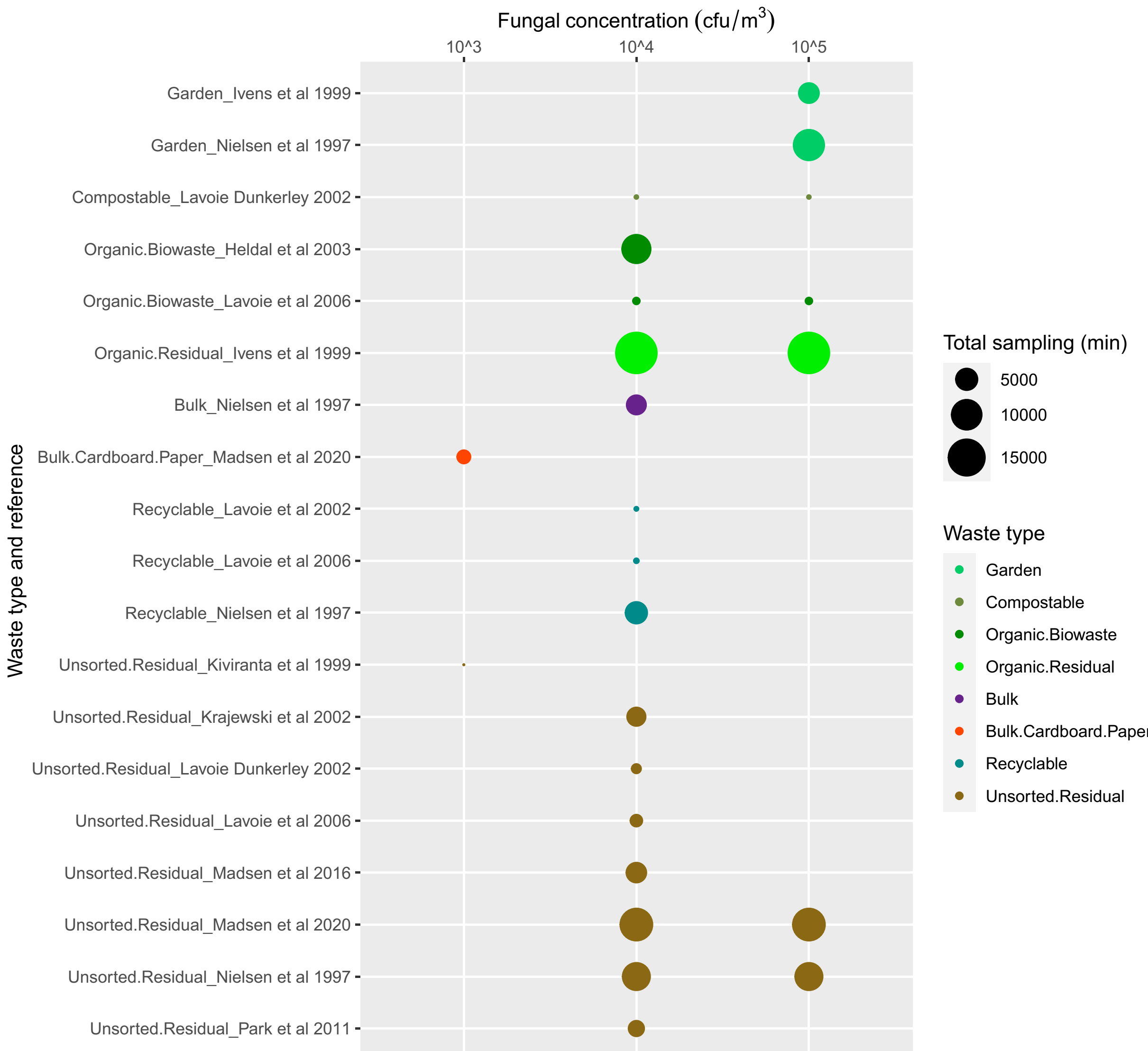

Fig. 6. Personal exposure to fungi (median or geometric mean) sorted by study and the waste fraction collected. The colour shows the waste fraction and the size of the bubbles illustrates the total sampling time of the study, which was estimated by multiplying the number of samples with the time sampled for each study.

(Neumann et al., 2002). A study from Korea showed that high relative humidity (RH) of the air was associated with lower exposure to endotoxin, bacteria, and fungi (Park et al., 2011). In studies from Europe RH is not mentioned as a significant factor.

3.4.4. Waste collection frequency

As may be expected, reducing the frequency of doorstep collection of household waste from weekly to fortnightly will potentially increase microbial colonisation of the waste and thus the potential for exposure to bioaerosols when that waste is handled. A significant effect of collection frequency has been found for fungal and endotoxin, but not for bacterial exposure in relation to collection of cardboard waste. Thus exposure to fungi and endotoxin increased when collection frequency was reduced. The microorganisms in the worker's exposures were identified, but it was not possible to conclude whether the microbial composition of the exposures were affected by collection frequency (Madsen et al., 2019). Measurements above containers with stored biowaste have shown concentrations of fungi increasing by time from day 1 to day 12; no bacteria and endotoxin were found above the containers (Nielsen et al., 1998). Gladding et al (Gladding, 2009) looked at mould species and mycotoxins. Food waste collected weekly yielded 25 *Penicillium* species, with 36 out of 48 samples containing more than 10^5 cfu *Penicillium*/g sample. Mycotoxins in these samples ranged between 75 and 19,000 μg/kg for mycophenolic acid, 40–920 μg/kg for roquefortine C, 35–7500 μg/kg for penitrem A, 20–2100 μg/kg for thomitrem A and 20–3300 μg/kg for thomitrem E. During other simulated waste disposal scenarios with residual waste and lightweight packaging materials increase in concentrations of bacteria has been found from week 1 to week 3 and then a decrease was found from week 3 to week 6. For *Aspergillus fumigatus*, an increase in exposure was found with a reduction of the sampling frequency from every 7 to 14 days, but after 14 days the concentration decreased. For endotoxin, no change was found from week 1 to week 5, but an increase was found from week 5 to week 7 and it was followed by a decrease from week 7 to week 8 (Gladding and Gwyther, 2017). The reasons why the levels of emitted airborne endotoxin declined is not discussed, but it may be natural changes of microbial communities over time, as observed with larger organic decomposition, e.g. (Steger et al., 2007). For percolate from biowaste, the concentration of endotoxin and total counts of bacteria did not differ significantly during a 14 days period, but concentration of anaerobic gram-negative bacteria increased with time, and the concentration of fungi was negligible (Nielsen et al., 1998).

Based on these studies, the combination of reduced collection frequency and the extension of sorting instructions may be of concern regarding occupational exposure to fungi, but for bacteria and endotoxin the effect of sampling frequency is less clear. Therefore there is an increased potential for those handling the waste to be exposed to higher concentrations of fungi unless suitable controls can be applied.

3.4.5. Waste containers and sacks

The design and properties of waste containers are governed by European Standard EN 840, parts 1–4 (BS EN, 2020), but research into bioaerosol emissions associated with container design has provided additional valuable practical data.

In apartment blocks, larger size containers are used and higher exposure to fungi, bacteria, and endotoxin was found than during waste collection from private housing with smaller containers (Neumann et al., 2002) but it is not clear whether this is related to the container size. For some of the large containers, automatic lifting devices, seem to be effective in keeping fungal exposure concentrations low (Neumann et al., 2002). In some studies, exposure has been measured during collection of waste in both sacks and containers, but as other factors have also differed, it has not been possible to conclude whether this affects the exposure level (Heldal et al., 1997; Nielsen et al., 1997b). In another study, the exposure of the loader to fungi and endotoxin seem to be lower if it is collected as sacks rather than as bins or containers (Ivens et al., 1999). A recent paper about the potential transmission of SARS-CoV-2 focuses on avoiding transmission of the virus from waste to the workers by preventing waste sorting from suspected positive households, by placing waste in bags sealed by strips, and by wearing face masks, eye protection, and gloves during waste handling (Di Maria et al., 2020).

A more preventive way would be to avoid the collection of organic waste altogether, such as the use of bins which serve as composting units and stay on site. Many systems have been studied and applied, although this is dependent on having the space to accommodate them. Recently, a type of waste container for decomposition of food waste at the source has been developed and it should reduce the amount of waste requiring collection (Burguillos and Caldona, 2020). With this system, there would be no need for collection organic waste and therefore no exposure to bioaerosol emissions for waste workers.

3.4.6. Technical design of vehicles and spatial segregation

In general, if physical separation can be achieved between the operative and any bioaerosol generating operation, such as tipping into a vehicle, this will reduce potential exposure. Spatial segregation is applied mainly for physical protection from potential injury, but this offers a dual benefit. Thus, automated skip emptying has decreased bioaerosol exposure burden by increasing the distance between the worker and the tipping operation, and by decreasing the exposure time period (Neumann et al., 2002).

Trucks with low loading height led to higher exposure to microorganisms, endotoxin, and dust for biowaste collection in the summer, but not in winter (Heldal et al., 1997). Factor analysis has shown that exposure to bacteria during collection of different fractions of household waste was significantly affected by loading height, with greater exposure from a low loading. Also the inflammatory potential, as measured in a human cell line, was higher for the exposure of workers using low loading height compared to loading from a greater height; for fungal exposure this difference was only seen as a trend (Madsen et al., 2020a). In another study, involving the collection of compostable household waste, exposure to fungi was also highest with low loading height; the data for bacteria showed the same tendency (Nielsen et al., 1997a). Lower exposure found with high loading height may be the result of greater distance between the waste and the worker, and the same tendency was found in another study with different truck type (Neumann et al., 2002). Based on the expectation that waste collection workers would be exposed to lower levels if they could maintain a greater distance from the waste during unloading of the containers, a group of workers were asked to keep as far away as possible from containers during waste unloading and to turn away from rather than look at the waste during unloading. The same group of workers were also asked to introduce more frequent cleaning of their truck cabs. While this did not lead to this group of workers being exposed to significantly lower concentrations of endotoxin and fungi and bacteria in general than their colleagues, it was found that their exposure to gram-negative bacteria was lower and the inflammatory potential of their exposure was lower (Madsen et al., 2020a).

Comparison of two types of compactor trucks showed that the standard compactor truck, in general, resulted in higher bioaerosol exposure levels than trucks with plastic curtains and ventilator systems (Breum et al., 1996b; Würtz et al., 1997). They presumed that the use of the air pollution control system, in combination with a change in the collection procedure towards a slower emptying of the containers, may be an important step in creating acceptable occupational conditions for waste collectors. Collection of mixed household waste with a compactor truck caused a lower exposure to fungi and bacteria if the truck was improved by the introduction of a local exhaust ventilation system (Nielsen et al., 1997b). To use a low negative pressure in the collecting system of the vehicle, coupled with spraying fogs to reduce dust emissions to as low as possible has also been suggested. Coupled to this, the design of tight closures would minimize dust emission during skip emptying and fugitive emissions while driving to the next location for container emptying (Missel, 2000).

A study to assess the effect of different waste storage systems on the potential of the waste to emit airborne dust, microorganisms and endotoxin successfully involved the use of a rotating drum to measure the dustiness of waste and its potential to emit bioaerosols (Breum et al., 1997). It was shown that storage systems influenced dustiness with respect to airborne *Aspergillus fumigatus* by at least a factor of 400,000. This method of testing dustiness of waste could be important for the design of waste collection equipment to improve air quality for the workers engaged in waste handling.

3.4.7. Technical design of the vehicles - ventilation in cabs

Microbial quality of air inside vehicle cabs is a major occupational health risk management issue in waste and recycling. The findings of one study indicated that fungal and bacterial concentrations in truck cabs was on average 111 and 8 times higher, respectively, than outdoor reference measurements, with identical fungal species often found both in a personal sample and in the same person's truck cab air (Madsen et al., 2016). An interventional study showed that motivation of waste collection workers to clean their truck cabs caused a reduced concentration of airborne fungi, but not bacteria, compared to reference workers. The concentration of both bacteria and fungi were reduced in the intervention truck cabs (Madsen et al., 2020a). Furthermore, working in vehicle cabs with windows closed was shown to afford protection from bioaerosols during waste loading (Neumann et al., 2002).

A study of vehicles used on composting facilities aimed to examine differences and discrepancies in protection factors between vehicles were performed by Schlosser et al. (Schlosser et al., 2012). The major goal was to estimate the mean protection efficiency of the vehicle cab environment against bioaerosols, with in-cab measurements to ascertain whether protection systems reduce workers' exposure to tolerable levels. Of eight vehicle types used to handle waste, four were fitted with positive pressurisation and high efficiency particulate air (HEPA) filtration systems, with the other four equipped only with pleated paper filters without pressurisation. Bacteria, fungi and endotoxin aerosols were measured simultaneously inside and outside the cab. A recently purchased front-end loader fitted with a pressurisation and HEPA filtration system, and with a clean cab, exhibited a mean protection efficiency of between 99.47% and 99.91% depending on the biological agent. Other vehicles demonstrated lower protection efficiency, probably caused by penetration through moderately efficient filters, by the absence of pressurisation, by leakage in the filter-sealing system, and by re-suspension of particles, which accumulated in dirty cabs. It was concluded that pressurisation and HEPA filtration systems could provide safe working conditions inside waste vehicles by reducing exposure to airborne bacteria, fungi and endotoxin. Mitigation of leakage in the filter-sealing system, would be necessary to achieve high levels of protection.

A report on effectiveness of cab filtration for dust control in the quarry industry has read-across to other dusty industries (Thorpe et al., 2018). It concluded that vehicle cab filtration may afford protection for workers but only if cabs are fitted with correct particulate filters, which are well maintained, and work if practices are adhered to, such as keeping doors and windows closed in dusty areas. In practice, for doorstep waste collection, it may be difficult to maintain protection if the vehicle cab doors are frequently being opened, and operators climbing in and out of cabs frequently will increase the likelihood of cross-contamination, thus emphasising the need for regular cab cleaning.

3.4.8. Cleaning and maintenance of vehicles

While in the previous section regular cab cleaning was considered to reduce exposure to microorganisms during refuse collection, Neumann et al. (2002) also estimated that there would be a considerable influence from thorough regular cleaning of the lifting device. Conversely however, Lavoie and Dunkerley (2002b) compared the emissions from a well cleaned truck with a externally dirty truck, which had been in use for a long period without cleaning. They did not consider a dirty truck to be an additional source of bioaerosols, but did recommend a drying step after cleaning a truck (usually done with a power jet washer). Missel (2000) confirms those results, concluding that dirty trucks did not contribute additionally to bioaerosol emissions. The act of vehicle cleaning itself would be a potential route of exposure. Madsen and Matthiesen (Madsen and Matthiesen, 2013) identified cleaning as the work task causing the highest exposure to aerosol components, especially high pressure cleaning (hpc). In their review, they found evidence that hpc leads to high exposures to bacterial endotoxin (Madsen and Matthiesen, 2013).

3.4.9. Management of welfare facilities and hand hygiene

It is a legal requirement throughout Europe to provide suitable welfare facilities for waste and recycling staff. However, their proximity to the waste handling facility could compromise their cleanliness. A study by Lis et al. evaluated the microbial air quality in offices on two landfill sites. It showed that both indoor and outdoor air were heavily contaminated with bacteria and fungi, in concentrations of bacterial aerosol up to 7.2×10^4 cfu/m^3 indoors, and up to 4.0×10^4 cfu/m^3 outdoors, and for fungal aerosol up to 7.3×10^3 cfu/m^3 indoors and 1.2×10^4 cfu/m^3 outdoors (Lis et al., 2004). The proximity of the weighing of refuse loads contributed to the increase of bacterial and fungal aerosol concentrations significantly in the offices, and species corresponded to bacterial and fungal characteristics of the waste. It is reasonable to assume that at least as much exposure would occur in the welfare rooms, and it was concluded that the quantitative and qualitative changes in the composition of the bacterial and fungal aerosols posed a possible health risk indoors at municipal waste landfill sites.

An interventional study making hand sanitizer available for a group of waste collection workers during the work day showed a reduction in the number of fungi, but not bacteria, on the hands at the end of the work day compared to a group of reference workers (Madsen et al., 2020a). A survey of waste facilities including where employees consumed their meals at work showed that in both sites studied there were separate rooms intended as a canteen and a ban on eating at the workplace. Despite that, 7% of staff admitted they sometimes ate their meals directly in their workplace, sometimes regularly (every day or several times a week). In analysing respondents' hand washing habits, the study found that all employees always washed their hands after finishing work in contact with waste and each time before a meal (Kozajda and Szadkowska-Stanczyk, 2009). In an American advisory report on a waste facility, the author advocated frequent hand washing, and avoiding eating and drinking whilst working (Delaney, 2003).

3.4.10. New technologies

Digital technologies are increasingly applied across almost all areas of waste collection (Berg et al., 2020). Important technological trends like robotics, cloud computing and artificial intelligence will help improve the sustainability of waste management systems. There have been major advancements in the pneumatic sorting process as a result of automation technology, which can be viewed as robotics. Robotic waste sorting stations are based on image recognition and IR scanning. For example, one robotic arm can pick more than 2000 items per hour, increasing its precision (often over 90%) in a learning process (Zen Robotics, 2020). These advancements produce defined waste streams of high purity which is essential for an efficient recycling process. Sensor supported containers collect data such as container location or filling level. Applications of artificial intelligence use image recognition, autonomous vehicles and sweeping robots. Artificial intelligence can also enable collection to take place at optimal times. For normal collection, skilled drivers and co-drivers are needed, but this technology allows for less experienced personnel and single crewed driving. Collection personnel can walk alongside the autonomous truck when emptying bins, which means less getting in and out of the truck, but may also potentially cause an increased risk of exposure and may be a cause of accidents. Thus the consequences of the implementation of digital technologies to waste collection on the exposure to waste working needs to be taken into account in any risk evaluation process.

3.5. Species identification for risk evaluation

Few studies have identified microorganisms in waste collection workers' exposure to genus or species level (Tables 1 and 2). Several studies have classified bacteria into gram-negative and gram-positive genera, and in several studies *Aspergillus fumigatus* has been the only fungal species identified (e.g. (Neumann et al., 2002; Nielsen et al., 1995). Across studies, *Penicillium*, *Aspergillus*, and *Cladosporium* are the dominating fungal genera (Table 2).

Biological agents are classified into four risk groups according to their level of risk of infection. Of these, risk group 2 microorganisms may cause infectious diseases in humans, but are unlikely to spread in the environment and related infections are possible to prevent or treat (*Off. J. Eur. Communities*, 2006). On the one hand, it has been demonstrated that several species classified into risk group 2 have been observed in workers' exposure: *Escherichia coli*, *Enterobacter cloacae*, *Klebsiella oxytoca*, *Salmonella* sp., *Staphylococcus aureus* (Madsen et al., 2019; Madsen et al., 2020b; Krajewski et al., 2002), *Aspergillus fumigatus* (e.g. (Gladding and Gwyther, 2017; Madsen et al., 2020b; Nielsen et al., 1997a)), and *A. flavus* (Madsen et al., 2016). While bacterial species richness is high (Table 1), and typically several different *Penicillium* species are present at the workplaces (Madsen et al., 2020b), the proportion of risk group 2 microorganisms is low. Furthermore, for many of the microbial species found in the workers' exposure, the information necessary to evaluate a potential risk is not available, as some species are not well described (Madsen et al., 2020b). Despite this, it can be concluded that the focus on infections has been limited and this might be because the risk of overt infection for waste collection workers may be relatively low. The potential for exposure to large numbers of microorganisms that could trigger not only an allergic response and sensitization but inflammation in general is greater.

Beside occupational infections considered in the risk groups, species may also be evaluated based on their allergenicity (reviewed in (Burzoni et al., 2020)), antibiotic resistance (He et al., 2020), biofilm forming capacity, mycotoxin production, cytotoxicity, or their ability to induce inflammation (Madsen et al., 2020b). There is no international document to evaluate this, but a German document about sensitizing substances for the airways exists (BAUA, 2008). Furthermore, fungal

Table 1
Dominating bacterial taxa found in waste collection workers' exposure or in percolate from waste.

Waste type	Family or genus	Genus and species	Method Id, selection, Quantified	Reference
In percolate from biowaste	14 genera	9 species	Bio., nm,%	(Delaney, 2003)
	Enterobacteriaceae	e.g. *Escherichia coli*		
	Lactobacillus	–		
	Pseudomonas	–		
	Bacillus	–		
Household	9 genera	13 species	Bio., typical isolates,%	(Gladding et al., 2003)
	Staphylococcus	e.g. *S. xylosus*		
	Bacillus	–		
	Pseudomonas	e.g. *P. mesophilica*		
Mixed household	10 genera, e.g.	0 species	API, nm (only gram-negative bacteria), NQ	(Nielsen et al., 1995)
	Enterobacter	–		
	Escherichia	–		
	Hafnia	–		
Municipal, unsorted	16 genera	4 species	Bio., nm but pathogens,%	(Park et al., 2011)
	Enterobacter	–		
	Pseudomonas			
		Enterococcus faecalis		
		Escherichia coli		
Domestic waste	14 genera	38 species	MALDI, nm, Q	(Ryckeboer et al., 2003)
		Micrococcus luteus		
		Brevibacterium aurantiacum		
		Kocuria rhizophila		
	Staphylococcus	–		
	Streptomyces	–		
Cardboard waste with used food packaging	33 genera	88 species	MALDI, all, Q	(Madsen et al., 2019)
		Kocuria palustris		
		Aerococcus viridans		
		Streptomyces badius		
		Sphingomonas aerolata		
Abattoir waste	14 genera	22 species	MALDI, nm, Q	(Degois et al., 2017)
		Bacillus cereus		
		Bacillus pumilus		
		Staphylococcus arlettae		
		Enterococcus faecalis		
Household waste	49 genera	180 species	MALDI, all, Q	(Alfaia et al., 2017)
		Brevibacterium aurantiacum		
		Staphylococcus equorum		
		Micrococcus luteus		
		Streptomyces badius		

Identification method: Bio = biochemical methods maybe combined with selective agar; MALDI = MALDI TOF-MS; API = API test kit; Mic = microscopy. Selection: how isolates for identification were selected: All = all isolates on a plate; nm = not mentioned; typical = typical isolates were selected; pathogens = expected pathogens were selected. Quantified: Q = yes quantified; NQ = not quantified; % = quantified as a fraction of positive samples or isolates.

species such as *Aspergillus niger, Aspergillus glaucus*, *Penicillium brevicompactum*, *Penicillium citrinum*, and *Rhizopus* spp., are often found in waste collection workers' exposure and have been identified as causative agents of health effects of the airways in different occupational settings (reviewed in (Madsen et al., 2020b)), and a waste worker has been diagnosed with hypersensitivity pneumonitis (HP) caused by *A. fumigatus* (Hagemeyer et al., 2013). Furthermore, some microbial species found in workers' exposure are described as emerging pathogens as e.g. *Rhizopus* (reviewed in (Madsen et al., 2020b)). However in general, the knowledge regarding the risk associated with the observed exposure, is incomplete and needs to be improved.

3.6. Exposure related health effects

Due to the fact that the main route of exposure is via the air, the respiratory system becomes the most important area in the human body that is affected by bioaerosols, i.e. living or dead bacteria and fungi and cell fragments. Occupational complaints and diseases of the upper and lower respiratory tract associated with waste-related bioaerosol exposure can be affected by various pathomechanisms. These may be triggered by the concentration of cell components and metabolic products, as well as the predisposition of the exposed individuals (Sigsgaard et al., 1994). While the exposure of waste collectors to dust alone could lead to particulate, unspecific airways irritation the microbial components of bioaerosols can cause infectious, allergic, and particularly irritant toxic diseases. Non-allergic toxic irritation of the respiratory tract, e.g. caused by β-glucans or endotoxin, is also known as 'mucus membrane irritation syndrome' (MMIS), and especially eye irritation should also be mentioned in this respect. Irritations of the respiratory tract include rhinitis, coughing, excess sputum production, and shortness of breath. Chronic exposure to bioaerosols has been linked to, in particular, inflammatory processes leading to complaints in the sense of chronic bronchitis, which can subsequently lead to chronic obstructive pulmonary disease (COPD). Chronic bioaerosol exposure may also be reflected in reduced lung function. Occasionally, work-related allergic bronchopulmonary aspergillosis (ABPA), hypersensitivity pneumonitis (HP) or allergic asthma have also been reported among waste management employees (Poole and Basu, 2017). It is important when assessing the respiratory health risk in waste collectors to take into account physical exertion and muscle work during their work tasks. Measurement of cardiovascular fitness of 8 waste collection workers has been measured to be able to calculate the ventilation rate during work, and it was 29.2 ± 86.2 l/min (Madsen et al., 2020b). This increased flow volume and respiratory frequency will increase the amount of aerosol inhaled, including not only airborne organic compounds, but also dust particles and vehicle exhaust fumes and gases.

Although the question of whether long-term exposure to bioaerosols increases the health risk of waste workers is best investigated in longitudinal studies, the vast majority of the health studies had a cross-sectional design. Additionally, in many of them confounders such as smoking were not taken into account e.g. for the assessment of biomarkers of inflammation, and they are too diverse to allow a

Table 2
Dominating fungal genera and species found in waste collection workers' exposure or in clinical waste.

Waste type	Genus and species	Methods Id, selection, Quantified	Reference
Biowaste	5 genera, 1 species *Penicillium* *Mucor/ Rhizopus* *Aspergillus fumigatus* *Cladosporium*	Mic., nm, NQ	(Viegas et al., 2020)
In clinical waste	7 genera, 32 species *Aspergillus niger* *Aspergillus fumigatus* *Aspergillus tubingensis* *Penicillium simplicissimum*	Mic., nm,%	(BAUA, 2008)
Mixed household waste	16 genera, 2 species *Aspergillus fumigatus* *Aspergillus niger* *Penicillium* spp. *Cladosporium* spp.	Mic., nm, NQ	(Nielsen et al., 1995)
Domestic waste	7 genera, 23 species *Penicillium digitatum* *Penicillium brevicumpactum* *Penicillium commune* *Penicillium italicum*	MALDI, nm, Q	(Ryckeboer et al., 2003)
Cardboard waste with used food packaging	10 genera, 29 species *Penicillium brevicompactum* *Penicillium expansum* *Penicillium italicum* *Cladosporium herbarum*	MALDI, all, Q	(Madsen et al., 2019)
Household waste	12 genera, 37 species *Penicillium brevicompactum* *Penicillium digitatum* *Penicillium italicum* *Penicillium glabrum*	MALDI, all, Q	(Alfaia et al., 2017)

Identification method: MALDI = MALDI TOF-MS; Mic = microscopy. Selection: how isolates for identification were selected: All = all isolates on a plate; nm = not mentioned. Quantified: Q = yes quantified; NQ = not quantified; % = quantified as a fraction of positive samples or isolates.

quantitative analysis. Therefore a narrative description of significant health effects from occupational health studies are presented.

3.6.1. Acute health effect of exposure to bioaerosols

Most of the cross-sectional studies aimed to describe the effects of exposure over a longer period of time, however, attempts have also been made to assess acute health effects that have usually occurred over a single working day or week. Dose-response analyses showing short-term changes in the function of the respiratory or immune system responses following exposure to bioaerosols may be helpful in creating reference values. However, a limitation in pursuing this goal is the the very high biodiversity of exposures combined with the small number of participating employees and heterogeneous methodological assumptions, which means that the statistical power of such studies is lower than when testing the effects of e.g. only one chemical.

3.6.1.1. Effects on the function of the respiratory system. The first group of studies are those in which spirometry was used, and the most frequently analyzed parameters include FEV_1, FVC, FEV_1/FVC, PEF, and MMEF. Considering that changes in FEV_1 values were a good measure of the impact of endotoxin on the respiratory system of cotton processing workers (Haglind and R, 1984; Castellan et al., 1987), attempts were made to use it also in relation to waste collectors. In the work of Heldal et al. (Heldal et al., 2003a) 25 workers had two spirometry measurements in the same week: One before work on Monday and Thursday, and within this period of approx. 72 h the mean values of FEV_1 decreased significantly ($p < 0.05$) by 0.12 L. the changes in FEV_1/FVC values at that time were not significant, but correlated with the percentage increase in neutrophils ($r = 0.51$; $p < 0.05$) and IL-8 ($r = 0.45$; $p < 0.05$) determined in induced sputum

In another study on Danish waste collectors, 50 employees performed PEF measurements on themselves over a two weeks period, with a minimum frequency of four measurements per day. The results obtained were compared with the data on exposure to cfu of *Aspergillus fumigatus*. It was shown that when the concentrations of this fungus exceeded to the level of 2×10^3 cfu/m^3, the daily variability of PEF measurement results was significantly higher ($p < 0.05$) than in workers characterized by lower exposure levels.

A study by de de Meer et al. (2007) included 16 male waste loaders: six with and ten without regular respiratory symptoms. There were only slight and statistically insignificant decreases in the values of FEV_1 and MMEF between Monday and Friday in both cases and controls. However, using the methacholine test, the values of the parameter called DRS (dose-response slope) were used, in which the percentage decrease in FEV_1 per mg of inhaled methacholine was calculated. Thus, it was found that between Monday and Friday in the studied period, after adjustment for smoking and the age of employees, the DRS values were significantly higher ($p = 0.02$) than in the control group. Taking into account all the limitations of this study, which are also cited by the authors, the results of this small study suggest exaggeration of pre-existent airway inflammation in symptomatic workers during a workweek of organic waste loading.

In contrast to these two studies, Thorn et al. (1998) found no significant differences in methacholine-induced FEV_1 decline in 25 workers collecting unsorted and compostable waste, compared to the control group. It should be noted that no significant relationship between the exposure to bioaerosols and the analyzed spirometric parameters was shown in the studies described above.

3.6.1.2. Effects on biomarkers of inflammation. More precise results, showing the dependence of the observed acute health effects on exposure, provide data on various cells (macrophages, neutrophils, eosinophils, lymphocytes) and soluble mediators of the immune system, such as pro-inflammatory cytokines IL-1β, IL-6, IL-8, TNF-α, macrophages, neutrophils, eosinophils, lymphocytes, and eosinophilic cationic protein (ECP) or the enzyme myeloperoxidase (MPO). In the few studies so far describing waste collectors, changes in the concentrations of the above biomarkers were analyzed in biological material collected from workers in the form of induced sputum, nasal lavage (NAL) fluid and blood.

In the aforementioned study by Heldal et al. (Heldal et al., 2003a), analysing induced sputum collected from 25 organic waste collectors (88% of which were current smokers), showed that in the period from Monday to Thursday the concentrations of neutrophils, eosinophils, and IL-8 increased significantly ($p < 0.05$). Moreover, levels of neutrophils and IL-8 correlated with an increase in the concentration of eosinophil cationic protein ECP protein, but also with a decrease in FEV1/FVC. However, the correlation analysis of the studied biomarkers with the measured bioaerosol components brought important data. There was a significant relationship between IL-8 concentrations and endotoxin concentrations ($r = 0.55$; $p < 0.05$), but no associations were found for fungal spores or bacteria counted by microscopy. In turn, in another study by Heldal et al. (Heldal et al., 2003b) NAL samples were collected on Monday and Thursday of the same week in 31 waste collectors. The concentrations of IL-8, ECP, MPO, epithelial cells, neutrophils, and eosinophils were determined. During the analyzed period, there was a significant increase in the percentage of neutrophils from 28% on Monday to 46% on Thursday. Moreover, the neutrophils concentrations significantly correlated with ECP and MPO. This study was able to demonstrate significant relationships between the assessed exposure and some biomarkers, including the concentrations of endotoxin and MPO ($r = 0.53$; $p < 0.01$), fungal spores and neutrophils ($r = 0.54$; $p < 0.01$), as well as (1 → 3)-β-D-glucans and IL-8 ($r = 0.47$; $p < 0.01$).

A slightly different approach in the assessment of the effects of exposure to bioaerosols was used by Wouters et al. (Wouters et al., 2002). In addition to the analysis of weekly variability, an attempt was made to examine changes in the concentrations of pro-inflammatory cytokines IL-1β, IL-6, IL-8, and TNF-α, before and after the work shift. NAL samples collected from 47 waste collectors and compared to 15 people in an unexposed control group. The authors showed that at the end of the week, both before and after the work shift, the concentrations of the total number of cells (mainly neutrophils and epithelial cells) and IL-8 increased significantly when compared with the control group. It was observed that the concentrations of this cytokine in the NAL samples after the work shift depended on the concentrations of organic dust and endotoxin ($p < 0.05$).

3.6.1.3. Effects on respiratory and gastrointestinal symptoms as measured by questionnaires and exposure measurements. As shown by several researchers, questionnaire studies can also be used to improve knowledge about the acute effects of exposure to bioaerosols. The response data obtained about the complaints reported by employees may help in better understanding this phenomenon, however, it should be compared with current data on exposure, preferably obtained using personal exposure assessments. Among the available literature, this condition is met by a small number of studies. An attempt to link the exposure with reported respiratory symptoms was also undertaken by Hansen et al. (Hansen et al., 1997). In this work, they compared the data from a survey of 1515 Danish waste collectors and the information on the level of exposure, obtained with personal exposure measurements and a job exposure matrix. Where measurement data were not available, an extrapolation method was used according to a specially prepared multiplicative model. Thus a trend was found, in which chronic bronchitis was reported more often ($p < 0.05$) in workers with increasing levels of exposure to culturable fungi, fungal spores and total microorganisms.

Linking reported complaints with exposure to bioaerosols were characterized by Heldal and Eduard (2004) and Ivens et al. (1999). The results obtained in the first study suggested that exposure to rod-shaped bacteria in the concentration range of 0–4 × 10^4 bacteria/m^3, was significantly associated ($p < 0.01$) with eye and nose irritation and unusual tiredness reported by 22 waste collectors. On the other hand, exposure to fungal spores (bd–230 × 10^4 fungal spores/m^3) determined the occurrence of headaches in workers ($p < 0.05$) and associated on the borderline to cough. No associations were found with gastrointestinal symptoms. Moreover, it has been shown that nasal irritation may result from exposure to endotoxin (bd–7.8 EU/m^3). The latter, as shown by the study by Ivens et al. (1999) also contributed to sensations of nausea and diarrhoea with high exposure to endotoxin among 189 waste collectors. Another study by Ivens et al. (1997) also demonstrated that especially the waste collector group with high exposure to fungal spores reported most diarrhoea symptoms in waste collectors. When analysing 1337 completed questionnaires, it was found that 210 people (15.7%) reported the occurrence of this symptom. Adjusted for the weekly dose of fungal spore exposure in the ranges: $<10^8$ cfu (control group); 10^8–10^9 cfu (low level); 10^9–10^{10} cfu (medium level) and $>10^{10}$ cfu (high level), diarrhoea was reported significantly more often ($p < 0.001$). No positive trend was found for total counts of fungi, or for total counts of microorganisms. It is unknown whether the measured level of airborne exposure was high enough to cause diarrhoea (via nasal entrapment and then swallowing of nasal mucus) or whether other pathways were also of importance. Other relevant pathways for the exposure were ingestion (dirty hands when eating/smoking) or psychological factors (the smell of the waste, or an unhealthy psychosocial work environment) have to be taken into account when evaluating self-reported information in questionnaires.

3.6.2. Long-term health effect among waste collectors

There have been some studies on long-term health effect among waste collectors, both respiratory and musculoskeletal as well as some reviews on these (Poulsen et al., 1995a; Kuijer et al., 2010). Most of them are cross-sectional studies using questionnaires, measurements of lung function parameters, and/or measurements of inflammatory markers in different parts of the body and especially the respiratory tract.

3.6.2.1. Monitoring of health effects using questionnaires. A cross-sectional study, of 65 waste collectors (62 males and 3 females) was carried out in Hamburg, Germany in 2015 (Garrido et al., 2015). The participants were first asked to answer a questionnaire regarding current and past health problems as well as ranking their health-related quality of life. All participants also underwent a clinical evaluation for a health check, including a general clinical examination, ECG, as well as lung function testing.

It was found that the most common health problems were musculoskeletal complaints, with back pain having the greatest prevalence (67%). Asthma or COPD were reported by 15% of the workers, which the author concluded is the same prevalence of that reported by the general German population. However, the clinical investigations revealed that more participants, as identified through the questionnaire, had respiratory problems. It was also found that the participant's evaluated their health related quality of life as being reduced, with 68% reporting problems, within which pain/discomfort was the most prevalent cause (64% of the workers) (Garrido et al., 2015).

In a cross-sectional study including 69 male domestic waste collectors from the Ruhr area in Germany (Schantora et al., 2015), the prevalence of work-related rhino-conjunctivitis and respiratory symptoms was studied using a customized testing protocol comprising a modified questionnaire, basic clinical examination, spirometry, and immunologic parameters. The workers were classified according to their work tasks into loaders, floaters and drivers. A high percentage of workers had complaints (eyes 29%, nose 39% and cough 35%) which were predominantly attributed to working conditions. Multiple logistic regression analyses indicated that duration of employment in waste collection (per 10 years) was associated with an increased prevalence of cough ($OR = 1.64$) and chronic bronchitis ($OR = 2.18$). An association between rhinitis and cough ($OR = 2.62$) was found, which supports the association between the prevalence of upper and lower airway disease. When adjusting for smoking status, atopic subjects suffered more frequently from irritation of the lower airway as indicated by cough ($OR = 2.71$).

The previously cited article by Wouters et al. (2002) showed that in addition to acute cross-shift effects of biomarkers, workers also reported numerous chronic respiratory symptoms, including: cough, phlegm cough, wheezing, stuffy nose and runny nose using questionnaires. Taking into account the previous findings, it is possible to indirectly link their presence with the concentrations of organic dust and endotoxin at workplaces.

3.6.2.2. Effects on lung function. A cross sectional study of 198 solid waste collectors in Egypt found an increased prevalence of respiratory symptoms, such as shortness of breath among waste collectors compared to service workers (Abou-ElWafa et al., 2014). In this study, lung function was also measured and waste collectors had significantly reduced FVC% and FEV_1% compared to service workers. The reductions in FVC% and FEV_1% among waste collectors were also found to correlate with employment duration, where those with more than 15 years of employment had lower values than those who had worked less than 15 years. Another cross sectional study, from Turkey, on 52 household waste collectors found that the waste collectors had reduced lung function (FVC%, FEV_1%, PEF% and $FEF_{25–75}$%) compared to waste truck drivers. This study showed that the measured respiratory function of the waste collectors was at 80% or below that of the comparator group, the truck drivers (Issever et al., 2002).

A study from Greece on 104 waste collectors found a statistically significant reduction of the forced vital capacity (FVC) among the waste collectors compared to office employees. These results were adjusted for smoking, age and education level. The waste collectors also had a higher prevalence of sore throat, coughing in the morning, coughing on exertion and phlegm production compared to the office workers (Athanasiou et al., 2010). Another study on 63 waste collectors in Italy found a statistically significant reduction in FEV_1 as well as reduction on the mean Tiffenau Index (FEV_1/FVC) among the waste collectors compared to office workers. These data were adjusted for smoking, BMI (body mass index) and age (Vimercati et al., 2016). Neither of these studies included exposure assessments, but participants were recruited according to occupation.

3.6.2.3. Effects on inflammatory biomarkers. In the same study group examined by (Schantora et al., 2015), a further aspect was the investigation of airway and blood inflammatory markers not only including the 69 current waste collectors but also 28 former waste collectors (Raulf et al., 2017). In both groups, 63% and 64% of workers reported complaints of the eyes, nose and/or upper airways. A higher prevalence of current and former waste collectors with employment duration ≤ 20 year reported symptoms associated with the upper respiratory tract. Only 9% of current workers and 3.6% of former workers had a positive IgE response to a mixture of extracts of common molds. More atopics suffered from rhinitis and conjunctivitis compared to non-atopics (64% vs. 40% in current workers; 71% vs. 40% in former workers). All inflammatory changes that were detectable in the waste collectors, examined by means of biomarker concentrations in induced sputum samples, exhaled NO and serum CC16, were very strongly influenced by the smoking habits of the study participants. No significant differences in biomarkers were detectable between current and former waste collectors.

An additional approach to the assessment of the effects of occupational exposure to bioaerosols among waste collectors has been presented (Daneshzadeh Tabrizi et al., 2010) where the presence of lung-specific surfactant-D (SP-D) protein in the blood is measured. SP-D protein is a hydrophilic protein produced primarily in the lungs (type 2 of pneumocytes) and seems to be a promising marker of inflammation and lung tissue damage commonly associated with cigarette smoking and COPD. However, as research suggests, its presence may also indicate contact with bioaerosols. The study covered a total of 778 employees, including 67 waste collectors, 316 employees of sewage treatment plants and 395 people from the control group. A slight increase in the concentration of SP-D, which depended on past exposure to endotoxin, was observed only among sewage treatment plant workers. In the case of people in contact with waste, no correlation was found between SP-D and endotoxin concentrations, as well as the FEV_1 and FVC spirometric parameters.

Immunoglobulins IgG and IgA in the blood of waste collectors have also been shown to correlate significantly with exposure to bacterial endotoxin (Coenen et al., 1997). Using data from a total of 63 people employed in waste collection, it was shown that blood IgG concentrations of about 13 g/l were found in the group of workers with individual endotoxin exposure above 10 EU/m^3. The IgG levels there were significantly higher ($p < 0.001$) than in the group of workers with lower exposure to this bacterial component, but do not exceed the reference values. The authors interpreted this as a sub-clinical response, because no clinical symptoms, related to an immune response, were observed among the waste collectors in this study. However, smoking as confounder was not taken into account that is why all conclusions should be taken with caution.

In Thorn et al. (1998) the authors proposed an analysis of the immune cells present in the blood and sputum of 25 workers. Compared to the analyzed control group ($n = 24$), significantly increased ($p <$ 0.05) concentrations of lymphocytes and monocytes were found in workers who had contact with waste. However, this study showed that increases in lymphocyte levels were correlated with concentrations of (1 → 3)-β-D-glucan ($r = 0.38$; $p < 0.001$), which were determined by individual measurements during the work shift. Additionally, the amount of ECP in blood was significantly lower among waste collectors compared to controls. In sputum samples of waste workers the number of macrophages were lower than in controls.

However, not all studies have found adverse effects on the respiratory system. A 5-year prospective cohort study on 52 waste collectors in Switzerland found no effect on the respiratory system. The authors concluded that this might be due to low exposure to microorganisms and endotoxin in the investigated group (Tschopp et al., 2011).

3.7. Medical survey of the workers and preventive measures

3.7.1. Information to workers

The first very important preventive measure is to inform the workers about the biological risks concerning exposure to both infectious and non-infectious agents. The information should include the general rules valuable for all occupations where workers could be at risk to be in contact with microorganisms. Due to the potential exposure to infectious microorganisms, workers should be informed about how to prevent the exposure. This should include: the identification of the hazards (type of waste, situation which could be a source of contamination), the route of transmission (inhalation, injury, dermal contact), the existing preventive measures (behaviour, hand hygiene, PPE, vaccination). Ideally, that information should be given to all new employees but also to the long-time employees who need to have a reminder of the good practices. PPE, as example respiratory protection or adapted gloves, should be available to each employee and workers should be involved in the choice of the PPE.

3.7.2. Preventive measures and medical visits

Concerning the medical visit to assess the routine and non-routine health checks, its frequency and its mandatory character will depend on the national legal aspects/specific guidance of each country. However, several recommendations concerning prevention of biological risks are more or less the same in most of the European countries. We found documentation in English and French for France (FORSAPRE (https://www.forsapre.fr/), UK (WISH)), a Danish document (Branchearbejdsmiljørådet, 2011), a German document (DGUV-Regel-114-601, 2016), and a Norwegian (Authority, 2021). A summary of these documents are presented in supplemental file. The main recommendation in terms of prevention in the waste sector are summarized in the Table 3.

4. Discussion and perspectives

In this review of the health effects associated with waste collection, we have focused mainly on risks associated with exposure to bioaerosols and the associated health effects. However, we are aware that household waste also contains chemical pollutants (Viczek et al., 2020) which may be also relevant to consider. The study was initiated based on the need of a basis to evaluate risks caused by waste collecting workers' exposure to bioaerosols, and to obtain knowledge about potential measures to reduce the exposure. This is further warranted based on the new regulations on waste sorting in EU, and the changing climate, which may cause increased growth of microorganisms in the waste before collection.

Occupational measurements of exposure to bioaerosols are usually presented as time-weighted averages of an exposure during a work day. From the review of studies, some patterns emerge on the overall exposure to microorganisms in the waste collection sector. Averages of these time-weighted averages of exposure to endotoxin were mostly in the 10 EU/m^3 range, though some studies found much higher average levels which were up to 100–500+ EU/m^3. Exposure to bacteria, in most studies, found average concentrations of 10^4 cfu/m^3. Fungal

Table 3
Summary of the measures to prevent biological risks in waste collection workers, according to national guidelines from Denmark, France, Germany, Norway, and UK.

Type of prevention	Recommended preventive actions
Information/education	• All workers must be aware of the procedures to follow to prevent the risk of diseases. • They must know what to do if unexpected hazardous waste is encountered (i.e. presence of needles, presence of rats etc.) • All the worker must be regularly informed about good personal hygiene (see below). • Information about the personal protective equipment and their maintenance (if necessary) must be given regularly.
Vaccination	Vaccination for hepatitis B, tetanus, poliomyelitis, hepatitis A and leptospirosis are recommended after medical examination.
Medical visit	Medical visits every one or two years: some aspects must be particularly investigated: Appreciation of individual risk factors: • for infection (congenital or acquired immune deficiency, medication, diabetes, history of pulmonary tuberculosis), • for immuno-allergic disease (history of atopy, presence of manifestations of atopy (rhinitis, asthma), • for sensitivity to the risk of inflammation of the airways linked to endotoxin (repeated monitoring of lung functions).
Hygiene	• Hand washing before eating, drinking, smoking or using the phone, taking medication, inserting contact lenses or before and after wearing gloves, using the toilet or after becoming contaminated with infected material. • Systematic disinfection and protection of small injuries. • Showers must be available for all the workers.
Blood exposure accident	In the case of blood exposure accident (injury with a syringe) or projection of biological liquid on the mucous membranes or the eye, a risk assessment must be done by a physician and a prophylaxis must be given if necessary. All the workers must be informed of this procedure and instructions must include the address of the emergency service.
PPE	• It is recommended to wear gloves and specific working clothes. These clothes must be changed after working hours so that microorganisms from the waste are not taken home. • In case of handling of particularly dusty waste or in case of risk of aerosol formation, a respiratory protection FFP2 is recommended. • Moreover, it is recommended to avoid decanting of organic waste, and if it is not possible, workers should use suitable respiratory protection such as full-face mask with P3 filter.

concentrations were similar, most studies found exposures in the 10^4 cfu/m^3 range and quite some in the 10^5 cfu/m^3 range. However, for endotoxin, bacteria, and fungi the average or median concentrations differed by up to a factor 500, 1000 and 100, respectively, between studies. Furthermore, the individual exposure vary even more. For example, in a study waste loaders were exposed to between <4 and 7182 EU/m^3 ($n = 27$) (Wouters et al., 2006b). Therefor the result of an evaluation of the risk associated with exposure during waste collection will differ dependent on whether the average of all workers' exposure or the individuals are considered. Furthermore, a previous study shows that waste collection workers stayed in the truck cab for 37% of the workday (Madsen et al., 2016), and only a short part of the day is expected to be spent with loading and unloading of the waste where the main exposure is expected to occur. Therefore the workers unloading the waste may be exposed to many short lasting peaks of high exposure during a workday. However, this has not been measured. How these suspected repeated peaks of exposure affect workers' health compared to e.g. a long-time and permanent exposure to a lower level of endotoxins is unknown. These repeated short peaks of high exposure could be responsible for acute symptoms such as e.g. organic dust toxic syndrome.

An issue that may camouflage the effect of waste type on differences in microbial concentrations is that different authors and different countries may use the same terms for different waste types. A way to mitigate this could be to use controlled trials, where the waste composition is kept similar while other measures are changed. All in all, the knowledge of how different waste fractions influence occupational exposure is important in order to assess the exposure and thereby the effects on workers and to find ways to minimize the exposure.

Based on the literature analysis, different attempts have contributed to the reduction of exposure to biological agents. Research points towards isolating the loaders as effectively as possible from the waste that is loaded into waste trucks. This can be done by high loading, installing curtains, fogging and negative pressure in waste trucks, which will reduce the spread of organic dust. Future adoption of technology including robotic collection will further separate waste collectors from exposure sources. Attention is also paid to the use of an effective ventilation system with HEPA filters in drivers' cabs, which should be combined with the personal care of the crews to keep the cabs clean. It is also recommended to allow workers access to hand sanitizer kits. In order for technical measures to be more effective, they should be supported by organisational measures. It should be noted that the work of waste collectors ought to be linked to system activities that are usually the responsibility of local authorities e.g. implementation of a pre-sorting system in households, with particular emphasis on the segregation of biowaste and the maximum limitation of its share in the waste stream that is collected. The waste prepared in this way should be tightly sealed in sacks. Moreover, an increased frequency of waste collection also requires consideration to reduce the emission of bioaerosols, which can be especially useful when temperatures and therefore microbial growth is high, e.g. in summer or in general if temperatures generally will rise in the future due to climate change (IPCC, 2014). In spite of these different attempts, we still think that waste collectors is an occupational group for which it is difficult to implement technical measures to reduce exposure. This is mainly due to the significant mobility of these employees, the work in various weather conditions, and the availability of different types of trucks.

In the past, microbial risk assessment in the waste sector has been based on overall microbial concentrations, endotoxin, and identification of a few species or groups of bacteria and fungi (e.g. grouped by the temperature in which they can grow). Nowadays, new methods have gained ground, which allows researchers to identify bacteria and fungi to genus and species level. These methods include next-generation-sequencing (NGS), which mainly identifies taxa to genus level, and MALDI-TOF-MS, which identifies bacteria and fungi to species level. While MALDI-TOF-MS has been used to assess the microbial community in waste collectors' work exposure, NGS has to our knowledge not yet been used yet, though it has been used in waste plants. However, these newer methods will allow risk assessments based on the identity of the microorganisms thereby making it more specific to each environment. As these methods becomes better and more species are being identified, it is also becoming clear that information about many of the species observed is lacking. Information about their effect on human health is crucial for making the most informative risk assessments. In addition, the importance of the viability of the different microorganisms for making risk assessments is also important to obtain more knowledge about. Consequently, this is an area where we may expect to see improvements in the future. As we gain such knowledge, future avenues of research within microbial risk assessments could be to build trait databases based on bacterial and fungal effects on human health. This could be based upon traits such as whether species cause infections/occupational infections or induce occupational allergic or toxic reactions, or are known to be resistant to antibiotics. An attempt to such a data base is the GESTIS-database on biological agents (https://bioagent.dguv.de/).

In addition to the exposure from the handling of waste, inter-personal contamination with infectious microorganisms is also possible, especially in the context of an epidemic (e.g. influenza, SARS-CoV-2 etc.). This may happen especially when more waste workers are present in the cab of the truck and when different teams share the same truck. Specific preventive measures must then be considered. While e.g. bus drivers use face masks during the SARS-CoV-2 pandemic, waste collection workers in Europe did not. This is probably due to the intensity of their physical activities is not compatible with the wearing of face masks. Therefore it is important that every precaution is taken to avoid transmission of infectious diseases between waste collection workers who may have no choice but to work closely together without face coverings. This may include regular lateral flow testing and employee temperature checks at the start of a team shift, to identify obvious signs of infection.

While the national guidelines among European countries to prevent biological risks in waste collection workers seem quite similar, a study based on observations and semi-structured interviews among solid waste collectors in a low economy country concluded that the workers needed more insight into occupational safety and health (Asibey et al., 2019). In general, we only found few papers about the biological working environment for waste collection workers in low economy countries.

Numerous studies suggest adverse health effects in the context of exposure to bioaerosols in the waste sector. The main route of exposure is air and therefore the respiratory system becomes the most important area in the human body that is affected by bioaerosols. Nevertheless, high incidence rates of gastrointestinal problems, irritation of the eye (like mucus membrane irritation syndrome) and skin and also symptoms of organic dust toxic syndrome (influenza-like symptoms, cough, muscle pains, fever, fatigue, and headache) have been reported among waste collection workers. In addition to inhalation, other routes of intakes like ingestion (transfer by dirty hands when eating/smoking) and skin contact may also be possible. Early symptoms and even 'minor' irritations and health complaints (such as eye redness, runny nose etc.) should be recognized and should be taken seriously and treated consistently; health complaints should not be accepted as part of the job. In the studies, sensitization and allergic symptoms are relatively rarely described among waste workers. The cause of this could be the so-called 'healthy- worker effect'.

Most of the studies on waste collectors with regard to occupational exposure to bioaerosols and health effects, which were included in this review, are cross-sectional studies. Of these, several reported a correlation with bioaerosol exposure and reduced lung function, both as short and long term effects. Also, waste collectors' occupational exposure to bioaerosols seems to give an inflammatory response in the workers. For some of the investigated inflammatory components a correlation has been found with exposure to some of the components in the bioaerosols, such as endotoxin and fungal spores. Based on these cross-sectional studies, there is a need for reducing the waste collectors' exposure to bioaerosols. However, to get a better understanding of the long term health effects, there is a need for longitudinal studies monitoring the health effects or symptoms and e.g. biomarkers of inflammation as well as exposure using standardized methods. Such longitudinal studies should preferably start at the beginning of the job career and subsequently continue each year and take into account confounders such as smoking habits, life-style, and protection measures.

5. Conclusions

Overall, we can conclude that waste collection workers can be exposed to a diverse spectrum of microorganisms and microbial compounds as well as high concentrations of microorganisms, which can give potential health problems. The EU has set fairly specific targets for waste recycling, and even though EU members are implementing different strategies to achieve these targets, this review shows that member states are facing similar issues regarding the exposure of waste collectors to biological agents, the associated health effects and the measures of prevention to reduce the risks. This review illustrates also that our understanding has been significantly improved in recent years. However, there is still considerable room for improvement in knowledge, particularly with regard to health effects and the respective contributions of the various biological agents to these effects. First of all, the composition of the bioaerosols need to be better characterized with respect to bacterial and fungal composition – but also for viruses. It is still unclear if specific bioaerosol components are major drivers of the observed health effects, or if these health effects are mainly a result of a co-exposure of several different components. This underlines the need to mobilise experts from all EU members for coordinated studies that will eventually fill the knowledge gaps and propose efficient preventive measures for waste collectors. Finally, the review focused on municipal waste collection but a similar work is need for sorting workers in dedicated waste plants.

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Anne Mette Madsen: Conceptualization, Investigation, Data curation, Writing – original draft, Visualization, Writing – review & editing, Supervision, Project administration. **Monika Raulf:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Philippe Duquenne:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Pål Graff:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Marcin Cyprowski:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Alan Beswick:** Investigation, Writing – original draft, Writing – review & editing. **Sirpa Laitinen:** Conceptualization, Investigation, Data curation, Writing – original draft, Visualization. **Pil Uthaug Rasmussen:** Formal analysis, Investigation, Data curation, Visualization, Writing – review & editing. **Manfred Hinker:** Investigation, Writing – original draft. **Annette Kolk:** Conceptualization, Writing – review & editing. **Rafał L. Górny:** Writing – review & editing. **Anne Oppliger:** Investigation, Writing – original draft, Writing – review & editing. **Brian Crook:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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